NASA/CR—2008-215144 TR07040

Future Aeronautical Communication Infrastructure Technology Investigation

Tricia Gilbert, Jenny Jin, Jason Berger, Steven Henriksen
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April 2008

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Prepared for the
International Civil Aviation Organization, Working Group of the Whole
sponsored by the Aeronautical Communications Panel
Montreal, Quebec, Canada, April 21–25, 2008

Prepared under Contract NNC–05CA85C

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

April 2008

This work was sponsored by the Fundamental Aeronautics Program at the NASA Glenn Research Center.

Level of Review: This material has been technically reviewed by NASA technical management.

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Preface

The following National Aeronautics and Space Administration (NASA) Contractor Report summarizes and documents the work performed to investigate technologies that could support long-term aeronautical mobile communications operating concepts, and includes the associated findings and recommendations of ITT Corporation and NASA Glenn Research Center to the Federal Aviation Administration (FAA) as of the end of December 2007. This work was completed under a NASA contract extension to the third and final phase of a multiyear technology assessment in support of an FAA/EUROCONTROL Cooperative Research Agreement (Action Plan 17 (AP–17)), commonly referred to as the Future Communications Study. A separate NASA contractor report (NASA/CR—2008-214987) on the third phase of the technology assessment, entitled "Additional Technologies and Investigations for Provision of Future Aeronautical Communications" was completed before sufficient information about two final technologies proposed by EUROCONTROL was made available. This final report includes an assessment of the final five candidate technologies, and also provides an overview of the entire technology assessment process, including final recommendations. All three phases of this work were performed in compliance with the Terms of Reference for the AP–17 agreement and with the general guidance of the FAA and EUROCONTROL available throughout this study.

Executive Summary

E.S.1 Background and Introduction

The Future Communication Study (FCS) is a cooperative research and development program of the United States Federal Aviation Administration (FAA), National Aeronautics and Space Administration (NASA), and EUROCONTROL. This study has several technical themes supporting the definition of a future globally interoperable communications system to support air traffic management (ATM) operations in the timeframe of 2020 and beyond. One of these themes calls for "investigation of potential communications technologies operating inside the very high frequency (VHF) band and outside the VHF band to support the long-term mobile communication operation concept considering terrestrial and satellite base infrastructure."

E.S.2 Objectives and Approach

The focus of this report, Final Report on Technology Investigations for Provision of Future Aeronautical Communications, is to address the FCS technical theme noted above. Specifically, work has been performed to investigate technologies that can support the long-term aeronautical mobile communications operating concept. The study was organized and carried out in three phases from 2004 through 2007: Technology Prescreening (Phase I, completed in December 2004), Technology Screening and Indepth Studies (Phase II, completed in May 2005), and Additional Technologies and Investigations for Provision of Future Aeronautical Communications (Phase III, completed in October 2007).

As decision making in the aeronautical environment can be complex, a structured methodology that accommodates stakeholder inputs was defined and applied in this study. This approach is shown in figure ES.1.

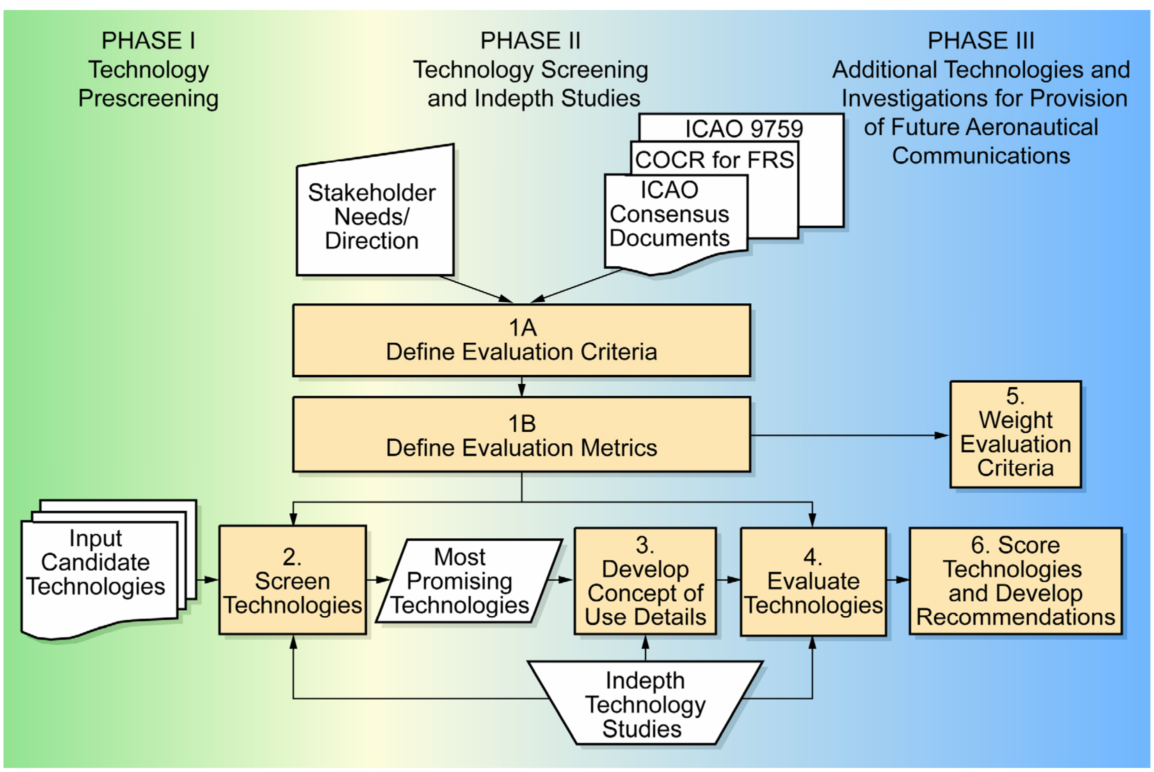


Figure ES.1.—FCS technology investigation methodology.

E.S.3 Study Outputs

E.S.3.1 Evaluation Criteria

The first set of activities in the evaluation process (Steps 1A and 1B) included derivation of evaluation criteria and metrics. Addressing stakeholder direction, a structured analysis of the Communications Operating Concept and Requirements (COCR) for the future radio system (FRS) was conducted to ensure traceability of criteria to requirements. This structured analysis, along with consideration of International Civil Aviation Organization (ICAO) recommendations for future communication systems captured in consensus documentation, was used to derive technical and viability evaluation criteria. The technical criteria account for functional and performance needs of aviation and safety in the aeronautical domain. The viability criteria address cost and risk elements associated with implementation of a technology in the future communication infrastructure. In all, eleven evaluation criteria were defined, as shown in figure ES.2.

For each evaluation criterion, a set of defined metrics gauged technology performance specific to the criterion. The general approach applied was to utilize a trilevel rating system, sometimes called a “stop light” rating system, where performance and compliance are assessed to be green, yellow, or red. Generic metric definitions for this rating system are shown in figure ES.3.

This trilevel rating system was selected for the technology evaluation for its low complexity and easy-to-understand barometer of performance and applicability of technology to the future aeronautical communication concept. For individual criteria, the rating values reflect specific performance requirements of the COCR, specific implementation needs (e.g., implementation timeframe based on the FCS roadmap), or factors that support relative comparison of technology performance and applicability.

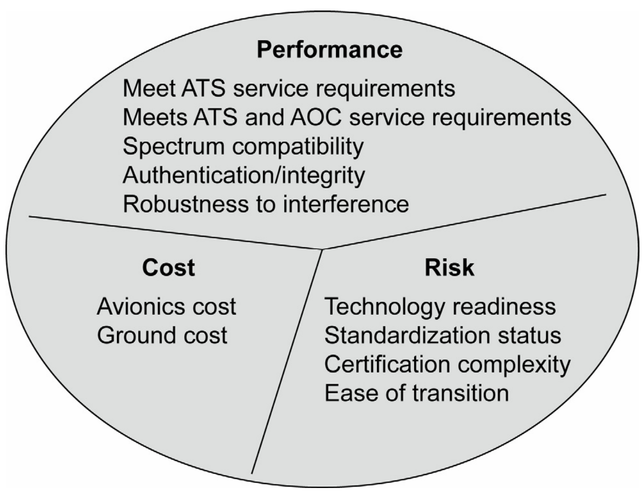


Figure ES.2.—FCS technology investigation evaluation criteria.

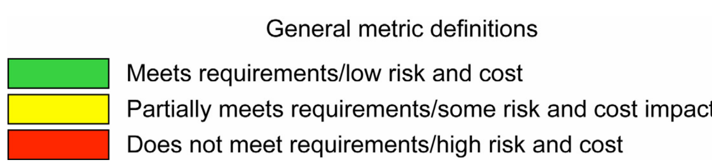


Figure ES.3.—Generic evaluation criteria metric definitions.

E.S.3.2 Technology Screening

Using the defined evaluation criteria, the next step in the evaluation process (Step 2) was to identify the most promising technology candidates. The technology screening process included an inventory of over 50 technologies. A screening process that applied a small set of key technical and viability evaluation criteria at a high level was performed. An initial screening of the technology inventory was conducted during the FCS Phase II study, which included the use of COCR Version 1 performance measures as reference values in the screening process. The screening process was reapplied during the FCS Phase III study to accommodate changes and updates in the COCR Version 2.

Results of the screening process included the identification of technologies for further consideration as general air/ground (A/G) communication solutions for continental airspace (airport (APT), terminal, and en route (ER) airspace) and technologies for further consideration in specific airspace domains with unique operating requirements (oceanic/remote and airport). Table ES.1 shows results of the screening process.

Of the candidates identified in table ES.1, two of the general solution candidates (i.e., candidates for provision of services in the APT, terminal maneuvering area (TMA), and ER domains) are currently being defined by EUROCONTROL. These technologies, named by EUROCONTROL as broadband–aeronautical multicarrier communications (B–AMC) and all-purpose multichannel aviation communication system (AMACS), were evolutionary extensions into the aeronautical L-band of technology concepts and definitions originally defined for VHF implementation. Since the technical details and supporting tests and simulations for these two technology concepts were still under development at the time of evaluation for this study, these two technologies were evaluated based on the information available at the time.

In March 2006, EUROCONTROL presented its current technology shortlist at the ICAO Aeronautical Communication Panel (ACP) Working Group C–10 (WG–C10) meeting (ref. 1). This shortlist (with slight revision) was presented again at the ICAO ACP/1 Meeting in May 2007 (ref. 2). It is instructive and informative to compare these screening results to the technology shortlist developed by EUROCONTROL. This comparison is provided in figure ES.4. It shows a significant overlap in

TABLE ES.1.—UPDATED TECHNOLOGY SCREENING RESULTS

Domain		Screened technologies
General	Continental domains (APT, TMA, ER, etc.)	• TIA–902 (P34) • LDL • WCDMA • B–AMC • AMACS
Domain specific	Oceanic/remote domain	• Inmarsat Swift Broadband • Custom Satellite System (e.g., SLDS)
	Airport domain	IEEE 802.16e

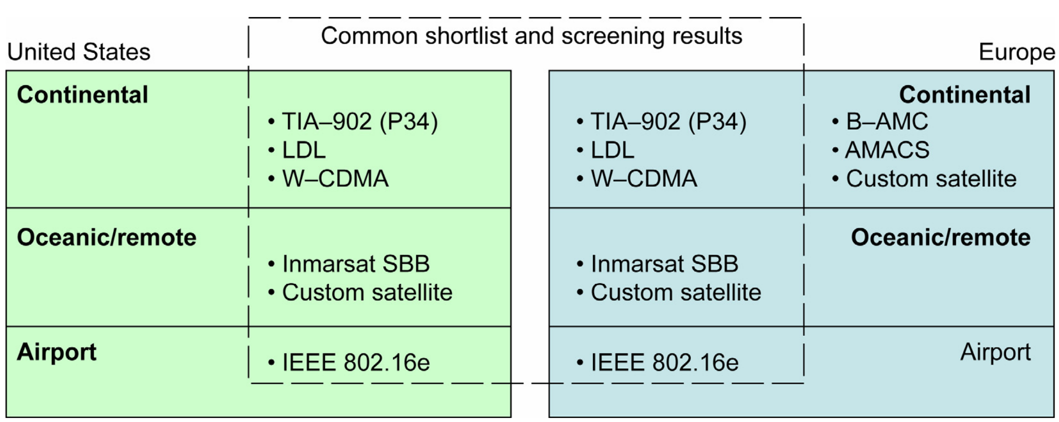


Figure ES.4.—Comparison of screening results to EUROCONTROL technology shortlist.

recommendations for the shortlist of technologies to consider for the FRS. This overlap is significant as member participants of the FCS and the ICAO ACP work toward harmonized technology solutions for the future communication infrastructure (FCI).

E.S.3.3 Supporting Assessments

A considerable number of indepth analyses were performed to support the technology evaluation process and to gain a better understanding of the applicability of the most promising technologies to the future aeronautical communication environment. Indepth studies were conducted as part of the FCS Phase II and Phase III study efforts. A full set of the indepth analyses and associated references are provided in table ES.2. Also indicated is a reference that identifies where the full study is documented. As technologies B–AMC and AMACS were still under development during the FCS Phase III study, no independent detailed indepth analysis was carried out by NASA/ITT for these two technologies.

TABLE ES.2.—FCS TECHNOLOGY INVESTIGATION INDEPTH STUDIES

	Indepth study topic	Location of study documentation (objectives, methodology, and results)
1	L-Band Air/Ground (A/G) Communication Channel Characterization	FCS Phase II interim report ("Identification of Technologies for Provision of Future Aeronautical Communications," NASA/CR—2006–214451, ITT Corp., July 2006), Section E.1.1
2	Project–34/Telecommunication Industry Association (TIA) 902 Series Standards (TIA–902 (P34)) Technology Performance Assessment	FCS Phase II interim report ("Identification of Technologies for Provision of Future Aeronautical Communications," NASA/CR—2006–214451, ITT Corp., July 2006), Section E.1.2 and E.1.4
3	TIA–902 (P34) Technology Intellectual Property Assessment	FCS Phase III interim report ("Phase III Additional Technologies and Investigations for Provision of Future Aeronautical Communications," NASA/CR—2008–214987, ITT Corp., May 2007), Section 4
4	L-Band Digital Link (LDL) Technology Performance Assessment	FCS Phase II interim report ("Identification of Technologies for Provision of Future Aeronautical Communications," NASA/CR—2006–214451, ITT Corp., July 2006), Section E.1.3 and E.1.4
5	Wideband Code Division Multiple Access (WCDMA) Functional Assessment	FCS Phase II interim report ("Additional Technologies and Investigations for Provision of Future Aeronautical Communications," NASA/CR—2008–214987, ITT Corp., May 2007), Section 3
6	L-Band Technology Cost Assessment for Ground Infrastructure	FCS Phase II interim report ("Identification of Technologies for Provision of Future Aeronautical Communications," NASA/CR—2006–214451, ITT Corp., July 2006), Section E.1.8
7	L-Band Interference Testing	FCS Phase III interim report ("Phase III Additional Technologies and Investigations for Provision of Future Aeronautical Communications," NASA/CR—2008–214987, ITT Corp., May 2007), Section 2
8	Satellite Technology Availability Performance	FCS Phase II interim report ("Identification of Technologies for Provision of Future Aeronautical Communications," NASA/CR—2006–214451, ITT Corp., July 2006), Section E.2
9	IEEE 802.16e Performance Assessment in Aeronautical C-Band Channel	FCS Phase II interim report ("Identification of Technologies for Provision of Future Aeronautical Communications," NASA/CR—2006–214451, ITT Corp., July 2006), Section E.3

E.S.3.4 Evaluation of Technologies to Criteria, Weighting Criteria, and Technology Scores

Technologies emerging from the screening process can be grouped into two general categories: those for consideration as a general solution for continental airspace (airport, terminal, and ER flight domains) and technologies for consideration in specific flight domains with unique operating environments (specifically, the airport surface and oceanic/remote). Those technologies identified for the specific flight domains included two satellite systems and concepts (Inmarsat Swift Broadband (SBB) and Custom Satellite Solution) for the oceanic/remote airspace and a single candidate (Institute of Electrical and Electronics Engineers (IEEE) 802.16e) for the airport surface domain.

The timeframe of the COCR operational concept is beyond the service horizon of current satellite offerings and details for follow-on or custom solutions are high-level at this time. Therefore, the value of full application of the evaluation criteria (as updated in Phase III) to candidate satellite aeronautical communication solutions is minimal; furthermore, the need to discriminate among candidate solutions to identify a single global recommendation is not clear. As a result, no additional evaluation of these technologies was performed in the FCS Phase III study. Instead, the use concepts and initial assessments performed in FCS Phase I/II were used to draw conclusions and formulate recommendations specific to satellite solutions.

For the airport surface domain, a single candidate emerged from the screening process. Thus, application of evaluation criteria (as updated in Phase III) to discriminate among other technologies was not meaningful. As a result, no additional evaluation of this technology was performed in the FCS Phase III study. Instead, the use concept, a detailed assessment of IEEE 802.16e in the anticipated aeronautical channel (C-band in this case), and initial evaluation of this technology to criteria in FCS Phase I/II were used to draw conclusions and formulate recommendations specific to the airport surface domain technologies (using aeronautical C-band).

The full evaluations focused on those technologies that could be implemented as general solutions (across continental airspace domains) for provision of future A/G data link aeronautical communication services. The use concept for these technologies is for implementation in the aeronautical L-band (960 to 1164 MHz). The remaining steps in the evaluation process (Steps 3 through 6) were applied to these technologies. Specifically, for Step 3, a concept of how the technology would be applied to the aeronautical environment described in the COCR was defined. Next, for Step 4, each technology was evaluated to the full complement of evaluation criteria. A summary of Step 4 evaluation results is provided in table ES.3.

TABLE ES.3.—SUMMARY OF TECHNOLOGY EVALUATION RESULTS

No.	Evaluation criterion		TIA–902 (P34)	LDL	WCDMA	B–AMC[a]	AMACS[a]
1	Provides ATS A/G data services within requirements (sans A–EXEC)	A—Capacity	[green]	[green]	[green]	[green]	[green]
		B—PIAC[b]	[green]	[green]	[green]	[green]	[green]
		C—QoS[c]	[green]	[green]	[green]	[green]	[green]
		D—Environment	[yellow]	[yellow]	[yellow]	[green]	[green]
2	Provides ATS AOC A/G data services within requirements (sans A–EXEC)	A—Capacity	[green]	[yellow]	[green]	[green]	[yellow]
		B—PIAC	[green]	[green]	[green]	[green]	[yellow]
		C—QoS	[green]	[green]	[green]	[green]	[green]
		D—Environment	[yellow]	[yellow]	[yellow]	[green]	[green]
3	Technical readiness level (TRL)		[yellow]	[yellow]	[green]	[yellow]	[red]
4	Standardization status		[yellow]	[yellow]	[yellow]	[red]	[red]
5	Certification		[yellow]	[yellow]	[red]	[red]	[red]
6	Ground infrastructure cost		[green]	[yellow]	[red]	[yellow]	[yellow]
7	Avionics cost		[yellow]	[yellow]	[yellow]	[yellow]	[yellow]
8	Spectrum		[yellow]	[yellow]	[red]	[yellow]	[yellow]
9	Authentication and integrity		[green]	[yellow]	[green]	[gray]	[gray]
10	Robustness to interference		[yellow]	[yellow]	[yellow]	[yellow]	[yellow]
11	Transition		[green]	[green]	[yellow]	[yellow]	[yellow]

[a]For developing technologies B–AMC and AMACS, authentication and integrity criterion is not ranked and marked as gray because of insufficient technology information at the time of the evaluation.
[b]PIAC is peak instantaneous aircraft count.
[c]QoS is quality of service.

The information in table ES.3 and supporting results of the indepth technical assessments can be used for the development of technology recommendations. As no one technology is a clear best performer, interpretation of results can be aided with an understanding of the relative importance of the evaluation criteria and review of results with this knowledge. This work was addressed by weighting criteria (Step 5 in the evaluation methodology). To explore a range of evaluation options and address concerns about the perceived complexity of a quantitative weighting, two criteria weighting approaches were implemented. The first was a qualitative ranking of criteria and the second was a more rigorous application of weights based on a process known as the analytical hierarchy process (AHP). Both approaches make use of documented stakeholder positions with regard to relative importance of factors influencing future communication system decisions.

In the qualitative approach to criteria weighting, based on documented stakeholder positions, evaluation criteria were organized into three categories.

- Most Important—in general, these factors have been specifically noted by stakeholders as important factors and should be given the greatest consideration; success with regard to these criteria is necessary to have an applicable aeronautical solution.
- Very Important—in general, these factors are also addressed in some manner by stakeholders and are also very important aspects of an aeronautical communication system decision; success with regard to these criteria is important for understanding the viability of an aeronautical solution.
- Important—these criteria have been found to not be specifically addressed in stakeholder position.

The resulting organization of criteria according to these qualitative weight definitions and the corresponding evaluation results are shown in table ES.4.

TABLE ES.4.—EVALUATION RESULTS WITH QUALITATIVE CRITERIA WEIGHTING APPLIED

	No.	Evaluation criterion		TIA–902 (P34)	LDL	WCDMA	B–AMC	AMACS
Most important	8	Spectrum						
	1	Provides ATS A/G Data services within requirements (sans A–EXEC)	A—Capacity					
			B—PIAC					
			C—QoS					
			D—Environment					
Very important	3	Technical readiness level (TRL)						
	6	Ground infrastructure cost						
	7	Avionics cost						
	2	Provides ATS AOC A/G data services within requirements (sans A–EXEC)	A—Capacity					
			B—PIAC					
			C—QoS					
			D—Environment					
Important	4	Standardization status						
	5	Certification						
	9	Authentication and integrity						
	10	Robustness to interference						
	11	Transition						

For developing technologies B–AMC and AMACS, ranking for the authentication and integrity criterion is marked as gray because of insufficient information of the technology at the time of the evaluation.

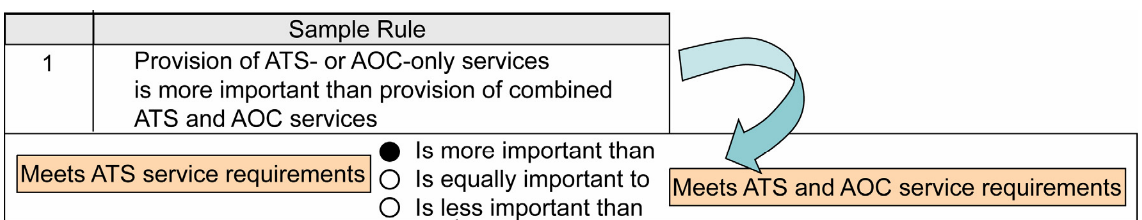
In addition to the qualitative weighting approach described above, a streamlined version of the AHP weighting process was applied to achieve quantitative weighting values for the evaluation criteria. In this process, criteria weighting granularity was kept to a simple three-level scale (more important, less important, or equally important). Stakeholder inputs were applied based on positions documented in stakeholder plans, recommendations, and positions. Finally, to apply documented “voice of the customer” information to develop a relative understanding of criteria importance, a roll-up of evaluation criteria was applied. This was performed by creating a hierarchy of criteria where each factor at the highest level of the hierarchy addressed a unique topic area such as technical maturity (a combination of the TRL criterion and standardization status criterion).

Stakeholder positions were used to generate rules to be applied to perform pair-wise comparisons of evaluation criteria and assess their relative importance. An illustration of this process is shown in figure ES.5.

The information in the matrix was used to develop a set of decision factor weights normalized to 1. Criteria weights were calculated for two stakeholder sets: aeronautical communication service providers and aeronautical users. Also, a combined stakeholder set weighting was also calculated. Results of decision factor weights for the combined stakeholder set is provided in figure ES.6.

The weights above were combined with the evaluation results to develop a specific technology score. Because some criteria were not ranked for B–AMC and AMACS because of insufficient information at the time of evaluation, their numerical values could not be provided for the AHP comparison matrix; therefore, the numerical score results are not provided for the B–AMC and AMACS technologies. A summary of the score results for Telecommunications Industry Association (TIA)–902 (P34), wideband code division multiple access (WCDMA), and L-band digital link (LDL) are provided in table ES.5.

The resulting technology scores are strongly influenced by the spectrum criterion evaluation results (a factor contributing to poor performance of WCDMA). This criterion was identified as having significant importance to all stakeholders, as would be expected. Other factors influencing results are technical maturity and ground infrastructure cost. Resulting scores for TIA–902 (P34) and LDL were in similar regions of the normalized scale, with TIA–902 (P34) achieving the highest technology rating.



	Meets ATS service requirements	Meets ATS and AOC service requirements	Technical maturity	Low-cost ground infrastructure	Low-cost avionics	Spectrum compatibility	Complexity—transition and certification
Meets ATS service requirements		3	3	3	3	1	3
Meets ATS and AOC service requirements	0.333		0.333	0.333	0.333	0.333	3
Technical maturity	0.333	3		1	3	0.333	1
Low-cost ground infrastructure	0.333	3	1		3	0.333	0.333
Low-cost avionics	0.333	3	0.333	0.333		0.333	3
Spectrum compatibility	1	3	3	3	3		3
Complexity—transition and certification	0.333	0.333	1	3	0.333	0.333	

Figure ES.5.—AHP comparison matrix.

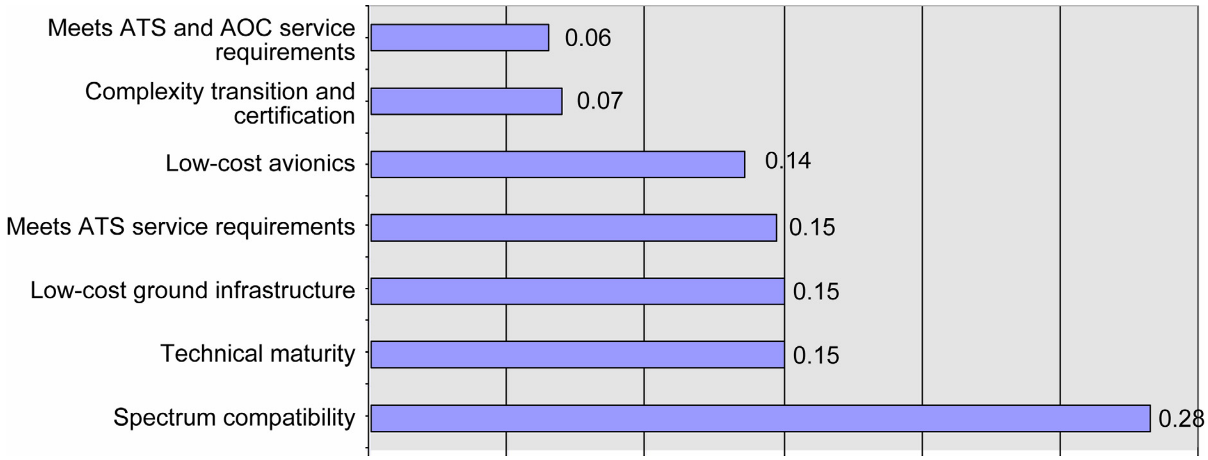


Figure ES.6.—Weighted decision factors—Combined.

TABLE ES.5.—TECHNOLOGY SCORE RESULTS

Technology	Service provider perspective score	User perspective score	Overall score
TIA–02 (P34)	0.68	0.63	0.65
WCDMA	0.41	0.36	0.37
LDL	0.52	0.50	0.50

TABLE ES.6.—COMPARISON OF CANDIDATE TECHNOLOGIES WITH DESIRABLE ATTRIBUTES FOR FRS

Desirable features	Technology candidates				
	TIA–902 (P34)	LDL	WCDMA	B–AMC	AMACS
Power efficient modulations within the defined L-band channel, specifically, multicarrier modulation techniques	Met	Not met	Partially met[a]	Met	Not met
Bandwidth efficient modulations	Met	Met	Met	Met	Met
Channels that are at most broadband, but not wideband	Met	Met	Not met	Met	Met
Low duty-cycle waveforms	Not met	Met	Not met	Met (long-term)	Met (long-term)
Efficient channel reuse	Met	Met	Met	Met	Met
Provision quality of service	Met	Met	Met	Met	Met
Flexibility to decouple sector coverage from radio coverage	Met	Partially met	Met	Met	Met
Provides authentication and integrity check	Met	Partially met	Met	TBD[b]	TBD[b]
Availability of existing commercial and/or aeronautical standards	Met	Partially met	Met	Not met	Not met
Available prototypes or products	Met	Partially met	Met	Not met	Not met
Implement service set specific to aeronautical needs	Met	Met	Not met	Met	Met

[a]WCDMA does not employ multicarrier modulation and is an interference-limited system; however, proper design can lead to good bit error rate (BER) performance and can be achieved for low E_b/N_0 (influenced by factors including spread bandwidth, number of interfering users, and information bit rate).
[b]Insufficient information for evaluation at this report time.

Note that the results in table ES.5 indicate that there is not a strong sensitivity to stakeholder positions on the importance of certain criteria. The differences in scores across the stakeholder groups are statistically insignificant.

Based on the specific candidate technologies evaluated and performance against defined evaluation criteria, technology attributes desirable for applicability of a technology in the context of an aeronautical L-band communication capability can be inferred. A list of these attributes and individual assessments of the evaluated technologies for the corresponding attributes is provided in table ES.6.

E.S.4 Findings and Observations

A wide range of technology candidates representative of the cellular standards derivatives; IEEE wireless standards; public safety radio standards; technologies and standards defined specifically for aviation; and military radio standards were evaluated to determine their applicability to the future aeronautical communication environment as described in the COCR for the FRS. First, a technology screening process identified leading contenders for applicability to the FRS. Indepth technical studies were then performed to gain a better understanding of the performance of the most promising technologies in the context of the future communication operational concept and the anticipated radiofrequency channel environment. Finally, technologies were considered with regard to evaluation criteria representative of technical performance, cost, and risk decision elements, with criteria weighting applied to understand evaluation results mindful of the relative importance of evaluation criteria. Based on these investigation efforts, the following findings and observations are made:

1. The new communication components introduced into the FCI should reuse emerging data communications technology and standards to the maximum extent possible.
    - The FCS has investigated a wide range of emerging technologies and standards that have the potential to support air traffic services (ATS) and aeronautical operational control (AOC) data communications. Although there will always be further developments in communication technology, due to the time to deploy new systems and the need for a stable technology solution, the choice of emerging systems offers the lowest risk option. Some of the technologies evaluated are available as commercial-off-the-shelf (COTS) solutions for the area of application for which they were designed.
    - However, this study has not identified any technology that does not require some form of modification. Therefore, a COTS solution that can be deployed as designed without any modification is not feasible. The minimum required modification is to change the frequency of operation to one of the FCI target bands to support safety critical aeronautical communications. Other changes are dependent on the design of the technologies and are typically related to modification of the physical layer, such as the modulation scheme. In any case, adopting or leveraging COTS components should be considered wherever possible to minimize design effort, reduce risk and to shorten time to deployment.
2. No single technology meets all future aeronautical communication requirements across all operational flight domains. The future aeronautical communications operating concept will require a complementary set of capabilities across multiple frequency bands to provide required voice and data communication services.
    - The FCS has identified four operational flight domains
        - Airport surface
        - Airport zone/TMA/ER
        - Oceanic/remote/polar
        - Autonomous operation area
    - To some extent, the propagation conditions determine which frequency band is able to support which flight domain.
        - The airport surface is best served by short range systems operating in the C-band due to the limited propagation distance at this frequency.
        - The airport zone, TMA and ER service volumes are currently served by the congested AM(R)S VHF band, which has good propagation properties. However, L-band propagation properties are also suitable for these domains.
        - The coverage areas of the oceanic, remote, and polar domains are typically beyond line of sight (LOS) of terrestrial systems and can only be realistically served by satellite based solutions.

3. Technologies that currently provide or are planned to provide aeronautical voice and data communications in the VHF band should be used to their fullest extent.
    - VHF aeronautical spectrum will continue to support DSB–AM voice communications and preserve the option for an initial data link capability that is outside the scope and timeframe of the FCS technology investigation.
    - A long-term strategy for use of the VHF aeronautical band requires further consideration.
    - Due to congestion in the VHF band to support near-term voice and data communication requirements, provision of future communication services outside the VHF band must be considered.
4. The aeronautical L-band spectrum (960 to 1164 MHz) is a candidate band for supporting a new data link communication capability.
    - This band contains a potentially large spectral region suitable for future aeronautical communication systems. However, it is a challenging environment for aeronautical communications due to its aeronautical channel propagation characteristics and the current usage of the band.
    - Estimated RMS delay spreads for the aeronautical L-band channel on the order of 1.4 μs can lead to frequency selective fading performance for some technologies.
    - Interference to/from existing aeronautical systems already in L-band systems from/to any proposed communication technology requires detailed examination, including validation measurements and testing.
    - Co-allocation of AM(R)S with the existing aeronautical radio navigation services (ARNS) allocation in a portion of this band (960 to 1164 MHz) is required. This was approved at the WRC–07.[1]
5. The aeronautical L-band spectrum (960 to 1164 MHz) provides an opportunity to support the objectives for a future global communication system. However, no evaluated technology (as currently defined) for supporting data communication in this band fully addresses all requirements and limitations of the operating environment.
    - Initial co-channel interference testing indicates that evaluated candidate technology waveforms cause potential interference to existing navigation systems. Further evaluation, including consideration of duty cycle effects on interference, is required to determine collocation feasibility (with on-tune channels, off-tune channels or cleared spectrum).
    - Each technology requires modification of its technical specifications to meet required objectives.
    - A technology adapted from existing standards is recommended for this band.
6. Desirable features for an aeronautical L-band (960 to 1164 MHz) technology include:
    - Use of an existing standard for a safety application with some validation work already performed (reducing time for standardization, increasing initial technical readiness level (TRL), and reducing risk of certification)
    - Multicarrier modulation (power efficient modulation for the aeronautical L-band fading environment)
    - A low duty cycle waveform with narrow-to-broadband channels (more likely to achieve successful compatibility with legacy L-band systems without clearing spectrum)
    - Adaptable/scalable features (improving flexibility in deployment and implementation, and adaptability to accommodate future demands)
    - Native mobility management and native IP interface (increasing flexibility and providing critical upper layer compatibility with worldwide data networking standards)

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[1]WRC approval took place after this study was completed.

7. For the aeronautical L-band (960 to 1164 MHz), some of the evaluated technologies include desirable features that could support a standardization effort, potentially reducing cost and risk.
   - Two options for an L-band Digital Aeronautical Communication System (L-DACS) were identified as shown in table ES.7. These options warrant further consideration before final selection of a data link technology.
   - The first option represents the state of the art in commercial developments employing modern modulation techniques and may lead to utilization/adaptation of COTS products and standards. The second capitalizes on experience from aviation specific systems and standards such as the VHF digital link (VDL) 3, VDL 4, and UAT.

TABLE ES.7.—L–DACS OPTIONS KEY CHARACTERISTICS

L–DACS option	Access scheme	Modulation type	Recommended technologies
1	Frequency division duplex (FDD)	Orthogonal frequency division multiplexing (OFDM)	B–AMC and TIA–902 (P34)
2	Time division duplex (TDD)	Continuous phase frequency shift keying (CPFSK)/GMSK type	LDL and AMACS

8. Evaluation of the economic feasibility of implementing an L-band aeronautical ground infrastructure considering life cycle costs indicates that a positive business case can be achieved for a commercial service provider within 4 years.
9. For the aeronautical C-band [(5000 to 5010 MHz, and/or 5010 to 5030 MHz), and/or 5091 to 5150 MHz], there is capacity that is not utilized. Given the severe path loss issues, this band is most applicable to the airport surface where the propagation distances are relatively short.
   - Some concepts for surface communications require substantially higher data rates than are needed in other airspace domains and may warrant a specific technology solution.
10. Specific to aeronautical C-band allocation, IEEE 802.16e is extremely well matched to the airport surface in terms of capability and performance.
   - This technology is designed to work in this band and initial IEEE 802.16e performance evaluations in the modeled aeronautical microwave landing system (MLS) band channel show favorable results.
   - Private service providers have shown interest in the 802.xx family of wireless protocols, given a favorable business case that may be driven by applications in addition to ATS and AOC communications.
11. Aeronautical satellite systems offer unique services that can be applied to large and/or remote geographic areas and can provide supplemental coverage to the terrestrial communication infrastructure.
   - Satellite systems provide communication capability in oceanic, remote and polar regions where typically, there is no other alternative that provides the needed capacity and performance.[2]
   - Satellite systems can be used to provide communication coverage to remote ER domains with historically sparse aircraft densities where it may be more cost effective than ground-based A/G communications systems.
   - Because the evaluated operation concept was beyond the service horizon of existing satellite service offerings, and because future satellite system details are not firm, the application of this study's evaluation criteria cannot provide adequate discrimination among satellite system candidates.

[2]This includes areas like the Gulf of Mexico, where terrestrial infrastructure cannot provide radio coverage.

12. This study assumed that the FRS will operate within an internet protocol (IP) networking environment. Further work on finalizing the selection of the FRS should include verification that the required performance can be achieved on end-to-end basis within the FCI. This should include appropriate methods of assuring that the required QoS for safety-related applications can be maintained across the entire communication system.

The foregoing findings can be summarized to indicate the applicability of technologies against airspace type (see table ES.8).

TABLE ES.8.—APPLICABILITY OF TECHNOLOGIES ACCORDING TO AIRSPACE TYPE

Airspace type	Applicable technology
Airport surface	IEEE 802.16e L–DACS may be possible in some areas
APT, TMA, ER	L–DACS Satellite-based may be possible in some areas
Oceanic/remote/polar	Satellite-based
Air/air	L–DACS

E.S.5 Recommendations

Based on the findings and observations noted above, a set of study recommendations were developed and are provided below. They are representative of the United States FCS technology evaluation team Phase III results through the end of the summer of 2007. At the conclusion of these activities, evaluation results and recommendations were brought forward to ICAO WG–T for further consideration. This is discussed in Section E.S.6.

Recommendations at the conclusion of FCS Phase I/II/III technology investigations include

E.S.5.1 C-Band—Airport Airspace

The C-band recommendations are

- Identify the portions of the IEEE 802.16e standard best suited for airport surface wireless mobile communications, identify and develop missing required functionalities, and propose an aviation specific standard to appropriate standardization bodies.
- Evaluate and validate the performance of an aviation specific standard wireless mobile communications network operating in the relevant airport surface environments through trials and testbed development.
- Propose a channelization methodology for allocation of safety and regularity of flight services in the band to accommodate a range of airport classes, configurations and operational requirements.
- Complete the investigation of compatibility of prototyped C-band components with existing systems in the C-band in the airport surface environment and interference with other users of the band.

E.S.5.2 Satellite-Band—Oceanic/Remote and Continental Airspace

The satellite-band recommendations are

- Continue monitoring the satellite system developments and assessment of specific technical solutions to be offered in the timeframe defined in the COCR as these next generation satellite systems become better defined.
- Update the existing AMS(R)S autonomous pulse record system (SARPs) performance requirements to meet future requirements.

- Consider the development of a globally applicable air interface (AI) standard for satellite systems supporting safety-related communications to support the new AMS(R)S SARPs.

E.S.5.3 L-Band—Continental Airspace

For ER and TMA airspace, the L-band was identified as the best candidate band for meeting the future aeronautical communications, primarily due to potential spectrum availability and propagation characteristics. L-band recommendations include the following:

- Define interference test requirements and associated outputs that can be used to determine compatibility of future candidate aeronautical communication technologies with existing aeronautical L-band systems.
- Pursue detailed compatibility assessment of candidate physical layers for an L-band aeronautical digital link, including interference testing.
- Pursue definition/validation of technology derived or adapted from existing standards for use as an L–DACS that can be used to initiate an aeronautical standardization effort (and meet ICAO requirements for such an effort).
- Complete the investigation of compatibility of prototyped L–DACS components with existing systems in the L-band particularly with regard to the onboard cosite interference and agree on the overall design characteristics.
- Considering the design tradeoffs, propose the appropriate L–DACS solution for input to a global aeronautical standardization activity.
- Considering that B–AMC, AMACS, and TIA–902 (P34) have provisions to support air-to-air (A/A) services, conduct further investigation of this capability as a possible component of L–DACS.

E.S.5.4 VHF-Band—Continental Airspace

The VHF-band recommendation is to

- In the longer term, reconsider the potential use of the VHF for new technologies when sufficient spectrum becomes available to support all or part of the requirements.

E.S.6 Harmonized Recommendations

As described earlier, the FCS technology investigation and assessment was undertaken in several phases through coordinated and cooperative efforts by independent United States and European teams. At the end of FCS Phase III, the technology evaluation results were compared, and the two teams came to similar conclusions with alternative methodologies. Many meetings were conducted between the two teams to discuss issues, findings, recommendations, and overall FCS investigation conclusions. A joint report on FCS final conclusions and recommendations (ref. 3) was presented at the ICAO ACP/WGT meeting in October 2007 in Montréal, Canada. In the final AP–17 report (ref. 3), harmonized key recommendations were presented for the new data link developments.

The outcome of the AP–17 activities show the FCI will be a system of systems infrastructure, integrating existing and new technological components, aimed at securing seamless operations continuation by safeguarding investments, facilitating required transitions, and supporting the future requirements.

In summary, the key recommendations out of AP–17 for new data link developments are the following (ref. 3):

- [R1] Develop a new system based on the IEEE 802.16e standard operating in the C-band and supporting the airport surface environment.
- [R2] Complete investigations (with emphasis in proving the spectrum compatibility with other systems) to finalize the selection of a data link operating in L-band (L–DACS) and supporting the continental airspace environment, aiming at a final decision by 2009, to enable system availability for operational use by 2020.
- [R3] Recognizing that satellite communications remain the prime candidate to support oceanic and remote environments and that the considered future satellite systems may also be able to support continental environments possibly complementing terrestrial systems, monitor and support developments that will lead to globally available ATS satellite communications.
- [R4] Recognizing the importance of spectrum for the realization of FCI, ensure the availability of the required spectrum in the appropriate bands.
- [R5] Promote/support activities that will enable/facilitate the airborne integration of the selected technologies.
- [R6] Incorporate in any new data link system, provisions for supporting high QoS requirements in an end-to-end perspective.

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1.0 Background and Introduction

1.1 Global Aeronautical Communication Objectives

The origin of current aeronautical communication objectives can be traced to results of the International Civil Aviation Organization (ICAO) Aeronautical Mobile Communication Panel (AMCP) from the year 2000 and the Eleventh Air Navigation Conference (ANConf/11), held in Montréal, Canada from 22 September through 3 October 2003. One result of the seventh meeting of the AMCP (AMCP/7) in March 2000 was the establishment of a task (Task CNS–9102 (communication, navigation, and surveillance) to carry out the fact-finding and conduct the necessary studies for the development of data links for air traffic services (ATS) and aeronautical operational control (AOC). In October 2000, the AMCP Working Group C (WG–C), addressing future air/ground (A/G) communications, held their first meeting, which included the establishment of an action (Action WGC/1–9) to develop a report with the objective to recommend a scenario in which a common global interoperable communication infrastructure could be ensured for the future. Finally, one of the highlights of the formal ICAO Air Navigation Conference was the official report of the "Technical and Operational Matters in Air Traffic Control Committee" (Committee B). This report noted the current state of aviation communications and made several recommendations to advance this state. The observations included

- The aeronautical mobile communication infrastructure has to evolve in order to accommodate new functions
- This evolution would likely require the definition and implementation of new terrestrial and/or satellite systems that operate outside the very high frequency (VHF) band
- A variety of somewhat divergent views had been presented with regard to the future evolution of aeronautical mobile communications
- The universally recognized benefits of harmonization and global interoperability of A/G communications should not be forgotten when pursuing optimization of local solutions
- The successful gradual introduction of data communications should be continued to complement and replace voice for routine communications

Based on these observations, several conference recommendations were made. These included

- Recommendation 7/4—Investigation of future technology alternatives for A/G communications. That ICAO
  - investigate new terrestrial and satellite-based technologies, on the basis of their potential for ICAO standardization for aeronautical mobile communications use, taking into account the safety-critical standards of aviation and the associated cost issues
- Recommendation 7/5—Standardization of aeronautical communication systems. That, for new aeronautical communication systems, ICAO
  - Continues to monitor emerging communication systems technologies but undertake standardization work only when the systems meet all of the following conditions:
    - Can meet current and emerging ICAO air traffic management (ATM) requirements; are technically proven; and offer proven operational benefits
    - Are consistent with the requirements for safety
    - Are cost beneficial
    - Can be implemented without prejudice to global harmonization of the CNS/ATM systems
    - Are consistent with the "Global Air Navigation Plan for CNS/ATM System" (Doc 9750)

At ANConf/11, there was a strong request particularly from the Airlines (International Air Transport Association (IATA)) for international cooperation to achieve the stated objectives and goals in a harmonized and globally interoperable manner. In part to address the ICAO actions and recommendations above, and in part to address frequency congestion and spectrum depletion in Core Europe and dense United States airspace, the Federal Aviation Administration (FAA) and EUROCONTROL embarked on a cooperative research and development program. The terms of this program are outlined in the Terms of Reference document for the program, which has been entitled the "Future Communications Study" (FCS). By agreement, joint FAA and EUROCONTROL research and development activities require terms of reference, which are referred to as "action plans" and are numbered sequentially. The terms of reference for the Future Communications Study are detailed in Action Plan 17 (AP–17), and the National Aeronautics and Space Administration (NASA), the FAA, and EUROCONTROL all have defined roles in the research and development activities.

1.2 Future Communication Study Technology Investigations

The terms of reference for the FCS organized the work program into six technical and three business themes supporting the definition of a future globally interoperable communications system to support ATM operations in the timeframe of 2020 and beyond. Three of the technical themes address key activities relating to the identification of the most suitable technology candidates for the future communication infrastructure. These include (1) identification of requirements and operating concepts, (2) technology alternatives assessment, and (3) development of a future communications roadmap.

The first theme has been addressed through the development of the communications operating concept and requirements (COCR) for the future radio system (FRS), a document that describes the future operating concepts and environment associated with safety and regularity of flight including ATS and safety-related AOC communications. The document also describes the operational and communication requirements associated with the radio components of a communication system, collectively referred to as the FRS. The second theme applies the material captured in the COCR to perform a technology assessment. Specifically, the FCS terms of reference call for "investigation of potential communications technologies operating inside the VHF band and outside the VHF band to support the long-term mobile communication operation concept considering terrestrial and satellite base infrastructure." Finally, based on current and planned operational aeronautical communication systems both within Core Europe and the United States, and considering results of the technology assessment, the final technical theme includes the definition of a communications roadmap that supports "planning for and achieving smooth transition" to recommended technologies.

The focus of this report is to describe work performed to support the second theme noted above, that is, to investigate technologies that can support the long-term mobile communications operating concept. NASA was tasked to provide the leading role in this effort. Specific investigations were performed in a sequence of three study phases: Technology Prescreening (Phase I), Technology Screening and Indepth Studies (Phase II), and Additional Technologies and Investigations for Provision of Future Aeronautical Communications (Phase III). Interim reports associated with results of the three study phases are available as follows:

- Phase I (completed December 2004): "Technology Assessment for the Future Aeronautical Communications System," NASA/CR—2005–213587 available at http://gltrs.grc.nasa.gov
- Phase II (completed July 2006): "Identification of Technologies for Provision of Future Aeronautical Communications," NASA/CR—2006–214451, available at http://gltrs.grc.nasa.gov
- Phase III (completed May 2007): "Additional Indepth Technology Studies for Provision of Future Aeronautical Communications Phase III Indepth Studies Report," available at http://gltrs.grc.nasa.gov

1.3 Stakeholder Inputs

During the course of the FCS, interim findings were briefed to FAA and EUROCONTROL senior management, ICAO, industry, and the United States Air Traffic Management Advisory Committee (ATMAC). There was significant feedback received on some of the interim study results. Some raised concern on moving to a new communication band because of perceived cost ramifications of additional ground infrastructure and either additional hull penetrations or costly equipment integration on aircraft. ATMAC defined a set of recommendations that related to future aeronautical communication capability that included the following (ref. 4):

- Sustain voice in VHF spectrum as long as possible, maintaining analog 25-kHz double side band-amplitude modulation (DSB–AM) until such time as spectrum pressures require reducing channel spacing to 8.33 kHz
- Pursue new technological solutions as a last resort
- Data link is important—commit to a technology and implement by 2015
- Keep AOC and ATS separate

The FAA indicates its intention to comply with the ATMAC recommendations, but also plans for the future. Should the capacity of the aeronautical VHF spectrum ever prove insufficient to provide the total data link capacity required, the FAA would support a new system to be ready and available to ensure that the communications needs of aviation are accommodated. This is completely inline with the ICAO ANConf/11 observation that “This evolution would likely require the definition and implementation of new terrestrial and/or satellite systems that operate outside the VHF band.” This same theme was reflected by EUROCONTROL, which has indicated that the European focus is consideration of an L-band system. EUROCONTROL also explored the potential of satellite systems; however, initial analysis work concluded that availability may preclude their use as a primary system in continental airspace. After receiving feedback on Phase I results, subsequent FCS technology investigation focus was made to support the understanding of issues associated with hosting a communications system in either L- or C-bands and with the potential use of satellites for flight-critical communications in some airspace domains.

Another significant set of comments on the Phase I results was received from the ICAO Aeronautical Communication Panel (ACP) at the working group of the whole meeting in June of 2005. Feedback to the study team on the evaluation process and criteria from the ICAO ACP indicated that the original scope of the FCS was too broad. Rather than specifying a technology that would meet all of the ATM communications requirements (including voice and data), it was recommended that the technology investigation focus on a data-only solution, keeping in mind that a future system would augment existing systems, not immediately replace them. Furthermore, the ACP indicated that the genesis of the original evaluation criteria (Phase I study criteria) was unclear. The panel asked that a set of evaluation criteria directly traceable to the COCR document be developed for the FRS, and that the technology screening process be repeated (ref. 5).

All of the received feedback influenced the direction of the study, helping to identify focus areas for indepth evaluations and tailoring of the applied evaluation methodology.

1.4 Purpose of This Report

This report documents the technology assessment and recommendations of the technology investigation task (Task 3.2) of AP–17. As such it documents the process applied for technology evaluation, a derived set of evaluation criteria traceable to the COCR, overview of indepth analyses supporting technology evaluation, and technology recommendations for meeting future aeronautical communication requirements.

2.0 Technology Assessment Approach

2.1 Approach Introduction and Overview

For many reasons, decision making in the aeronautical environment can be considered complex. There are a large number of stakeholders with differing needs and desires. There are many and sometimes conflicting factors that influence stakeholder technology decisions with regard to the aeronautical environment. Specific to the FRSs, there are many alternative technologies to consider. To be responsive to stakeholder feedback received on the initial technology prescreening effort as well as to identify a technology assessment approach to accommodate a complex decision making environment, a range of decision-making methodologies were investigated. Methodologies of particular interest were those that are integral parts of business process improvement strategies, such as Six Sigma.[3]

One identified methodology thought to be particularly applicable to the FRS technology investigation task is the analytical hierarchy process (AHP). This methodology is process oriented, accommodates multicriteria decisions, and employs customer-focused strategies. It is also utilized in major decision-making software applications, such as Expert Choice. Like all decision-making methodologies, the AHP has both strengths and weaknesses. It can accommodate many aspects of a decision, organized into a decision hierarchy: group decision making can be supported; a clear and comprehensive structure is applied to the decision-making process; and it provides a means of assessing relative importance of decision factors.

With these benefits come some limitations. Specifically, there is an implied assumption that identified decision factors are independent, which is not always the case. Additionally, the calculations supporting the process are complex and often require custom software. Finally, the process can be time intensive to implement, and difficult for the casual observer to comprehend. To be considerate of these drawbacks, but take advantage of the benefits of such a structured process, elements of the AHP were used to help formulate the technology investigation task approach. Specifically, a six-step methodology (fig. 1) was defined and followed. The activities included in the methodology were performed in the context of three study phases: Technology Prescreening (Phase I), Technology Screening and Indepth Studies (Phase II), and Additional Indepth Technology Studies for Provision of Future Aeronautical Communications (Phase III).

The first set of activities in the evaluation process depicted in figure 1 (steps 1A and 1B) included derivation of evaluation criteria and metrics. Addressing stakeholder direction, a structured analysis of the COCR was undertaken to ensure traceability of criteria to requirements. This structured analysis, along with consideration of ICAO recommendations for future communication systems captured in consensus documentation, was used to derive technical and viability evaluation criteria. The technical criteria account for functional and performance needs of aviation and safety in the aeronautical domain. The viability criteria address cost and risk elements associated with implementation of a technology in the future communication infrastructure.

Using the defined evaluation criteria, the next step in the evaluation process (step 2) is to identify the most promising technology candidates. The technology screening process included an inventory of over 50 technologies. This included technologies collected through requests for information from NASA to industry; EUROCONTROL inputs from European manufacturers; and ICAO ACP WG–C member state inputs and represented technologies defined for current and planned commercial applications; as well as standards and prototypes developed specifically for aviation. A screening process applied a small set of key technical and viability evaluation criteria at a high level. The output of this work was a subset of the most promising technologies to be subject to indepth analysis and further consideration for use in the future aeronautical communication infrastructure.

The remaining steps in the evaluation process (steps 3 through 6) contribute to detailed assessment of the most promising candidate technologies. A concept of how the technology would be applied to the aeronautical environment described in the COCR was defined, followed by evaluation of a technology

[3]Six Sigma is a system of practices to systematically improve business process. It is a rigorous and disciplined methodology that utilizes data and statistical analysis to measure and improve a company's operational performance, practices, and systems.

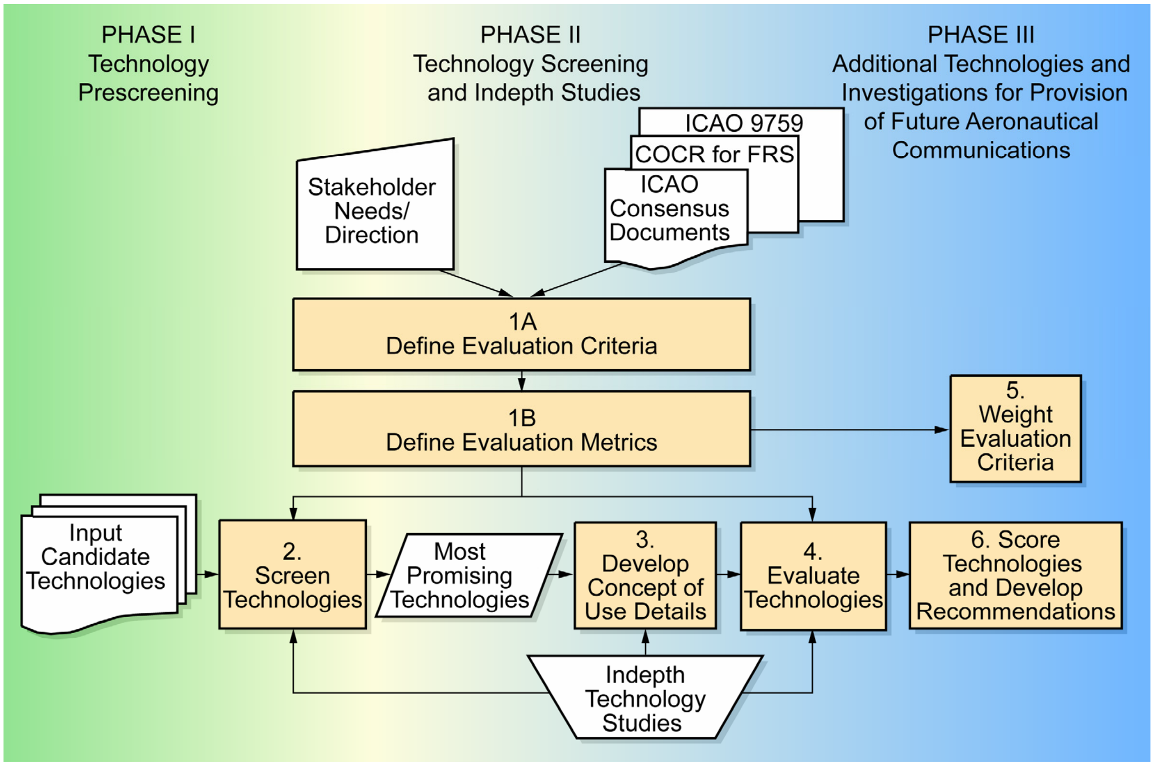

Figure 1.—FCS technology investigation methodology.

to the full complement of evaluation criteria. Supporting these steps was indepth analysis of the considered technologies. The process continues considering the relative importance of criteria and the use of this information to identify the best performing technology. All evaluation results were used to determine the applicability of the candidate technologies for meeting future aeronautical communication needs and the development of communication recommendations. The last process (step 7) concludes the overall FCS investigations by developing a set of harmonized conclusions and recommendations with the European team; the results are published in the joint AP–17 Final Conclusions and Recommendations Report resulting from the ACP/WG–T meeting in October 2007.

Additional approach details are provided in the following subsections and organized as follows:

- Section 2.2: Defining Evaluation Criteria
- Section 2.3: Technology Screening
- Section 2.4: Detailed Technology Evaluation Activities

2.2 Defining Evaluation Criteria

The definition of evaluation criteria was a task that has, in part, spanned all three phases of the FCS technology investigation. An initial set of criteria were derived in 2004 FCS Phase I Technology Prescreening task. In this effort, three major classifications of evaluation criteria were defined: technical performance, cost, and risk. Technical criteria addressed the required performance and functions of the FRS, while cost and risk criteria, also called institutional criteria, addressed the strategic objectives of the FCS or the elements of a technology that make it a viable solution. All categories of criteria were deemed to have significance to the selection of technology, and this categorization was maintained throughout the FCS technology investigations.

To derive technical criteria, a rigorous COCR analysis was performed (primarily as part of the Phase II evaluation efforts). This work included a functional analysis of the concept of operations for the FRS (as defined in the COCR) to identify required functional capabilities and applicable performance specifications. The applied approach was responsive to feedback received on 2004 Phase I Technology Prescreening task in which direction from the ACP WG–W recommended evaluation criteria be traceable to documented requirements of the COCR (ref. 5). Because cost and risk criteria address strategic elements of a communication implementation not explicitly identified in the COCR, a different approach was required for deriving these criteria. Specifically, ICAO consensus documents were reviewed to identify strategic elements to be considered for future aeronautical system implementations. These elements were translated into evaluation criteria. A summary of the application of source information to derive evaluation criteria is shown in figure 2.

For each of the evaluation criterion, a set of metrics was defined to be used to gauge technology performance specific to the criterion. The general approach applied was to utilize a trilevel rating system, sometimes called a "stop light" rating system where performance and compliance are assessed to be green, yellow, or red. Generic metric definitions for this rating system are shown in figure 3.

This trilevel rating system was selected for the technology evaluation because it is not complex, and it provides an easy to understand barometer of performance and applicability of technology to the future aeronautical communication concept. For individual criteria, the rating values were tailored to reflect specific performance requirements of the COCR, specific implementation needs (e.g., implementation timeframe based on the FCS roadmap), or factors that support relative comparison of technology performance and applicability.

COCR V2 section	Definition	Inputs for technical criteria
1. Introduction	Provides the background, scope, and context of the document	N/A
2. Operational services	Describes future air traffic services and aeronautical operational control services	Functional requirements
3. Operational concept, environment, and scenarios for communication	Describes the application of the defined operational services in the context of the future operating environment and as a series of communication scenarios addressing gate-to-gate operation	Functional requirements
4. Operational, safety, and security requirements	Provides operational requirements for individual services, describing associated continuity, integrity, and availability values; also provides a safety assessment and security requirements	Security
5. Performance requirements	Provides voice service requirements (latency/availability) and Required Communication Technical Performance (RCTP) for data services for the FRS	Latency (performance/ capacity) availability/ continuity/integrity
6. Communication loading analyses	Provides an estimate of FRS load for ATS and AOC services (for Phase I and Phase II operations)	PIAC (capacity); data rate (capacity)
7. Conclusions	N/A	N/A

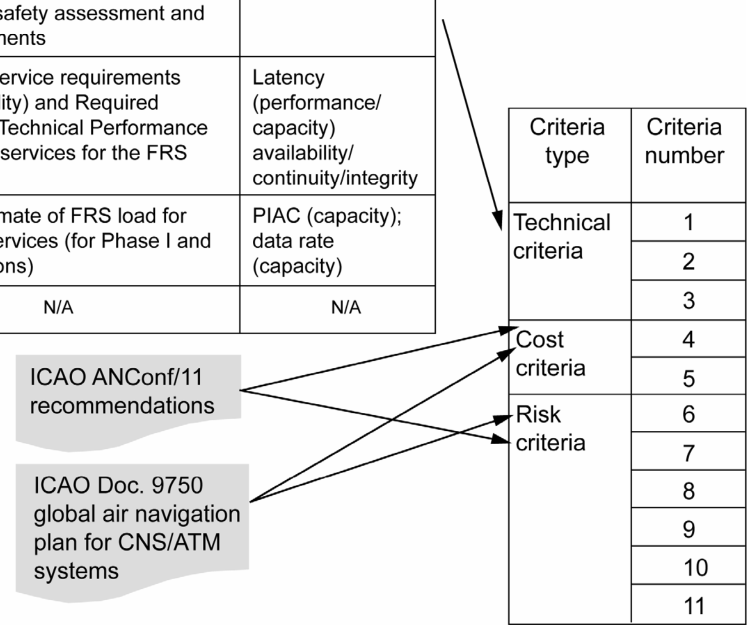

Figure 2.—Deriving evaluation criteria.

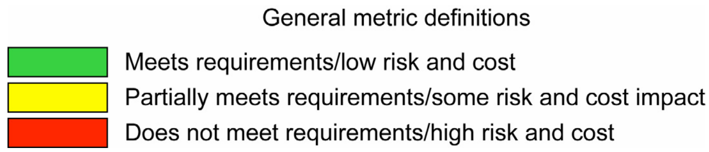

Figure 3.—Generic evaluation criteria metric definitions.

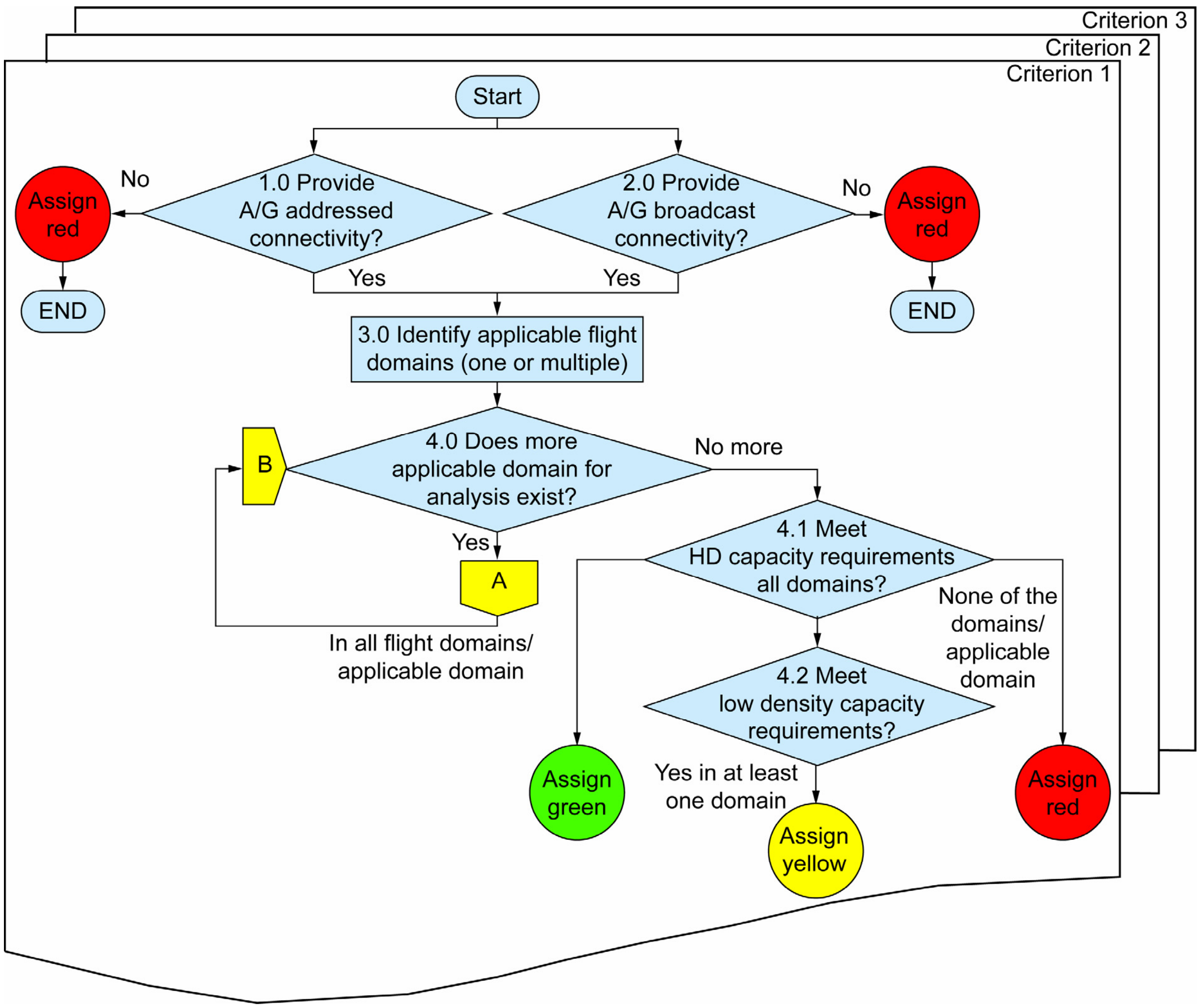

Figure 4.—Criteria evaluation process diagrams.

As noted previously, the significant work to derive the applied set of evaluation criteria was performed during the FCS Phase II technology investigation task. Efforts undertaken during the FCS Phase III study period included the modification of criteria and metrics to reflect updates in the COCR between versions 1 and 2 (Version 2 was released in spring 2007). This included accommodating updated FRS performance specifications in COCR Version 2. In this report (Sections 3.1 and 3.2), a summary of the evaluation criteria and associated metrics are provided. Details of the analysis to derive evaluation criteria from the COCR and ICAO consensus documents are provided in the FCS Phase II technology investigation interim report (ref. 6).

After defining evaluation criteria and associated metrics, evaluation process flow diagrams were developed to describe specific steps to be performed and decisions to be made to conduct technology assessment and lead to an evaluation output. A diagram or set of diagrams was developed for each evaluation criteria, as shown in figure 4.

The flow diagrams include documentation of required technology information needed for the assessment and appropriate actions and decisions that lead to specific trilevel rating results.

2.3 Technology Screening

To perform a technology assessment, a set of technologies for evaluation needs to be defined. In the initial FCS Phase I technology investigation task (2004), a multifaceted approach was used to identify candidate technologies for evaluation. This approach included

- Two NASA-released requests for information, soliciting technology candidate inputs from industry
- Inputs to EUROCONTROL received from European manufacturers
- Identification by the ICAO ACP WG–C of several technologies of special interest to member states, or thought to be potentially applicable
- An independent survey of widely used and successful commercial and military technologies

Applying the approach above, over 50 technology candidates were identified. During the Phase II study period, the candidate technology list was augmented to accommodate new technologies specifically suggested through ICAO ACP WG–C. These technologies were identified through ACP meeting participation, review of ACP WG–C meeting reports, and review of technology definition technical papers. Additional modifications to the technology inventory, to account for evolving technical definition of a small set of candidates, were made in this final study phase of technology investigation.

A focus of the technology screening process was to define a clear and COCR-traceable screening measure that would support the identification of most applicable FRS technology candidates within technology families (i.e., groups of technologies characterized by similarities in user requirements, services offered, and reference and physical architectures). To select the screening measure during the Phase II technology evaluation study period, evaluation criteria were reviewed to identify those criteria reflective of a threshold of applicability (e.g., if the technology could not meet some aspect of the criteria, then it could not be implemented in an aeronautical environment) and/or are reflective of overall COCR performance requirements. Specifically, the selected screening measures included the ability to use protected (safety and regularity of flight) spectrum (one aspect of the spectrum criterion); the data loading capability (one aspect of "meets ATS/AOC service requirements criteria"); and the technology communication range (relating to "meets ATC/AOC service requirements" and "cost" criteria), where specific threshold values for loading and range are traceable to the COCR.

A technology that inherently relies on unprotected spectrum (i.e., cannot be deployed in Aeronautical Mobile (Route) Spectrum (AM(R)S) or Aeronautical Mobile Satellite (Route) Spectrum (AMS(R)S)) was considered not to be a viable candidate for the FRS. Therefore, if a technology is a specific implementation that utilizes unprotected spectrum, the technology was removed from further consideration.

As calculated, the COCR capacity specifications reflect all COCR performance requirements. Specifically, the specified data rate requirements are associated with the maximum number of users, with values calculated to meet the required quality of service (QoS) while meeting latency requirements. Additionally, data rate requirements are directly proportional to technology coverage volumes. These parameters were considered to be appropriate selections for the technology screening filter. The data loading screening measures were developed from COCR capacity specifications.

Data rate thresholds to consider for the screening process were determined by inspecting the data rate requirements of the COCR. These included sector-based requirements (used for evaluation of terrestrial-based technologies) and per-user requirements (used for evaluation of satellite-based technologies). COCR Phases 1 and 2 (corresponding to operational environment evolution over time) data rate requirements were parsed to identify the maximum data rate requirements across all flight domains for ATS-only traffic, as well as for ATS and AOC combined traffic loads.[4]

Supporting the application of the screening criteria was the task to define high-level technology use concepts for the future aeronautical environment. The use concept can be considered a mapping of a technology into a system; specific to this task, it provides the basic description of how the required COCR services would be provisioned by a technology implementation. This information was needed to support the assessment of how the technology performs against the defined screening criteria. To create the use concept material for the technologies, several steps were performed during Phases I and II study efforts. These included

1. Review of a list of available services and architecture configurations for a technology and identification of the service(s) and/or architecture most appropriate for aeronautical communications
2. Review of modes of operation for a technology and identification of the most applicable for this application
3. Definition of the set of physical architecture parameters supporting the implementation of the identified services and operational modes (e.g., modulation, coding, data rate, and range)
4. Creation of a description of the integration of the candidate's architecture for aeronautical communications into the existing aeronautical infrastructure

Many of the high-level use concepts for each technology (organized by technology family) are provided in the FCS Phase I technology investigation report (ref. 7). Key technology features and performance values were extracted from these use concepts and summarized in the Phase II technology investigation report (ref. 6). As needed in Phase II and again during the FCS Phase III technology investigation study period, the use concept and technology performance definitions were updated to reflect the latest information available for specific technologies and new technologies added to the technology inventory. A summary of the technology information used for the screening process is addressed in Section 4.1 and appendix B of this report.

To perform the technology screening, technologies were first considered with regard to the "ability to use protected spectrum" threshold. Technologies that inherently relied on unprotected spectrum were removed from the candidate list. Next, technologies were considered with regard to data loading capability and communication range (range component for terrestrial technologies only). Specifically, the following representative sector-based capacity values published in COCR Version 2 (max. capacity across all domains) were considered.

COCR Phase 1 ATS-only, kbps	9
COCR Phase 1 ATC and AOC, kbps	30
COCR Phase 2 ATS-only, kbps	40
COCR Phase 2 ATS and AOC, kbps	200

These values were plotted as reference lines on a graph used to build a graphical visualization of the screening threshold. In addition to the reference lines, red/yellow/green shading provide a means to visualize which technologies can meet all specified requirements (i.e., provides capacity greater than the COCR Phase 2 ATS and AOC requirements); or has potential to provide a role in future aeronautical communications (i.e., capacity is, at a minimum, greater than COCR Phase 1 ATS-only requirements). A depiction of the reference capacity requirements (for terrestrial technologies) is provided in figure 5.

[4]Note that AOC-only data loads were not considered as AOC-only traffic is not a focus of this study. Although the COCR specifies separate requirements for uplink traffic, downlink traffic, and combined, data rates considered for screening thresholds were only combined uplink and downlink traffic requirements (to provide more conservative consideration of required capacity).

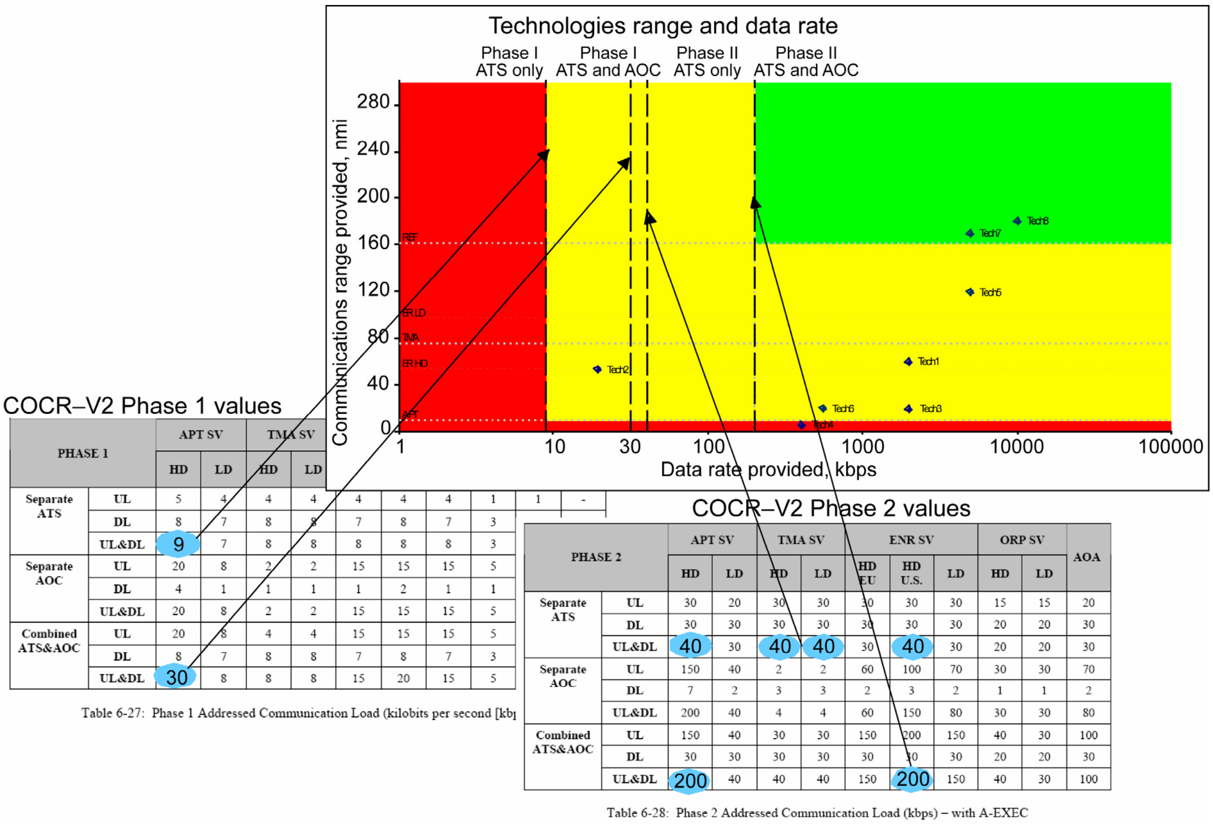

Figure 5.—Reference sector-based capacity requirements for technology screening.

In figure 5, red shading is applied to data rates below the Phase 1 ATS-only capacity requirement (9 kbps); yellow shading is applied to data rates between the Phase 1 ATS-only capacity requirement and Phase 2 ATS and AOC capacity requirement; and green shading is applied to data rates above the Phase 2 ATS and AOC capacity requirements.

In figure 5, reference lines and associated shading are also applied to the vertical access (terrestrial technologies only). Five communication range reference values were captured for the screening filter. These included airport (APT) range; terminal maneuvering area (TMA) range; low-density en route (ER) range; high-density ER range, and radio horizon reference range. Specific values of required communication range for airport, TMA, and ER environments were derived from information provided in the COCR. Specifically, domain description information of the COCR was used to calculate the maximum communication range for each flight domain assuming a worst-case transmitter location (i.e., on the edge of the coverage volume).[5] Range values that exceeded all domain-specific derived range requirements and the radio horizon range were colored with green shading; values that could not meet the minimum communication range requirement (i.e., APT domain range requirement) and therefore have minimum applicability to the aeronautical environment were shaded red; and all values between shaded yellow.

For consideration of satellite and over-the-horizon candidate technologies, the COCR Version 2 "per-user" data capacity requirements were reviewed, including the following:

COCR Phase 1 ATS-only, kbps per user 7
COCR Phase 1 ATC and AOC, kbps per user 8
COCR Phase 2 ATS-only, kbps per user 30
COCR Phase 2 ATS and AOC, kbps per user 40

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[5]Additional detail relating to the derivation of reference range values is provided in ref. 7, Section 3.2.

Similar to the screening filter graph created for evaluation of terrestrial-based technologies, these values were plotted as reference lines on a graph. Red/yellow/green shading was applied to provide a means to visualize those technologies that would meet all specified requirements (i.e., provide per-user capacity greater than the COCR Phase 2 ATS and AOC per-user requirements); or would have the potential to provide a role in future aeronautical communications (i.e., per-user capacity is, at a minimum, greater than COCR Phase 1 ATS-only per-user requirements). A depiction of the reference capacity requirements for satellite-based (and over horizon) technologies is provided in figure 6.

Note that in figure 6, the graphical depiction of the screening threshold for satellite-based technologies only includes the capacity threshold (and not the range threshold). This is because communication range does not provide a meaningful discriminator for satellite and over-horizon technologies.

As noted above, technologies that fall within the green zone of the screening plots are candidates likely to perform well (meet or exceed requirements) with regard to capacity (and range for terrestrial candidates) and were brought forward as a promising candidate technology for the FRS. Additionally, technologies on the terrestrial screening plots that fell close to within the green zone were also brought forward from the screening process for further analysis.

As the per-user requirements were used for assessment of satellite and over-the-horizon technologies applicable to oceanic/remote airspace, which has a unique operating environment and associated requirements, consideration was also given to technologies that would perform well in the APT domain. This is another domain that can be considered operationally unique. For the APT domain, high-capacity performance is of considerable interest, but propagation range performance only to the anticipated APT boundaries is needed. Therefore, technologies that offered high capacity and at a minimum could be deployed to accommodate range requirements for the APT environment were reviewed for relevance to this domain-specific application.

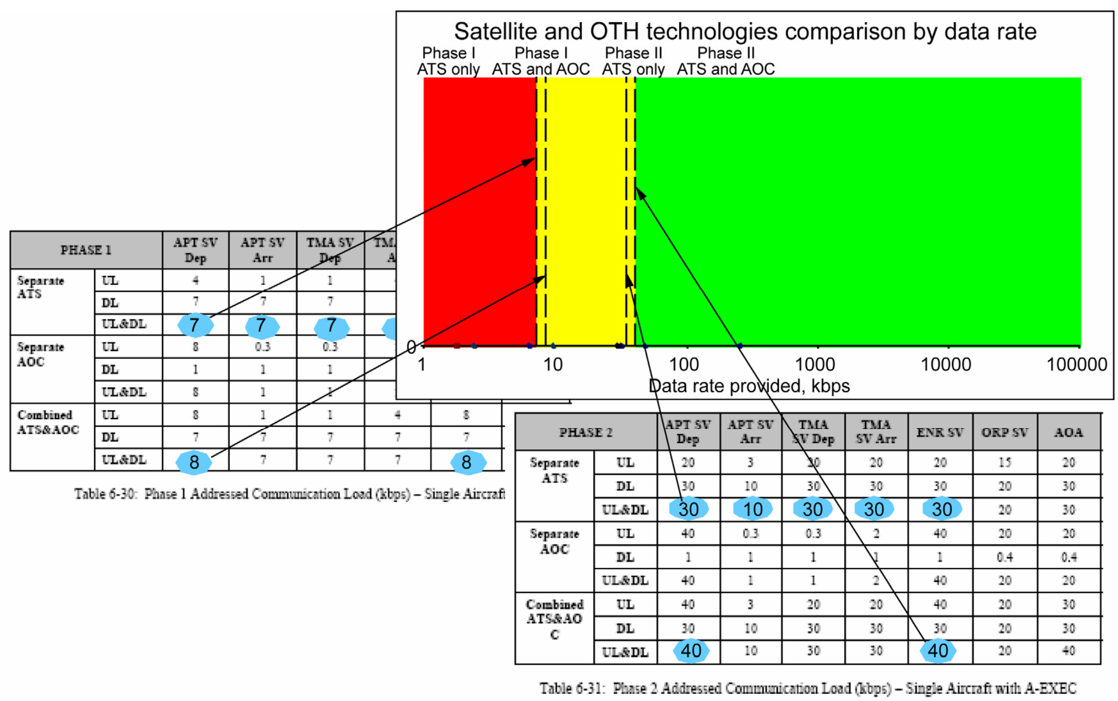


Figure 6.—Reference per-user capacity requirements for technology screening.

Results of the technology screening process are addressed in Section 4.3. Upon completion of the latest technology screening process (applying latest technology information and COCR Version 2 performance values), the results obtained were compared to analogous screening activities performed by EUROCONTROL.

2.4 Detailed Technology Evaluation Activities

After down-selecting from the technology inventory to the most promising candidates (steps 1A, 1B, and 2, see fig. 1) detailed technology investigation and evaluation activities were performed. There are four steps in approach methodology supporting this work, including

- Step 3: Develop Concept of Use Details (Section 2.4.1)
- Step 4: Evaluate Technologies (Section 2.4.2)
- Step 5: Weight Evaluation Criteria (Section 2.4.3)
- Step 6: Score Technologies and Develop Recommendations (Section 2.4.4)

The approach used to carry out each of these individual steps is addressed in the following subsections.

2.4.1 Develop Concept of Use Details

The technologies that emerged from the screening process were subjected to further investigation to better understand their applicability to the future aeronautical communication environment and to further evaluate them against the full complement of evaluation criteria. As noted above, two categories of technologies resulted from the screening process: those applicable to continental airspace domains (APT, TMA, and ER) for consideration as a general aeronautical air-ground communication solution, and those applicable to specific airspace domains with unique operational requirements. For domain-specific candidates, a smaller subset of candidates was identified, and sufficient detail was deemed available in the initially defined use concept for further evaluation and assessment. For those candidates brought forward for consideration as general, continental domain candidate solutions, a more detailed understanding of how these candidates could be applied to the future aeronautical communication infrastructure, was desired. This additional detail was needed to perform a more thorough assessment of candidates to criteria and to obtain a better understanding of the relative performance of the candidates for meeting FRS requirements.

Thus, for those candidates brought forward as continental domain candidates, additional detail was added to the high-level understanding of technologies used for the screening process. A driver for the type of material captured in the more detailed concept of use was the flow diagrams created to describe the assessment process for individual evaluation criterion. The flow diagrams identify specific technology information required for the assessment, and this information was to be captured in the technology concept of use. A depiction of the traceability of concept of use material to evaluation process diagrams (and essentially, back to evaluation criteria) is shown in figure 7.

The material captured in the detailed concept of use for the technologies included technology options and selected implementation for evaluation; identification of architecture elements and how they would provide COCR services; deployment concept and how the concept would be applied to support common evaluation scenarios.[6]

[6]Common evaluation scenarios are an extension of the requirements in the COCR. The scenarios describe service volumes larger than the sector-based volumes defined in the COCR and document associated PIACs and associated capacity requirements (applying same assumptions used in COCR for loading analysis) for service volumes. These volumes support the evaluation of technologies whose deployment concept might include larger service volumes as compared to those defined in the COCR. The scenarios and associated requirements are documented in ref. 1.

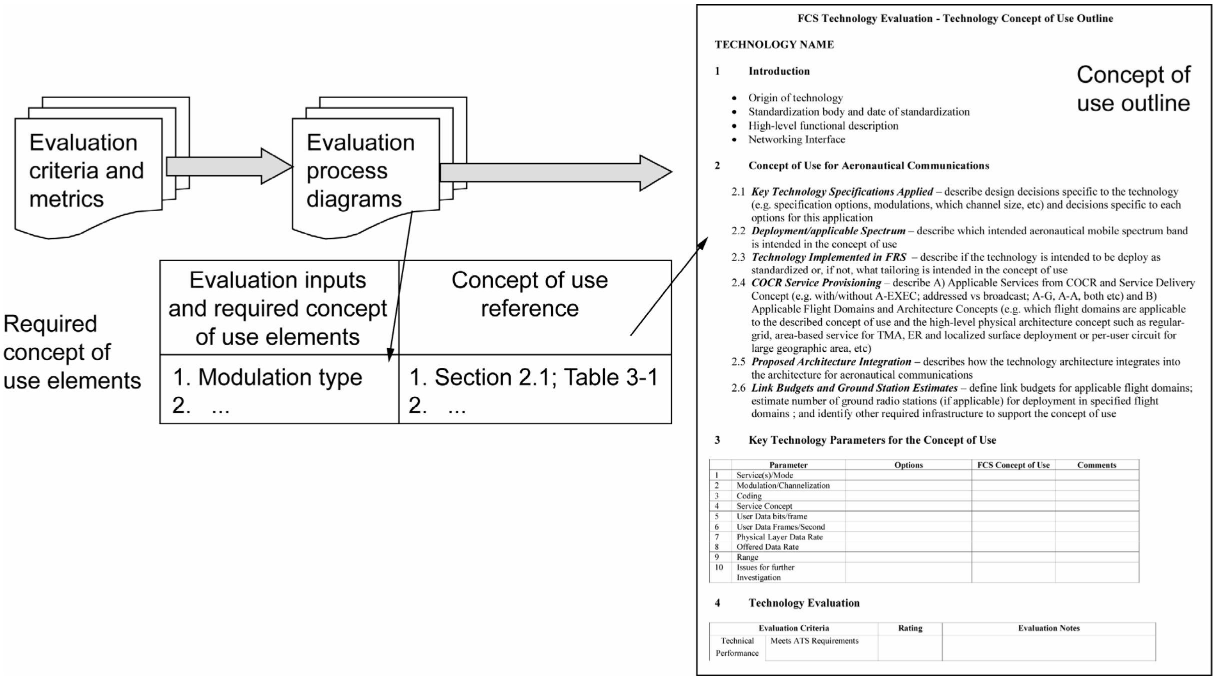


Figure 7.—Traceability of concept of use material to evaluation inputs (for evaluation process diagrams).

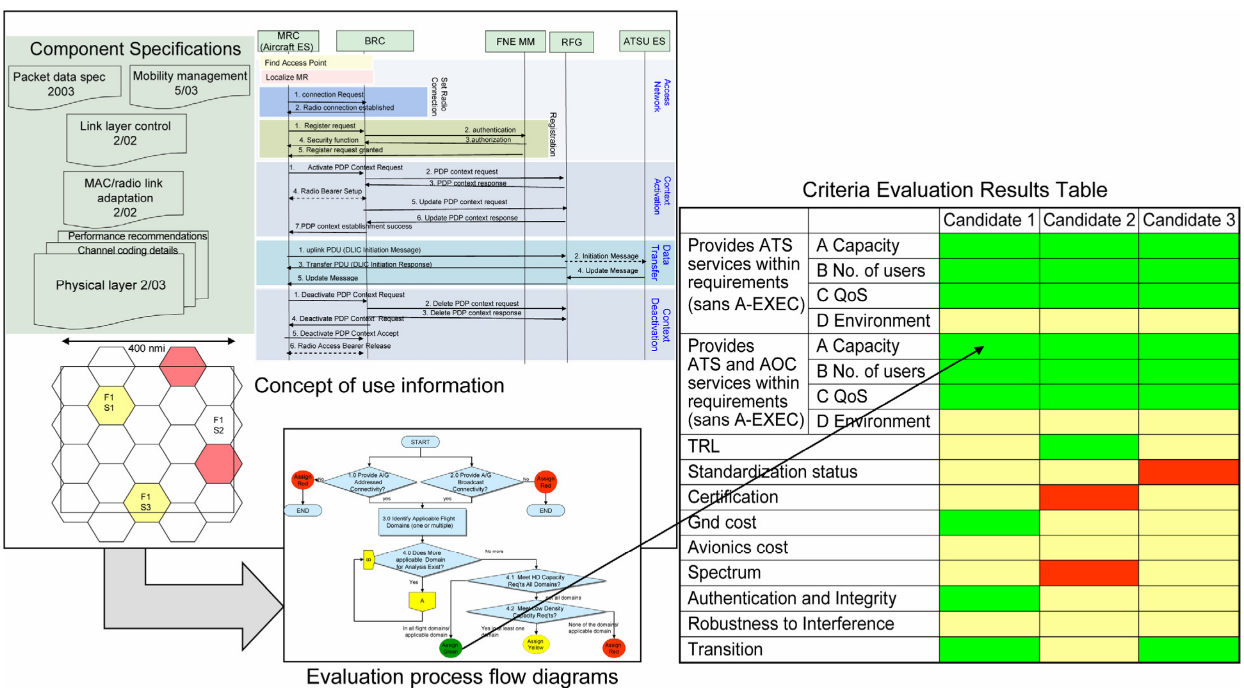


Figure 8.—Overview of technology assessment to evaluation criteria.

2.4.2 Evaluate Technologies

The next step in the approach methodology, Step 4, was evaluation of technology to criteria. This included applying the concept of use material to the evaluation criteria process diagrams and results in a technology assessment value for all criteria. A summary of the assessment results was captured in a criteria evaluation results table. A high-level view of the evaluation process and results table is provided in figure 8. Note that associated with each of the assessment results in the results table (but not shown), is the documentation that describes the important drivers and outputs of the technology assessment and information that support the assignment of the assessment value.

A considerable number of indepth assessments were performed to support the technology evaluation process and to gain a better understanding of the applicability of the most promising technologies to the future aeronautical communication environment. Indepth studies were conducted as part of the FCS Phases II and III study efforts. A full set of the indepth analyses is provided in table 1. Also indicated is a reference that identifies where the full study is documented (including a description of the study objectives, methodology, and results).

TABLE 1.—FCS TECHNOLOGY INVESTIGATION INDEPTH STUDIES

	Indepth study topic	Location of study documentation (objectives, methodology, and results)
1	L-Band Air/Ground (A/G) Communication Channel Characterization	FCS Phase II interim report (“Identification of Technologies for Provision of Future Aeronautical Communications,” NASA/CR—2006–214451, ITT Corp., July 2006), Section E.1.1
2	Project–34/Telecommunication Industry Association (TIA) 902 Series Standards (TIA–902 (P34)) Technology Performance Assessment	FCS Phase II interim report (“Identification of Technologies for Provision of Future Aeronautical Communications,” NASA/CR—2006–214451, ITT Corp., July 2006), Section E.1.2 and E.1.4
3	TIA–902 (P34) Technology Intellectual Property Assessment	FCS Phase III interim report (“Phase III Additional Technologies and Investigations for Provision of Future Aeronautical Communications,” NASA/CR—2008–214987, ITT Corp., May 2007), Section 4
4	L-Band Digital Link (LDL) Technology Performance Assessment	FCS Phase II interim report (“Identification of Technologies for Provision of Future Aeronautical Communications,” NASA/CR—2006–214451, ITT Corp., July 2006), Section E.1.3 and E.1.4
5	Wideband Code Division Multiple Access (WCDMA) Functional Assessment	FCS Phase II interim report (“Additional Technologies and Investigations for Provision of Future Aeronautical Communications,” NASA/CR—2008–214987, ITT Corp., May 2007), Section 3
6	L-Band Technology Cost Assessment for Ground Infrastructure	FCS Phase II interim report (“Identification of Technologies for Provision of Future Aeronautical Communications,” NASA/CR—2006–214451, ITT Corp., July 2006), Section E.1.8
7	L-Band Interference Testing	FCS Phase III interim report (“Phase III Additional Technologies and Investigations for Provision of Future Aeronautical Communications,” NASA/CR—2008–214987, ITT Corp., May 2007), Section 2
8	Satellite Technology Availability Performance	FCS Phase II interim report (“Identification of Technologies for Provision of Future Aeronautical Communications,” NASA/CR—2006–214451, ITT Corp., July 2006), Section E.2
9	IEEE 802.16e Performance Assessment in Aeronautical C-Band Channel	FCS Phase II interim report (“Identification of Technologies for Provision of Future Aeronautical Communications,” NASA/CR—2006–214451, ITT Corp., July 2006), Section E.3

This report does not provide a full documentation of all indepth analysis work. Rather, appendix D provides a summary of the key results of the indepth evaluations conducted during the Phases II and III study time period.

2.4.3 Weight Evaluation Criteria

Step 5 in the evaluation methodology is the weighting of evaluation criteria. To explore a range of evaluation options and address concerns about the perceived complexity of a quantitative weighting based on the AHP, two criteria weighting approaches were implemented. The first was a qualitative ranking of criteria and the second was a more rigorous application of the AHP. Both approaches make use of documented stakeholder positions with regard to relative importance of factors influencing future communication system decisions. Stakeholder information used for the assessment came from the following stakeholders and sources:

- ICAO/FAA/EUROCONTROL—FCS steering committee direction, documented positions and plans, meeting reports and recommendations, and published reports specific to future aeronautical systems
- FCS roadmap—systems and implementation timeframe for the roadmap reflects stakeholders view specific to voice and data systems supporting communications
- Airline presentations on data link
- ATMAC recommendations
- Voice of the customer documentation for aviation (including views of Aircraft Owners and Pilots Association (AOPA), IATA, Air Traffic Association (ATA), etc.)

The process defined to apply the stakeholder positions developed a set of rules that reflect implied relative importance of evaluation criteria for a specific group of stakeholders. For example, if a stakeholder has a documented position that indicates that ATS and AOC services should be maintained as separate communication systems, then an implied position specific to the evaluation criteria is that provision of ATS services only or AOC service only is of relative more importance than provision of combined ATS and AOC services on a single communication connection.

In the qualitative approach to criteria weighting, based on documented stakeholder positions, evaluation criteria were organized into three categories.

- Most important—in general, these factors have been specifically noted by stakeholders as important factors and should be given the greatest consideration; success with regard to these criteria is necessary to have an applicable aeronautical solution
- Very important—in general, these factors are also addressed in some manner by stakeholders and are also very important aspects of a aeronautical communication system decision; success with regard to these criteria is important for understanding the viability of an aeronautical solution
- Important—these criteria have been found to not be specifically addressed in stakeholder position

Documented stakeholder positions were used to rank the evaluation criteria within these categories, as shown in figure 9.

In addition to the qualitative weighting approach described above, a streamlined version of the AHP weighting process was also applied to achieve quantitative weighting values for the evaluation criteria. Typically, the AHP process employs mechanisms that require direct stakeholder involvement in criteria ranking, such as consensus building sessions or surveys. During the Phase II study period, a trial of a survey approach was implemented. This approach was successful in gaining some direct stakeholder inputs in the evaluation process, but had many limitations. The initial survey process had limited participation among the full set of applicable stakeholders, and the steps needed to achieve widespread stakeholder participation, especially from key decision makers within stakeholder groups, was deemed unachievable within the study framework and schedule. Additionally, the need to educate survey participants on the criteria and process and the need to hold follow-up review and consensus-building sessions post-survey were identified as necessary steps for proper implementation. This was identified as a considerable hurdle because of time and resource constraints.

Therefore, the AHP weighting process actually applied for this study was a much simpler implementation compared to that explored during the Phase II study period. The criteria weighting granularity was kept to a simple three-level scale: more important, less important, or equally important.

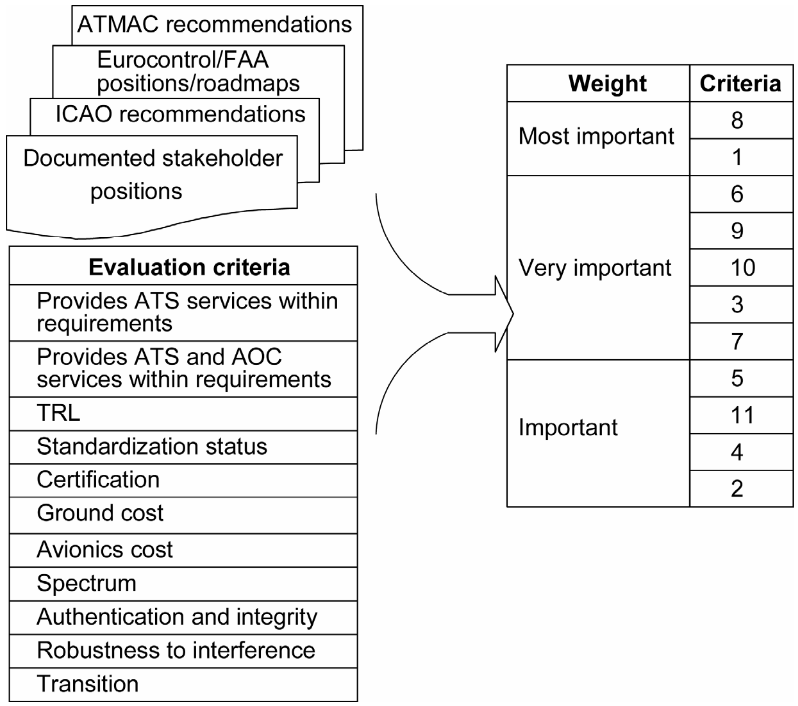


Figure 9.—Qualitative ranking of evaluation criteria.

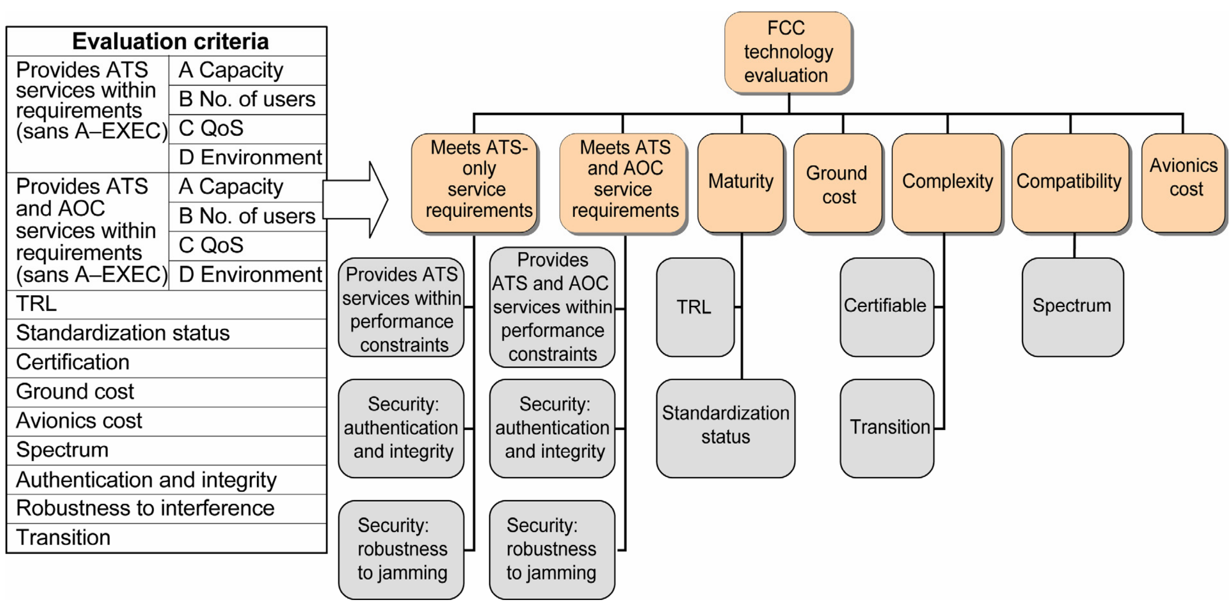


Figure 10.—Roll-up of evaluation criteria.

Additionally, surveys were not conducted, rather stakeholder positions were gathered from documented plans, recommendations, and positions. Finally, to apply documented "voice of the customer" information to develop a relative understanding of criteria importance, a roll-up of evaluation criteria was applied. This was performed by creating a hierarchy of criteria where each factor at the highest level of the hierarchy addressed a unique topic area, such as technical maturity (a combination of the TRL criterion and standardization status criterion), as shown in figure 10.

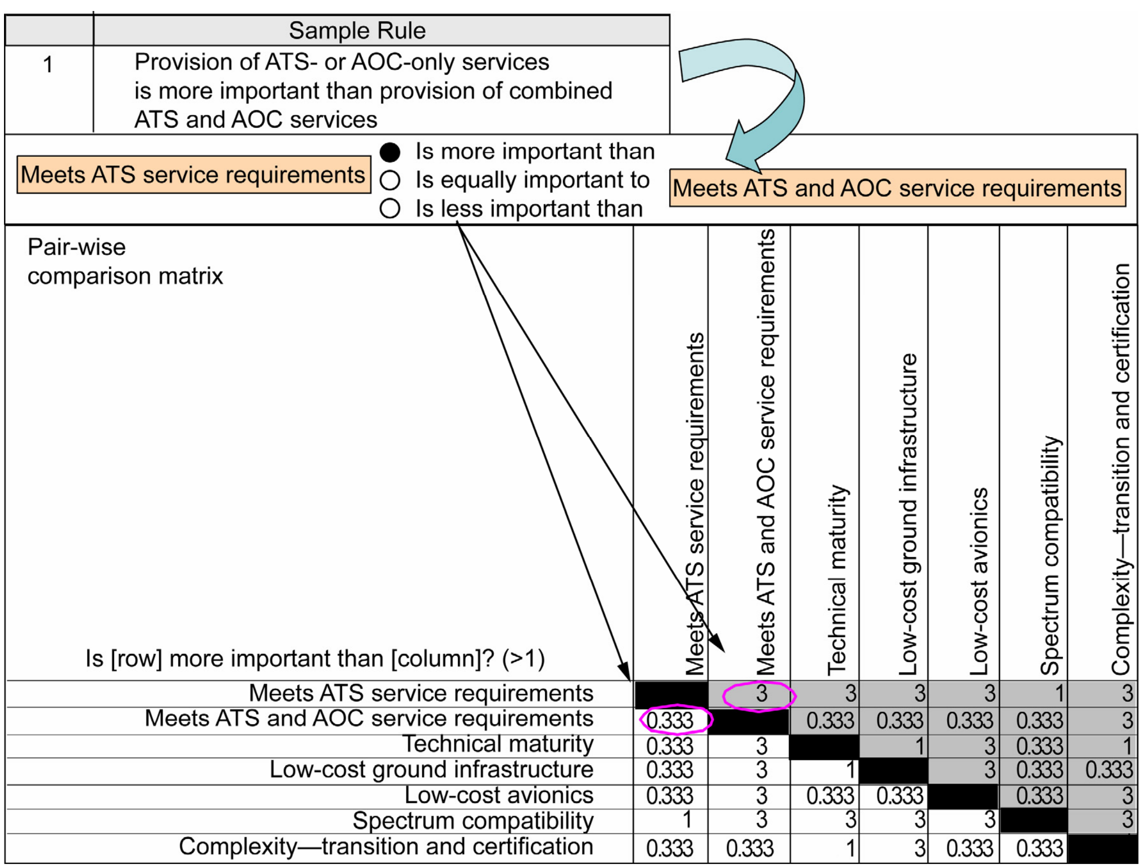
The definition of the evaluation criteria hierarchy (or decision factor hierarchy as it is called in the AHP) ensures that a manageable set of unique decision factors can be used in a meaningful way (hence the name AHP). In figure 10, the top-level factors of the hierarchy are identified as the Level-1 decision factors decomposed (as applicable) into lower level decision factors.

The first step in deriving criteria weights was to define a set of rules that reflect stakeholder positions in documented material. Specifically, a rule set reflective of the aeronautical communication user stakeholders (e.g., reflective of AOPA, IATA, National Business Aviation Association (NBAA), and ATMAC) was captured, and a separate rule set reflective of aeronautical communication service provider stakeholders (e.g., FAA, EUROCONTROL, and CANSO) was also developed. These rules were used to populate a pair-wise comparison matrix of the defined evaluation factors (from evaluation criteria hierarchy defined above). In this matrix, numerical scores were applied to representative relative importance of decision factors.

The scale applied in the AHP typically ranges from 1 to 9, where "equally preferred" is designated by 1, and increments of odd numbers are used to express increasing preference (e.g., 3 = moderately preferred, 5 = strongly preferred, etc.) (ref. 8). The same principles can be applied using a smaller scale, such as the three-point scale proposed for this study. Here, 1 is used to designate equally preferred and 3 to designate a stronger preference for (and equivalently, 1/3 to designate less preference for). Specific values used include

- More important than: 3
- Equally important to: 1
- Less important than: 1/3

In the AHP, a pair-wise comparison of evaluation factors is made and one value (from the set above) is recorded for the comparison in a comparison matrix. In this study, the stakeholder rule set was used to determine the comparison value; an example of this process shown in figure 11. Note that in this figure,



	Meets ATS service requirements	Meets ATS and AOC service requirements	Technical maturity	Low-cost ground infrastructure	Low-cost avionics	Spectrum compatibility	Complexity—transition and certification
Meets ATS service requirements		3	3	3	3	1	3
Meets ATS and AOC service requirements	0.333		0.333	0.333	0.333	0.333	3
Technical maturity	0.333	3		1	3	0.333	1
Low-cost ground infrastructure	0.333	3	1		3	0.333	0.333
Low-cost avionics	0.333	3	0.333	0.333		0.333	3
Spectrum compatibility	1	3	3	3	3		3
Complexity—transition and certification	0.333	0.333	1	3	0.333	0.333	

Figure 11.—AHP comparison matrix.

the decision factors in the column can be considered “decision factor X,” and those in the row across the top can be considered “decision factor Y” when applying the statement “decision factor X is more, less, or equally important to decision factor Y.”

The comparison matrix in figure 11 can be generated to reflect a single stakeholder set (e.g., aeronautical communication service users or service providers), or averaged across stakeholder sets. To calculate averaged results, the geometric mean of each individual comparison score is computed.

The final part of the AHP is the calculation of decision factor weights using the pair-wise comparison results. This step requires matrix mathematics, including determining the eigenvalues of the matrix, determining the eigenvector corresponding to the largest eigenvalue, and then normalizing the resulting eigenvector. This results in a set of decision factor weights ranging from 0 to 1 where the sum of all weights equals 1. A sample set of decision factor weights is shown in table 2.

TABLE 2.—SAMPLE DECISION FACTOR WEIGHTS

Decision factor	Weight
6	0.2329
1	0.2329
4	0.1324
3	0.1233
5	0.1142
7	0.0868

2.4.4 Score Technologies and Develop Recommendations

The final steps in the technology evaluation include (1) develop technology evaluation scores, (2) document the applicability of technologies based on their evaluated performance to the evaluation criteria, (3) identify technology shortfalls and issues that need to be addressed for deploying a FRS, and (4) develop technology recommendations.

To address these objectives, several steps were performed, including

1. Identify technology performance scores specific to evaluation criteria
2. Identify features and capabilities specific to each technology applicable to the FRS requirements and are applicable to a viable implementation
3. Identify shortcomings specific to each technology for meeting the FRS requirements or the anticipated operational environment for the FRS
4. Develop technology recommendations

To perform the first step noted above, the technology evaluation results were compared with the qualitative and quantitative criteria weighting outputs. For the qualitative weights, this simply resulted in the reshuffling of the order of the evaluation results presented in the evaluation results table. The reordered results grouped together those criteria deemed most important, very important and important (see fig. 12).

To apply the quantitative criteria weights, technology evaluation results are translated into a raw score that reflects the decision factor hierarchy and also normalizes the metrics to a uniform value between 0 and 1. Specifically, the following steps are performed:

1. For technology evaluation results, assign green = 1, yellow = 0.5, and red = 0
2. To translate criteria evaluation results into evaluation decision factors scores, consider all applicable subcriteria and/or evaluation criteria that comprise a decision factor equally, and combine these factors such that the resultant decision factor score is normalized to 1

This process is shown in figure 13. The example shown shows the combining of the TRL and standardization status criteria evaluation results into a decision factor score for “maturity.” Specifically, TRL score of green (1) and standardization status of yellow (0.5) are combined as follows:

1. There are two component criteria for "maturity," so each contributes (1/2) to the decision factor score
2. Compute the decision factor score equation as: (1/2) (TRL score) + (1/2)(standardization score) = (1/2)(1) + (1/2)(0.5) = 0.75. This is the resulting decision factor evaluation score for "maturity"

The decision factor scores are combined with the quantitative decision factor weights using simple multiplication. For each technology, the sum of the scores associated with individual decision factors

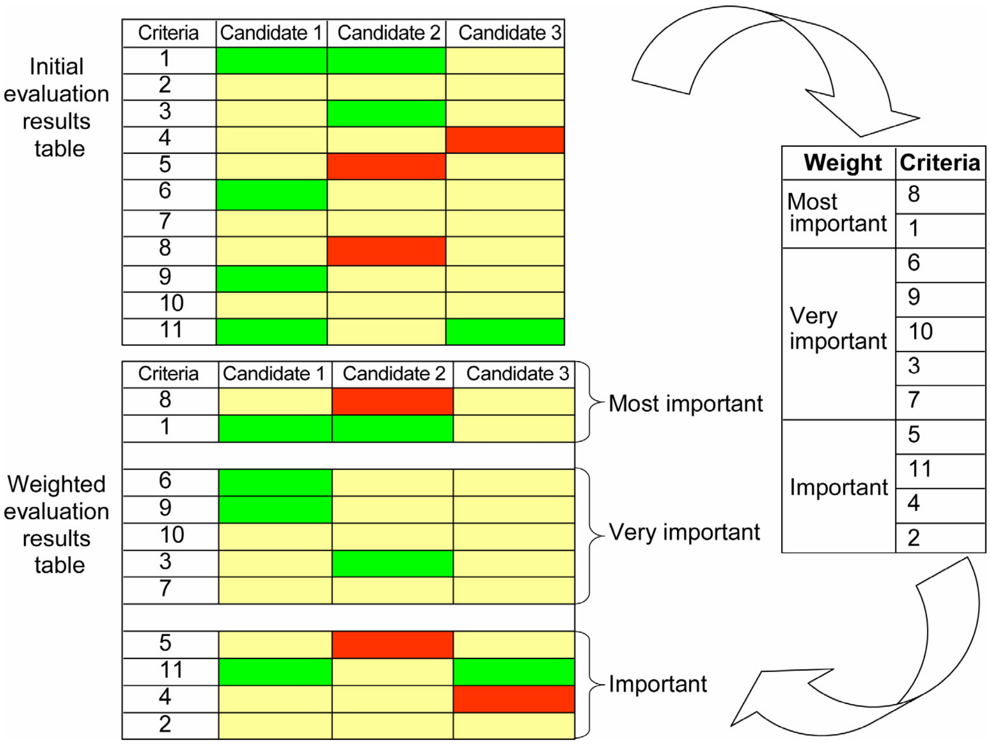
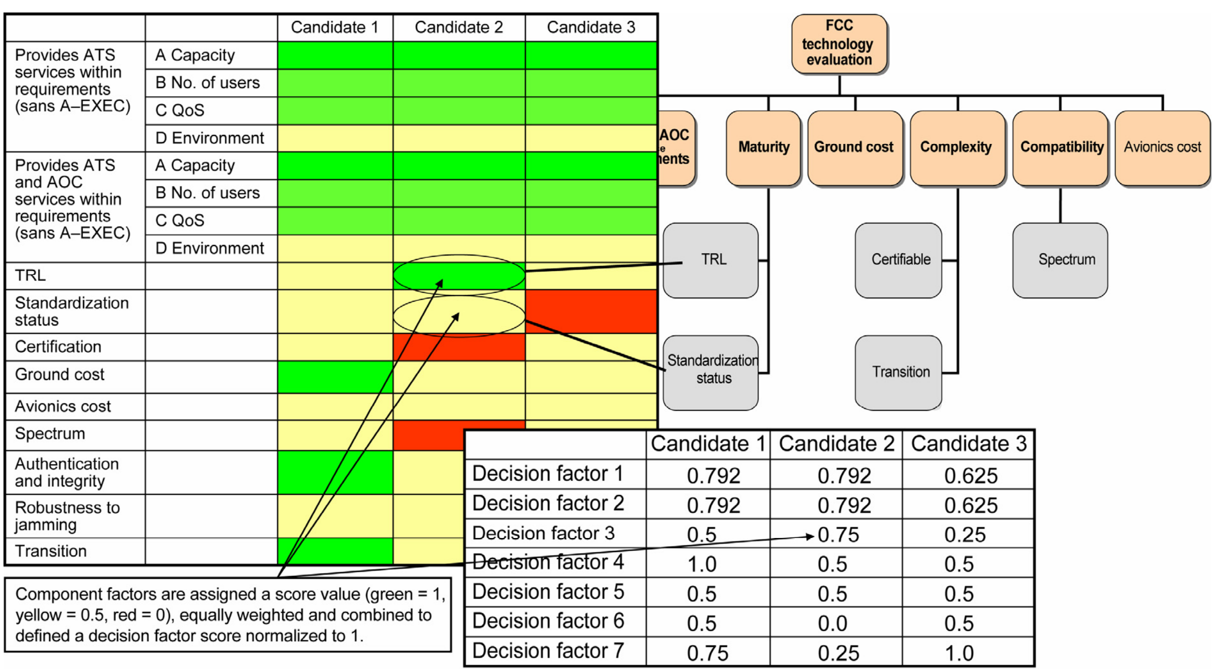


Figure 12.—Generating qualitative weighted evaluation results.



	Candidate 1	Candidate 2	Candidate 3
Decision factor 1	0.792	0.792	0.625
Decision factor 2	0.792	0.792	0.625
Decision factor 3	0.5	0.75	0.25
Decision factor 4	1.0	0.5	0.5
Decision factor 5	0.5	0.5	0.5
Decision factor 6	0.5	0.0	0.5
Decision factor 7	0.75	0.25	1.0

Figure 13.—Computing decision factor scores.

Technology under evaluation:	Sample			
				TRUE
Selected ranking perspective:	Comm service provider			

Technology scoring				
Decision factor		Evaluation score	Weight, percent	Overall SCORE
Meets ATS service requirements	☑	0.79	25.89	0.20
Meets ATS and AOC service requirements	☑	0.79	6.51	0.05
Technical maturity	☑	0.50	14.34	0.07
Low-cost ground infrastructure	☑	1.00	14.34	0.14
Low-cost avionics	☑	0.50	6.51	0.03
Spectrum compatibility	☑	0.50	25.89	0.13
Complexity—Transition and certification	☑	0.75	6.51	0.05
			TOTAL	0.68

Figure 14.—Sample calculation of technology score.

(weighted) results in an overall technology score (normalized to 1). A sample calculation of a notional technology score is shown in figure 14.

To perform a sensitivity analysis, subsets of the decision factors can be isolated and technology scores recomputed. Additionally, scores can be calculated for specific stakeholder groups. Several sets of analysis results are included in this study.

Results of the application of the methodology described above are included in the subsequent sections of this report. Based on outputs of the technology evaluation, identified areas of applicability, issues to overcome for the technologies, and the full set of results from the indepth evaluations, a number of technology recommendations were defined, as presented in Section 7.

3.0 Evaluation Criteria

One of the first steps in the technology investigation task was the selection of evaluation criteria. Responsive to feedback on interim FCS results presented to ICAO WG–C, technical evaluation criteria were derived from requirements and operating concepts included in the COCR. Additionally, other evaluation criteria that address cost and risk factors reflective of the viability of a FRS solution were derived from ICAO consensus recommendations and documents. The majority of the work performed to derive evaluation criteria was completed during the FCS Phase II study period and detailed documentation of the derivation process is described in the FCS interim study report for Phase II (ref. 6). An initial set of criteria metrics was also defined in both FCS Phase I and Phase II.

Evaluation criteria definitions and metrics were defined and developed in all three phases of FCS study. In Phase III, evaluation criteria definitions and metrics were updated to reflect changes included in COCR Version 2 and evaluation flow diagrams were specified to document specific steps to be completed to perform technology assessments. This section documents the final set of the evaluation criteria used for technology evaluations (including traceability of the criteria to the COCR and/or consensus ICAO material); and documents the evaluation metrics associated with the criteria. Detailed descriptions of the evaluation process flow diagrams can be found in appendix A.

3.1 Evaluation Criteria

As noted in Section 2.2, evaluation criteria were derived employing a structured analysis of the COCR and considering ICAO recommendations for future communication systems (ANConf/11 Recommendations; Global Air Navigation Plan for CNS/ATM Systems—ICAO Doc 9750). This work included review of each section of the COCR to identify functional and performance specifications for the FRS and translation of these parameters into evaluation criteria. Additionally, cost and risk factors specifically identified in ANConf/11 Recommendations and ICAO Doc. 9750 to be considered for evaluation of future communication systems or future aeronautical systems were translated into evaluation

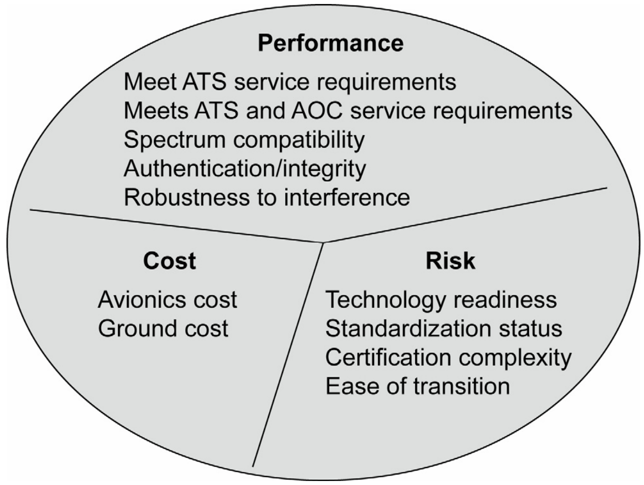


Figure 15.—FCS technology investigation evaluation criteria.

TABLE 3.—REVIEW OF THE COCR TO IDENTIFY TECHNICAL PERFORMANCE REQUIREMENTS

COCR V2 section	Definition	Inputs for technical criteria
1. Introduction	Provides the background, scope, and context of the document	
2. Operational services	Describes future air traffic services (ATS) and aeronautical operational control (AOC) services; includes implementation options including air/ground (A/G) (addressed/broadcast) and A/A (air-to-air) (addressed broadcast)	Functional requirements
3. Operational concept, environment, and scenarios for communication	Describes the application of the defined operational services in the context of the future operating environment and as a series of communication scenarios addressing gate-to-gate operation	Functional requirements
4. Operational, safety, and security requirements	Provides operational requirements for individual services, describing associated continuity, integrity, and availability values; also provides a safety assessment and security requirements	Security
5. Performance requirements	Provides voice service requirements (latency/availability) and required communication technical performance (RCTP) for data services for the FRS	Latency (performance and capacity) and availability, continuity, and integrity
6. Communication loading analyses	Provides an estimate of FRS load for ATS and AOC services (for Phases I and II operations) for addressed (A/G service implementations) and broadcast (air-broadcast services)	Queue definitions and characteristics; PIAC (capacity); and data rate (capacity)
7. Conclusions		

criteria. A majority of the work to derive these criteria and captured traceability is documented in the FCS interim report for Phase II (ref. 6). A high-level summary of the factors considered when deriving evaluation criteria is provided in figure 15.

In figure 15, technical factors that address required communication capability and performance to provision COCR services are addressed in a category called “Performance.” These were derived directly from the COCR. Specifically, each section of the COCR was reviewed to identify material and elements that are related to technical performance. A summary of the results of this COCR review is provided in table 3. Note that this table varies slightly from similar tables provided in FCS interim Phase II results, as the sections and some of the material has been updated in the COCR Version 2.

Note in table 3, some of the performance requirements of the COCR were not directly translated into performance criteria. For example, availability and integrity requirements reflective of a specific architecture implementation and not supporting a discriminatory evaluation of technology specifications were not specifically addressed in evaluation criteria. Additionally, functional and performance (peak instantaneous aircraft count (PIAC), latency, and capacity) requirements were addressed collectively in two evaluation criteria: one addressing the ability of technologies to provision an ATS-only A/G data capability, and one addressing the ability of technologies to provision a combined ATS and AOC A/G data communication capability. The mapping of the COCR elements into these two criteria reflects the following stakeholder direction and analysis assumptions:

- ICAO ACP WG–W recommended focus of technology investigation should be on a data link capability (to augment current and/or planned voice systems) (ref. 5); therefore, voice requirements were considered to be allocated to current and/or planned voice systems
- COCR capability results are provided for ATS-only, AOC-only, and combined ATS and AOC service sets. As combined ATS and AOC services included the most conservative requirement, this organization of services was considered applicable to technology evaluation; additionally, as there was expressed interest by some stakeholders to maintain ATS and AOC communication capabilities separate, provisioning of ATS-only services (assuming AOC communications are maintained separately) was also considered. As the capacity values included in the COCR for these service sets are reflective of all performance requirements (latency, PIAC, and data rates), these factors were considered collectively in a single evaluation criterion.
- Air-to-air (A/A) communication capability and associated air-broadcast services and requirements[7] were not explicitly considered in the evaluation criteria
- In the context of the FCS roadmap, required air-broadcast capability was assumed to be allocated to existing or planned air-broadcast communication systems. Although A/A capability was not evaluated explicitly in the evaluation criteria, when capturing applicability and features of the most promising technologies to the FRS, ability to provision A/A services (address or broadcast) was identified.[8]

In addition to application of COCR material to derive evaluation criteria, as noted above, ICAO ANConf/11 recommendations and the Global Air Navigation Plan for CNS/ATM Systems—ICAO Doc. 9750 were used to identify additional elements to be addressed in the consideration of future communication/aeronautical systems. Specifically, Recommendation 7/5 from the ANConf/11 reads:

> Continue to monitor emerging communication systems technologies but undertake standardization work only when the systems meet all of the following conditions:
>
> (1) meet current and emerging ICAO ATM requirements
> (2) be technically proven and offer proven operational benefits
> (3) be consistent with the requirements for safety
> (4) be cost beneficial
> (5) be consistent with the global plan for CNS/ATM Systems

To further understand recommendation number 7/5, the global plan for CNS/ATM systems was reviewed. The global plan indicates in Section 5.14 (Future Communication) trends that the "most important question to be asked when considering a new system is whether it meets existing or emerging

[7]Note that in the COCR, all air-to-air communication services are identified as able to be provisioned over an air-broadcast capability; this implementation was used in the calculation of broadcast service capacity values in Section 6.5 of COCR Version 2.

[8]Further work is planned to determine if the available air-to-air communication capabilities meet specified COCR and could be applied to the future aeronautical communication infrastructure.

operational and user requirements. Other factors to be considered are standardization, certification, harmonious deployment by various users, and cost benefit considerations.”

The Global Plan also includes a Statement of ICAO Policy on CNS/ATM Systems Implementation and Operation (appendix A to Chapter 2). This statement outlines requirements for implementation and operation of future CNS/ATM systems including the requirements for flexible transition; the ability to provide continuous service with specified integrity; and with required priority, security, and interference protection.

The factors above led to the definition of criteria that reflect the ability to achieve a viable solution, also called institutional criteria, addressing cost and risk considerations. The complete set of evaluation criteria applied in the final technology evaluation during FCS Phase III is provided in table 4. Included in this table is traceability to applicable source material.

TABLE 4.—SUMMARY OF TECHNOLOGY EVALUATION CRITERIA

No.	Evaluation criterion		Description	Traceability
1	Provides ATS A/G data services within requirements (sans A–EXEC)	A—Capacity B—Number of users (PIAC) C—QoS D—Environment	Measure of the ability of a technology to provide sufficient functional and performance capability to meet operational and environmental requirements of the COCR for ATS services (data services)	• COCR-based functional communication capability (COCR Sections 2 and 3) • COCR security requirements (Section 4.3.6, Table 4–15) • COCR performance requirements (Sections 5.2.2, 6.4.2, and 6.4.3) • FRS Environment (Sections 2, 3.2.1, 3.4.1, and 6.2)
2	Provides ATS and AOC A/G Data services within requirements (sans A–EXEC)	A—Capacity B—Number of users (PIAC) C—QoS D—Environment	Measure of the ability of a technology to provide sufficient functional and performance capability to meet operational and environmental requirements of the COCR for ATS and AOC services (data services)	• COCR-based functional communication capability (COCR Section 2; Section 3) • COCR security requirements (Section 4.3.6, Table 4–15) • COCR performance requirements (Sections 5.2.2, 6.4.2, and 6.4.3) • FRS environment (Sections 2, 3.2.1 3.4.1, and 6.2)
3	Technical readiness level		Provides an indication of the technical maturity of the proposed technology in the context of the FCS communication roadmap	• 11th ICAO Air Navigation Conference (Sept/Oct 2003) Recommendation 7/5, Number 2
4	Standardization status		Indicates the relevance and maturity of a proposed technology’s standardization status	• Global Air Navigation Plan for CNS/ATM Systems—ICAO Doc. 9750 (5.14) • 11th ICAO Air Navigation Conference (Sept/Oct 2003) Recommendation 7/5, Number 3
5	Certification		Provides a relative measure of the candidate’s complexity	• Global Air Navigation Plan for CNS/ATM Systems—ICAO Doc. 9750 (5.14) • 11th ICAO Air Navigation Conference (Sept/Oct 2003) Recommendation 7/5, Number 3
6	Ground infrastructure cost		Estimates relative cost to service provider to provision services to a geographically large area	• Global Air Navigation Plan for CNS/ATM Systems— ICAO Doc. 9750 (5.14) • 11th ICAO Air Navigation Conference (Sept/Oct 2003) Recommendation 7/5, Number 4

TABLE 4.—CONCLUDED.

No.	Evaluation criterion	Description	Traceability
7	Avionics cost	Estimates relative cost to upgrade avionics with new technology	• Global Air Navigation Plan for CNS/ATM Systems—ICAO Doc. 9750 (5.14) • 11th ICAO Air Navigation Conference (Sept./Oct. 2003) Recommendation 7/5, Number 4
8	Spectrum	Gauges the likelihood of obtaining the proper allocation of the target spectrum and the compatibility of proposed technology with existing aeronautical systems in target band (second component not included in prescreening)	• Global Air Navigation Plan for CNS/ATM Systems—ICAO Doc. 9750 (statement of ICAO policy on CNS/ATM systems implementation and operation, appendix A to chapter 2, pp. I to 2–8)
9	Security—authentication and integrity	Provides an assessment of technology authentication and data integrity capabilities	• COCR security requirements (Section 4.3.6, Table 4–15) • Global Air Navigation Plan for CNS/ATM Systems—ICAO Doc. 9750 (statement of ICAO policy on CNS/ATM systems implementation and operation, appendix A to chapter 2, pp. I to 2–8)
10	Security—robustness to interference	Provides a relative assessment of technology robustness to interference	• COCR security requirements (Section 4.3.6, Table 4–15)
11	Transition	Assesses acceptable transition characteristics, including • Return on partial investment • Ease of technical migration (spectral and physical) • Ease of operational migration (air and ground users)	• Global Air Navigation Plan for CNS/ATM Systems—ICAO Doc. 9750 (statement of ICAO policy on CNS/ATM systems implementation and operation, appendix A to chapter 2, pp. I to 2–8)

3.2 Criteria Metrics

Metrics provide a measure of technology performance specific to particular evaluation criteria. As described in Section 2.2, the approach for defining metrics for the FCS technology evaluation applied performance requirements of the COCR; specific implementation needs (e.g., timeframe based on the FCS roadmap); or characteristics that support relative comparison of technology performance and/or applicability to develop a trilevel rating system. This rating system included measures associated with green (meets/proven to meet requirements/most applicable), yellow (partially meets requirements, partially applicable or can be easily modified to do so), and red (does not meet requirements/is not applicable and cannot be easily modified to do so) for each criterion.

An initial set of criteria metrics was defined during the FCS Phase I study period and updated during the Phase II study period. During the FCS Phase III technology investigation study period, metrics were reviewed and updated to reflect stakeholder feedback received on interim evaluation results as well as updates to the COCR. A full set of evaluation metrics associated with the derived evaluation criteria is provided in table 5.

TABLE 5.—EVALUATION CRITERIA METRIC DEFINITIONS

	Evaluation criterion		Metrics
1	Provides ATS A/G data services within requirements (sans A–EXEC)	A—Capacity	• GREEN: Provides capability to provision ATS services meeting capacity requirements for Phase II/high density across all continental flight domains (or applicable domain for domain-specific analysis) • YELLOW: Provides capability to provision ATS services meeting capacity requirements for Phase II/high density in at least one (but not all) flight domain (or in the applicable flight domain for domain-specific analysis); or meeting capacity requirements for low density in at least one flight domain (or in the applicable flight domain for domain-specific analysis), when high density capacity requirements are not met in any flight domains • RED: Does not provide sufficient capability to provision ATS services meeting capacity requirements for Phase II high and low density in any flight domain (or for the applicable domain for domain-specific analysis)
		B—Number of users (PIAC)	• GREEN: Provides capability to provision ATS services meeting PIAC requirements for Phase II/high density across all continental flight domains (or applicable domain for domain-specific analysis) • YELLOW: Provides capability to provision ATS services meeting PIAC requirements for Phase II high density in at least one (but not all) flight domain (or in the applicable flight domain for domain-specific analysis); or meeting PIAC requirements for low density in at least one flight domain (or in the applicable flight domain for domain-specific analysis), when high density capacity requirements are not met in any flight domains • RED: Does not provide sufficient capability to provision ATS services meeting PIAC requirements for Phase II high and low density in any flight domain (or for the applicable domain for domain-specific analysis)
		C—QoS	• GREEN: Provides capability to offer CoS (e.g., prioritization) capability for ATS services • YELLOW: Technology can be readily modified to offer CoS (e.g., prioritization) capability for ATS services • RED: Technology cannot be easily modified to offer CoS (e.g., prioritization) capability for ATS services
		D—Environment	• This provides a measure of a technology's ability to provision ATS services within the COCR-defined airspace environment (accounts for time-varying and time-dispersive channel effects) • GREEN: Technology performance in intended channel is characterized by flat/slow fading • YELLOW: Technology can be readily modified to be characterized by flat/slow fading (e.g., physical layer modifications and equalization techniques) • RED: Technology cannot be easily modified to be characterized by flat/slow fading
2	Provides ATS and AOC A/G data services within requirements (sans A–EXEC)	A—Capacity	• GREEN: Provides capability to provision ATS and AOC services meeting capacity requirements for Phase II/high density across all continental flight domains (or applicable domain for domain-specific analysis) • YELLOW: Provides capability to provision ATS and AOC services meeting capacity requirements for Phase II/high density in at least one (but not all) flight domain (or in the applicable flight domain for domain-specific analysis); or meeting capacity requirements for low density in at least one flight domain (or in the applicable flight domain for domain-specific analysis),when high density capacity requirements are not met in any flight domains • RED: Does not provide sufficient capability to provision ATS and AOC services meeting capacity requirements for Phase II high and low density in any flight domain (or for the applicable domain for domain-specific analysis)

TABLE 5.—CONTINUED.

	Evaluation criterion		Metrics
2	Provides ATS and AOC A/G data services within requirements (sans A–EXEC)	B—Number of users (PIAC)	• GREEN: Provides capability to provision ATS and AOC services meeting PIAC requirements for Phase II/high density across all continental flight domains (or applicable domain for domain-specific analysis) • YELLOW: Provides capability to provision ATS and AOC services meeting PIAC requirements for Phase II high density in at least one (but not all) flight domain (or in the applicable flight domain for domain-specific analysis); or meeting PIAC requirements for low density in at least one flight domain (or in the applicable flight domain for domain-specific analysis), when high density capacity requirements are not met in any flight domains • RED: Does not provide sufficient capability to provision ATS and AOC services meeting PIAC requirements for Phase II high and low density in any flight domain (or for the applicable domain for domain-specific analysis)
		C—QoS	• GREEN: Provides capability to offer class of service (CoS) (e.g., prioritization) capability for ATS services • YELLOW: Technology can be readily modified to offer CoS (e.g., prioritization) capability for ATS services • RED: Technology cannot be easily modified to offer CoS (e.g., prioritization) capability for ATS services
		D—Environment	• This provides a measure of a technology's ability to provision ATS services within the COCR-defined airspace environment (accounts for time varying and time dispersive channel effects) • GREEN: Technology performance in intended channel is characterized by flat/slow fading • YELLOW: Technology can be readily modified to be characterized by flat/slow fading (e.g. physical layer modifications and equalization techniques) • RED: Technology cannot be easily modified to be characterized by flat/slow fading
3	Technical readiness level		• Anticipated need (per FCS roadmap) is implementation in about 12 years; TRL 6 or above is consider to be achievable with low risk; TRL 3 or below has significant risk • GREEN: Technology is at level 6 or above • YELLOW: Technology assessed at level 4 or 5 • RED: Technology is assessed at level 3 or below
4	Standardization status		• This criterion is an indicator of technology maturity. Existence of some standardized technical descriptions is indicative of some level of technology maturity. Existence of aeronautical specifications, required for an aeronautical system, e.g., ICAO, Radio Technical Commission for Aeronautics (RTCA), Eurocae specs, is indicative of a high level of maturity for the application of interest (e.g., FRS). The existence of aeronautical standards is significant risk mitigation factor for implementation; standardization of the technology in other forums (e.g., commercial forums) provides some implementation risk mitigation • GREEN: Technology has publicly available aeronautical standards • YELLOW: Technology are supported by a publicly available commercial standard • RED: Technology for which supporting standards does not exist or is not publicly available
5	Certification		• This criteria is another indicator of technical maturity; technologies that are certified or are in the certification process pose significantly less risk for implementation, while those technologies specifically developed for safety-related services may also provide risk mitigation for meeting certification requirements • GREEN: Technology (products) developed for the aviation industry and either currently certified or known to be in the certification process • YELLOW: Technology developed for safety-related services (public safety and the like) but not currently in the aviation certification process • RED: All other cases other than green or yellow

TABLE 5.—CONTINUED.

	Evaluation criterion	Metrics
6	Ground infrastructure cost	• Relative cost to replace or upgrade infrastructure with the necessary availability and diversity requirements for critical services, as a replacement to VHF DSB–AM It is evaluated as the relative cost to provision services in the defined evaluation scenarios (as either a sector- or area-based implementation). A candidate not able to project a signal at a large range from a single ground station would require multiple replacement ground stations; the evaluation accounts for unusual maintenance requirements of a candidate (to include leased services, maintenance of Network Operational Centers, extraordinary Telco bandwidth requirements, etc.) • GREEN: low relative cost • YELLOW: moderate relative cost • RED: high relative cost
7	Avionics cost	• This criterion provides a measure of the relative cost to upgrade avionics with a new technology relative to the cost to upgrade avionics with new candidate data link technology but maintain VHF DSB–AM capability • GREEN: low relative cost • YELLOW: moderate relative cost • RED: high relative cost
8	Spectrum	• Gauges the likelihood of obtaining the proper allocation of the target spectrum and the compatibility of proposed technology with existing aeronautical systems in target band (second component not included in prescreening) • GREEN: Technology proven (e.g., tested) to be deployable in target spectrum band without either reallocation of existing equipment frequencies or requiring modification to existing aeronautical equipment (based on cosite tests) • YELLOW: Technology considered to be deployable in the intended band without either reallocation of existing equipment or requiring modification to existing aeronautical equipment (based on cosite considerations) • RED: Technology requires reallocation of existing equipment frequencies or modification to existing aeronautical equipment for deployment in target spectrum band
9	Security—Authentication and integrity	• Provides an assessment of technology authentication and data integrity capabilities to address COCR FCI security requirements on this topic (R.FCI–Sec2.a, R.FCI–Sec2.b "…FCI shall support message authentication and integrity…") • GREEN: Candidate technology provides authentication and integrity functionality • YELLOW: Candidate technology can be modified to provide authentication and integrity functionality • RED: Candidate cannot support and cannot be modified to provide authentication and integrity functionality
10	Security—Robustness to interference	• Provides a relative assessment of technology robustness to interference to address COCR security requirements that indicate need for FCI to provide "reliability and robustness to mitigate denial of service attacks;" Inherent technology capability (e.g., frequency hopping multiple access techniques) may address these requirements; excess link margin in technology deployment can also support these requirements • GREEN: Technology provides significant robustness to interference (e.g., technology uses specific techniques for interference protection (such as frequency hopping) or can be effectively deployed with significant excess margin (e.g., ≥12 dB)) • YELLOW: Technology provides moderate robustness to interference (e.g., technology does not provide specific techniques for interference protection, but can be effectively deployed with excess margin (3 to 11 dB)) • RED: Technology does provide specific techniques for interference protection nor can it effectively be deployed with excess link margin (e.g., margin is less than 3 dB)

TABLE 5.—CONCLUDED.

	Evaluation criterion	Metrics
11	Transition	• Assesses acceptable transition characteristics, including • Return on partial investment • Ease of technical migration (spectral and physical) • Ease of operational migration (air and ground users) • GREEN: Technology meets all of the following conditions: • Can be deployed to achieve return on investment (ROI) (i.e., service provision and/or benefit) without requiring full investment/deployment • Can be operated simultaneously (in adjacent airspace) with legacy A/G communication systems (i.e., you can bring the new system up incrementally while bringing down the legacy system incrementally) • Initial transition can be nearly operationally transparent (i.e., initially users do not have to significantly alter procedures) or features that drive changes in operational procedures can be employed incrementally • YELLOW: Cases other than defined in green or red • RED: Technology meets all of the following conditions: • Provides little or no ROI without full investment/deployment • Requires operation of legacy A/G communication to be widely discontinued in order to operate • Initial transition requires significant changes to operational procedures

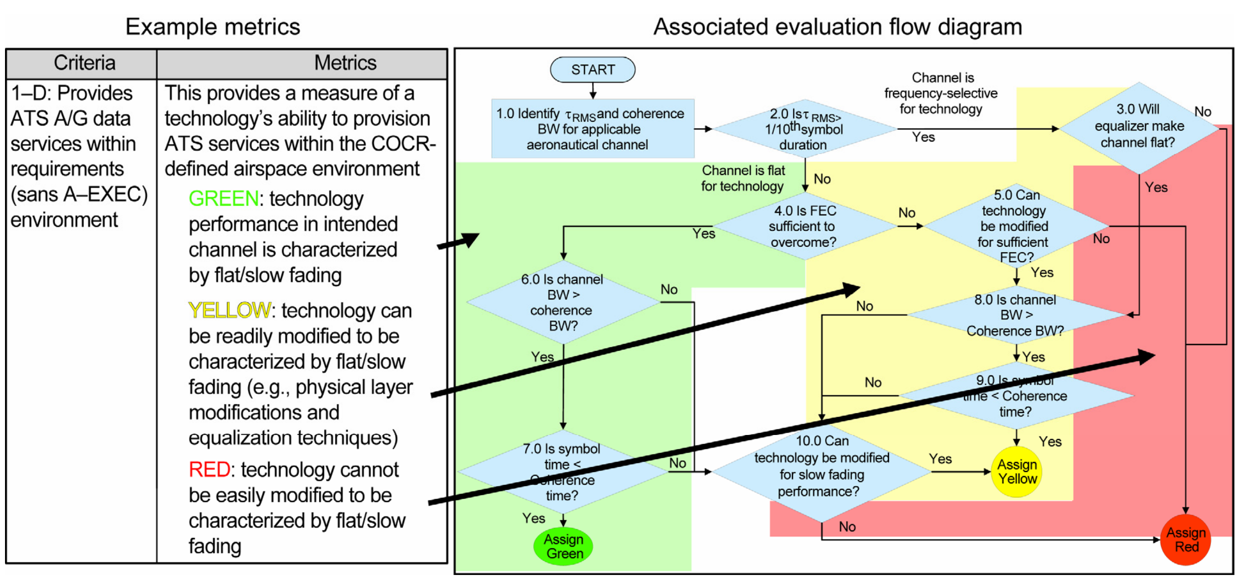


Figure 16.—Translating metrics into evaluation process flow diagrams.

3.3 Evaluation Process Flow Diagrams

To uniformly apply the evaluation criteria to the technologies, a set of evaluation process diagrams were created. These diagrams document the steps performed to conduct technology analysis using a flow diagram format. Each evaluation flow diagram uses metric definitions to define analysis steps and decision items that led to a green, yellow, or red rating result. An example of how metrics were translated into flow diagrams is provided in figure 16.

In figure 16, for the criterion addressing performance of a technology in the anticipated aeronautical channel, a green rating is assigned to technology performance characterized by flat/slow fading. The flow diagram includes several steps to identify the RMS delay spread (τ_{RMS}) and coherence time of the channel and uses this information with consideration of technology characteristics (including symbol duration, coding capability, and channel bandwidth) to assess whether the channel will be considered a flat/slow fading channel for the given technology. If so, following the green path through the flow diagram, a green score is achieved. A similar set of steps corresponding to yellow and red rating definitions are also included in the diagram.

Similar flow diagrams developed for all evaluation criteria. Each includes flow paths that correspond to green, yellow, and red ratings specific to the criterion metrics. The full set of evaluation flow diagrams used for the FCS technology investigation criteria is provided in appendix A.

4.0 Technology Screening

This section describes the work performed to identify the set of technologies from the technology inventory most applicable to a FRS based on operating concepts defined in COCR. Performing a technology screening helps identify the most promising technology candidates on which to focus detailed technology evaluations. An inventory of technologies were surveyed, studied, and evaluated in the FCS Phase I study. An initial screening of the technology inventory was conducted during the FCS Phase II study, which included the use of COCR Version 1 performance measures as reference values in the screening process. The screening process was reapplied during the FCS Phase III study to accommodate changes and updates in COCR Version 2.

The following subsections describe the technology inventory considered in the FCS, how they are evaluated in the screening process, and technology screening results. A final subsection provides a comparison of the provided screening results with the set of technologies down-selected by the EUROCONTROL FCS team for further assessment as FRS candidates.

4.1 Complete Technology Inventory

As noted previously, the majority of the effort to identify technologies for consideration in the FCS was performed during the FCS Phase I investigation (2004). Through technology surveys and NASA's release of requests for information (RFIs), a set of over 50 technologies was identified for consideration as FRS candidates (ref. 7). The identified technologies were grouped into larger technology families, characterized by similarities in user requirements, services offered, and reference and physical architectures. During the FCS Phase II task, the identified technology inventory was augmented to include three additional technologies introduced and described in meetings and working papers, including those presented at ICAO ACP WG–C and other aeronautical communication forums including the NASA Integrated Communication, Navigation, and Surveillance Conference and Workshop. Specifically, these three additional technologies include

- L-band digital link (LDL) (refs. 9 to 11)—This candidate is the proposed narrowband VHF digital link mode 3 (VDL3) technology band-shifted for broadband implementation (with a redesigned physical layer)
- L-band enhanced time division multiple access (E–TDMA) (ref. 12)—This candidate is the proposed narrowband E–TDMA technology band-shifted for broadband implementation (with a redesigned physical layer)
- Custom Satellite System (ref. 13)—This candidate is a custom-designed satellite implementation (similar to proposals for satellite data link system (SDLS)) specifically designed for aeronautical communications.

In the Phase II interim report, it was noted that other technology concepts had been recently conceptualized or named in aeronautical forums; however, no technical description yet existed to support technology evaluation and therefore those concepts were not added to the inventory. Other modifications to the technology inventory made in Phase II study were to accommodate the following observations:

- For the cellular technology family, there is a clear evolutionary path from first-generation systems to second- and third-generation systems and beyond. Because of the strong evolutionary environment, the first- and second-generation systems are being superseded, and the corresponding older technologies are slowly becoming obsolete. Therefore, the consideration of older technologies provides no value for aeronautical communications technology analysis, and cellular standards directly replaced by mature standards were not maintained as stand-alone technology candidates. Affected candidates include IS136 (superseded by global system for mobile communications (GSM) and code division multiple access (CDMA)2000), IS–95 A/B (superseded by CDMA2000), and CDMA 2000 1xRTT (superseded by CDMA 2000 1xEV).

- For the 802 wireless technologies, the European Telecommunications Standards Institute (ETSI) and IEEE standards bodies are working to harmonize the defined standards. In some cases, the ETSI standards are a subset of the IEEE standards definition (e.g., HIPERMAN standard is a subset of 802.16). In other cases, the similarities are such that separate consideration of the standards is not warranted. As a result, HIPERMAN, HIPERPAN, and HIPERLAN are not explicitly defined as candidates; rather, they are considered under the umbrella of 802.16, 802.15, and 802.11, respectively.
- Association of Public-Safety Communications Officers (APCO_ P25 has been defined for two phases of operation (namely, Phases I and II). Phase I has mature standards for a digital frequency division multiple access (FDMA) trunked and conventional radio configuration using 12.5-kHz channels. Development of the Phase II standards, for a two-slot time division multiple access (TDMA) configuration on 12.5-kHz frequency division multiplexing (FDM) channels, is ongoing. At this time, the Phase II standards are not publicly available, and consideration of this mode as a separate technology candidate is not warranted. As such, the P25 technology candidate is only for the Phase I definition.
- Project MESA, within the public safety radio standards family, is a concept for ETSI and Telecommunications Industry Association (TIA) to collaborate on a mobile broadband specification for public safety. Available documents specific to Project MESA include a statement of requirements and system overview. The system overview indicates that this specification is a communication architecture, rather than a specific waveform specification (ref. 14). Because of a lack of specific technical specifications and its definition as a communication architecture, this concept was not maintained in the technology inventory.
- VDL3 and VDL3 with single antenna interference cancellation (SAIC) are essentially the same technology with VDL3 with SAIC proposed as a means of increasing VDL3 channel capacity through the use of a receiver signal processing enhancement. Separate consideration of this capability as a separate technology is not warranted; thus only one VDL3 technology candidate was considered.
- Enhanced position location reporting system (EPLRS) is a military technology with essentially the same air-interface and functions as Link-16. While defined for 400-MHz ground tactical operations, its Link-16 counter part is defined for 1 GHz (more in line with L-band channel of interest) with available avionics. Because of the technology similarities, better applicability of Link-16 to civil aeronautical applications, and more readily available technical information for Link-16, EPLS was removed from the inventory. It was noted, however, that if Link-16 was found to perform well, that additional consideration should be given to EPLRS.
- Finally, joint tactical radio system (JTRS) is defined as a common architecture framework for software radios rather than a specific waveform. As such, it is not truly a technology candidate and was not maintained in the inventory.

Some additional changes were made to the technology during the FCS Phase III task year. They included the following:

- Change custom broadband candidate “B–VHF (MC–CDMA) (at L-band)” to “broadband aeronautical multicarrier communications (B–AMC)” to reflect an evolution of the technology concept that includes the definition of the technology for the aeronautical L-band spectrum and accommodation of both A/G and A/A communication capabilities.

- Change custom broadband candidate “L-band E–TDMA” to “all-purpose multichannel aviation communication system (AMACS)” to reflect an evolution of the technology concept that includes combining the best features of E–TDMA, VDL Mode 4 (VDL4) and potential aspects of universal access transceiver (UAT) and LDL for definition of a custom aeronautical communication solution defined for implementation in the aeronautical L-band spectrum.
- Remove Link-16 as this candidate is defined for use in the JTRS architecture framework and current deployment in the aeronautical L-band spectrum (the identified applicable band for use of this technology as a future aeronautical data link) has reached its maximum pulse density saturation. Direction from the FCS steering group participants (specifically, FAA spectrum office representatives) and documented analysis of this technology in FAA reports (ref. 15) have indicated that this is not a viable candidate for aeronautical communications in L-band.
- Remove Connexion by Boeing as it was announced on August 17, 2006, that the service was to be discontinued.

Accommodating the changes noted above, the resulting candidate set of technologies investigated in this study is shown in table 6.

TABLE 6.— FCS TECHNOLOGIES INVENTORY (FINAL)

Technology family	Candidates
Cellular telephony derivatives	WCDMA (U.S.)/UMTS FDD (Europe), TD–CDMA (U.S.)/UMTS TDD (Europe), CDMA2000 3x, CDMA2000 1xEV, GSM/GPRS/EDGE, TD–SCDMA, DECT
IEEE 802 wireless derivatives	IEEE 802.11, IEEE 802.15, IEEE 802.16, IEEE 802.20
Public safety and specialized mobile radio	APCO P25, TETRA Release 1, TETRAPOL, IDRA, iDEN, enhanced digital access communications system (EDACS), APCO P34, TETRA Release 2 (TAPS), TETRA Release 2 (TEDS)
Satellite and other over-horizon communication	SDLS, Swift Broadband (Aero B–GAN), Iridium, GlobalStar, Thuraya, Integrated Global Surveillance and Guidance System (IGSAGS), HF Data Link, Digital Audio Broadcast, Custom Satellite System
Custom narrowband VHF solutions	VDL Mode 2, VDL Mode 3, VDL Mode E, VDL Mode 4, E–TDMA
Custom broadband	Airport data link (ADL), Flash–OFDM, UAT, Mode–S, B–AMC, LDL, AMACS
Military	SINCGARS, HAVEQUICK
Other	Airline passenger communications (APC) Telephony

The first part of the technology evaluation process specific to candidate technologies was to screen the technologies to identify those most promising for applicability to the FRS. To apply the screening process, a high-level use concept for how the technology would be applied in the context of a future aeronautical communication infrastructure was required. During the Phase I study, each technology family was described and a use concept for individual technology candidates describing applicable services and high-level architecture concepts was defined (ref. 15).

During the Phase II study, a summary of the technology descriptions and key performance characteristics required for technology screening were documented in the interim FCS Phase II report. This information, updated to reflect changes in the technology inventory during Phase III study, is provided in this report in appendix B.

4.2 Technology Screening

Section 2.3 describes the methodology applied to perform technology screening. A first step in the screening process was to identify those technologies that inherently rely on unprotected spectrum and remove them from consideration. The technologies removed from further consideration based on this screening step included GlobalStar, Digital Audio Broadcast, and APC Telephony.

The next step in the screening was to consider technology performance specific to the defined screening measures. As noted in Section 2.3, the applied screening measures included the ability to use protected (safety and regularity of flight) spectrum (one aspect of the spectrum criterion); the data loading capability (one aspect of “meets ATS/AOC service requirements” criteria); and the technology communication range (relating to “meets ATC/AOC service requirements” and “cost” criteria), where specific values for loading and range are traceable to the COCR. To perform this part of the screening, information captured during the definition of the technology use concepts was required. Table 7 provides a set of key use concept parameters for screening summarizing material captured in appendix B.

TABLE 7.—SUMMARY OF TECHNOLOGY CONCEPT OF USE PARAMETERS FOR SCREENING

Technology	Data capacity, kbps	Communication range, nmi	Operational configuration and notes
1. WCDMA(U.S.)/ UMTS FDD (Eur)	[a]960	[b]162	In general this technology is considered for deployment in the DME band. The concept of use for cellular services assumes the use of packet data services.
2. TD–CDMA(U.S.)/ UMTS TDD (Eur)	2000 (ref. 7)	16.2 (ref. 7)	
3. CDMA2000 3x	[c]460.8	[d]54	
4. CDMA 1xEV	[e]153.6	[f]54	
5. GSM/GPRS/EDGE	400 (ref. 7)	18.9 (ref. 7)	
6. TD–SCDMA	[g]2000	[g]16.2	
7. DECT	[g]552	[g]0.2	
8. IEEE 802.11	[g]54000	[g]0.54	For the IEEE 802 family, the applicable aeronautical frequency band is specified to be the MLS band; it can accommodate wideband signals and is within the design range of both 802.16 and 802.11 standards. Because of short design range and support for low-speed mobile platforms, 802.11 and 802.16 limited to consideration for the APT domain. Applicable bearer services include Unsolicited Grant Service and Real-Time Polling Service
9. IEEE 802.15	[g]55000	[g]0.005	
10. IEEE 802.16	[h]13800	[i]19.9	
11. IEEE 802.20	2000 (ref. 7)	24.3 (ref. 8)	
12. APCO P25	[j]9.6	18.9 (ref. 7)	Public safety technology candidates are considered in the context of the L-band aeronautical spectrum. Specific services applicable to the FRS varied some with technology specific offerings, but all included packet data services. For TIA–902 (P34), two physical layer standards are available. The SAM physical layer standard was selected for this application (ref. 8).
13. TETRA Release 1	[k]30.375	9.5 (ref. 7)	
14. TETRAPOL	8 (ref. 19)	15.1 (ref. 19)	
15. IDRA	64 (ref. 19)	21.6 (ref. 19)	
16. iDEN	64 (ref. 19)	21.6 (ref. 19)	
17. EDACS	9.6 (ref. 19)	[l]160	
18. APCO P34	[m]173	[n]162	
19. TETRA Release 2 (TAPS)	473 (ref. 22)	2.7 (ref. 22)	
20. TETRA Release 2 (TEDS)	691(ref. 23)	2.7 (ref. 8)	
21. Custom Satellite System (e.g., SDLS)[o]	30 (per user)[p]	NA	When formulating concepts of use for satellite systems, several issues were noted. These include the need to investigate provisioned availability; the possible constraints associated with expensive, heavy, and high-power consumption satellite avionics; and call setup times. For the satellite systems, the concepts of use generally follow close to use concepts offered to existing mobile users. An exception is the Inmarsat where concept that included uplink to the satellite from the ATC facility on an L-band connection (e.g., as a fixed mobile) was proposed. A similar architecture was proposed for consideration for the Iridium candidate (ref. 8).
21. Inmarsat Swift Broadband	32 (per user, QoS low end); 256 (per user, QoS high end) (ref. 24)	NA	
23. Iridium	2.4 (per user) (ref. 8)	NA	
24. Thuraya	9.6 (per user) (ref. 8)	NA	
25. IGSAGS	30 (per user) (ref. 8)	NA	
26. HF Data Link	1.8 (per user) (ref. 8)	NA	
27. VDL Mode 2	[q]10	[r]195	The custom narrowband technologies were each designed for the needs of aviation and thus provide an array of connection-oriented and connectionless services. The focus on this study is on the data services provided. As such, the focus for VDL3 is the 3T service.
28. VDL Mode 3	[s]14.4	[t]185.1	
29. VDL Mode E	4.8 (ref. 8)	[u]185.1	
30. VDL Mode 4	[v]14.4	[w]202.5	
31. E–TDMA	[x]14.4	[y]200	

TABLE 7.—CONTINUED.

Technology	Data capacity, kbps	Communication range, nmi	Operational configuration and notes
32. ADL	2048 (ref. 8)	[z]30	This family addresses a range of wideband technologies; some are currently implemented to provide aeronautical surveillance services; others are specific to wireless commercial standards and yet others are proposed custom solutions for meeting the needs of aviation. It should be noted that UAT and Mode S cannot support addressed data and thus their concept of use is limited to broadcast applications. For LDL, assume a data-only configuration (i.e., mode 5T or another mode using only data slots).
33. Flash-OFDM	3200 (ref. 30)	2.2 (ref. 30)	
34. UAT	[aa]3.712 (per user)	[bb]200	
35. Mode-S	[cc]0.112 (per user)	[dd]100	
36. B–AMC	[ee]421.2	[ff]200	
37. LDL	[gg]100	268 (ref. 12)	
38. AMACS	[hh]100	[ii]200	
39. SINCGARS	16 (ref. 8)	21.6 (ref. 8)	The military technologies provide many services that are similar to the functional needs of an ATS communication system.
40. HAVEQUICK	16 (ref. 8)	260.7 (ref. 8)	

[a]The system capacity is limited by the uplink data rate. (ref. 16). The data rate is asymmetric and the system capacity is limited by the uplink data rate. The maximum uplink data rate is 960 kbps. This limit occurs because the TDM 10-ms frames provide up to 9600 CDMA user data bits (maximum value assuming minimum CDMA spreading factor of 4). (100 frames times 9600 bits per frame gives the max. uplink data rate of 960 kbps.) Assume CDMA spreading factor of 4 to maximize data capacity (and mobile antenna diversity and high-gain antennas are not necessarily available).

[b]Although there are no explicit limitations, the study identifies cell-size drivers including propagation environment, type of antennas used and antenna diversity (ref. 16). The study indicates that in the C-band environment, cell sizes from 10 to 100 km can be achieved (with the latter employing antenna diversity on mobile user and high-gain, sectorized antennas on the ground). For the VHF environment, the study calculates cell size ranges from 300 to 600 km (with the latter accounting for antenna diversity on the mobile and high-gain ground antennas). Since the WCDMA concept of use may not employ mobile antenna diversity and high-gain ground antennas, we use the maximum derived range (300 km) without employing these techniques. 300 km = 162 nmi.

[c]CDMA2000 3x comprises multiple (3) CDMA2000 1xEV components. The maximum reverse link rate for CDMA2000 1xEV was multiplied by 3 to arrive at this data rate.

[d]Assumed to be the same as CDMA2000 1xEVDO.

[e]The maximum reverse link (MS to BS) is 153.6 kbps (range is 9.6 kbps through 153.6 kbps). The maximum forward link is 2.5 Mbps (range is 38.4 kbps through 2.4576 Mbps) (ref. 17).

[f]“CDMA2000 has a maximum cell size of 100 km. This limit is traceable to the design feature that uses a common spreading code from all ground stations with a phase offset large enough to unambiguously distinguish cell transmissions from that of its neighbors.” (ref. 7).

[g] Ref. 7 shows that up to 2 Mbps peak data rate is supported by a single channel in a TD–SCDMA system.

[h]This value is the minimum assuming 10-MHz channel, Tb or 22 2/9 μs and Tg = 1/4 of this (and QPSK modulation); see concept of use in ref. 7 for additional detail.

[i]Calculated from link budget in ref. 19. The link budget provides an allowable (free space) path loss of 128 nmi, which corresponds to 12.9 nm for a frequency of 2.5 GHz. or 6.28 nmi at 5.150 GHz without range extension methods (mesh hops or higher power Txs); however, the link budget included 10 dB for “penetration” loss. This is because the WiMAX concept accommodates subscriber equipment inside of houses. This wall penetration factor was not deemed applicable for APT surface applications. Hence, a total loss of 138 dB was used, which corresponds to 19.9 nmi at 5150 MHz.

[j]From TSB–102A: Data transmission over the radiofrequency (RF) link shall be allowed by the system at a minimum gross bit rate of 9600 bps with minimal retransmissions. The net bit rate available after deduction of overhead for error correction and retransmission is 5.8 kbps. Because of the concept of use (direct mode conventional system, with voice and data shared on the same channel) the system will not provide much data capacity.

[k]ETSI EN 300 392–2 V2.4.2 (2004–02); Terrestrial Trunked Radio (TETRA); voice plus data (V+D); Part 2: Air Interface (AI): 4.7 Modulation—the modulation scheme is Pi/4-shifted differential quaternary phase shift keying (Pi/4-DQPSK) with root-raised cosine modulation filter and a rolloff factor of 0.35. The modulation rate is 36 kbit/s.

[l]In ref. 19, EDACS is FDM, and the comm. range is design-dependent. We assume the technology is power limited, and assign it a max. range commensurate with LOS at FL 180.

[m]The TIA–902 (P34) air interface varies between 81.4 and 799.2 kbps for the optional air interface (IOTA). The data rate provided depends on modulation complexity and channel bandwidth. The rate shown is for the 100-kHz channel with a 2ASK modulation type (lowest possible modulation complexity). The 150 kHz channel with 2ASK modulation provides higher data rate (266.4); however, this is not needed. Also, 8ASK, while providing a much higher data rate, would not be appropriate for an area communications system (insufficient range). Meanwhile the 2ASK meets the COCR sector requirements and likely closes the link in the specified distance (ref. 20).

[n]Total guard time includes ramp-down plus additional allocated guard time. Per ref. 20, the ramp-down plus guard time is equal to 1 ms. This is equivalent to range of 162 nm.

TABLE 7.—CONCLUDED.

Technology	Data capacity, kbps	Comm. range, nmi	Operational configuration and notes

[o]Note that SDLS and Custom Satellite System have been combined; Custom Satellite System is a more generic representation of SDLS. Requirements for SDLS are still underdeveloped, so they may accommodate derived requirements for a future aeronautical communication system as those of a custom satellite system. These items are essentially the same; one is a more general representation.

[p]SDLS requirements indicate that spot beam provides between 6.4 and 30 kbps in spot beams; for a general custom satellite solution, this value is responsive to maximum required value (per-user) of 28.6 (ref. 8).

[q]Ref. 7 shows fixed at 31.5 kbps raw channel burst data rate but with channel access mechanism (CSMA) MAC, throughput is less than 20 kbps. Note that the CSMA reduces effective information throughput to less than 10 kbps. 10 kbps is used repeatedly in industry glossies on this technology and was used here; however, theory would indicate that the actual throughput will be somewhat less, perhaps as low as 28 percent of 31.5 kbps, or 8.82 kbps.

[r]See ref. 24, fig. 1.22. From this figure, the maximum range was (uplink) above FL 350; the value was taken from RC trials.

[s]Mode 3T has up to 3 bursts per frame (120 ms) that can be used for user data. Each burst provides 192 symbols for user data. Each symbol is 3 bits. This is not the information throughput, as channel coding is included in the above calculation, i.e., the 14.4 is a raw channel data rate and the info throughput is less (by the coding overhead) (ref. 26).

[t]We have assumed the smallest guard time is between an uplink M-burst and a downlink V/D burst, or about 65 symbol periods between LBACS, minus the length of an uplink M-burst (53 symbols) or about 12 symbols. At a rate of 10 500 symbols/s, this gives a maximum communications slant range of 185 nmi. See ref. 25 for more details.

[u]Assumed that the same assumptions as for VDL3 apply.

[v]The maximum number of time slots per transmission is 75 (refs. 26 and 27); each time slot has 192 bits for user data.

[w]Per ref. 27, Segment E is the guard interval of duration of about 1250 μs (equivalent to about 205 nmi guard range), which includes segment D.

[x]No information was provided for data rate so VDL3 max. throughput rate is assumed since PHYS layer proposed to use D8PSK

[y]The use of statistical self synchronization and a small guard band seems to indicate that the technology may become unstable at very large distances. Regardless, RLOS was used here.

[z]ADL Technology Description in ref. 28.

[aa]The ground station is allocated one 464 byte frame/s, which is much higher than any of the aircraft allocations. This value is used to derive provided data throughput (ref. 7).

[bb]Maximum range supported: Similar to VHF: 200 nm at 30 000 ft, 80 nm at 5000 ft. The UAT proposes a series of ground stations to provide coverage over the U.S. at low (5000 ft) altitude. We assume that the UAT maximum range is limited by LOS (ref. 29).

[cc]Reference Mode S technology description.doc. Used the data per squitter (112 bits) divided by the max squitter rate (1/s).

[dd]Reference Mode S technology description.doc. Maximum range assuming LOS exists; range performance depends on traffic density and the 1090 MHz interference environment (i.e., ADS–B uses the same frequency as ATC transponder-based surveillance). In low-density environments, range performance is typically 100+ nmi, while in a high-traffic density and 1090 interference environments, the range performance is on the order of 50 to 60 nmi with current receiver techniques (improved processing techniques have been identified that are expected to provide range performance to 90 nm in dense environments).

[ee]Assumption based on B–VHF capabilities (ref. 6–Appendix page indicates a maximum of 280.8 ksymbols/s as a theoretical maximum signal rate. Using 64 quadrature amplitude modulation(QAM) as the modulation type, this equates to a maximum bit rate of 1263.6 kbps (64 QAM and rate 3/4 coding). However, we cannot expect to close the link with this type of modulation. As a conservative measure, and as was done for all of the other adaptive modulation technologies, the lowest complexity modulation scheme and lowest coding rate was chosen. Hence, the data rate given is for QPSK, 280.8 kS/s, and rate 3/4 coding (there is a rate = 1 coding defined, but is not likely that we can get by with no coding)); number to be revised as B–AMC specific values become available.

[ff]Assumption (B–VHF estimated range was provided in ICAO ACP Working paper (ref. 28); number to be revised as B–AMC details become available).

[gg]The specifics of the air interface are under development. Initial suggestions of 62.5 kbps are flexible. 100 kbps was selected to ensure competition with technologies.

[hh]Insufficient data is available, thus this is an assumed data rate (technology is being specified as an FRS candidate in L-band. Therefore, it should provide data rate similar to other custom aeronautical standards (e.g., LDL)).

[ii]Communication range value is assumed; it is envisioned that a custom broadband solution would be engineered with a long communication range.

Based on the information defined in the technology use concepts and summarized in table 7, the screening filter was applied to the technology candidates, providing a comparison of technology data rate performance (and range for terrestrial-based technologies) against reference values derived from the COCR. As described in Section 2.3, this comparison was captured using “tricolor” screening charts with unacceptable, marginal, and good screening performance regions inferred from COCR requirements, as introduced in figures 5 and 6 and repeated in figure 17.

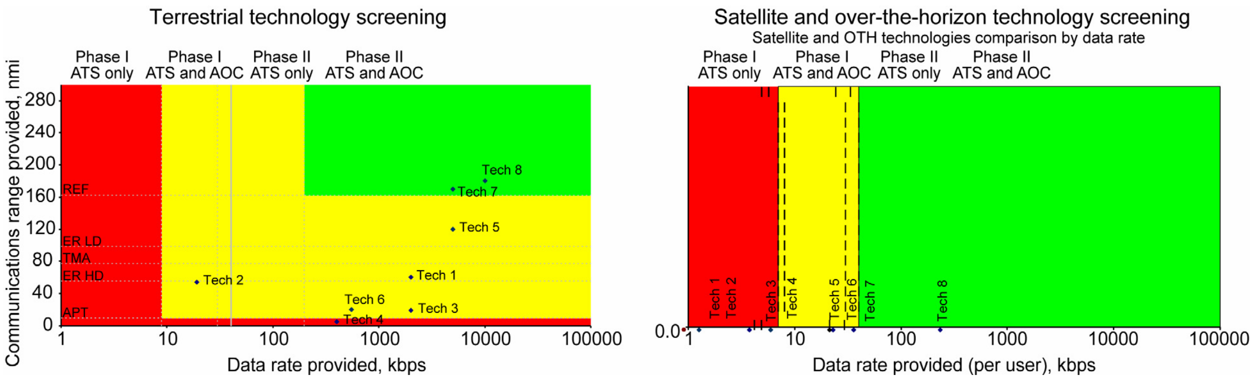


Figure 17.—Reference screening plots.

The reference values used in the initial screening process, which drive the location of color-coded regions of the screening graphs, corresponded to information provided in COCR Version 1.[8] To address updates in COCR Version 2, which resulted in new reference values and changes to the color-coded regions of the graphs, the screening process was reapplied during the Phase III study.

Each technology was assessed and plotted on the tricolor charts. The evaluated technology data rate corresponded to the technology physical layer capability and did not explicitly account for protocol overhead, as applicable, and thus was a barometer of ability to accommodate reference capacity requirements. The most promising technologies from each technology family were selected to bring forward from the screening process for detailed evaluation. Depending on family performance, none, one, or multiple technology candidates were selected.

Figure 18 provides a summary of the screening process applied to all terrestrial technologies. Note that technologies within families that provide good communication range and provide a capability that may meet or come close to meeting COCR-defined data loading requirements for the COCR Phase 2 concept of operations were selected to bring forward from the screening process.

After application of the "ability to use protected spectrum" screening metric, satellite and over-the-horizon technologies were considered with regard to data loading capability. Figure 19 provides a summary of the screening process applied to these technologies. Technologies that meet or come close to meeting COCR-defined data loading requirements for the COCR Phase 2 concept of operations were selected to bring forward from the screening process.

Upon review of the screening results, it was noted that satellite over-the-horizon results could be considered in the context of providing a general communication solution or a solution that would address service requirements specific to the oceanic/remote airspace domain, a domain with a unique operational environment and requirements. Because of prior assessments of existing satellite system availability performance,[9] consideration of existing satellite and over-the-horizon solutions was limited to service provisioning in oceanic/remote airspace. It was also considered constructive to consider terrestrial screening results in the context of specific airspace domains that may have unique operational environments. The APT domain fits this consideration and therefore terrestrial technology screening results were also examined to consider applicable technologies for provisioning of services specifically in the APT domain. This domain has the highest capacity requirements (as defined in the COCR), but the required communication range is relatively small. Reevaluation of terrestrial screening outputs led to the identification of an additional technology for further consideration (see fig. 20).

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[8]Shading was applied to help visualize which technologies would be able to (green) meet all specified requirements or (yellow) have potential to provide a role in future aeronautical communications, and exceeded all domain-specific derived range requirements and the radio horizon range, or (red) could not meet the minimum communication range requirement and therefore have minimum applicability to the aeronautical environment.

[9]Additional detail can be found in the FCS Phase II technology investigation report, ref. 8.

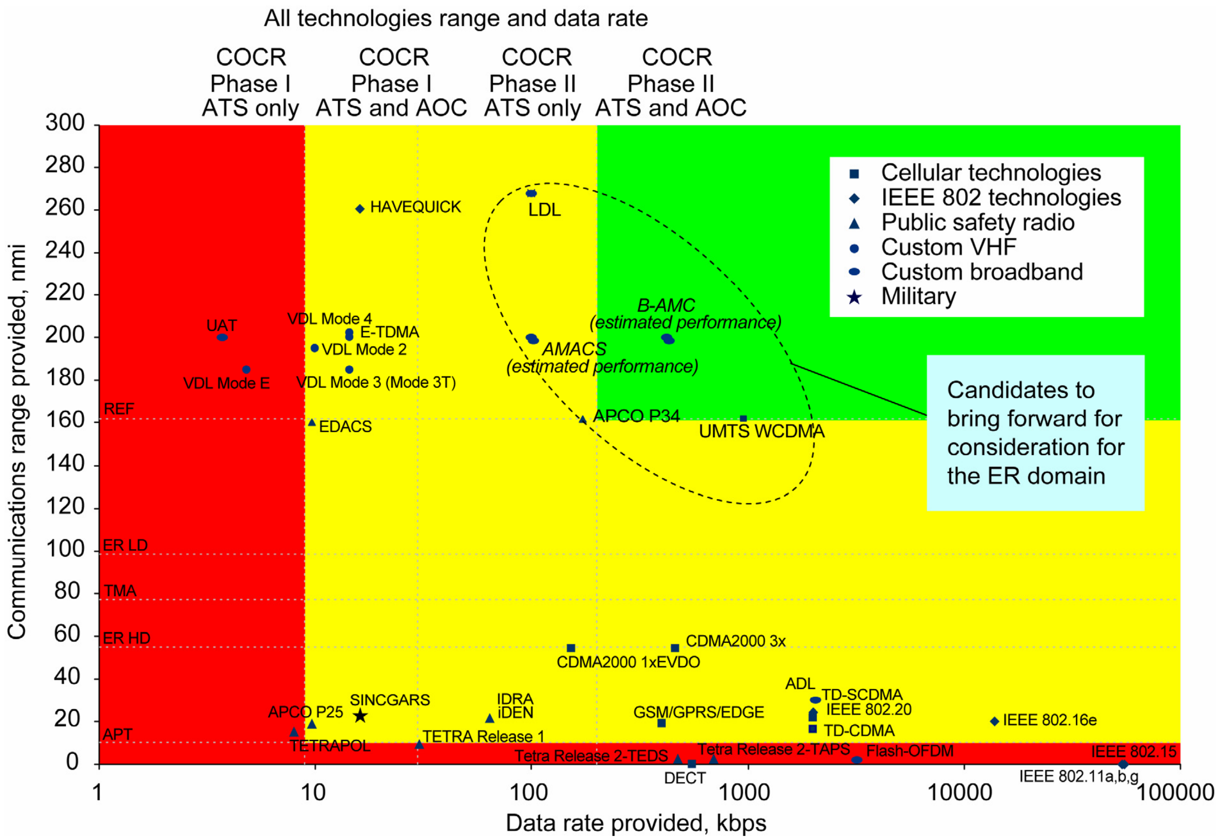


Figure 18.—Updated terrestrial technology screening results (Phase III results).

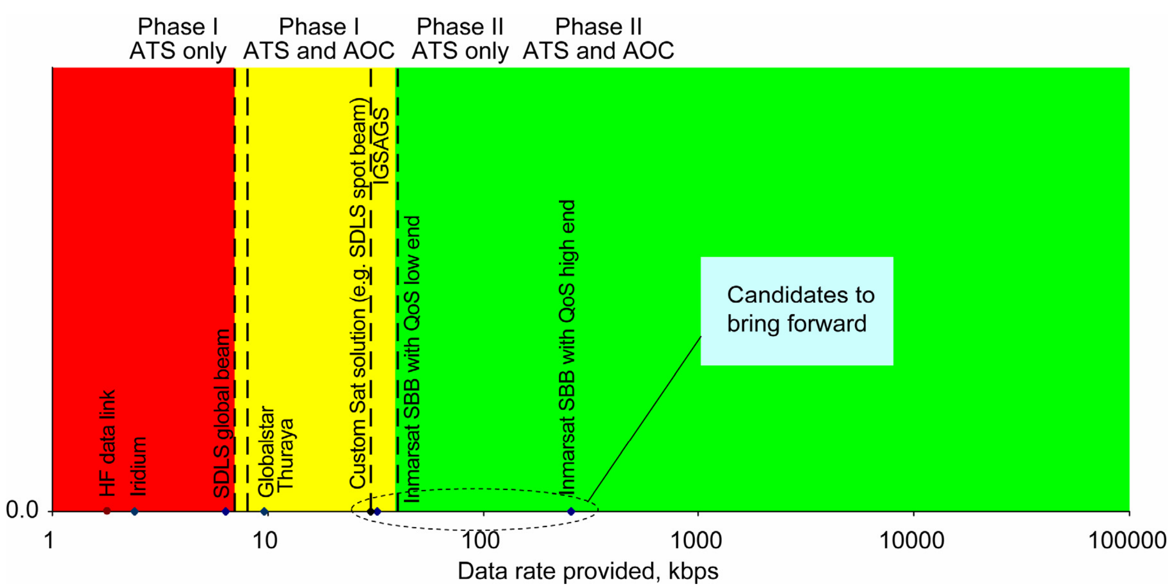


Figure 19.—Updated satellite/over-the-horizon technology screening results (Phase II results).

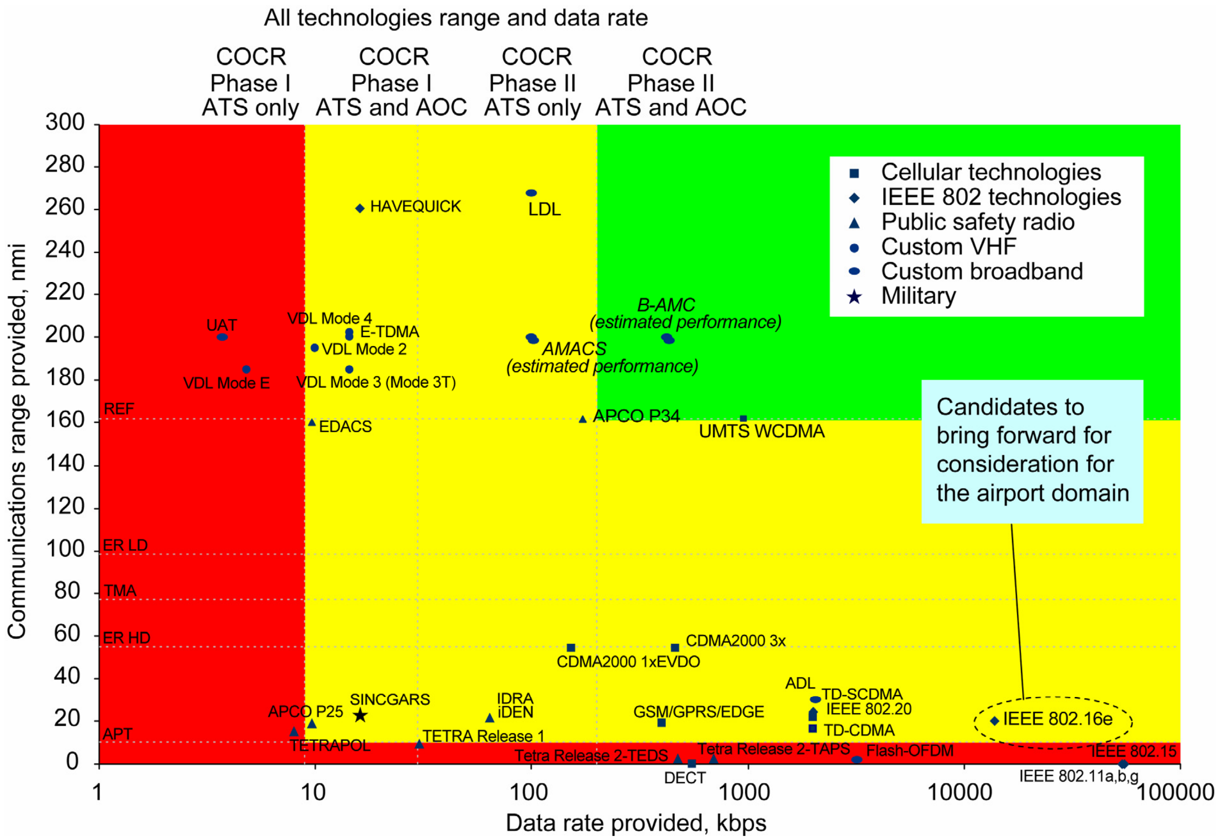


Figure 20.—Updated terrestrial technology screening results—airport domain candidates (Phase III results).

TABLE 8.—UPDATED TECHNOLOGY SCREENING RESULTS

Domain		Screened technologies
General	Continental domains (APT, TMA, ER, etc.)	• TIA–902 (P34) • LDL • WCDMA • B–AMC • AMACS
Domain specific	Oceanic/remote domain	• Inmarsat Swift Broadband • Custom Satellite System (e.g., SLDS)
	APT domain	• IEEE 802.16e

4.3 Screening Results and Comparison to EUROCONTROL Shortlist

As a result of the technology screening process, eight technologies were identified as candidates to bring forward for further consideration. These candidates are summarized in table 8.

Of these candidates, two of the general solution candidates (i.e., candidates for provision of services in the APT, TMA, and ER domains) are currently being defined by EUROCONTROL. These technologies, named B–AMC and AMACS by EUROCONTROL, were evolutionary extensions into the aeronautical L-band of technology concepts and definitions originally defined for VHF implementation. Since the technical details for these two technology concepts as well as testing and simulations were still under development at the time of evaluation, these two technologies were evaluated based on the information available at the time. A few evaluation criteria were not provided with a specific rank because of insufficient information; these areas are marked as gray.

The remaining technologies emerging from the screening process fall into two categories. They include candidates for a general aeronautical communication solution for the FRS (also called a continental solution because the solution applies to all continental flight domains including APT, TMA, and ER) and technologies identified as best performers in the context of specific flight domains that have a unique environment and may warrant separate technology consideration (i.e., oceanic and APT domains).

As noted in table 8, for a general continental solution, technologies coming forward from the screening process include TIA–902 (P34), LDL, and wideband code division multiple access (WCDMA). APCO Project 34 is an EIA/TIA standardized system (902 standard series) for provision of packet data services in an interoperable dispatch-oriented topology for public safety service providers. The defined standards correspond to the layered TIA–902 (P34) protocol stack. As designed for public safety applications, TIA–902 (P34) uses frequency division duplex (FDD). The scalable adaptive modulation (SAM) physical layer is a multicarrier coherent TDMA modulation (specifically, orthogonal frequency division multiplexing (OFDM)). The base channel size is 50-kHz, with extensions defined to 100-kHz and 150-kHz, where each 50 kHz provides 96 to 288 kbps (modulation and/or coding can adapt with E_b/N_0). The technology specifies three frame formats, random access inbound (used for short signaling and requesting inbound channel bandwidth); reserved access inbound (used for payload data transfer and data acknowledgments); and outbound (used for payload data transfer and confirmed data acknowledgments).

A second technology brought forward from the screening process is an evolutionary technology proposed by the United States, namely LDL. Sufficient details were documented and available to enable evaluation of this evolutionary technology. Specifically, LDL is derived from the UAT physical layer standards and VDL3 upper layer standards. The technology uses binary continuous phase frequency shift keying (CPFSK) with a channel size of 62.5- to 100-kHz (to be optimized). The technology builds upon the TDMA structure defined for VDL3, using management bursts for exchange of configuration and administrative data and bandwidth reservation, and data bursts for exchange of payload data.

The third technology emerging from technology screening is WCDMA. This candidate is a third-generation cellular standard, emerging from the Universal Mobile Telecommunications System (UMTS) and GSM evolutionary thread. WCDMA technology partitions RF resources through a combination of FDMA, CDMA, and TDMA. A frequency band assignment for WCDMA is divided into multiple pairs of 5-MHz channels that include dedicated uplink and downlink channels separated by a large guard band. CDMA is the primary means of portioning the channel. The WCDMA specification offers multiple physical layer modulations and associated coding rate configurations for both uplink (mobile-to-ground station) and downlink (ground station-to-mobile) connections.

The fourth technology, AMACS, is a multipurpose communication system, with narrowband (50 to 400 kHz) channels, operating in the lower aeronautical L-band (960 to –975 MHz). AMACS is not a standardized technology, but was developed from a baseline of the existing UAT/GSM and VDL4 systems to operate in the aeronautical L-band. AMACS physical layer reuses appropriate UAT and GSM specifications; the MAC layer is based on the existing E–TDMA MAC layer concept. Also AMACS uses existing VDL4 broadcast and reservation protocols.

The fifth technology, B–AMC, was developed by EUROCONTROL based on the B–VHF (broadband VHF) system concept to operate in the aeronautical L-band. B–VHF, cofunded by the European Commission, is a multicarrier based wideband communication system that supports aeronautical communications. The B–VHF system demonstrated a good potential for satisfying the needs of future aeronautical communications. But because of current spectrum congestion, there is no spectrum available in the VHF band for a dedicated B–VHF implementation. Meanwhile, FAA and EUROCONTROL share a common view that a new data link system for the year 2020 and beyond shall be preferred to be implemented in the aeronautical L-band. Therefore the objective of the B–AMC study was to design a system similar to B–VHF and capable of operating in the L-band. The L-band B–AMC A/G system specification reused B–VHF system concepts to maximum possible extent; adjustments at physical layer and data link layer were made due to the special L-band conditions. The main physical changes include the duplex scheme, the forward link access-scheme, the OFDM parameter set and framing structure. B–AMC offers a large coexistence potential in L-band as it reuses B–VHF sidelobe suppression concepts, and tailors coding and interleaving to combat L-band interference. B–AMC allows systematic adjustments to L-band use by optimizing link efficiency and robustness and minimizing interference to legacy systems.

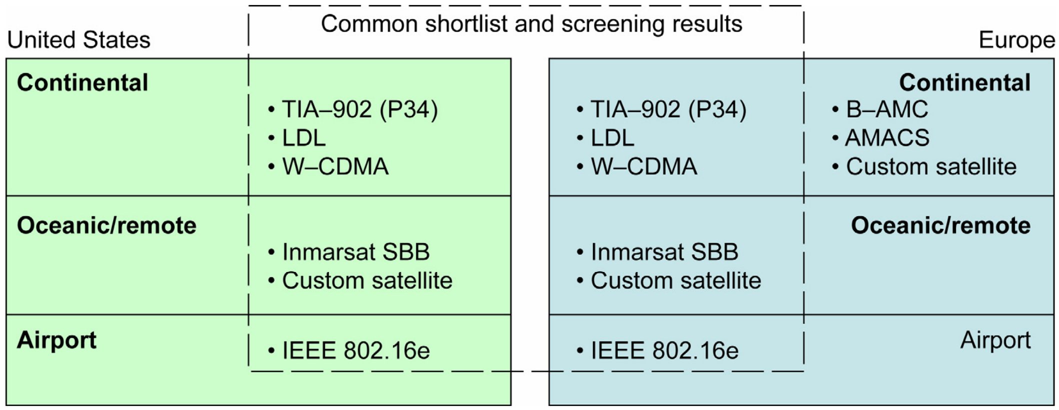


Figure 21.—Comparison of screening results to EUROCONTROL technology shortlist.

Specific to the oceanic domain, candidates identified in the screening process for further consideration included Inmarsat Swift Broadband (SBB) and the custom satellite solution. The Inmarsat SBB concept builds upon an evolving set of aeronautical services offered by Inmarsat including "classic" Inmarsat Aeronautical Mobile Satellite Services and Swift 64. The SBB service is a new offering of the Inmarsat IV satellites, currently operational, but which may be late in their lifecycle in the implementation timeframe of the FRS. For the custom satellite solution, satellite payloads or architectures specifically designed for aviation have been identified as having promise for meeting oceanic domain communication requirements. The custom satellite solutions considered included Satellite Data Link System (SDLS), a European Space Agency initiative that defines a bent-pipe geostationary satellite architecture implementing CDMA at L-band for aeronautical application, and multifunctional transport satellite (MTSAT), a Japanese operational primary/backup geostationary satellite architecture providing aeronautical services.

For the APT domain, candidate applicable technologies included those from the cellular and 802 technology families. Of the candidates in those families that meet the requirements for the APT, 802.16e has the largest data capacity; a simple ground infrastructure; a developed standard; and appears to be the most applicable. Reference the cellular and 802 family concepts of use in the FCS Phase I technology investigation report (ref. 7).

In March 2006, EUROCONTROL presented its current technology shortlist at the ICAO ACP WG–C10 meeting (ref. 1). This shortlist (with slight revision) was presented again at the ICAO ACP/1 meeting in May 2007 (ref. 2). It is instructive and informative to compare the current screening results to the technology short list developed by EUROCONTROL. This comparison is provided in figure 21. It shows a significant overlap in recommendations for the "short list" of technologies to consider for the FRS. This overlap is significant as member participants of the FCS and the ICAO ACP work toward harmonized technology solutions for the future communication infrastructure.

The following sections of this report document the work performed to further assess the most promising technology candidates through indepth analyses and consideration with regard to the full set of evaluation criteria.

5.0 Indepth Support Studies: Technology and Interference

The following list identifies the range of indepth assessments performed during the FCS to support the evaluation of candidate technologies. These included

1. L-Band A/G Communication Channel Characterization
2. Project–34/Telecommunication Industry Association (TIA) 902 Series Standards (TIA–902 (P34)) Technology Performance Assessment
3. TIA–902 (P34) Technology Intellectual Property Assessment

4. L-Band Digital Link (LDL) Technology Performance Assessment
5. Wideband Code Division Multiple Access (WCDMA) Functional Assessment
6. L-Band Technology Cost Assessment for Ground Infrastructure
7. L-Band Interference Testing
8. Satellite Technology Availability Performance Evaluation
9. IEEE 802.16e Performance Assessment in Aeronautical C-Band Channel

These studies were performed during the FCS Phases II and III studies. As such, the study objectives, methodology and results are fully documented in the interim FCS Phases II and III technology investigation reports. A summary of findings and references to the full study documentation is provided in appendix D.

5.1 Summary of Indepth Assessment Results

As noted above, indepth technical assessments were performed during the FCS Phases II and III studies. These assessments were conducted to gain a better understanding of the performance of the most promising technology candidates as well as to support the overall evaluation of technologies. Many of the technology evaluation results were influenced by the results of these studies, thus to provide insight into the studies performed and applicable results, an overview of the study objectives, methodologies, and results are provided in appendix D.

The specific studies conducted as part of the FCS Phases II and III are noted below. Included is a reference to the appendix section of this study where the summary material is documented. Additional references to applicable sections of the Phases II or III report, documenting additional study details, is provided with the study summaries. The indepth assessments include

- Section D.1: L-Band Air/Ground (A/G) Channel Characterization
- Section D.2: TIA–902 (P34) Performance Assessment
- Section D.3: TIA–902 (P34) Technology Intellectual Property Assessment
- Section D.4: LDL Performance Assessment
- Section D.5: WCDMA Functional Assessment
- Section D.6: L-Band Technology Cost Assessment for Ground Infrastructure
- Section D.7: L-Band Interference Analysis and Testing
- Section D.7.1: DME Interference Assessment
- Section D.7.2: UAT Interference Modeling
- Section D.7.3: Mode S Interference Modeling
- Section D.7.4: L-Band Interference Measurements
- Section D.8: Satellite Technology Availability Performance
- Section D.9: C-Band Technology (IEEE 802.16e) Performance

6.0 Detailed Technology Evaluation

Technologies emerging from the screening process can be categorized into two general categories: those for consideration as a general solution for continental airspace (APT, terminal, and ER flight domains), and technologies for consideration in specific flight domains with unique operating environments (specifically, the APT surface and oceanic/remote). Those technologies identified for the specific flight domains included two satellite systems/concepts—Inmarsat SBB and custom satellite solution—for the oceanic/remote airspace and a single candidate (IEEE 802.16e) for the APT surface domain.

The timeframe of the COCR operational concept is beyond the service horizon of current satellite offerings, and details for follow-on or custom solutions are high-level at this time. Therefore, the value of full application of the evaluation criteria (as updated in Phase III) to candidate satellite aeronautical communication solutions is minimal; furthermore, the need to discriminate among candidate solutions to identify a single global recommendation is not clear. As a result, no additional evaluation of these technologies was performed in the FCS Phase III study. Instead, the use concepts and initial assessments performed in FCS Phases I and II were used to draw conclusions and formulate recommendations specific to satellite solutions.

For the APT surface domain, a single candidate emerged from the screening process. Thus, application of evaluation criteria (as updated in Phase III) to discriminate with other technologies is not meaningful. As a result, no additional evaluation of this technology was performed in the FCS Phase III study. Instead, the use concept, detailed assessment of IEEE 802.16e in the anticipated aeronautical channel (C-band in this case), and initial evaluation of this technology to criteria in FCS Phases I and II have been used to draw conclusions and formulate recommendations specific to the APT surface domain technologies using the aeronautical C-band.

The focus, therefore, of this section is on the evaluation of the most promising technologies for provision of future data link aeronautical communication services focusing on A/G communications. The use concept for these technologies is for implementation in the aeronautical L-band (960 to 1164 MHz). Additional details on the concepts for applying these technologies to the future aeronautical communication infrastructure are provided in Section 6.1. This information is followed by the technology evaluation results (Section 6.2); the weighting of evaluation criteria (Section 6.3); and scoring technology performance (Section 6.4).

6.1 Detailed Technology Concept of Use Material

An initial description of how candidate technologies could be applied to provide future aeronautical communication services was described in the FCS Phase I report (ref. 7). That material describes the technology families, including discriminating factors for the family; technology services and key features; functional architecture; air-interface; the applicable frequency domain; and integration architecture concepts.

Upon definition of evaluation criteria and associated process flow diagrams that document the steps to be followed to perform technology assessments, additional details for the concept of use needed to support evaluations were identified. During the FCS Phase III activities, these additional details were developed. This material was combined with key elements previously described to create a full set of technology information to support the evaluations. The concept of use details are documented in appendix C of this report and include:

- Definition of available standards and standards status
- Available technology services and those identified as applicable for a future aeronautical data link
- Air-interface description and definition of options; identification of applicable features/options for evaluated implementation
- Functional architecture and mapping into ATM context
- Mapping of one or more COCR services into technology captured in sequence diagrams
- Service concepts and provision of services in evaluation scenarios
- Channelization concepts
- Cost considerations (e.g., specialized equipment required and number of ground stations required to provide services in evaluation scenarios)

As noted above, one of the new information items captured for each technology was a definition of how the technology would provision services for a defined set of evaluation scenarios. Common evaluation scenarios that extend the COCR to larger service regions were defined to support the evaluation of technologies that may be deployed to cover service volumes other than those previously defined in the COCR. The COCR concept incorporates the idea of growing current sectors and provides requirements along these lines. Some technologies may be deployed using a regular grid cellular concept. In these cases, the evaluation scenarios help to identify required capacity for associated service volumes and support evaluation of technology ability to meet service requirements. They also can be used to provide a relative comparison of technology performance and cost (e.g., evaluate number of ground sites, channels required to provide services) for the defined evaluation scenarios. A full set of evaluation scenario definitions is provided in “Future Communication Infrastructure Technology Investigations Evaluation Scenarios,” EUROCONTROL/FAA FCS Team.

6.2 Evaluating Technologies

The technology evaluation process included the application of the evaluation criteria, following the steps in the associated flow diagrams for the concept of use defined for a technology, to develop technology scores. Each individual criterion had a defined set of metrics that describe the trilevel rating measures used for evaluations (see table 5). Following the steps of the evaluation process flow diagrams and documenting key factors and results that drive an evaluation score, technology performance was rated as green, yellow, or red for each factor. These scores provide an applicability barometer for how technology is meeting the requirements, and rates the operational environment for a future aeronautical A/G data link, where green indicates criteria for which the technology meets requirements or provides low cost and risk performance; red indicates areas for which the technology cannot meet requirements and/or has significant hurdles to being an applicable, viable solution; and yellow covers the areas between. For B–AMC and AMACS technologies, as they are both technologies currently under development, the evaluations of these two were carried out based on available documents and information. For some criteria there was insufficient information to provide a rank. For those criteria, the evaluation result areas are colored gray.

The evaluation results for TIA–902 (P34) are provided in table 9. Results in the table indicate the TIA–902 (P34) standard performs well technically with regard to capacity and security. The standard employs multicarrier modulation (providing time-dispersive channel protection) and multiple channel sizes that use QPSK, QAM–16, and QAM–64 to support high-capacity requirements. It is a layered standard for which the air interface (AI) alone can be deployed, but standards that support mobility management and internet protocol (IP) interface (supporting cellular implementation with potential cost gains) are also defined. The technology can be deployed as a regular grid of ground standards (applicable to the ER domain), decoupling sector definitions from radio coverage volumes.

TABLE 9.—TIA–902 (P34) EVALUATION RESULTS

Evaluation criterion			Results	Evaluation notes
1	Provides ATS A/G data services within requirements (sans A–EXEC)	A—Capacity		• Cellular deployment concept for ER domain • 50-, 100-, and 150-channels with QPSK or QAM–16 provide sufficient capacity to meet requirements (reference OPNET simulation results and offered data rates significantly greater than estimated requirements)
		B—PIAC		• Expected to accommodate PIAC (no explicit limitations) • Capacity results reflect ability to provide services within requirements to estimated users in service volumes
		C—QoS		• Technology provides up to 16 priority levels
		D—Environment		• Evaluation of pilot structure indicates that adjustments may be required to accommodate high mobile speeds; however, simulated performance indicates good bit error rate (BER) performance
2	Provides ATS and AOC A/G data services within requirements (sans A–EXEC)	A—Capacity		• Multiple channel sizes (50-, 100-, and 150-channels with QPSK or QAM–16) provide sufficient capacity to meet requirements (reference OPNET simulation results (offered data rates significantly greater than estimated requirements))
		B—PIAC		• Expected to accommodate PIAC (no explicit limitations) • Capacity results reflect ability to provide services within requirements to estimated users in service volumes
		C—QoS		• Technology provides up to 16 priority levels
		D—Environment		• Evaluation of pilot structure indicates that adjustments may be required to accommodate high mobile speeds; however, simulated performance indicates good BER performance

TABLE 9.—CONCLUDED.

Evaluation criterion		Results	Evaluation notes
3	Technical readiness level		• Technology concept and requirements defined • Technology developed and standardized • Prototype has been demonstrated in public safety environment (700-MHz implementation) • Assessed to be at TRL–5
4	Standardization status		• Commercial standards are published • No specific aeronautical standards are published
5	Certification		• No current products are certified for aviation (or known to be in certification process) • Technology had been developed for public safety application; user set includes terrestrial and aeronautical mobiles • Layered protocol can be incrementally implemented (e.g., air interface only, full complement of standards)
6	Ground infrastructure cost		• Layered protocol can be incrementally implemented (e.g., air interface only with full complement of standards) • For defined service volume (conservative estimate 100 nmi), single radio station can provide coverage/capacity • Requires implementation of radio control equipment and RF interface and mobility management systems (if this feature is desirable)
7	Avionics cost		• New avionics need to be developed • May require interference suppression bus
8	Spectrum		• Interference measurements indicate there is potential for implementing in L-band, but likely would require physical layer modifications (and perhaps off-tuning from DMEs); investigation of the effect of duty cycle on interference susceptibility recommended • Prototype transmitters may be required to address specific channelization techniques
9	Authentication and integrity		• Technology provides authority and integrity check capabilities
10	Robustness to interference		• Technology does not implement specific features to address interference (e.g., frequency hopping) but deployment concept includes margin to provide some resistance to interference
11	Transition		• Can be deployed incrementally (support ROI) • Can be operated simultaneously with legacy equipment • Can transition in an operationally transparent manner

Key areas of concern for TIA–902 (P34) are physical layer performance in the aeronautical L-band. Co-channel interference measurements indicate that the waveform conservatively modeled as a continuous transmission may cause desensitization of distance measuring equipment (DME); further evaluation of the gated TIA–902 (P34) waveform and gating/pulsing effects in general, including duty-cycle effects, is needed. Additionally, further evaluation of the pilot structure should be explored to determine if it is sufficient to compensate for the anticipated Doppler environment. There are existing commercial standards for this technology, and it has been demonstrated in the public safety environment; however, no aeronautical standards, avionics, or aeronautical demonstrations of this technology have been identified.

The evaluation results for WCDMA are provided in table 10. Here, results indicate the WCDMA is a mature technology that performs well technically, with regard to capacity and security. The technology can be deployed in a cellular fashion and offers robust modulation and specification flexibility to accommodate a range of capacity requirements (including high-capacity requirements). There are mature commercial standards defined for this technology, which include the support for mobility management and interface to IP networks. The standard also includes security features that can be used to accommodate authentication and integrity requirements.

TABLE 10.—WCDMA EVALUATION RESULTS

	Evaluation criterion		Results	Evaluation notes
1	Provides ATS A/G data services within requirements (sans A–EXEC)	A—Capacity		• Cellular deployment concept • Specification offers flexibility in spreading factors and initial deployment concepts and evaluations indicate sufficient capacity to meet requirements (reference Roke Manor simulation results and offered data rates significantly greater than estimated requirements)
		B—PIAC		• Expected to accommodate PIAC (no explicit limitations) • Capacity results reflect ability to provide services within requirements to estimated users in service volumes
		C—QoS		• Accommodates priority levels
		D—Environment		• No detailed evaluation of performance for anticipated mobile environment/channel environment identified simulation work (Roke Manor) suggests two-antenna diversity may be required
2	Provides ATS and AOC A/G data services within requirements (sans A–EXEC)	A—Capacity		• Specification offers flexibility in spreading factors and initial deployment concepts and evaluations indicate sufficient capacity to meet requirements (reference Roke Manor simulation results and offered data rates significantly greater than estimated requirements)
		B—PIAC		• Expected to accommodate PIAC (no explicit limitations) • Capacity results reflect ability to provide services within requirements to estimated users in service volumes
		C—QoS		• Accommodates priority levels
		D—Environment		• No technical evaluation of performance for anticipated mobile environment/channel environment identified; concept defined includes multiple antennas to account for diversity
3	Technical readiness level			• Technology concept and requirements defined • Technology developed and standardized • Prototypes have been developed[a] • Assessed to be at TRL–6
4	Standardization status			• Commercial standards are published • No specific aeronautical standards are published
5	Certification			• No current products are certified for aviation (or known to be in certification process) • Technology had been developed for commercial applications • Integrated standards required full implementation of many functional components (complexity impact)
6	Ground infrastructure cost			• Integrated standards required full implementation of many functional components • For defined service volume (max. estimate 50 to 80 nmi), single radio station can provide coverage/capacity; but defined concept identifies dual-antenna radio sites (other concepts include use of sectorized antennas) • Requires implementation of Radio Network Control Equipment, Core Network (SGSN, GGSN, and HLR)
7	Avionics cost			• New avionics need to be developed
8	Spectrum			• Interference studies and measurements indicate clear spectrum required for implementation (with 5-MHz guard bands) • Physical layer redesign for collocated with DMEs would essentially be new technology definition
9	Authentication and integrity			• Technology provides authority and integrity check capabilities

TABLE 10.—CONCLUDED.

	Evaluation criterion	Results	Evaluation notes
10	Robustness to interference		• Technology does not implement specific features to address interference (e.g., frequency hopping) but deployment concept includes margin to provide some resistance to interference
11	Transition		• Requirement for full complement of functional elements limits incremental deployment options • Can be operated simultaneously with legacy equipment • Can transition in an operationally transparent manner

[a]An example is that WirelessCabin developed a prototype of the communication network. The demonstrator was qualified and certificated for aeronautical usage. A test flight on September 13, 2004, from Toulouse to Corsica and back demonstrated the emerging technologies including GSM/UMTS for mobile telephony, with IEEE 802.11, and Bluetooth for mobile computing services.

Similar to TIA–902 (P34), a key area of concern for WCDMA is compatibility with legacy L-band aeronautical systems. Co-channel performance studies and interference measurements have indicated that this technology would need to be deployed in clear spectrum with as much as 5-MHz guard bands to address DME desensitization. The defined standard integrates several functional components to perform standard communication functions (such as context activation), and it is estimated that a full complement of functionality would be required upon initial deployment of the technology. There are no aeronautical standards or existing aeronautical avionics for this technology, nor has it been specifically designed for aeronautical or public safety applications.

The evaluation results for LDL are provided in table 11. LDL is a layered standard for which the AI alone can be deployed; however, standards that specifically support mobility management and IP interface are not defined. Therefore, implementation in a cellular configuration and interface to commercial network standards requires proper network layer and/or gateway functionality. The envisioned concept for deploying LDL should accommodate provision of ATS services (sufficient capacity) and support incremental deployment.

Results in table 11 (spectrum) indicate that LDL performance with regard to co-channel interference requires further assessment. While promising results were identified during interference testing for frequency offsets greater than 10 MHz, likely because of the gating structure of the waveform, which may have a transmit duty cycle less than 40 percent, testing limitations prohibited full validation of compatibility. Of the technologies evaluated, the LDL design offers the lowest capacity. It may be suitable for ATS applications, but accommodating ATS and AOC communications may require multiple channels per ground site or smaller service volume configurations. Further evaluation of its ability to meet COCR service performance requirements is needed.

The LDL technology has been designed specifically for the aeronautical application and was developed based on existing aeronautical standards; however, there are no existing standards specific to this technology, and its functionality (especially new physical layer functionality) has not been demonstrated. A key concern for this technology is its performance in the aeronautical L-band channel. The L-band aeronautical channel estimation effort indicated that RMS delay spread may be on the order of 1.4 μs. Comparing this value to LDL symbol time indicates that frequency-selective fading may be experienced, even with consideration given to noncoherent detection. Therefore, mitigation techniques such as equalization may need to be considered.

TABLE 11.—LDL EVALUATION RESULTS

	Evaluation criterion		Results	Evaluation notes
1	Provides ATS A/G data services within requirements (sans A–EXEC)	A—Capacity		• Defined deployment concepts can be defined so that capacity can be achieved
		B—PIAC		• Expected to accommodate PIAC (changes to M-burst structure can increase Aircraft ID address space) • Capacity results reflect ability to provide services within requirements to estimated users in service volumes
		C—QoS		• Technology's upper layer (based on VDL–3) provides four priority levels
		D—Environment		• Evaluation of LDL in aeronautical channel model indicates frequency selective fading channel operations (consider equalization techniques; further investigation of performance)
2	Provides ATS and AOC A/G data services within requirements (sans A–EXEC)	A—Capacity		• Defined deployment concepts can be defined so that capacity can be achieved, but may require use of two ground channels per service volume or small service volumes
		B—PIAC		• Expected to accommodate PIAC (changes to M-burst structure can increase Aircraft ID address space) • Capacity results reflect ability to provide services within requirements to estimated users in service volumes
		C—QoS		• Technology's upper layer (VDL–3) provides different levels of priority groups, provides COS capability to accommodate COCR-defined COS
		D—Environment		• Evaluation of LDL in aeronautical channel model indicates frequency selective fading channel operations (consider equalization techniques; further investigation of performance)
3	Technical readiness level			• Technology concept defined • Technology takes advantage of existing aeronautical standards, but no full set of standards specific to this technology exist • Prototypes for standards that LDL is built upon existing, but no models specific to LDL itself • Assessed to be at TRL–3
4	Standardization status			• Technology is defined based on components of existing aeronautical standards; however, modifications, especially physical layer modifications, would need to be developed
5	Certification			• No current products are certified for aviation (or known to be in certification process) • Technology was developed for aeronautical applications
6	Ground infrastructure cost			• Layered protocol can be incrementally implemented (e.g., air interface only and full complement of standards) • For defined service volume (on the order of 100 nmi), but two radio channels may be required for capacity • Required implementation of radio control equipment and ground network interface
7	Avionics cost			• New avionics need to be developed
8	Spectrum			• Interference measurements at frequency offsets greater than about 10 MHz indicate technology offers sufficient co-channel protection for collocation with DMEs, likely due to gating structure of the waveform; test limitation can only verify performance at this distance; initial data for on-tune frequencies indicate some channel offset will be needed; further testing is required for validation and addressing specific channelization techniques
9	Authentication and integrity			• Basic feature to request user authentication at net entry supported; technology can be modified to provide authentication and integrity at the network layer

TABLE 11.—CONCLUDED.

	Evaluation criterion	Results	Evaluation notes
10	Robustness to interference		• Technology does not implement specific features to address interference (e.g., frequency hopping) but deployment concept includes margin to provide some resistance to interference
11	Transition		• Can be deployed incrementally (support ROI) • Can be operated simultaneously with legacy equipment • Can transition in an operationally transparent manner

The evaluation results for B–AMC are provided in table 12. Results in the table indicate that B–AMC performs well technically, with regard to capacity with certain deployment considerations. B–AMC can be operated at only 0.5 MHz offset to the next DME channels when frequency planning is applied. Also, in order for the B–AMC protocol to provide the desired performance, the physical layer frame error rate has to be less than 10–2. The B–AMC physical layer design indicating that B–AMC performance in the intended channel is characterized by flat/slow fading,[10] means that B–AMC can provide sufficient functional and performance capability to meet operational and environmental requirements of the COCR data services.

The B–AMC A/G system may include the option to assign frequencies to B–AMC channels in areas where they are not used locally by DME. This requires the establishment of a relation between potential B–AMC assignments and existing DME assignments. To combat interference from DME and other legacy systems in the L-band, B–AMC offers significant coexistence potential in L-band as it uses B–VHF sidelobe suppression concepts, tailors coding, and uses interleaving. Simulations show this code design can almost completely combat the influence of the interference. B–AMC allows systematic adjustments to L-band use by optimizing link efficiency and robustness and minimizing interference to legacy systems. Sidelobe suppression techniques developed for B–VHF are applied to B–AMC to minimize the out-of-band radiation of the B–AMC system, thereby minimizing the influence of the B–AMC on the legacy L-band systems.

TABLE 12.—B–AMC EVALUATION RESULTS

	Evaluation criterion		Rank	Evaluation notes
1	Provides ATS A/G data services within requirements (sans A–EXEC)	A—Capacity		• B–AMC computer modeling and simulation results capacity (ref. 30) indicate B–AMC can provide sufficient capacity to meet capacity requirements for Phase II high density across all continental flight domains with certain deployment considerations.[a]
		B—PIAC		• Expected to accommodate PIAC (no explicit limitations) • B–AMC computer modeling and simulation results on B–AMC capacity indicate ability to provide services within requirements to estimated users in service volumes with certain deployment considerations as stated in subcriterion A evaluation notes.
		C—QoS		• B–AMC report (ref. 31) states that B–AMC A/G subsystem provides bidirectional forward link/reverse link (FL/RL) unicast addressed data links as well as FL multicast and broadcast capabilities with the envisaged capacity and COCR QoS adequate for supporting existing and future ATS and AOC services. • B–AMC concept provides QoS to accommodate COCR–defined CoS.
		D—Environment		• Technology performance in intended channel is characterized by flat/slow fading.[b]

[10]For the channel to be considered "slow fading" the following two conditions must be met: first, the coherence time of the channel, TC, must be much greater than the symbol duration, TS, and second, the baseband signal bandwidth, BS, must be much greater than the maximum Doppler shift, BD. For B–AMC, the symbol duration is 120 μs, which is a fraction of the coherence time of the channel. The channel bandwidth is 500 kHz, which is much greater than the maximum Doppler shift. Therefore, both conditions are met for a slow fading channel. One-tenth the symbol duration of B–AMC is 12 μs, which is greater than the mean RMS delay spread so the channel is considered flat. Even if the channel was frequency selective fading, the insertion of pilot symbols could mitigate the effects.

TABLE 12.—CONTINUED.

	Evaluation criterion		Rank	Evaluation notes
2	Provides ATS and AOC A/G data services within requirements (sans A–EXEC)	A—Capacity		• B–AMC computer modeling and simulation results on capacity (ref. 30) indicate B–AMC can provide sufficient capacity to meet capacity requirements for Phase II high density in most of the continental flight domains with certain deployment considerations as stated in subcriterion A evaluation notes.
		B—PIAC		• B–AMC computer modeling and simulation results on B–AMC capacity (ref. 30) indicate ability to provide services within requirements to estimated users in service volumes with certain deployment considerations as stated in subcriterion A evaluation notes.
		C—QoS		• B–AMC concept provides QoS to accommodate COCR–defined CoS.
		D—Environment		• Technology performance in intended channel is characterized by flat/slow fading.
3	Technical readiness level			• Technology concept defined. • Technology takes advantage of existing aeronautical standards, full set of standards specific to this technology are being defined. • Component or breadboard validation in lab environment is available. • No component or breadboard validation in ground or space environment. • Assessed to be at TRL–4.
4	Standardization status			• Work-in-progress standards are being published. • No commercial standards are published. • No specific aeronautical standards are published.
5	Certification			• No B–AMAC products have been developed for the aviation industry and they are not in the aviation certification process.
6	Ground infrastructure cost			• Layered protocol can be incrementally implemented (e.g., air interface only, full complement of standards). • FL/RL radio channels required for capacity and performance. • Required implementation of radio control equipment and ground network interface.
7	Avionics cost			• The preferred B–AMC A/G subsystem deployment option is B–AMC as data-only system. This neither requires a dedicated B–AMC airspace segregated from other airspace types nor mandatory carriage of B–AMC radios (however, it does not preclude implementation based on mandatory carriage of B–AMC equipment). Equipped users would receive B–AMC services with associated benefits via the B–AMC airborne radio operating in the A/G mode. Other users would be able to continue to use the narrowband data link equipment (e.g., VDL Mode 2) as long as it remains supported. • Need new avionics.
8	Spectrum			• The B–AMC A/G system is considering the option (OPTN2) to assign frequencies to B–AMC channels in areas where they are not used locally by DME; this requires the establishment of a relation between potential B–AMC assignments and existing DME assignments. • B–AMC is considered to be deployable in the intended band without either reallocating existing equipment or requiring modification to existing aeronautical equipment.
9	Authentication and integrity			• Insufficient information to support evaluation.
10	Robustness to interference			• Technology physical layer is tailored (strong channel coding together with interleaving) to combat L-band interference; the duplex scheme for A/G communication relieves co-location interference situation at aircraft. Also the technology allows systematic adjustment to lead to minimized interference to legacy systems. But simulation and performance data is yet to be finalized to provide a value for excess margin.

TABLE 12.—CONCLUDED.

	Evaluation criterion	Rank	Evaluation notes
11	Transition		• Technology can be deployed to achieve ROI (service provision benefit) without requiring full investment/deployment. • Can be operated simultaneously with legacy equipment. • Can transition in an operationally transparent manner.

[a]B–AMC can be operated at only 0.5 mHz offset to the next DME channels when frequency planning is applied. Also, in order for the B–AMC protocol to provide the desired performance the physical layer frame error rate has to be less than 10^{-2}.

[b]The B–AMC symbol duration is 120 µs, which is a fraction of the coherence time of the channel. The channel bandwidth is 500 kHz, which is much greater than the maximum Doppler shift. Therefore, both conditions are met for a slow fading channel. One-tenth the symbol duration of B–AMC is 12 µs, which is greater than the mean RMS delay spread so the channel is considered flat. Even if the channel exhibited frequency selective fading, the insertion of pilot symbols could mitigate the effects.

[c]There is no specific mention of authentication and integrity check in the B–AMC reports. So far, data encryption in the DLS layer was considered but not defined. Further investigation will be done on this. With respect to authentication, no decision has been made yet. The authentication method is a crucial issue. A B–VHF system shall not grant access to users who are not able to authenticate properly.

The B–AMC technology has been designed specifically for the aeronautical application and was developed based on existing aeronautical standards. A full set of standards specific to this technology is being defined with no commercial or aeronautical standards published. Further standardization and certification steps are needed. Also, B–AMC standards that specifically support authorization and authentication have not yet been fully defined.

The evaluation results for AMACS are provided in table 13. Results indicate that AMACS can provide sufficient capacity to meet ATS services requirements, but can only provide ATS and AOC combined service capacity in some flight domains, but not in all. The AMACS physical layer design indicates that AMACS performance in intended channel is characterized by flat and/or slow fading.[10] This indicates that AMACS can provide sufficient functional and performance capability to meet operational and environmental requirements of the COCR data services. Authorization and authentication are not mentioned in the evaluated AMACS documentation.

TABLE 13.—AMACS EVALUATION RESULTS

	Evaluation criterion		Rank	Evaluation notes
1	Provides ATS A/G data services within requirements (sans A–EXEC)	A—Capacity		• AMACS performance analysis results (ref. 32) indicate AMACS can provide sufficient capacity to meet capacity requirements for Phase II high density across all continental flight domains.
		B—PIAC		• AMACS performance analysis results (ref. 32) indicate ability to provide services within requirements to estimated users in service.
		C—QoS		• AMACS concept provides QoS to accommodate COCR-defined CoS.
		D—Environment		• Technology performance in intended channel is characterized by flat/slow fading.[a]
2	Provides ATS and AOC A/G data services within requirements (sans A–EXEC)	A—Capacity		• AMACS performance analysis results (ref. 32) indicate AMACS can provide sufficient capacity to meet ATS and AOC combined service capacity only in some flight domains, but not in all.
		B—PIAC		• AMACS performance analysis results (ref. 32) indicate ability to provide services within requirements to estimated users in ATS and AOC combined service in some domains, but not in all.
		C—QoS		• AMACS concept provides QoS to accommodate COCR-defined CoS.
		D—Environment		• Technology performance in intended channel is characterized by flat/slow fading.

TABLE 13.—CONCLUDED.

	Evaluation criterion	Rank	Evaluation notes
3	Technical readiness level		• Technology concept defined. • Technology takes advantage of existing aeronautical standards, but no integrated standards specific to this technology are defined. • Critical functions/characteristics of the technology have been defined. • No component or breadboard validation in lab environment available • Assessed to be at TRL–3.
4	Standardization status		• No commercial-integrated standards are published. • No aeronautical standards are published.
5	Certification		• No AMACS products have been developed for the avionics industry and they are not in the avionics certification process.
6	Ground infrastructure cost		• AMACS reuses UAT and GSM specifications for physical layer where appropriate, which gives some advantage in the costs associated with the development of the technology, but a full set of functional components may be needed.
7	Avionics cost		• New avionics need to be developed.
8	Spectrum		• Technology is designed and considered to be deployable in the intended band without either reallocation of existing equipment or requiring modification to existing aeronautical equipment based on cosite considerations, but no proven cosite tests or simulations are available to determine whether the technology is deployable in the target band.
9	Authentication and integrity		• No specific mentioning of security in the AMAC report, therefore insufficient information to evaluate.
10	Robustness to interference		• Technology does implement specific features (pulse blanking techniques) to address interference to reduce the effect of strong interference, but simulation and performance are needed to provide a value for excess margin.
11	Transition		• Control site infrastructure and core network need to be essentially completed before service can be offered. Requirement for full complement of functional elements limits incremental deployment options. • Transition is expected to be operated simultaneously with legacy equipment because different frequency band is used.

[a]The AMACS symbol duration is 1.851 μs, which is also a fraction of the coherence time of the channel. The channel bandwidth is 400 kHz, which is much greater than the maximum Doppler shift. Therefore both conditions are met for a slow fading channel. One-tenth the symbol duration of AMACS is 0.185 μs, which is less than the mean RMS delay spread so the channel is considered frequency selective. It is not certain how AMACS mitigates the frequency selective fading, but using very robust error correction coding is mentioned in the documentation for a flat channel.

AMACS technology is targeted to be deployable in the aeronautical L-band without either reallocation or modification of existing equipment. Cosite tests or simulations can validate this. AMACS implements pulse blanking techniques to reduce the effect of strong interference. Power control mechanisms are used to reduce the level of interference from point-to-point sources. Simulation and analysis are needed to provide a value for appropriate excess margin.

The AMACS technology concept has been defined specifically for the aeronautical application and takes advantage of existing aeronautical standards, but no integrated standards specific to this technology are defined. A full set of standards specific to this technology is yet to be developed. Further standardization and certification steps are needed.

A summary of the evaluation results for all technologies is provided in table 14. The results indicate that all technologies perform well in some areas, and for those criteria, the technologies would be applicable to a future aeronautical communication infrastructure. The results also indicate that all technologies have areas where they are not applicable, and would require adaptations to address technical shortfalls and/or acceptance of stakeholders to tolerate high risk and cost elements.

TABLE 14.—SUMMARY OF TECHNOLOGY EVALUATION RESULTS

No.	Evaluation criterion		TIA–902 (P34)	LDL	WCDMA	B–AMC[a]	AMACS[a]
1	Provides ATS A/G data services within requirements (sans A–EXEC)	A—Capacity					
		B—PIAC[b]					
		C—QoS[c]					
		D—Environment					
2	Provides ATS AOC A/G data services within requirements (sans A–EXEC)	A—Capacity					
		B—PIAC					
		C—QoS					
		D—Environment					
3	Technical readiness level						
4	Standardization status						
5	Certification						
6	Ground infrastructure cost						
7	Avionics cost						
8	Spectrum						
9	Authentication and integrity						
10	Robustness to interference						
11	Transition						

[a]For developing technologies B–AMC and AMACS, authentication and integrity criterion is not ranked and marked as gray because of insufficient technology information at the time of the evaluation.
[b]PIAC is peak instantaneous aircraft count.
[c]QoS is quality of service.

The information in table 14 and supporting results of the indepth technical assessments contributed to the development of the technology recommendations. As no one technology is a clear best performer, interpretation of the results can be aided by an understanding of the relative importance of the evaluation criteria and review of the results in this context. This work is addressed in the following subsections.

6.3 Weighting Decision Factors

To view the technology evaluation results with consideration given to the importance of criteria as reflected in stakeholder positions, two approaches to weighting evaluation criteria were applied. The first was a qualitative organization of criteria into the following three categories.

- Most important—in general, these factors have been specifically noted by stakeholders as important factors and should be given the greatest consideration; success with regard to these criteria is necessary to have an applicable aeronautical solution.
- Very important—in general, these factors are also addressed in some manner by stakeholders and are also very important aspects of an aeronautical communication system decision; success with regard to these criteria is important for understanding the viability of an aeronautical solution.
- Important—these criteria have been found to not be specifically addressed in stakeholder positions.

To bin the evaluation criteria into these categories, documented stakeholder positions were reviewed and applied. The resulting categorization and references to applicable stakeholder positions is provided in table 15.

TABLE 15.—QUALITATIVE WEIGHTING OF EVALUATION CRITERIA

Weight	Criteria	Notes
Most important	Spectrum Meets ATS requirements	• These are key aspects relating to the need for a new data link service to be pursued only after exhausting other options. A new data link is viable only if it meets requirements and has the ability to use the target spectrum band: compatibility with legacy equipment is required. • WRC–07 Preparation Material proposing AM(R)S allocation in 960 to 1024 MHz indicates compatibility with existing systems is required (i.e., cause no harmful interference to nor claim protection from existing systems) (refs. 33 and 34); compatibility with legacy equipment is required; no interest in moving DME allocations has been identified. • Many stakeholders reflected the position that existing systems should be used to their fullest extent (refs. 3, 4, and 35); a new data link system, for which technologies are evaluated, would only be needed when ATS requirements can no longer be met. Thus the ability to meet ATS requirements is necessary. • ATMAC indicated a desire to maintain ATS and AOC separately (ref. 4) and FAA has indicated they will follow ATMAC recommendations.
Very important	Technical readiness level	• The Future Communication Roadmap identifies the initial need for new data link capability in the 2020 time period; this is supported by an indication that VHF saturation has been reached in Europe (ref. 36).
	Ground cost	• Costs for implementation of a new ground infrastructure were estimated in response to FCS Phase I results (prompting further cost assessment in FCS Phase II).[a] • Organizations such as CANSO also show concern for ground infrastructure costs (it is raised many times in their published information paper) (ref. 35).
	Avionics cost	• The CANSO information paper also identifies the need to consider cost constraints on avionics (ref. 35). • The ATMAC position recommending pursuit of new technology solutions, only after all nonequipment alternatives are explored, clearly is indicative of cost concerns (ref. 4).
	Meets ATS and AOC requirements	• EUROCONTROL notes that the Link 2000+ Business Case indicates that benefits will be maximized with a shared infrastructure used for AOC and ATC applications (ref. 35).
Important	Standardization status Security—authentication and integrity Security—robustness to interference Certification Transition	• These factors were not found to be explicitly addressed or raised in reviewed stakeholder positions regarding data link or future aeronautical communications.

[a]FAA FCS Steering Committee response to FCS Phase I results.

A second approach used for criteria weighting was the application of the AHP process to generate quantitative criteria weights, which support development of technology scores. As described in Section 2.4.3, the first step was to perform a roll-up of evaluation criteria. The criteria were organized into a hierarchy such that those factors at the highest level of the hierarchy represent unique topics (e.g., TRL and standardization status are grouped together under the heading “maturity”). The definition of the evaluation criteria hierarchy (or decision factor hierarchy as it is called in the AHP) ensures that a manageable set of unique decision factors can be used to support an evaluation process. This also eases the application of stakeholder information, which typically addresses decision considerations at a high level. The resulting decision factor hierarchy defined for the technology evaluation criteria is shown in figure 22.

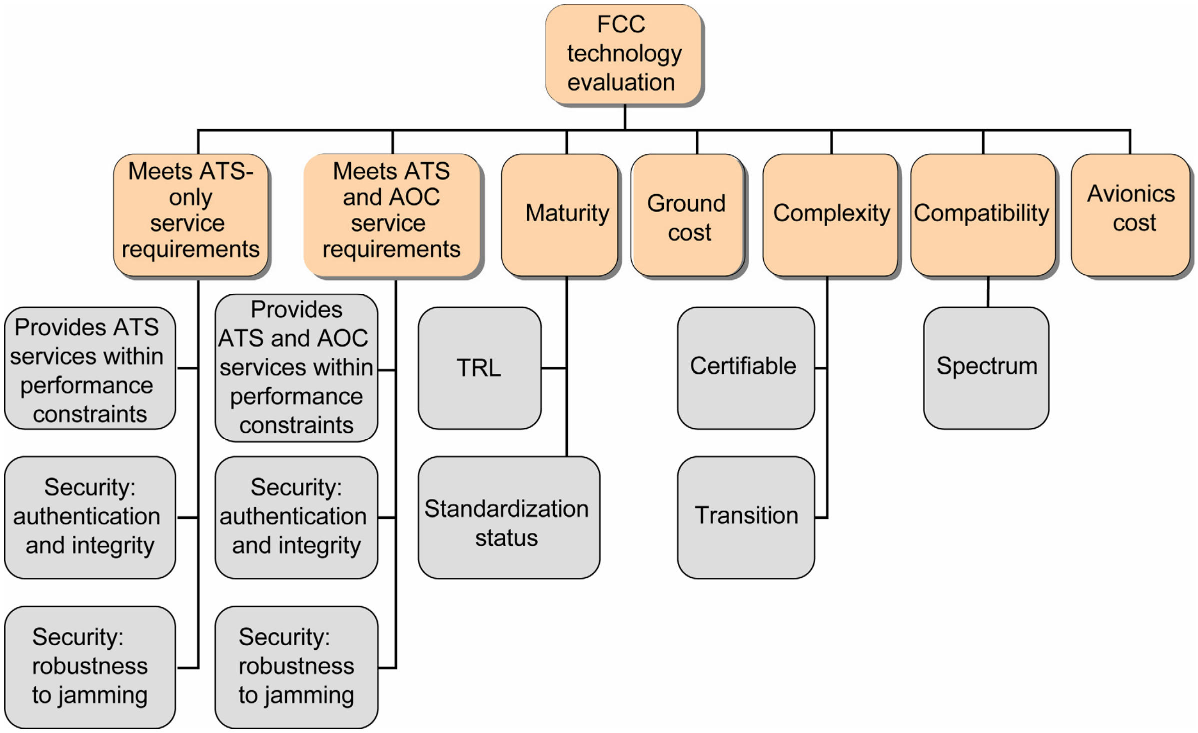


Figure 22.—Roll-up of evaluation criteria into evaluation decision factors.

In figure 22, there are two factors that address technology technical capability: one for providing ATS services, and one for providing ATS and AOC services together. Each of these decision factors addresses performance criteria (provide services within service constraints and for the defined operational environment) and security criteria (authentication and integrity and robustness to interference). The technology maturity decision factor includes TRL criteria and the standardization status criteria, both reflective of a technology developmental status. Two cost decision factors, ground cost and avionics cost, map directly to associated cost evaluation criteria. The complexity decision factor includes certification and transition evaluation criteria. The complexity of a technology implementation is reflected in both of these criteria. Finally, the compatibility decision factor maps directly to the spectrum criterion (addressing spectral compatibility of technologies with legacy systems).

To develop criteria weights, stakeholder rule sets were defined based on documented stakeholder positions. One rule set was defined for communication service providers (e.g., FAA, EUROCONTROL, and ANSPs (e.g., CANSO)), and a second rule set was defined for service users (e.g., AOPA, IATA, NBAA, and ATMAC). These rule sets supported the pair-wise comparison of criteria and population of associated comparison matrices used to define criteria weights. The rule sets for service providers and service users are provided in tables 16 and 17, respectively.

To perform the AHP weighting process, the defined rule sets were used to populate an AHP decision matrix that documents a pair-wise comparison of all decision factors. Each set of factors were evaluated to determine if one was equal to, more important than, or less important than the second factor. Results of this assessment, made using the evaluation rules defined from the stakeholder rule sets, are shown in figures 23 and 24.

TABLE 16.—SERVICE PROVIDER RULE SET SUPPORTING CRITERIA WEIGHTING

	Rules	Notes
1	Spectrum compatibility and Providing ATS services (meeting performance requirements) are equally important and more important than all other criteria	• These are key aspects relating to the need for a new data link service to be pursued only after exhausting other options. A new data link is viable only if it meets requirements and has the ability to use the target spectrum band; compatibility with legacy equipment is required. • WRC–07 Preparation Material proposing AM(R)S allocation in 960 to 1024 MHz indicates compatibility with existing systems is required (i.e., cause no harmful interference to nor claim protection from existing systems) (refs. 33 and 35); Compatibility with legacy equipment is required; no interest in moving DME allocations has been identified. • Many stakeholders reflected the position that existing systems should be used to their fullest extent (refs. 3, 4, 35); a new data link system, for which technologies are evaluated, would only be needed when ATS requirements can no longer be met. Thus the ability to meet ATS requirements is necessary. • ATMAC indicated a desire to maintain ATS and AOC separately (ref. 4) and FAA has indicated they will follow ATMAC recommendations.
2	Ground infrastructure cost and technical maturity are equally important and are more important than factors other than those identified in Rule 1	• Cost of new ground infrastructure and the ability to deploy a new data link in time to address planned spectral constraints and service needs is noted in many service stakeholder positions and has been noted in feedback received on FCS results. • Cost for implementation of a new ground infrastructure was raised in response to FCS Phase I results (prompting further cost assessment in FCS Phase II).[a] • Organizations such as CANSO also show concern for ground infrastructure costs (raised many times in their published information paper) (ref. 35). • The Future Communication Roadmap identifies the initial need for new data link capability in the 2020 time period; this is supported by an indication that VHF saturation has been reached in Europe (ref. 36).
3	All other factors (other than those noted in Rules 1 and 2) are equally important	• No real distinguishing positions are noted with regard to meets ATS and AOC service needs, low-cost avionics, and complexity. Stakeholder views address these issues, but do not offer firm evidence of relative importance of these factors.

[a]FAA FCS Steering Committee response to FCS Phase I results.

TABLE 17.—SERVICE USER RULE SET SUPPORTING CRITERIA WEIGHTING

	Rules	Notes
1	Spectrum compatibility and low-cost avionics are equally important and more important than all other decision factors	• This rule reflects key aspects relating to the ability to use the target spectrum band (compatibility with legacy equipment is required) and the user positions that implementation of a new data link should only be considered after all other alternatives are exhausted (cost concerns). • The ATMAC position recommending pursuit of new technology solutions only after all nonequipment alternatives are explored clearly is indicative of cost concerns (ref. 4). • The Aircraft Owners and Pilots Association (AOPA) president interview emphasized the need to focus on cost considerations (ref. 37).
2	Ground cost and technical maturity are also important; consider them equally important and more important than factors other than those identified in rule 1	• User stakeholders also recognized the need to consider ground infrastructure cost (as this also has an impact on user costs); and capacity constraints should not constrain demand. Technologies being considered should be implemented when needed and need to be sufficiently mature. • The AOPA president interview noted the need to have FAA reduce costs (ref. 37); the ATA president interview identified the need to reduce the costs of the current system (ref. 37).
3	Meets ATS-only service requirements is more important than meeting ATS and AOC service requirements	• Some stakeholders have indicated a desire to maintain ATS and AOC separately; as such, the future data link under evaluation needs to meet ATS requirements, but not necessarily ATS and AOC requirements (reflects ATMAC recommendations).
4	All other factors (other than those noted in rules 1, 2) are equally important (with the exception of the condition noted in rule 3 (e.g., meets ATS-only service requirements is equally important to complexity)	• No real distinguishing views or evidence of relative importance noted for complexity and transition were found in the documented positions.

Is [row] more important than [column]? (>1)	Meets ATS service requirements	Meets ATS and AOC service requirements	Technical maturity	Low-cost ground infrastructure	Low-cost avionics	Spectrum compatibility	Complexity—transition and certification
Meets ATS service requirements		3	3	3	3	1	3
Meets ATS and AOC service requirements	0.333		0.333	0.333	1	0.333	1
Technical maturity	0.333	3		1	3	0.333	3
Low-cost ground infrastructure	0.333	3	1		3	0.333	3
Low-cost avionics	0.333	1	0.333	0.333		0.333	1
Spectrum compatibility	1	3	3	3	3		3
Complexity—transition and certification	0.333	1	0.333	3	1	0.333	

Figure 23.—Decision factor evaluation matrix—Aeronautical communication service provider.

Is [row] more important than [column]? (>1)	Meets ATS service requirements	Meets ATS and AOC service requirements	Technical maturity	Low-cost ground infrastructure	Low-cost avionics	Spectrum compatibility	Complexity—transition and certification
Meets ATS service requirements		3	3	3	3	0.333	1
Meets ATS and AOC service requirements	3		0.333	0.333	1	0.333	1
Technical maturity	3	3		1	3	0.333	3
Low-cost ground infrastructure	3	3	1		3	0.333	3
Low-cost avionics	3	3	3	3		1	3
Spectrum compatibility	3	3	3	3	1		3
Complexity—transition and certification	1	1	0.333	0.333	0.333	0.333	

Figure 24.—Decision factor evaluation matrix—Aeronautical communication service user.

A combined decision matrix, which weighs both stakeholder sets equally and combines results using geometric means, was also created. The resulting decision matrix is shown in figure 25.

Using this matrix, matrix mathematics was applied to calculate the matrix eigenvalues. The largest eigenvalue was used to find the associated eigenvector for the matrix. The normalized eigenvector values are the resulting relative importance weights associated with each decision factor. The weighted results for each stakeholder set (aeronautical communication service providers and users) are shown in figure 26, and the combined weighted results are shown in figure 27.

Is [row] more important than [column]? (>1)	Meets ATS service requirements	Meets ATS and AOC service requirements	Technical maturity	Low-cost ground infrastructure	Low-cost avionics	Spectrum compatibility	Complexity—transition and certification
Meets ATS service requirements		3	1	1	1	0.577	1.732
Meets ATS and AOC service requirements	0.333		0.333	0.333	0.577	0.333	1
Technical maturity	1	3		1	1	0.333	3
Low-cost ground infrastructure	1	3	1		1	0.333	3
Low-cost avionics	1	1.732	1	1		0.577	1.732
Spectrum compatibility	1.732	3	3	3	1.732		3
Complexity—transition and certification	0.577	1	0.333	0.333	0.333	0.333	

Figure 25.—Decision factor evaluation matrix—Combined.

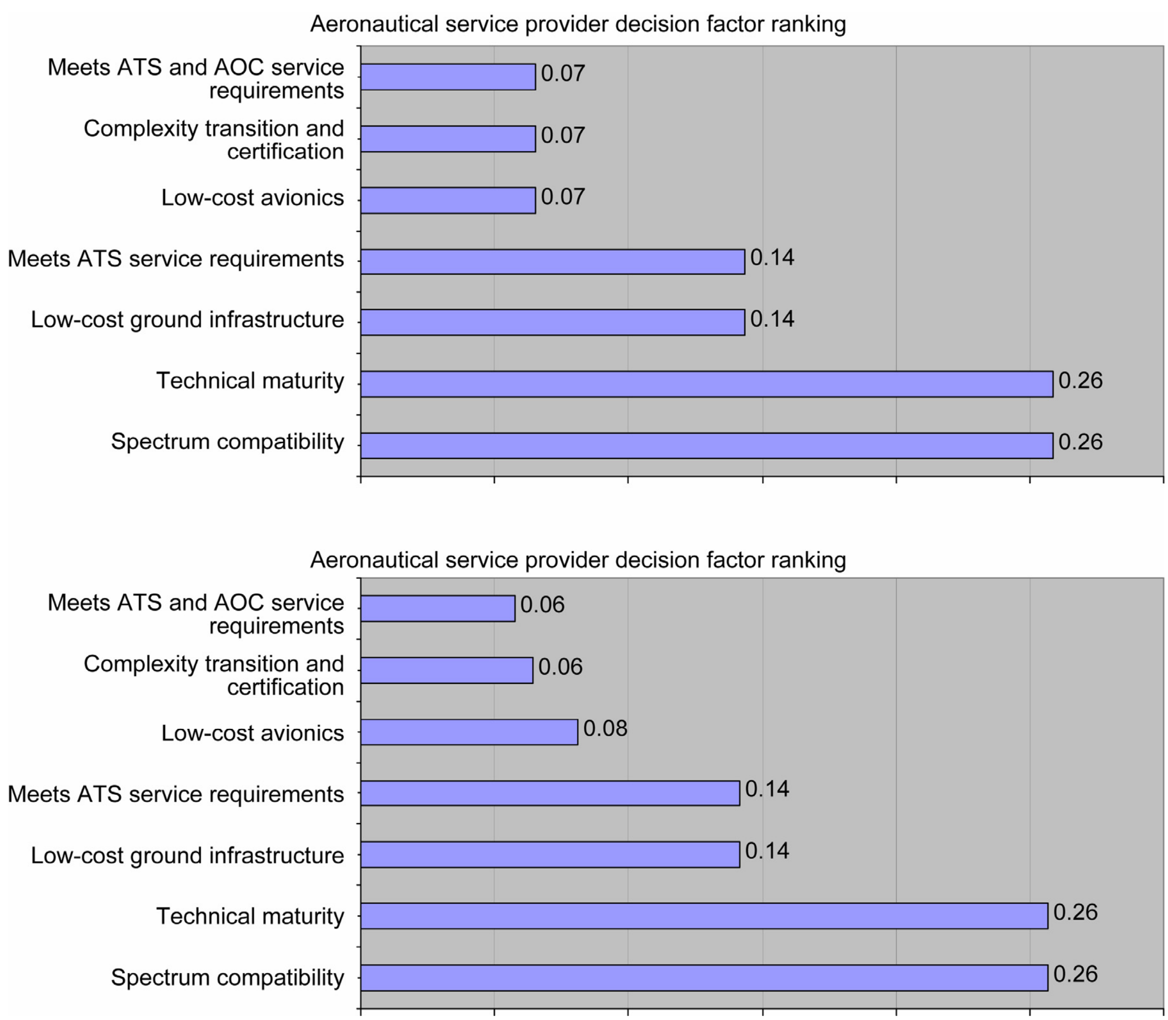


Figure 26.—Weighted decision factors—Aeronautical service providers and users.

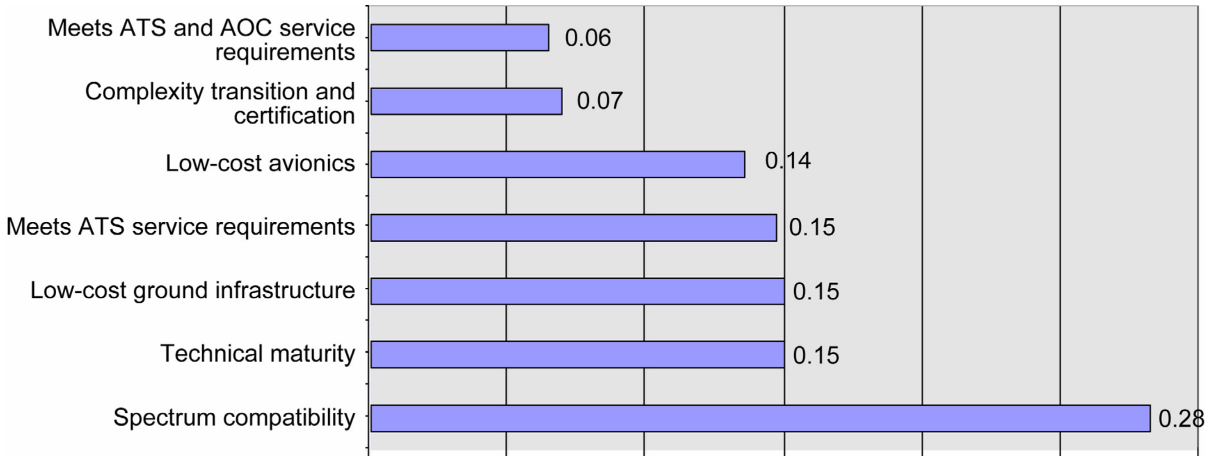


Figure 27.—Weighted decision factors—Combined.

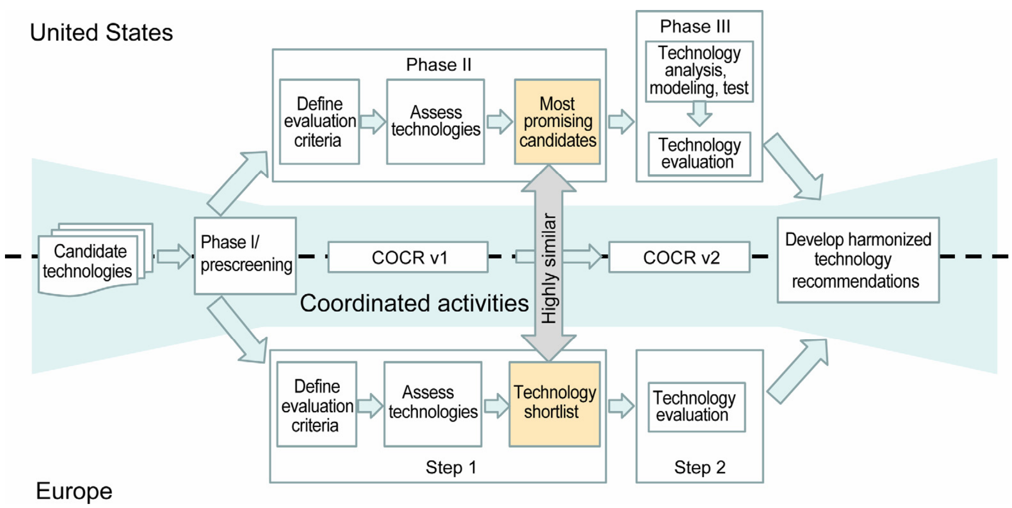


Figure 28.—Harmonized United States and European efforts.

In figure 28, the most important decision factor for the FRS technology evaluation considering all stakeholder positions was spectrum compatibility. This is recognized as an essential factor for introduction of a new data link technology. Other factors that have high relative importance include technical maturity, ground infrastructure costs, meeting ATS service requirements, and low-cost avionics. Both stakeholder groups have documented positions that recognize the need to consider these factors in future aeronautical communication decisions.

6.4 Scoring Technology Performance

Evaluation results can be viewed in the context of the proposed criteria weights. When considering the qualitative weight definitions, the corresponding evaluation results are as shown in table 18.

Considering the results from this perspective, TIA–902 (P34) and LDL both score well for the most important criteria. However, each has significant hurdles to address. Initial results of DME interference testing indicate that compatibility with waveforms (with the possible exception of those with gated and pulsed features with low duty cycles) may not achieve without reassignment of DME channels, but conclusive evidence has not been achieved. Additionally, for LDL, simulations indicate that the performance in the aeronautical channel may be frequency selective, requiring mitigation techniques. For the most important criteria, WCDMA has a significant issue to overcome. Interference assessment and

TABLE 18.—EVALUATION RESULTS WITH QUALITATIVE CRITERIA WEIGHTING APPLIED

	No.	Evaluation criterion		TIA–902 (P34)	LDL	WCDMA	B–AMC	AMACS
Most important	8	Spectrum						
	1	Provides ATS A/G Data services within requirements (sans A–EXEC)	A—Capacity					
			B—PIAC					
			C—QoS					
			D—Environment					
Very important	3	Technical readiness level						
	6	Ground infrastructure cost						
	7	Avionics cost						
	2	Provides ATS AOC A/G data services within requirements (sans A–EXEC)	A—Capacity					
			B—PIAC					
			C—QoS					
			D—Environment					
Important	4	Standardization status						
	5	Certification						
	9	Authentication and integrity						
	10	Robustness to interference						
	11	Transition						

initial DME interference testing indicate that this technology is not compatible with DMEs and would require DME channel reassignment (both for the 5-MHz bandwidth and 5-MHz guard bands).

Both B–AMC and AMACS score well with regard to the most important criteria. The B–AMC A/G system developers are considering the option (OPTN2) to assign frequencies to B–AMC channels in areas where they are not used locally by DME. This requires the establishment of a relation between potential B–AMC assignments and existing DME assignments. B–AMC is considered to be deployable in the intended band without either reallocating existing equipment or requiring modification to existing aeronautical equipment. Further compatibility testing is needed to validate the approach. AMACS is designed for and considered to be deployable in the intended band without either reallocation of existing equipment or requiring modification to existing aeronautical equipment based on cosite considerations. However, no proven cosite tests or simulation are available to determine whether the technology is deployable in the target band.

When considering other important criteria, TIA–902 (P34), LDL, and B–AMC were the technologies without a significant issue to overcome (no red scores), but maturity is a risk factor. AMACS is identified as high risk with regard to technical maturity, although the technology is defined based on existing aeronautical standards. AMACS has a new proposed physical layer, and no standards or validation activity specific to AMACS have been performed. Finally, for WCDMA, another risk area associated with the very important criteria is ground infrastructure cost, as a full complement of WCDMA functionality appears to be required for deployment. The AI alone cannot be deployed and incremental deployment opportunities are limited.

To apply the AHP quantitative criteria weights, the process described in Section 2.4.4 was implemented. Because some criteria were not ranked for B–AMC and AMACS because of insufficient information, their numerical values could not be provided for the AHP comparison matrix. Therefore, B–AMC and AMACS technologies were not included in the AHP process.

For the AHP process, the technology evaluation results were translated into a raw score that reflected the decision factor hierarchy and the metrics were normalized to a value between 0 and 1. Specifically, the following steps were performed:

- For technology evaluation results, assign green = 1, yellow = 0.5, and red = 0.
- To translate criteria evaluation results into evaluation decision factors scores, consider all applicable subcriteria/evaluation criteria that comprise a decision factor equally, and combine these factors such that the resultant decision factor score is normalized to 1.

The decision factor scores were combined with the quantitative decision factor weights using simple multiplication. For each technology, the sum of the scores associated with individual decision factors (weighted) resulted in an overall technology score (normalized to 1).

A sample technology score is shown in table 19. The far left column identifies the decision factors. The next column identifies the specific technology evaluation rating for the technology score (accounting for trilevel evaluation results and criteria roll-up into decision factors). The second column from the right identifies the weight associated with each decision factor based on the AHP matrix calculations. Finally, the far-right column includes the score components as well as the total score for the technology.

Table 20 shows the results of calculating scores for each technology. The resulting technology scores were strongly influenced by the spectrum criterion evaluation results, a factor contributing to poor performance of WCDMA. This criterion was identified as having significant importance to all stakeholders, as would be expected. Other factors influencing results were technical maturity and ground infrastructure costs. Resulting scores for TIA–902 (P34) and LDL were in similar regions of the normalized scale, with TIA–902 (P34) achieving the highest technology rating.

Note that the results shown in table 20 indicate that there is not a strong sensitivity to stakeholder positions on the importance of certain criteria. The differences in scores across the stakeholder groups are statistically insignificant, and in all cases, the same technology ranking was realized: TIA–902 (P34), followed by LDL, and then WCDMA.

TABLE 19.—CALCULATION OF TECHNOLOGY SCORES

Technology Scoring			
Decision factor	Evaluation score	Weight, percent	Overall score
Meets ATS service requirements	0.79	25.89	0.21
Meets ATS and AOC service requirements	0.79	6.51	0.05
Technical maturity	0.75	14.34	0.11
Low-cost ground infrastructure	0.00	14.34	0.00
Low-cost avionics	0.50	6.51	0.03
Spectrum compatibility	0.00	25.89	0.00
Complexity—transition and certification	0.25	6.51	0.02
TOTAL			0.41

TABLE 20.—TECHNOLOGY SCORE RESULTS

Technology	Service provider perspective score	User perspective score	Overall score
TIA–02 (P34)	0.68	0.63	0.65
WCDMA	0.41	0.36	0.37
LDL	0.52	0.50	0.50

6.5 Evaluation Observations

Based on the specific candidate technologies evaluated, and along with performance against defined evaluation criteria, technology attributes desirable for an aeronautical L-band communication capability can be inferred. A list of these attributes and motivation for their identification as desirable is provided in table 21. Note that this work was not a clean-sheet identification of desirable attributes and that these were not requirements for a FRS; rather these were technology attributes that led to favorable evaluation results.

A comparison of technologies to desirable attributes based on evaluation results is provided in table 22.

TABLE 21.—DESIRABLE ATTRIBUTES FOR FRS (BASED ON TECHNOLOGY EVALUATIONS)

Attribute	Notes
Power efficient modulations within the defined L-band channel, specifically, multicarrier modulation techniques	Modulation scheme performance is often measured in terms of power efficiency and bandwidth efficiency (ref. 38). Power efficiency is a measure of the ability to preserve fidelity of a digital message at low power levels, that is, the amount by which the signal level needs to be increased to achieve a certain level of fidelity (e.g., BER). It is often expressed as a ratio of E_b/N_0 for a certain probability of error (e.g., 10^{-5}). The characterization of the L-band aeronautical channel indicates that RMS delay spreads up to 1.4 µs may be experienced. To consider the channel effects specific to technologies, a rule of thumb frequency applied is if RMS delay spread is at least one-tenth the symbol duration, then the channel is frequency selective (where time dispersion of the transmitted symbols would occur, resulting in intersymbol interference). This effect results in an irreducible BER floor. In multicarrier modulations, a channel bandwidth is divided into a number of equal L-bandwidth subchannels and information is transmitted simultaneously over the subchannels (frequency division multiplexing); each subchannel has small data rate as compared to single channel modulations, and as a result, the corresponding symbol duration is longer which leads to better performance in the defined L-band aeronautical channel. This is not to say that single-channel modulations could not work, but symbol durations close to 14 µs (corresponding to 71 kbps or greater) are likely to require special mitigation techniques to address ISI (e.g., equalization).
Bandwidth efficient modulations	As noted above, this is a second measure of modulation performance, typically expressed in terms of the ratio of throughput data rate per Hertz (bps/Hz). Implementation of a communication technology in the aeronautical L-band is a challenging task. More efficient use of the available bandwidth increases the likelihood that a technology can be engineered for compatibility (not to say this is the only criteria for compatibility) while still providing required capacity.
Channels that are at most broadband, but not wideband	Narrow to broadband channels have the best opportunity to share spectrum and/or be inlayed with DMEs. Depending on interference compatibility requirements, it may be possible to directly inlay or deploy with geographic sensitivity to DME frequencies. Because of cosite interference effects specific to DMEs, it is very unlikely that any wideband technology can be engineered for compatibility within the aeronautical L-band without reassignment of DMEs and generating clear spectrum.
Low duty-cycle waveforms	Previous experience with UAT development and deployment as well as initial interference measurements indicate that low duty-cycle waveforms are more likely to be compatible with collocated or adjacent DME channels. Further validation of this feature is required, but appears to be a correlation of duty cycle and DME BSOP.
Efficient Channel Reuse	To accommodate capacity requirements of the COCR, technologies that have good co-channel interference rejection (e.g., low D/U) can be reused at closer distances and provide a greater increase in number of available channels. Additionally, technologies designed for cellular-type deployment with low frequency reuse factors also provide system-wide efficiency. Here, fewer channel assignments are needed, which may help develop a viable channelization scheme.
Provision QoS	The operational services of the COCR have a wide range of performance requirements (reference COCR Version 2, Tables 5–7 and 5–8). Communication service classes are a meaningful way to support the operational services; and a representative service class organization (using latency/priority as drivers for categorization and maintaining ATS and AOC separate) is provided in the COCR (Tables 6–18, 6–19, and 6–20). Capability to provide QoS is a feature required to ensure operational performance requirements are met.
Flexibility to decouple sector coverage from radio coverage	Long-term infrastructure cost and flexibility gains may be realized by providing service without requiring a radio channel for each ATC sector. To implement this regular grid of ground channel service volumes, native mobility management capability or other protocol features that can be used to provision necessary addressing are needed.
Provides authentication and integrity check	COCR Version 2 includes security requirements R.FRS-Sec.2a/2b and R.FRS-Sec.3a/3b (Table 4–15) that indicate that the FRS should support message authentication and integrity as an option to prevent message alteration attacks and entity authentication as an option to mitigate impersonation attacks.
Availability of existing standards	Development risk (and potentially costs) can be reduced if the technology for the FRS has existing standards to be adapted for L-band aeronautical communications. The existence of standards by reputable standards bodies is also indicative of some level of support for the technology.
Available prototypes or products	Development risk (and potentially costs) can be reduced if the prototypes or products are already available for the technology.
Implement service set specific to aeronautical needs	Technologies with a focused set of services and functions have less complexity, which can ease the certification and transition process. There may also be associated cost gains.

TABLE 22.—COMPARISON OF CANDIDATE L–BAND TECHNOLOGIES WITH DESIRABLE ATTRIBUTES

Desirable features	TIA–902 (P34)	LDL	WCDMA	B–AMC	AMACS
Power-efficient modulations within the defined L-band channel, specifically, multicarrier modulation techniques	Met	Not met	Partially met[a]	Met	Not met
Bandwidth efficient modulations	Met	Met	Met	Met	Met
Channels that are at most broadband, but not wideband	Met	Met	Not met	Met	Met
Low duty-cycle waveforms	Not met	Met	Not met	Met[b] (long term)	Met[c] (long term)
Efficient channel reuse	Met	Met	Met	Met	Met
Provision QoS	Met	Met	Met	Met	Met
Flexibility to decouple sector coverage from radio coverage	Met	Partially met	Met	Met	Met
Provides authentication and integrity check	Met	Partially met	Met	TBD[d]	TBD[d]
Availability of existing commercial and/or aeronautical standards	Met	Partially met	Met	Not met	Not met
Available prototypes or products	Met	Partially met	Met	Not met	Not met
Implement service set specific to aeronautical needs	Met	Met	Not met	Met	Met

[a]WCDMA does not employ multicarrier modulation and is an interference limited system; however, proper design can lead to good BER performance achievable for low E_b/N_0 (influenced by factors including spread bandwidth, number of interfering users, and information bit rate).
[b]Reference 39 report states: "In [B–AMC D4] it has been concluded that in order not to disturb other onboard L–band receivers, the duty-cycle of an airborne B–AMC Tx should be kept as low as possible." The maximum duty cycle for a data-only B–AMC system was estimated as 11 percent during about 60 ms, with the typical long-term average value far below this value (0.65 percent). The operational impact of such a duty cycle upon other systems requires further investigation, but it may be regarded as acceptable.
[c]Reference 40 states: "On the other hand the impact of AMACS onboard implementation on DME or SSR/Mode S will be limited by providing a frequency separation between the AMACS channel and the first DME receiving channel (i.e., 978 MHz) and by taking into account the small duty cycle of AMACS (0.15 percent is the minimum duty cycle per aircraft on the basis of a 3-ms usable slot duration, on average the aggregated duty cycle per aircraft should not 0.5 percent)."
[d]Insufficient information for evaluation.

7.0 Findings, Observations, and Recommendations

7.1 Findings and Observations

1. A wide range of technology candidates representative of the cellular standards derivatives; IEEE wireless standards; public safety, radio standards; technologies and standards defined specifically for aviation; and military radio standards were evaluated to determine their applicability to the future aeronautical communication environment as described in the COCR. First, a technology screening process to identify leading contenders for applicability to the FRS was applied. Indepth technical studies were then performed to gain a better understanding of the performance of the most promising technologies in the context of the future communication operational concept and the anticipated RF channel environment. Finally, technologies were considered with regard to evaluation criteria representative of technical performance, cost, and risk decision elements, with criteria weighting applied to understand evaluation results mindful of the relative importance of evaluation criteria. Based on these investigation efforts, the following findings and observations are made: The new communication components introduced into the FCI should reuse emerging data communications technology and standards to the maximum extent possible.
    - The FCS has investigated a wide range of emerging technologies and standards that have the potential to support air traffic services (ATS) and aeronautical operational control (AOC) data communications. Although there will always be further developments in communication technology, due to the time to deploy new systems and

the need for a stable technology solution, the choice of emerging systems offers the lowest risk option. Some of the technologies evaluated are available as commercial-off-the-shelf (COTS) solutions for the area of application for which they were designed.
- However, this study has not identified any technology that does not require some form of modification. Therefore, a COTS solution that can be deployed as designed without any modification is not feasible. The minimum required modification is to change the frequency of operation to one of the FCI target bands to support safety-critical aeronautical communications. Other changes are dependent on the design of the technologies and are typically related to modification of the physical layer, such as the modulation scheme. In any case, adopting or leveraging COTS components should be considered wherever possible to minimize design effort, reduce risk and to shorten time to deployment.

2. No single technology meets all future aeronautical communication requirements across all operational flight domains. The future aeronautical communications operating concept will require a complementary set of capabilities across multiple frequency bands to provide required voice and data communication services.
    - The FCS has identified four operational flight domains
        - Airport surface
        - Airport zone/TMA/ER
        - Oceanic/remote/polar
        - Autonomous operation area
    - To some extent, the propagation conditions determine which frequency band is able to support which flight domain.
        - The airport surface is best served by short range systems operating in the C-band due to the limited propagation distance at this frequency.
        - The airport zone, TMA and ER service volumes are currently served by the congested AM(R)S VHF band, which has good propagation properties. However, L-band propagation properties are also suitable for these domains.
        - The coverage areas of the oceanic, remote, and polar domains are typically beyond line of sight (LOS) of terrestrial systems and can only be realistically served by satellite-based solutions.
3. Technologies that currently provide or are planned to provide aeronautical voice and data communications in the VHF band should be used to their fullest extent.
    - VHF aeronautical spectrum will continue to support DSB–AM voice communications and preserve the option for an initial data link capability that is outside the scope and timeframe of the FCS technology investigation.
    - A long-term strategy for use of the VHF aeronautical band requires further consideration.
    - Due to congestion in the VHF band to support near-term voice and data communication requirements, provision of future communication services outside the VHF band must be considered.
4. The aeronautical L-band spectrum (960 to 1164 MHz) is a candidate band for supporting a new data link communication capability.
    - This band contains a potentially large spectral region suitable for future aeronautical communication systems. However, it is a challenging environment for aeronautical communications due to its aeronautical channel propagation characteristics and the current usage of the band.
    - Estimated RMS delay spreads for the aeronautical L-band channel on the order of 1.4 μs can lead to frequency selective fading performance for some technologies.

- Interference to/from existing aeronautical systems already in L-band systems from/to any proposed communication technology requires detailed examination, including validation measurements and testing.
- Co-allocation of AM(R)S with the existing aeronautical radio navigation services (ARNS) allocation in a portion of this band (960 to 1164 MHz) is required. This was approved at the WRC–07.

5. The aeronautical L-band spectrum (960 to 1164 MHz) provides an opportunity to support the objectives for a future global communication system. However, no evaluated technology (as currently defined) for supporting data communication in this band fully addresses all requirements and limitations of the operating environment.
    - Initial co-channel interference testing indicates that evaluated candidate technology waveforms cause potential interference to existing navigation systems. Further evaluation, including consideration of duty cycle effects on interference, is required to determine collocation feasibility (with on-tune channels, off-tune channels or cleared spectrum).
    - Each technology requires modification of its technical specifications to meet required objectives.
    - A technology adapted from existing standards is recommended for this band.
6. Desirable features for an aeronautical L-band (960 to 1164 MHz) technology include:
    - Use of an existing standard for a safety application with some validation work already performed (reducing time for standardization, increasing initial technical readiness level (TRL), and reducing risk of certification)
    - Multicarrier modulation (power-efficient modulation for the aeronautical L-band fading environment)
    - A low duty cycle waveform with narrow-to-broadband channels (more likely to achieve successful compatibility with legacy L-band systems without clearing spectrum)
    - Adaptable/scalable features (improving flexibility in deployment and implementation, and adaptability to accommodate future demands)
    - Native mobility management and native IP interface (increasing flexibility and providing critical upper layer compatibility with worldwide data networking standards)
7. For the aeronautical L-band (960 to 1164 MHz), some of the evaluated technologies include desirable features that could support a standardization effort, potentially reducing cost and risk.
    - Two options for an L-band Digital Aeronautical Communication System (L–DACS) were identified as shown in table ES.7. These options warrant further consideration before final selection of a data link technology.
    - The first option represents the state of the art in commercial developments employing modern modulation techniques and may lead to utilization/adaptation of COTS products and standards. The second capitalizes on experience from aviation specific systems and standards such as the VHF digital link (VDL) 3, VDL 4, and UAT.

TABLE 23.—L–DACS OPTIONS KEY CHARACTERISTICS

L–DACS option	Access scheme	Modulation type	Recommended technologies
1	Frequency division duplex (FDD)	Orthogonal frequency division multiplexing (OFDM)	B–AMC and TIA–902 (P34)
2	Time division duplex (TDD)	Continuous phase frequency shift keying (CPFSK)/gaussian frequency shift keying (GFSK) type	LDL and AMACS

8. Evaluation of the economic feasibility of implementing an L-band aeronautical ground infrastructure considering life cycle costs indicates that a positive business case can be achieved for a commercial service provider within 4 years.
9. For the aeronautical C-band [(5000 to 5010 MHz, and/or 5010 to 5030 MHz), and/or 5091 to 5150 MHz], there is capacity that is not utilized. Given the severe path loss issues, this band is most applicable to the airport surface where the propagation distances are relatively short.
    - Some concepts for surface communications require substantially higher data rates than are needed in other airspace domains and may warrant a specific technology solution.
10. Specific to aeronautical C-band allocation, IEEE 802.16e is extremely well matched to the airport surface in terms of capability and performance.
    - This technology is designed to work in this band and initial IEEE 802.16e performance evaluations in the modeled aeronautical microwave landing system (MLS) band channel show favorable results.
    - Private service providers have shown interest in the 802.xx family of wireless protocols, given a favorable business case that may be driven by applications in addition to ATS and AOC communications.
11. Aeronautical satellite systems offer unique services that can be applied to large and/or remote geographic areas and can provide supplemental coverage to the terrestrial communication infrastructure.
    - Satellite systems provide communication capability in oceanic, remote and polar regions where typically, there is no other alternative that provides the needed capacity and performance.
    - Satellite systems can be used to provide communication coverage to remote ER domains with historically sparse aircraft densities where it may be more cost effective than ground-based A/G communications systems.
    - Because the evaluated operation concept was beyond the service horizon of existing satellite service offerings, and because future satellite system details are not firm, the application of this study's evaluation criteria cannot provide adequate discrimination among satellite system candidates.
12. This study assumed that the FRS will operate within an IP networking environment. Further work on finalizing the selection of the FRS should include verification that the required performance can be achieved on end-to-end basis within the FCI. This should include appropriate methods of assuring that the required QoS for safety-related applications can be maintained across the entire communication system.

The foregoing findings can be summarized to indicate the applicability of technologies against airspace type (see table 24).

TABLE 24.—APPLICABILITY OF TECHNOLOGIES ACCORDING TO AIRSPACE TYPE

Airspace type	Applicable technology
Airport surface	IEEE 802.16e L–DACS may be possible in some areas
APT, TMA, ER	L–DACS Satellite-based may be possible in some areas
Oceanic/remote/polar	Satellite-based
Air/air	L–DACS

7.2 Proposed Recommendations and Next Steps

Based on the findings and observations noted above, a set of study recommendations were developed and are provided below. They are representative of the United States FCS technology evaluation team Phase III results through the end of the summer of 2007. At the conclusion of these activities, evaluation results and recommendations were brought forward to ICAO WG–T for further consideration. This is discussed in Section 7.3. Discussed below are the concluding recommendations of FCS Phase I, II, and III technology investigations.

7.2.1 C-Band—Airport Airspace Recommendations

The C-band recommendations are to

- Identify the portions of the IEEE 802.16e standard best suited for APT surface wireless mobile communications, identify and develop missing required functionalities, and propose an aviation specific standard to appropriate standardization bodies
- Evaluate and validate the performance of an aviation-specific standard wireless mobile communications network operating in the relevant APT surface environments through trials and testbed development
- Propose a channelization methodology for allocation of safety and regularity of flight services in the band to accommodate a range of APT classes, configurations, and operational requirements
- Complete the investigation of compatibility of prototyped C-band components with existing systems in the C-band in the APT surface environment and interference with other users of the band

7.2.2 Satellite-Band—Oceanic/Remote and Continental Airspace Recommendations

The satellite-band recommendations are to

- Continue monitoring the satellite system developments and assessment of specific technical solutions to be offered in the timeframe defined in the COCR as these next generation satellite systems become better defined
- Update the existing AMS(R)S autonomous pulse record system (SARP) performance requirements to meet future requirements
- Consider the development of a globally applicable AI standard for satellite systems supporting safety-related communications to support the new AMS(R)S SARPs

7.2.3 L-Band—Continental Airspace Recommendations

For ER and TMA airspace, the L-band was identified as the best candidate band for meeting the future aeronautical communications, primarily because of potential spectrum availability and propagation characteristics. L-band recommendations include the following:

- Define interference test requirements and associated outputs that can be used to determine compatibility of future candidate aeronautical communication technologies with existing aeronautical L-band systems
- Pursue detailed compatibility assessment of candidate physical layers for an L-band aeronautical digital link, including interference testing
- Pursue definition/validation of technology derived or adapted from existing standards for use as an L–DACS that can be used to initiate an aeronautical standardization effort (and meet ICAO requirements for such an effort)
- Complete the investigation of compatibility of prototyped L–DACS components with existing systems in the L-band particularly with regard to the onboard cosite interference and agree on the overall design characteristics
- Considering the design tradeoffs, propose the appropriate L–DACS solution for input to a global aeronautical standardization activity

- Considering that B–AMC, AMACS, and TIA–902 (P34) have provisions to support A/A services, conduct further investigation of this capability as a possible component of L–DACS

7.2.4 Very High Frequency (VHF)-Band—Continental Airspace Recommendations

The VHF-band recommendation is to

- In the longer term, reconsider the potential use of the VHF for new technologies when sufficient spectrum becomes available to support all or part of the requirements

7.2.5 Proposed Next Steps

To address the recommendations above, several areas of future work have been identified. These include

- Perform interference assessments/test that characterizes the relationship between FCS technology duty-cycle and interference susceptibility
- Investigate combined effects of existing aeronautical L-band systems and proposed communication technologies on legacy L-band aeronautical system susceptibility
- As applicable technical details and resources are available, evaluate applicability of B–AMC and AMACS to the future aeronautical communication infrastructure, including assessment to defined evaluation criteria
- If a custom LDL technology is under definition (new system or adaptations of an evaluated technology), conduct interference assessments with prototype transmitters
- Define and assess the gap between existing standards and standardization required for aeronautical implementation of the consensus FCS data link technology recommendations for the DME band

7.3 Harmonized Recommendations and Actions

The FCS technology investigation and assessment was undertaken in several phases through coordinated and cooperative efforts by two independent teams: the European team and the United States (FAA/NASA/ITT) team. The two teams used similar methodologies following a common approach that included the identification and prescreening of candidate technologies; a screening process to down-select the most promising candidates; and an indepth evaluation of the most promising technologies leading to development of technology recommendations. This common approach is shown in figure 15.

During FCS Phase I, the two investigation teams participated in a closely coordinated initial prescreening of technologies that included identification of candidate technologies; definition of concepts of use for the technologies within the future aeronautical environment; initial definition of evaluation criteria; and preliminary assessment of technologies. The initial evaluation criteria and results were presented at the ACP/WGW meeting in June 2005 in Montréal, Canada.

In the FCS Phase II down-selection and technology evaluation activities, the United States team reevaluated the technologies with refined criteria based on inputs received from the international stakeholder community via ICAO/ACP; while the European team worked in parallel and conducted an alternative evaluation process. Technology evaluation and assessment results were reported in ACP/WGC meeting in September 2006 in Brussels, Belgium.

At the end of FCS Phase III, the technology evaluation results were compared, and the two teams came to similar conclusions with alternative methodologies. Many meetings were conducted between the two teams to discuss issues, findings, recommendations, and overall FCS investigation conclusions. A joint report on FCS final conclusions and recommendations (ref. 3) was presented at the ICAO ACP/WGT meeting in October 2007 in Montréal, Canada. In the final AP–17 report, harmonized key recommendations, and proposed actions were presented for the new data link developments as follows (ref. 3):

The outcome of the AP–17 activities identify that the FCI will be a system of systems infrastructure, integrating existing and new technological components aiming to secure seamless continuation of operations by safeguarding investments, facilitating required transitions, and supporting the future requirements.

In summary, the key recommendations out of AP–17 for new data link developments are the following:

- [R1] Develop a new system based on the IEEE 802.16e standard operating in the C-band and supporting the APT surface environment
- [R2] Complete investigations (with emphasis in proving the spectrum compatibility with other systems) to finalize the selection of a data link operating in L-band (L–DACS) and supporting the continental airspace environment, aiming at a final decision by 2009, to enable system availability for operational use by 2020
- [R3] Recognizing that satellite communications remain the prime candidate to support oceanic and remote environments and that the considered future satellite systems may also be able to support continental environments possibly complementing terrestrial systems, monitor and support developments that will lead to globally available ATS satellite communications
- [R4] Recognizing the importance of spectrum for the realization of FCI, ensure the availability of the required spectrum in the appropriate bands
- [R5] Promote and support activities that will enable/facilitate the airborne integration of the selected technologies
- [R6] Incorporate in any new data link system, provisions for supporting high QoS requirements in an end-to-end perspective

The suggested action items are

C-band data link (Actions 1.X supporting recommendation R1)

- [A1.1] Identify the portions of the IEEE standard best suited for airport surface wireless communications, identify and develop any missing functionality and propose an aviation specific standard to appropriate standardization bodies
- [A1.2] Evaluate and validate the performance of the aviation specific standard to support wireless mobile communications networks operating in the relevant airport surface environments through trials and testbed development
- [A1.3] Propose a channelization methodology for allocation of safety and regularity of flight services in the band to accommodate a range of airport classes, configurations and operational requirements

L-band data link (Actions 2.X supporting recommendation R2)

- [A2.1] Refine and agree on the interference environment and assumptions for the L-band compatibility investigations
- [A2.2] Develop L–DACS prototypes for testing and trials to facilitate the technology investigations for the selection of the L-band data link
- [A2.3] Complete the investigation of compatibility of candidate L-band data link with existing systems in the L-band particularly with regard to the onboard cosite interference and agree on the overall design characteristics
- [A2.4] Complete evaluation of performance of candidate L-band data link against the appropriate requirements in the various environments

- [A2.5] Considering the design tradeoffs, propose the appropriate L–DACS solution for input to a global aeronautical standardization activity
- [A2.6] Evaluate and validate the performance of the proposed solution in the relevant environments through trials and testbed development

Satellite data link (Actions 3.X supporting recommendation R3)

- [A3.1] Continue monitoring the satellite system developments and assessment of specific technical solutions to be offered in the timeframe defined in the COCR as these next generation satellite systems become better defined
- [A3.2] Update existing AMS(R)S SARPs performance requirements to meet future requirements
- [A3.3] In order to support the new AMS(R)S SARPs, consider the development of a globally applicable AI standard for satellite communication systems supporting safety-related communications

Spectrum (Actions 4.X supporting recommendation R4)

- [A4.1] Continue to provide rationale to spectrum regulators on the need for additional AM(R)S spectrum to facilitate advances in aeronautical communication capabilities
- [A4.2] Provide support for compatibility studies between the FCI and other incumbent systems in any newly-allocated AM(R)S bands. This will include studies within ICAO regarding FCI compatibility with other aeronautical systems, and studies within the ITU regarding FCI compatibility with nonaeronautical systems
- [A4.3] Continue to support the need for priority to AMS(R)S in the satellite L-band
- [A4.4] In the longer term, reconsider the potential use of the VHF-band for new technologies when sufficient spectrum becomes available to support all or part of the requirements

Appendix A—Evaluation Process Flow Diagrams

Evaluation criteria definitions and metrics were defined and developed in all three phases of FCS study. In the final phase of FCS study, Phase III, evaluation criteria definitions and metrics were updated to reflect COCR changes included in COCR Version 2 (released in spring 2007), evaluation flow diagrams were specified to document-specific steps to be completed to perform technology assessments. This appendix documents the metrics associated with the evaluation criteria and the associated evaluation process flow diagrams defined to guide the technology assessments.

A separate subsection is provided for each evaluation criterion. Within each section, an introduction to the criterion is first provided and includes a definition, evaluation assumptions, and associated metrics. This material is followed by the process flow diagram (figs. 29 through 51) and a table (tables 25 through 41) that identify required technology inputs for the evaluation process.

A.1 Criterion 1

Criterion 1	Provide ATS Services Within Performance Constraints

Criterion definition	• This criterion measures the ability of a technology to provide sufficient functional and performance capability to meet operational and environmental requirements of the COCR for ATS services (data services)
	• Evaluation is based on the defined concept of operation for the technology specific to the future aeronautical application
	• Includes four component evaluations
	  • 1A: Provide sufficient capacity for ATS-only services
	  • 1B: Accommodates expected PIACs
	  • 1C: Provides QoS mechanism
	  • 1D: Performs in aeronautical channel and airspace environment
	  • Ability to operate in the intended channel for defined mobile speeds

Assumptions	Each component performance measure is evaluated separately; resulting “scores” are then combined into a technology rating
Metrics	Check 1A, 1B, 1C, and 1D

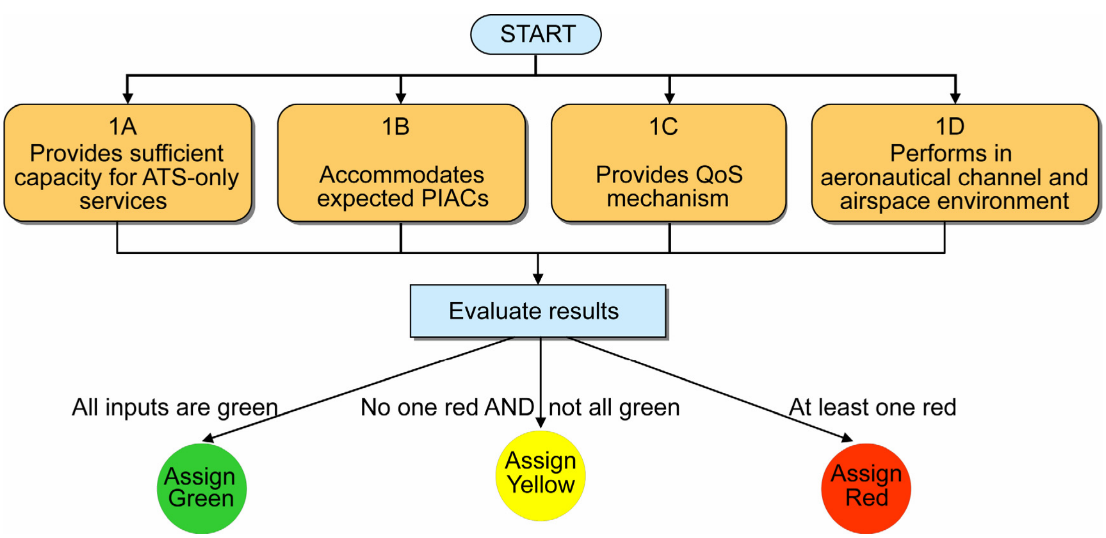


Figure 29.—Process flow diagram for Criterion 1.

A.1.1 Criterion 1A

Criterion 1A	Provides Sufficient Capacity for ATS-Only Services
Criterion definition	• This is a measure of a technology to provide sufficient functional and performance capability to meet ATS service capacity requirements as defined in the COCR for the FRS • The assessment excludes A–EXEC and air-broadcast services
Assumptions	• Phase II timeframe • ATS services are provided as data communications • CoS (Phase II) • ATS services are organized into seven service classes (not all required for all domains and/or phases) as defined in COCR v2.0 Table 6–21 The following Phase II classes are not accounted for: • DG–B for A–EXEC (analysis excludes A–EXEC) • DB–A and DB–B for ADS–B/WAKE (analysis excludes air-broadcast services) • DA–B for PAIR–APP (service is treated as an air-broadcast service) • Service class requirements are as defined in COCR v2.0 Table 6–18 Applicable flight domain(s)—technology is applicable to one or more of the following: • Surface only • Continental (surface, TMA, and ER) • ER and TMA • Continental and oceanic/remote/polar (ORP)
Metrics	• GREEN: Provides capability to provision ATS services meeting capacity requirements for Phase II/ high density across all continental flight domains (or applicable domain for domain-specific analysis) • YELLOW: Provides capability to provision ATS services meeting capacity requirements for Phase II/high density in at least one (but not all) flight domain (or in the applicable flight domain for domain-specific analysis); or meeting capacity requirements for low density in at least one flight domain (or in the applicable flight domain for domain-specific analysis) when high density capacity requirements are not met in any flight domains • RED: Does not provide sufficient capability to provision ATS services meeting capacity requirements for Phase II high and low density in any flight domain (or for the applicable domain for domain-specific analysis)

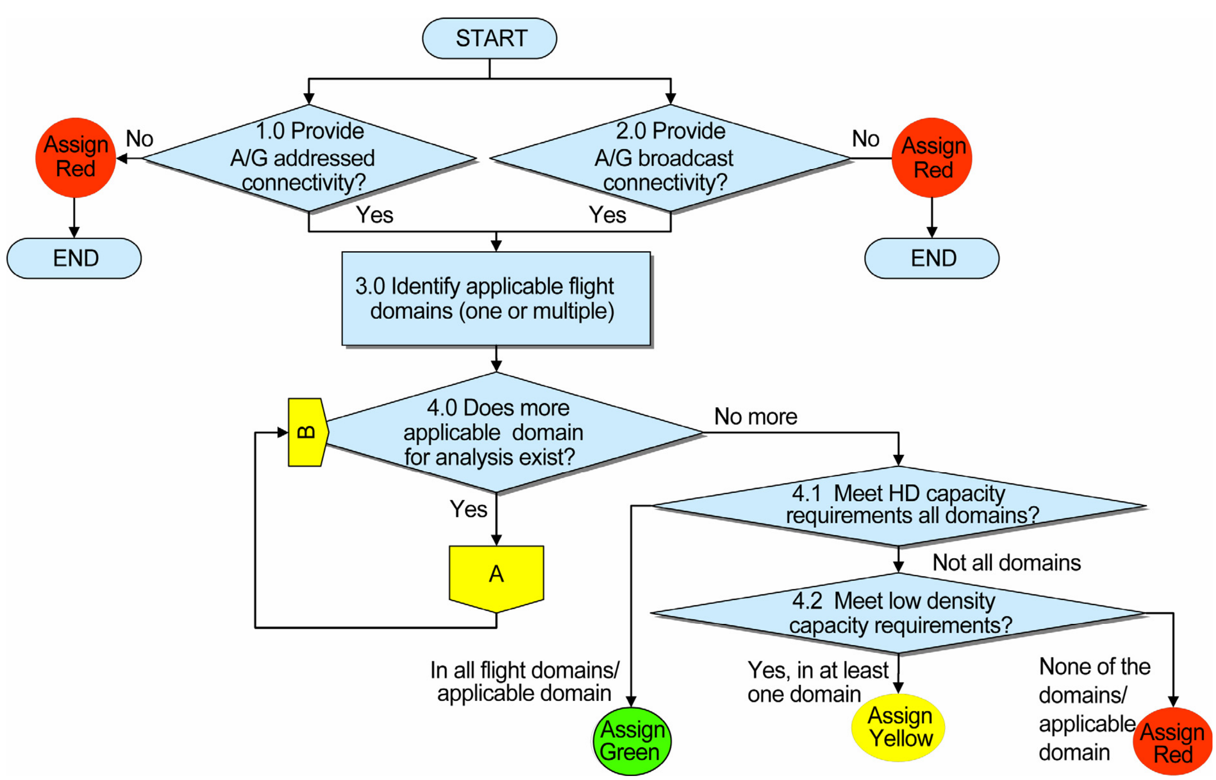


Figure 30.—Process flow diagram for Criterion 1A(1).

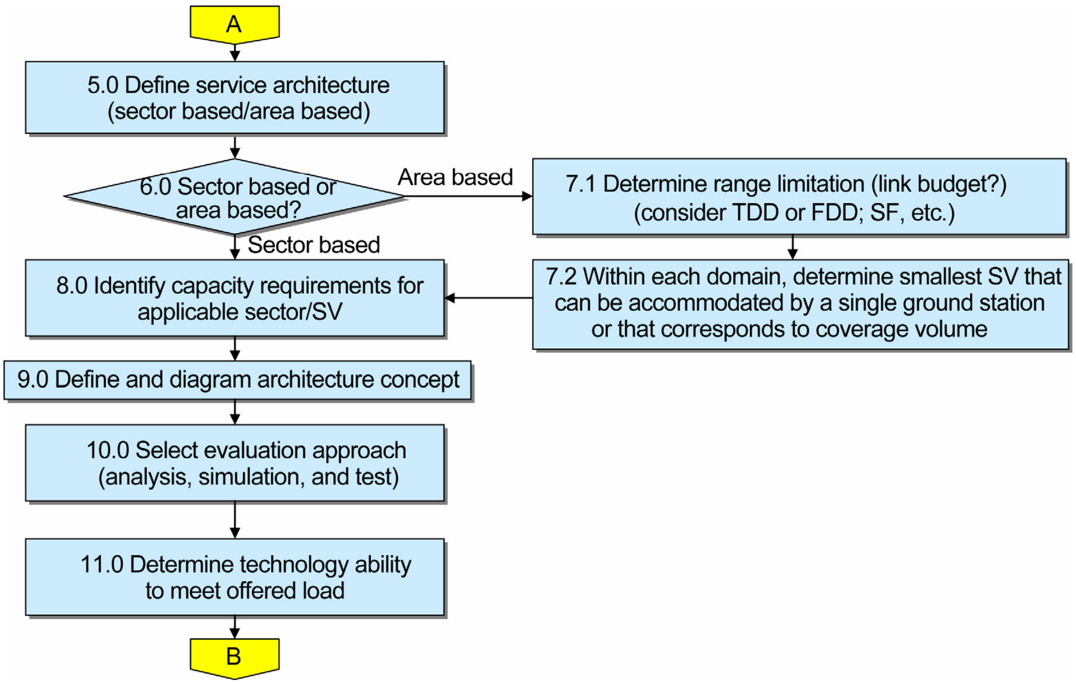


Figure 31.—Process flow diagram for Criterion 1A(2).

TABLE 23.—EVALUATION INPUTS FOR CRITERION 1A

Process step	Step name	Required input	Source(s)
1.0/2.0	Provide A/G Address/Broadcast Capability	• Technology service description	• Technology specifications • Technology technical description documents
3.0	Identify Applicable Flight Domains	• Estimated technology range and maximum data rate (for specified modulation and/or coding) • Identified applicable flight domains	• Technology specifications • Technology technical description documents • FCS Prescreening Assessment
5.0	Define Service Architecture	• Technology PHY layer definition (physical layer data rate and channel access techniques) • Estimated technology range and maximum data rate (for specified modulation and/or coding) • Identified service concept	• Technology specifications • Technology technical description documents • FCS Prescreening Assessment
7.1	Determine Range Limitation	• Technology link budget (modulation, coding, symbol rate, and channel size) • Technology PHY layer definition	• Technology specifications • Technology technical description documents
8.0	Identify Capacity Requirements for Applicable Sector/LAV	• COCR capacity requirements • FCS communication loading scenarios	• COCR for FRS • FCS communication loading scenarios document

A.1.2 Criterion 1B

Criterion 1B	Accommodates Expected PIACs
Criterion definition	This is a measure of a technology's ability to meet COCR PIAC requirements

Assumptions	• Phase II timeframe
	• Applicable flight domain(s)—technology is applicable to one or more of the following:
	  • Surface only
	  • Continental (surface, TMA, and ER)
	  • ER and T
	  • Continental and ORP

Metrics	• GREEN: Provides capability to provision ATS services meeting PIAC requirements for Phase II/high density across all continental flight domains (or applicable domain for domain-specific analysis) • YELLOW: Provides capability to provision ATS services meeting PIAC requirements for Phase II high density in at least one (but not all) flight domain (or in the applicable flight domain for domain-specific analysis); or meeting PIAC requirements for low density in at least one flight domain (or in the applicable flight domain for domain-specific analysis) when high density capacity requirements are not met in any flight domains • RED: Does not provide sufficient capability to provision ATS services meeting PIAC requirements for Phase II high and low density in any flight domain (or for the applicable domain for domain-specific analysis)

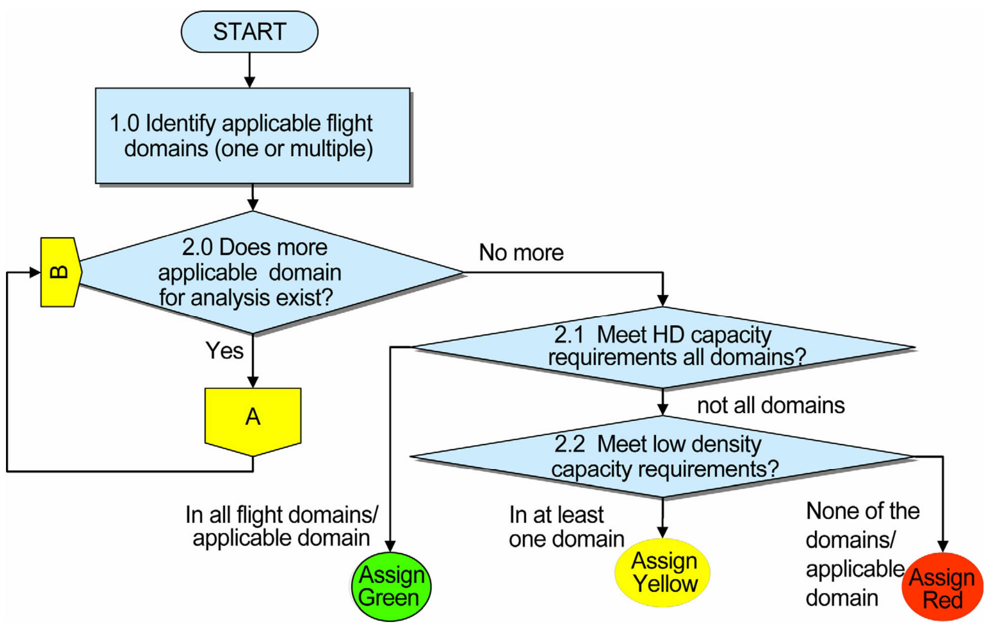


Figure 32.—Process flow diagram for Criterion 1B(1).

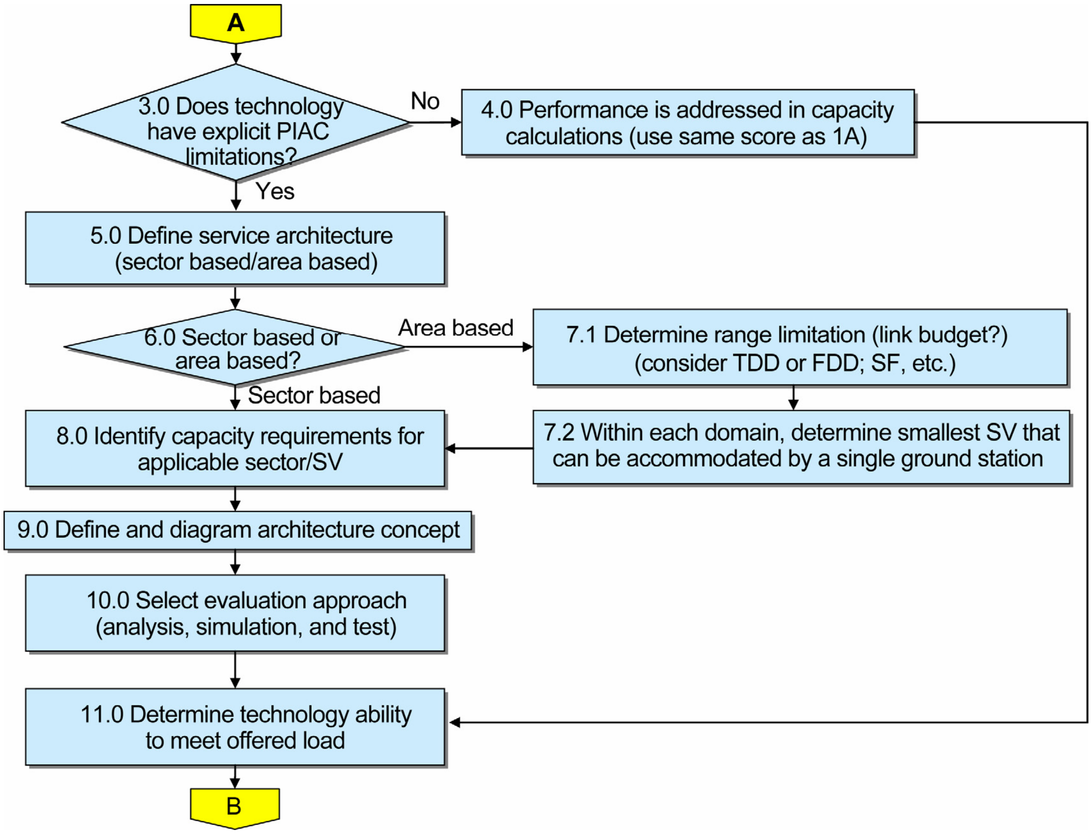


Figure 33.—Process flow diagram for Criterion 1B(2).

TABLE 24.—EVALUATION INPUTS FOR CRITERION 1B

Process step	Step name	Required input	Source(s)
1.0	Identify Applicable Flight Domains	• Estimated technology range and maximum data rate (for specified modulation and/or coding) • Identified applicable flight domains	• Technology specifications • Technology technical description documents • FCS Prescreening Assessment
3.0	Define Service Architecture	• Technology PHY layer definition (physical layer data rate and channel access techniques) • Estimated technology range and maximum data rate (for specified modulation and/or coding) • Identified service concept	• Technology specifications • Technology technical description documents • FCS Prescreening Assessment
7.1	Determine Range Limitation	• Technology link budget (modulation, coding, symbol rate, and channel size) • Technology PHY layer definition	• Technology specifications • Technology technical description documents
8.0	Identify PIAC Requirements for Applicable Sector/LAV	• COCR PIAC requirements • FCS communication loading scenarios	• COCR for FRS • FCS communication loading scenarios document

A.1.3 Criterion 1C

Criterion 1C	Provides QoS Mechanism
Criterion definition	This is a measure of a technology's ability to provision QoS for ATS services
Assumptions	• CoS categories similar to those defined for the COCR loading assessment will be required by the FRS • Number of services classes • Service class definitions
Metrics	• GREEN: Provides capability to offer CoS (e.g., prioritization) capability for ATS services • YELLOW: Technology can be readily modified to offer CoS (e.g., prioritization) capability for ATS services • RED: Technology cannot be easily modified to offer CoS (e.g., prioritization) capability for ATS services

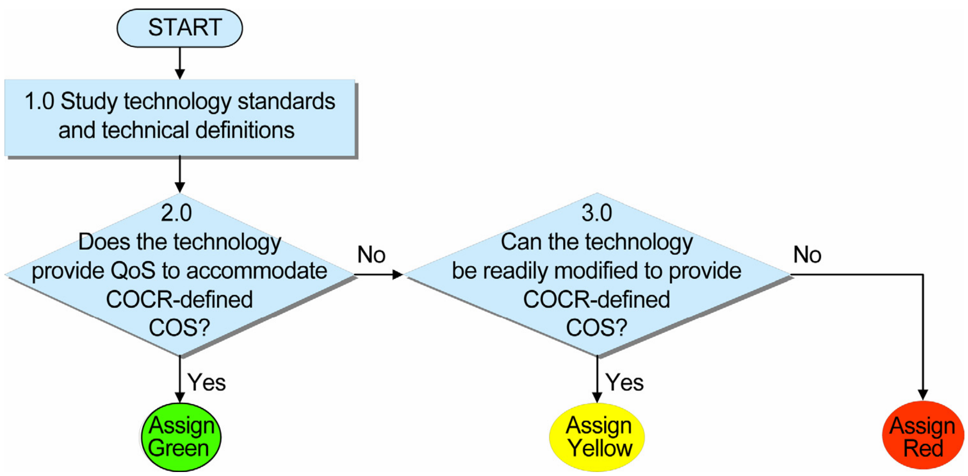


Figure 34.—Process flow diagram for Criterion 1C.

TABLE 25.—EVALUATION INPUTS FOR CRITERION 1C

Process step	Step name	Required input	Source(s)
All	Varies	• Technology PHY layer definition (physical layer data rate and channel access techniques) • Technology MAC/Link layer definition (service class and priority capability)	• Technology specifications • Technology technical description documents • FCS Prescreening Assessment

A.1.4 Criterion 1D

Criterion 1D	Performs in Aeronautical Channel and Airspace Environment
Criterion definition	• This is a measure of the ability of a technology to provide sufficient functional and performance capability to meet operational and environmental requirements of the COCR for ATS and AOC services (data services) • Accounts for time-varying and time-dispersive channel effects
Assumptions	NA
Metrics	• GREEN: Technology performance in intended channel is characterized by flat and/or slow fading • YELLOW: Technology can be readily modified to be characterized by flat and/or slow fading (e.g., physical layer modifications and equalization techniques) • RED: Technology cannot be easily modified to be characterized by flat and/or slow fading

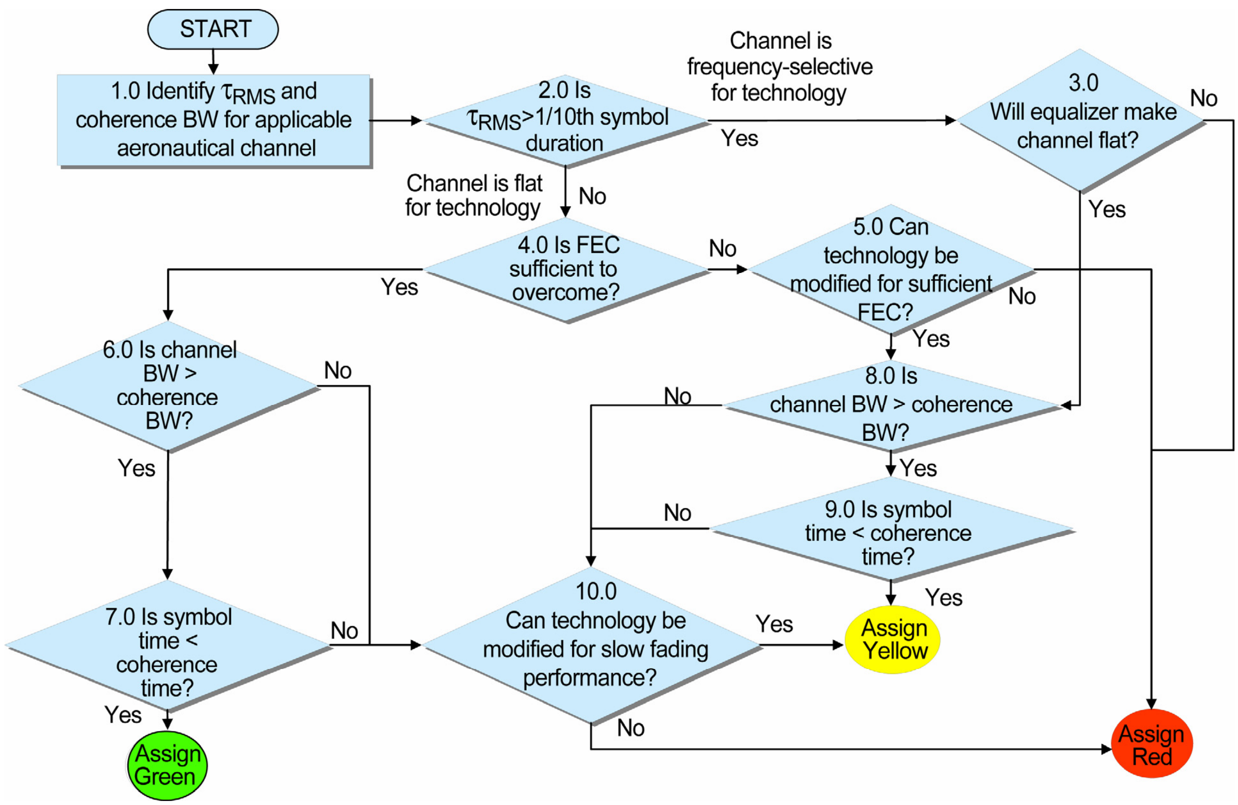


Figure 35.—Process flow diagram for Criterion 1D.

TABLE 26.—EVALUATION INPUTS FOR CRITERION 1D

Process step	Step name	Required input	Source(s)
All	Varies	• Intended aeronautical band for each technology • Aeronautical channel fading characterization (RMS delay spread; coherence bandwidth/coherence time calculations) • Technology PHY layer definition (channel bandwidth and symbol rate)	• Aeronautical channel characterization studies (including FCS channel modeling analysis) • Technology specifications • Technology technical description documents

A.2 Criterion 2

Criterion 2	Provide ATS and AOC Services Within Performance Constraints

Criterion definition	• This criterion measures the ability of a technology to meet performance requirements of the COCR for the FRS for provisioning both ATS and AOC services
	• Evaluation is based on the defined concept of operation for the technology specific to the future aeronautical application
	• Includes four component evaluations
	  • 2A: Provide sufficient capacity for ATS-only services
	  • 2B: Accommodates expected PIACs
	  • 2C: Provides QoS mechanism
	  • 2D: Performs in aeronautical channel and airspace environment
	• This criterion and associated metrics/evaluation process diagrams are very similar to those defined for Criterion 1
	• Difference is in capacity requirements used in the assessment of a technology to provision sufficient capacity (2B)

Assumptions	As with criterion 1, each component performance measure (e.g., 2A, 2B, etc.) is evaluated separately; resulting "scores" are then combined into a technology rating
Metrics	Check 2A, 2B, 2C, and 2D

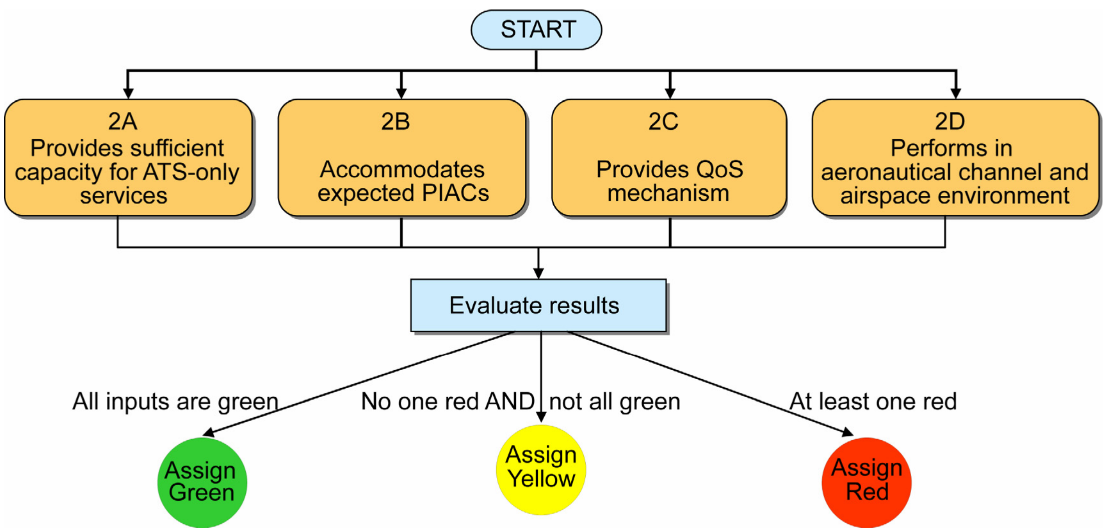


Figure 36.—Process flow diagram for Criterion 2.

A.2.1 Criterion 2A

Criterion 2A	Provides Sufficient Capacity for ATS and AOC Services
Criterion definition	• This is a measure of a technology to provide sufficient functional and performance capability to meet ATS and AOC (combined) service capacity requirements as defined in the COCR for the FRS • The assessment excludes A–EXEC and air-broadcast services

Assumptions	• Phase II timeframe
	  • ATS services are provided as data communications
	  • CoS (Phase II)
	  • ATS Services are organized into seven service classes (not all required for all domains/phases) as defined in COCR v2.0 Table 6–21
	• The following Phase II classes are not accounted for:
	  • DG–B for A–EXEC (analysis excludes A–EXEC)
	  • DB–A and DB–B for ADS–B/WAKE (analysis excludes air-broadcast services)
	  • DA–B for PAIR–APP (service is treated as an air-broadcast service)
	  • Service class requirements are as defined in COCR v2.0 Table 6–18
	  • AOC services are organized into three service classes as defined in COCR v2.0 Table 6–22 (with service class requirements as defined in COCR v2.0 Table 6–18)
	• Applicable flight domain(s)—technology is applicable to one or more of the following:
	  • Surface only
	  • Continental (surface, TMA, and ER)
	  • ER and TMA
	  • Continental ORP

Metrics	• GREEN: Provides capability to provision ATS and AOC services meeting capacity requirements for Phase II/high density across all continental flight domains (or applicable domain for domain-specific analysis) • YELLOW: Provides capability to provision ATS and AOC services meeting capacity requirements for Phase II/high density in at least one (but not all) flight domain (or in the applicable flight domain for domain-specific analysis); or meeting capacity requirements for low density in at least one flight domain (or in the applicable flight domain for domain-specific analysis) when high density capacity requirements are not met in any flight domains • RED: Does not provide sufficient capability to provision ATS and AOC services meeting capacity requirements for Phase II high and low density in any flight domain (or for the applicable domain for domain-specific analysis)

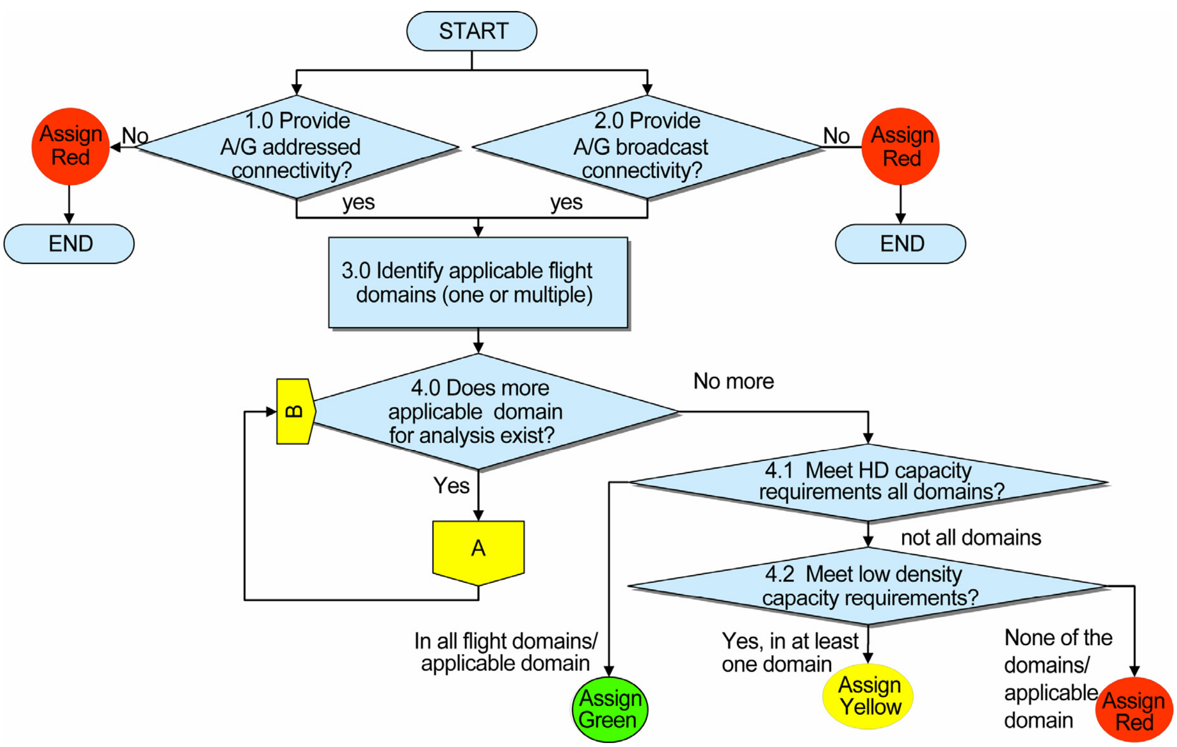


Figure 37.—Process flow diagram for Criterion 2A(1).

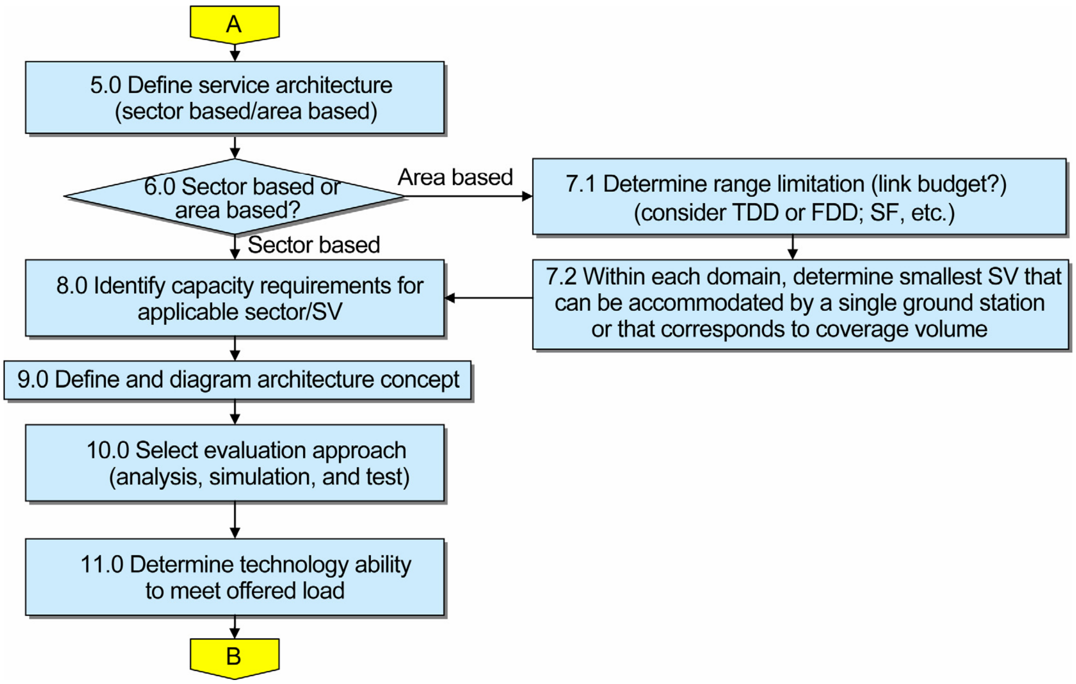


Figure 38.—Process flow diagram for Criterion 2A(2).

TABLE 27.—EVALUATION INPUTS FOR CRITERION 2A

Process step	Step name	Required input	Source(s)
1.0/2.0	Provide A/G Address/Broadcast Capability	• Technology service description	• Technology specifications • Technology technical description documents
3.0	Identify Applicable Flight Domains	• Estimated technology range and maximum data rate (for specified modulation and/or coding) • Identified applicable flight domains	• Technology specifications • Technology technical description documents • FCS Prescreening Assessment
5.0	Define Service Architecture	• Technology PHY layer definition (physical layer data rate and channel access techniques) • Estimated technology range and maximum data rate (for specified modulation and/or coding) • Identified service concept	• Technology specifications • Technology technical description documents • FCS Prescreening Assessment
7.1	Determine Range Limitation	• Technology Link Budget (modulation, coding, symbol rate, and channel size) • Technology PHY layer definition	• Technology specifications • Technology technical description documents
8.0	Identify Capacity Requirements for Applicable Sector/LAV	• COCR capacity requirements • FCS communication loading scenarios	• COCR for FRS • FCS communication loading scenarios document

A.2.2 Criterion 2B

Criterion 2B	Accommodate Expected PIACs
Criterion definition	This is a measure of a technology's ability to meet COCR PIAC requirements
Assumptions	• Phase II timeframe Applicable flight domain(s)—technology is applicable to one or more of the following: • Surface only • Continental (surface, TMA, and ER) • ER and TMA • Continental and ORP
Metrics	• GREEN: Provides capability to provision ATS and AOC services meeting PIAC requirements for Phase II/high density across all continental flight domains (or applicable domain for domain-specific analysis) • YELLOW: Provides capability to provision ATS and AOC services meeting PIAC requirements for Phase II high density in at least one (but not all) flight domain (or in the applicable flight domain for domain-specific analysis); or meeting PIAC requirements for low density in at least one flight domain (or in the applicable flight domain for domain-specific analysis) when high density capacity requirements are not met in any flight domains • RED: Does not provide sufficient capability to provision ATS and AOC services meeting PIAC requirements for Phase II high and low density in any flight domain (or for the applicable domain for domain-specific analysis)

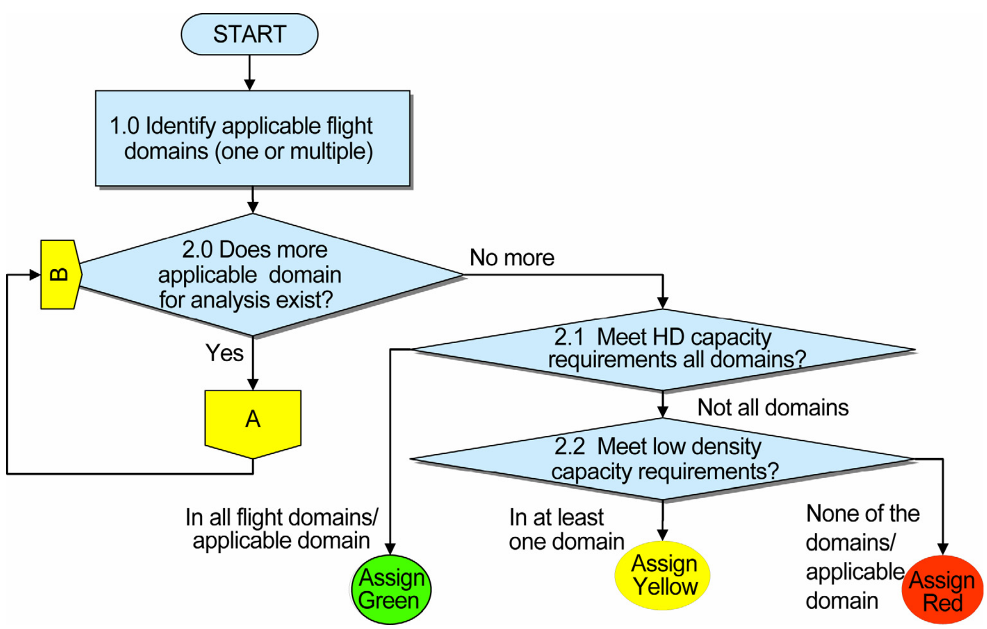


Figure 39.—Process flow diagram for Criterion 2B(1).

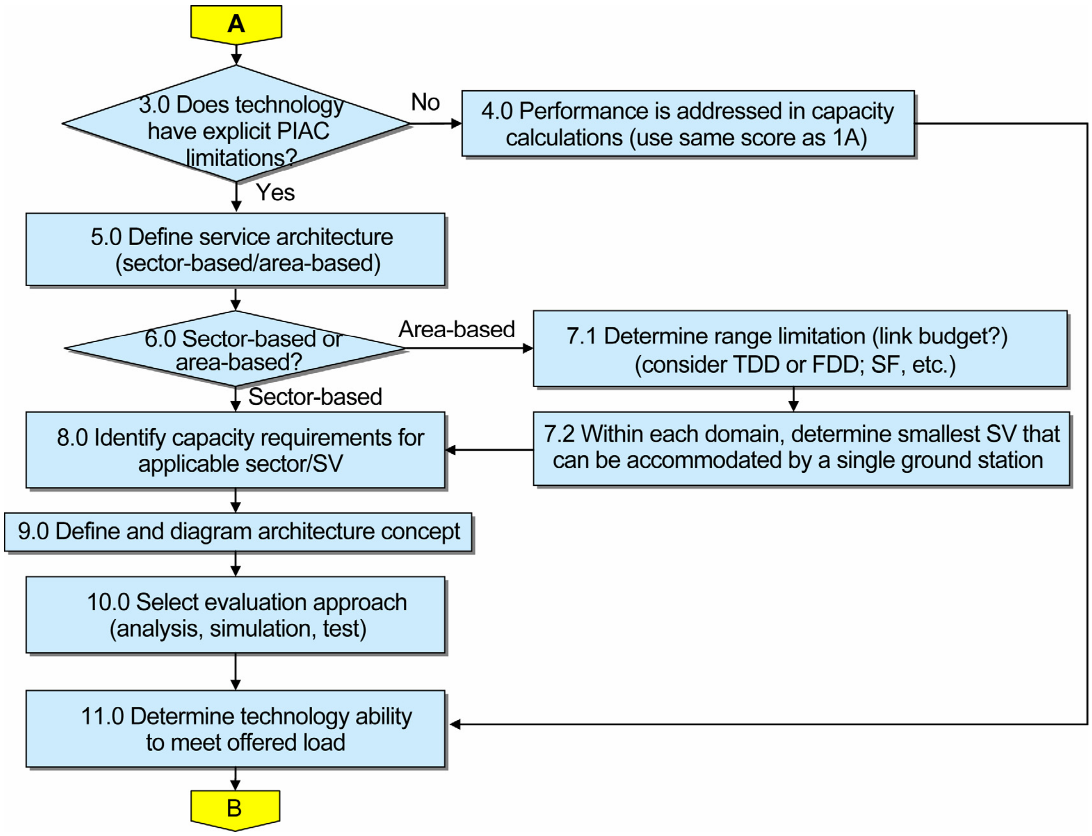


Figure 40.—Process flow diagram for Criterion 2B(2).

TABLE 28.—EVALUATION INPUTS FOR CRITERION 2B

Process step	Step name	Required input	Source(s)
1.0	Identify Applicable Flight Domains	• Estimated technology range and maximum data rate (for specified modulation and/or coding) • Identified applicable flight domains	• Technology specifications • Technology technical description documents • FCS Prescreening Assessment
3.0	Define Service Architecture	• Technology PHY layer definition (physical layer data rate and channel access techniques) • Estimated technology range and maximum data rate (for specified modulation and/or coding) • Identified service concept	• Technology specifications • Technology technical description documents • FCS Prescreening Assessment
7.1	Determine Range Limitation	• Technology link budget (modulation, coding, symbol rate, and channel size) • Technology PHY layer definition	• Technology specifications • Technology technical description documents
8.0	Identify PIAC Requirements for Applicable Sector/LAV	• COCR PIAC requirements • FCS communication loading scenarios	• COCR for FRS • FCS communication loading scenarios document

A.2.3 Criterion 2C

Criterion 2C	Provides QoS Mechanism
Criterion definition	This is a measure of a technology's ability to provision QoS for ATS and AOC services
Assumptions	• CoS categories similar to those defined for the COCR loading assessment will be required by the FRS • Number of services classes • Service class definitions
Metrics	• GREEN: Provides capability to offer CoS (e.g., prioritization) capability for ATS and AOC services • YELLOW: Technology can be readily modified to offer CoS (e.g., prioritization) capability for ATS and AOC services • RED: Technology cannot be easily modified to offer CoS (e.g., prioritization) capability for ATS and AOC services

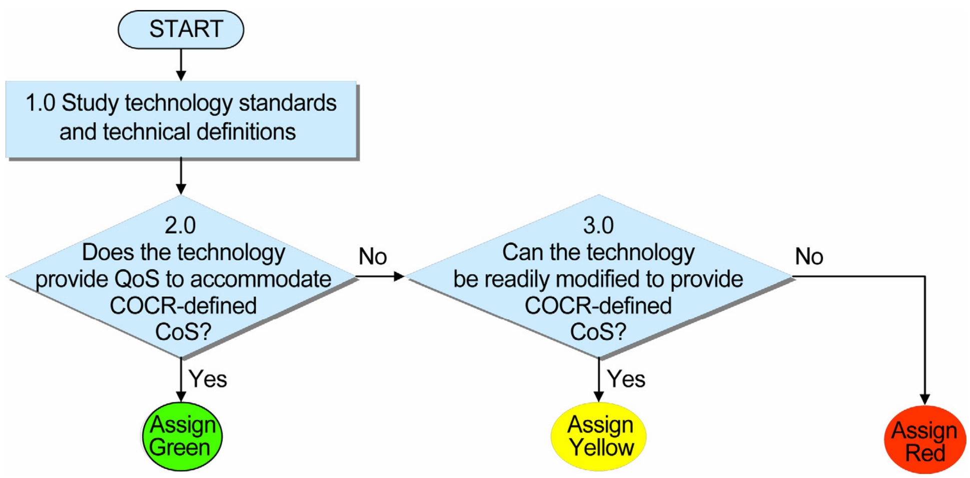


Figure 41.—Process flow diagram for Criterion 2C.

TABLE 29.—EVALUATION INPUTS FOR CRITERION 2C

Process step	Step name	Required input	Source(s)
All	Varies	• Technology PHY layer definition (physical layer data rate and channel access techniques) • Technology MAC/link layer definition (service class and priority capability)	• Technology specifications • Technology technical description documents • FCS Prescreening Assessment

A.2.4 Criterion 2D

Criterion 2D	Performs in Aeronautical Channel and Airspace Environment
Criterion definition	• This is a measure of a technology's ability to provision ATS and AOC services within the COCR-defined airspace environment • Accounts for time-varying and time-dispersive channel effects
Assumptions	NA
Metrics	• GREEN: Technology performance in intended channel is characterized by flat/slow fading • YELLOW: Technology can be readily modified to be characterized by flat/slow fading (e.g., physical layer modifications and equalization techniques) • RED: Technology cannot be easily modified to be characterized by flat/slow fading

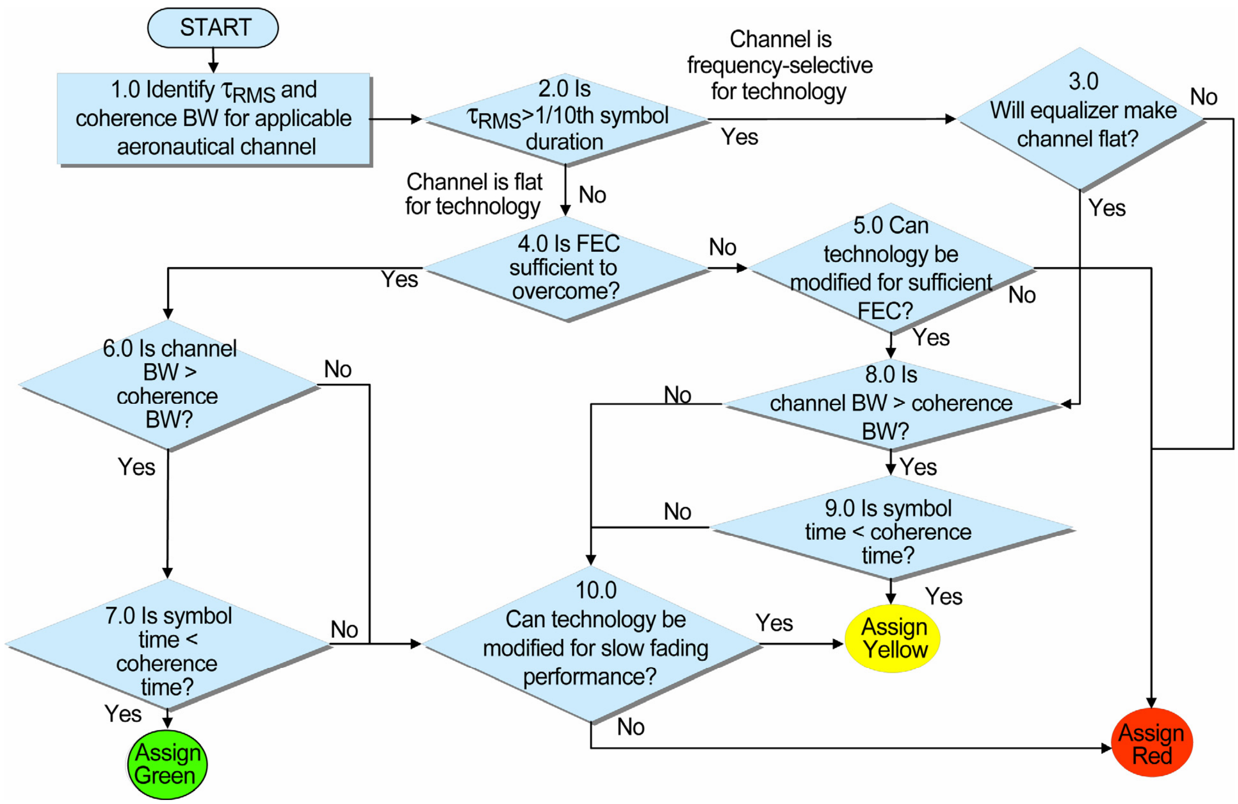


Figure 42.—Process flow diagram for Criterion 2D.

TABLE 30.—EVALUATION INPUTS FOR CRITERION 2D

Process step	Step name	Required input	Source(s)
All	Varies	• Intended aeronautical band for each technology • Aeronautical channel fading characterization (RMS delay spread and coherence bandwidth and/or coherence time calculations) • Technology PHY layer definition (channel bandwidth and symbol rate)	• Aeronautical channel characterization studies (including FCS channel modeling analysis) • Technology specifications • Technology technical description documents

A.3 Criterion 3

Criterion 3	Technical Readiness Level
Criterion definition	• This criterion provides indication of the maturity of a technology in the context of the FCS communication roadmap • Roadmap identifies earliest required implementation of FRS capability as 2020 • TRLs provide a method of measuring a technology's maturity relative to a development scale • Some uncertainty exists in time to move up TRL scale; however, when TRL is mapped to state-specific implementation processes (e.g., FAA implementation readiness level (IRL)), estimates of minimum time required to implement a new communication capability can be made
Assumptions	Based on FRS need (implementation in 12 years), minimum risk is for technologies with TRL–6 and above; TRL below 3 has significant risk in meeting required implementation need
Metrics	• GREEN: Technology is at level 6 or above • YELLOW: Technology assessed at level 4 or 5 • RED: Technology is assessed at level 3 or below

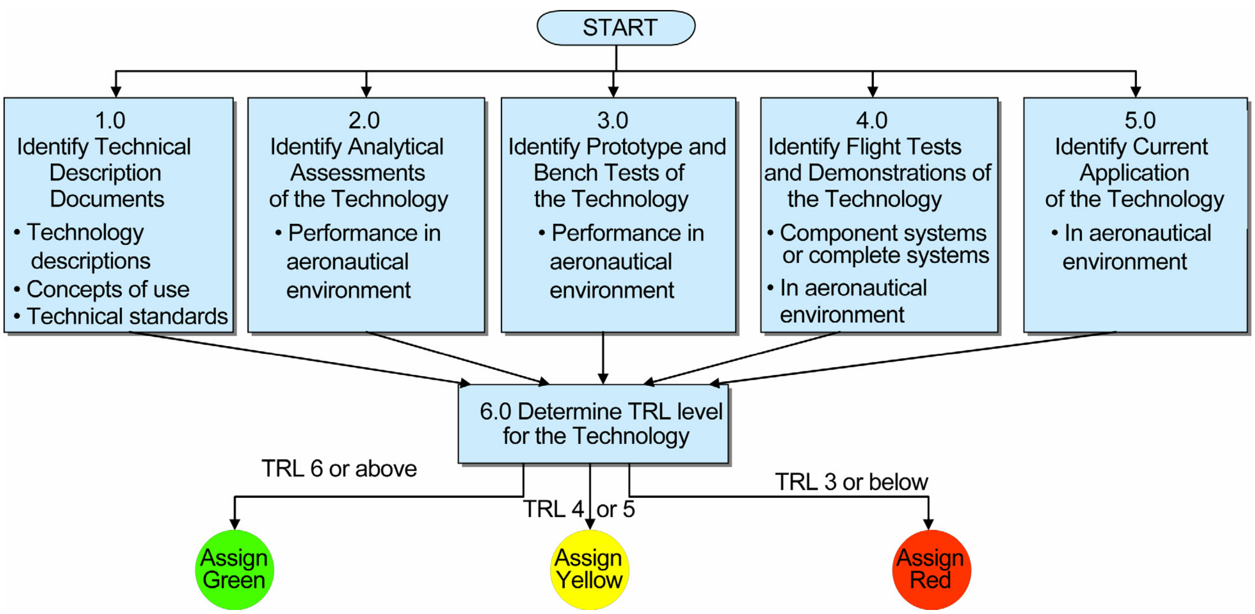


Figure 43.—Process flow diagram for Criterion 3.

TABLE 31.—EVALUATION INPUTS FOR CRITERION 3

Process step	Step name	Required input	Source(s)
1.0; 2.0; 3.0; 4.0; 5.0	Varies	• Technology specifications and technical descriptions • Technology assessments (analytical and simulation, testing (including bench/flight tests) • Technology prototype and development efforts, technology implementations	• Technology specifications • Technology technical description documents • Academic/commercial/military/other assessment, prototype, and implementation documentation

A.4 Criterion 4

Criterion 4	Standardization Status
Criterion definition	This criterion is an indicator of technology maturity • Existence of some standardized technical descriptions is indicative of some level of technology maturity • Existence of aeronautical specifications required for an aeronautical system, (e.g., ICAO, RTCA, Eurocae specs), is indicative of high level of maturity for the application of interest (e.g., FRS) • The existence of aeronautical standards is significant risk mitigation factor for implementation; standardization of the technology in other forums (e.g., commercial forums) provides some implementation risk mitigation
Assumptions	NA
Metrics	• GREEN: Technology has publicly available aeronautical standards • YELLOW: Technology are supported by a publicly available commercial standard • RED: Technology for which supporting standards does not exist or is not publicly available

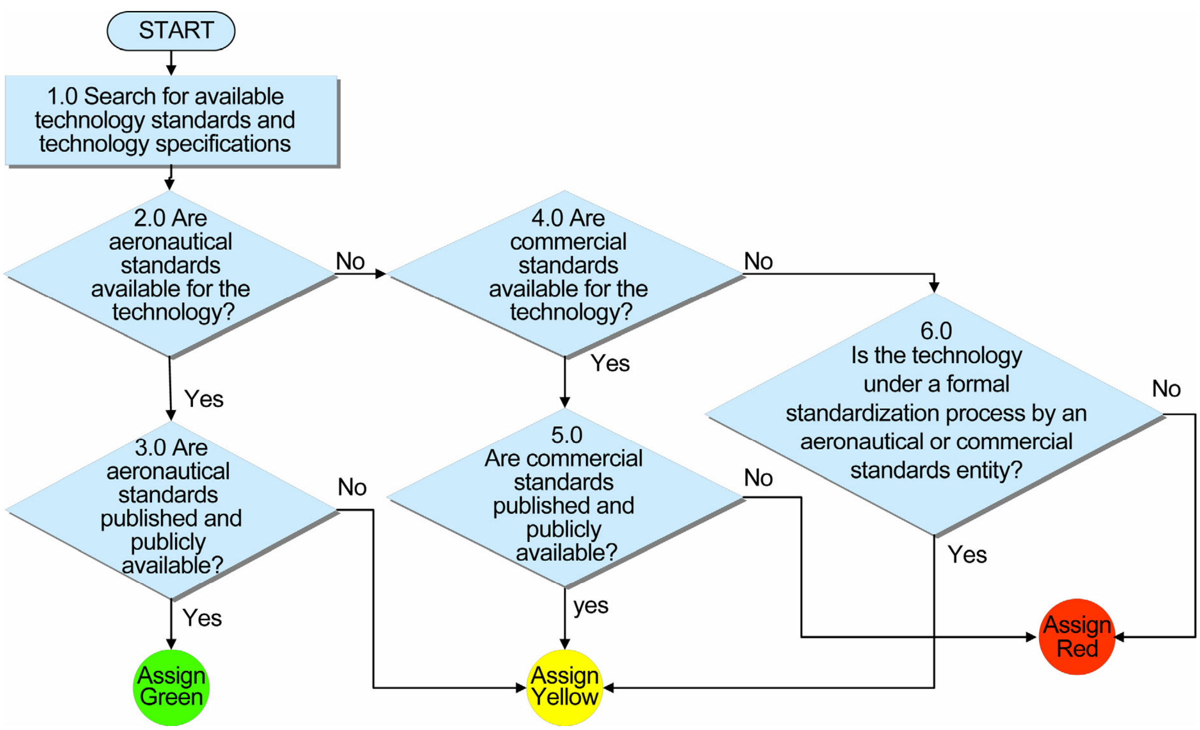


Figure 44.—Process flow diagram for Criterion 4.

TABLE 32.—EVALUATION INPUTS FOR CRITERION 4

Process step	Step name	Required input	Source(s)
All	Varies	• Technology specifications and technical descriptions • Draft technology specifications and technical descriptions	• Technology specifications • Technology technical description documents • Standards committee work plans or draft documentation

A.5 Criterion 5

Criterion 5	Certification
Criterion definition	• This criterion is another indicator of technology complexity • Technologies that are certified or are in the certification process pose significantly less risk for implementation • Those technologies specifically developed for safety-related services may also provide risk mitigation for meeting certification requirements
Assumptions	NA
Metrics	• GREEN: Technology (products) developed for the aviation industry and either currently certified or known to be in the certification process • YELLOW: Technology developed for safety-related services (public safety and the like) but not currently in the aviation certification process • RED: All other cases other than green or yellow

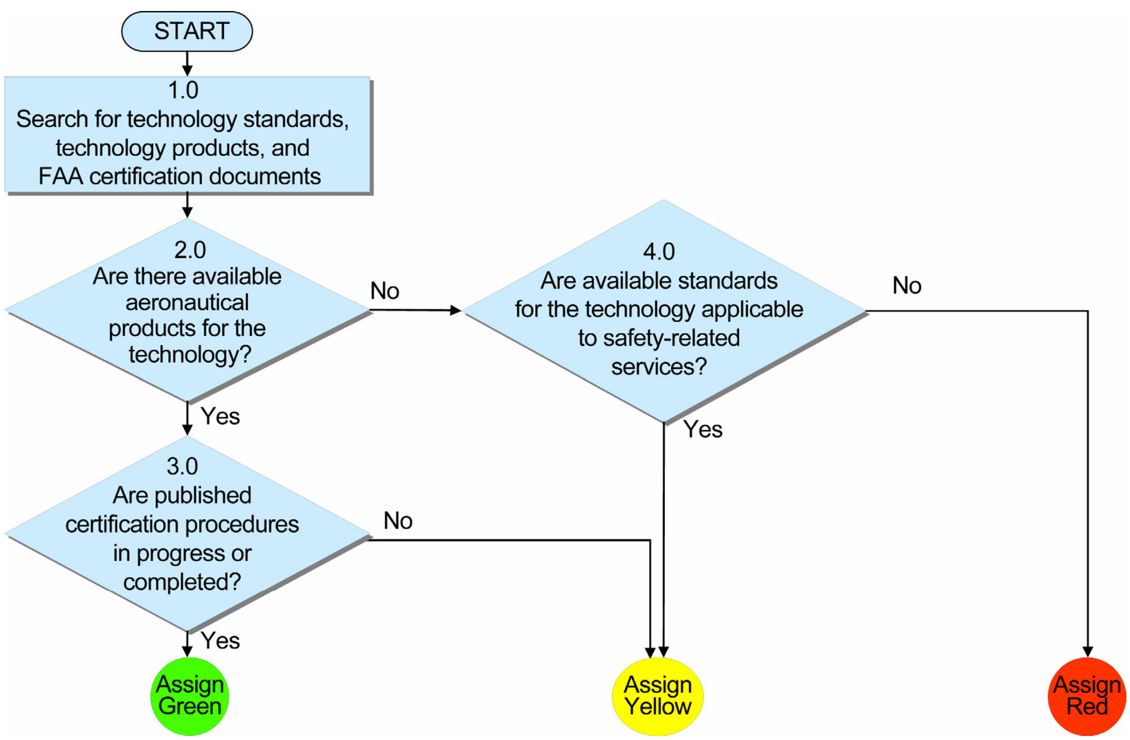


Figure 45.—Process flow diagram for Criterion 5.

TABLE 33.—EVALUATION INPUTS FOR CRITERION 5

Process step	Step name	Required input	Source(s)
1.0; 2.0; 3.0; 4.0	Varies	• Technology specifications and technical descriptions • Certification documents	• Technology specifications • Technology technical description documents • FAA certification documents

A.6 Criterion 6

Criterion 6	Ground Infrastructure Cost
Criterion definition	• This criterion is a measure of estimated relative cost to service provider to provision services to a geographically large area • Relative cost to replace or upgrade infrastructure with the necessary availability and diversity requirements for critical services, as a replacement to VHF DSB–AM • It is evaluated as the relative cost to provision services in the defined evaluation scenarios (as either a sector-based or area-based implementation) • A candidate not able to project a signal at a large range from a single ground station would require multiple replacement ground station; the evaluation accounts for unusual maintenance requirements of a candidate (to include leased services, maintenance of network operational centers, extraordinary Telco bandwidth requirements, etc.)
Assumptions	NA
Metrics	• GREEN: low relative cost • YELLOW: moderate relative cost • RED: high relative cost

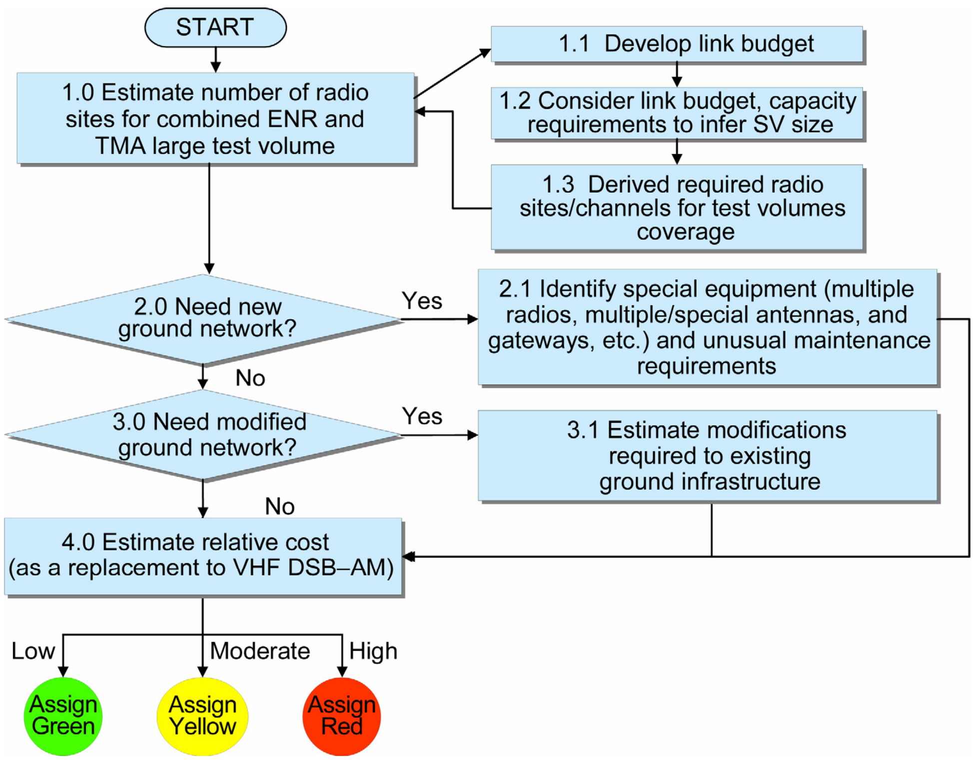


Figure 46.—Process flow diagram for Criterion 6.

TABLE 34.—EVALUATION INPUTS FOR CRITERION 6

Process step	Step name	Required input	Source(s)
1.0	Develop Link Budget	• Technology link budget (modulation, coding, symbol rate, and channel size) • Technology PHY layer definition	• Technology specifications • Technology technical description documents
2.1	Estimate Amount of Unusual Maintenance Requirements	• Technology specifications • Required technology ground network functionality and equipment	• Technology specifications • Technology technical description documents
3.1	Estimate Modifications Required to Existing Ground Infrastructure	• Technology specifications • Required technology ground network functionality and equipment • Existing infrastructure descriptions	• Technology specifications • Technology technical description documents • NAS Architecture; NAS and Technical Description Documents

A.7 Criterion 7

Criterion 7	Avionics Cost
Criterion definition	• This criterion provides a measure of the estimated relative cost to upgrade avionics with a new technology • Relative cost to upgrade avionics with new candidate data link technology but maintain VHF DSB–AM capability
Assumptions	NA
Metrics	• GREEN: low relative cost • YELLOW: moderate relative cost • RED: high relative cost

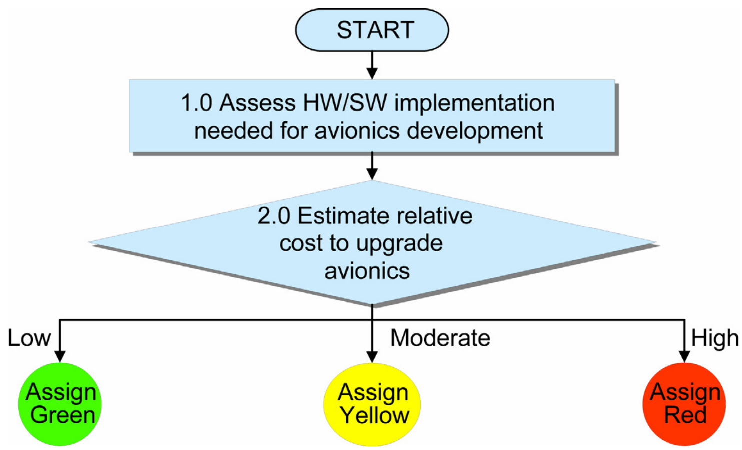


Figure 47.—Process flow diagram for Criterion 7.

TABLE 35.—EVALUATION INPUTS FOR CRITERION 7

Process step	Step name	Required input	Source(s)
1.0	• Assess hardware/software (HW/SW) implementation needed for avionics development	• Technology protocol description/specifications	• Technology specifications • Technology technical description documents

A.8 Criterion 8

Criterion 8	Spectrum
Criterion definition	This criterion gauges the likelihood of obtaining the proper allocation of the target spectrum and the compatibility of proposed technology with existing aeronautical systems in target band (second component not included in prescreening)
Assumptions	NA
Metrics	• GREEN: Technology proven (e.g., tested) to deployable in target spectrum band without either reallocation of existing equipment frequencies or requiring modification to existing aeronautical equipment (based on cosite tests) • YELLOW: Technology considered to deployable in intended band without either reallocation of existing equipment or requiring modification to existing aeronautical equipment (based on cosite considerations) • RED: Technology requires reallocation of existing equipment frequencies or modification to existing aeronautical equipment for deployment in target spectrum band

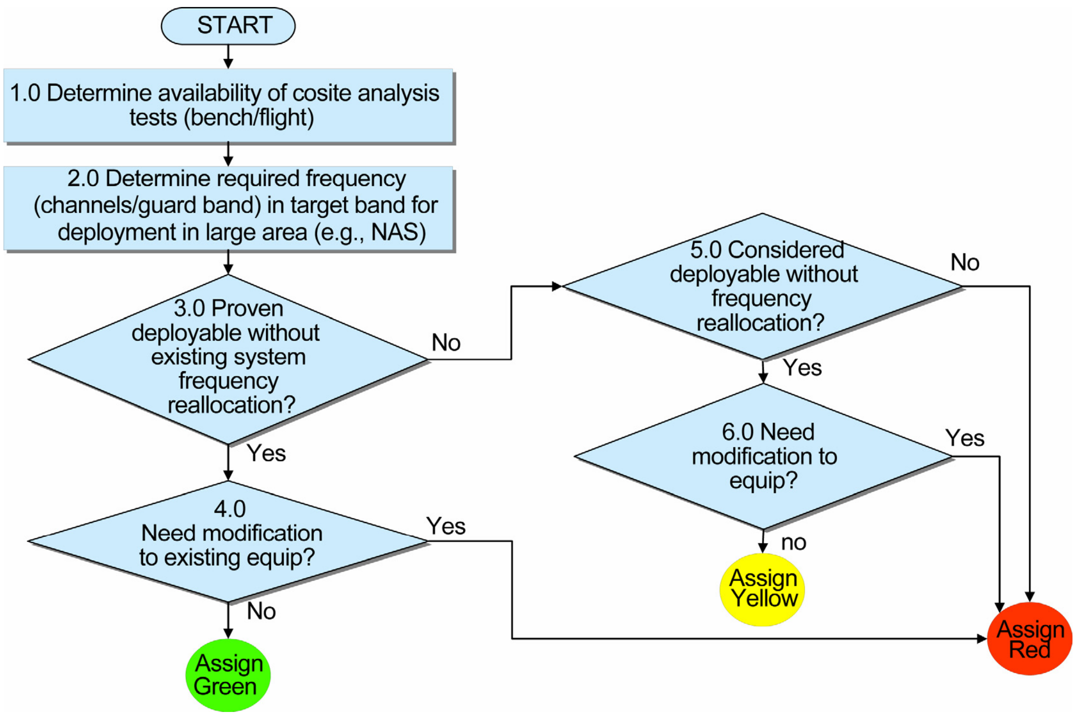


Figure 48.—Process flow diagram for Criterion 8.

TABLE 36.—EVALUATION INPUTS FOR CRITERION 8

Process step	Step name	Required input	Source(s)
All	Varies	• Identification of target deployment band • Cosite performance tests results • Cosite performance assessment results • Channelization and frequency reuse plan • Required channels for NAS-wide implementation	• Technology interference assessment/test reports • Technology Specifications and Technical Description Documents • Technology Concept of Use (FCS)

A.9 Criterion 9

Criterion 9	Security—Authentication and Integrity
Criterion definition	• Provides an assessment of technology authentication and data integrity capabilities to address COCR FCI security requirements on this topic • COCR FCI security requirements directly address authentication and integrity • R.FCI–Sec2.a, R.FCI–Sec2.b "…FCI shall support message authentication and integrity…" • This capability in the FRS is significant in meeting these requirements
Assumptions	NA
Metrics	• GREEN: Candidate technology provides authentication and integrity functionality • YELLOW: Candidate technology can be modified to provide authentication and integrity functionality • RED: Candidate cannot support and cannot be modified to provide authentication and integrity functionality

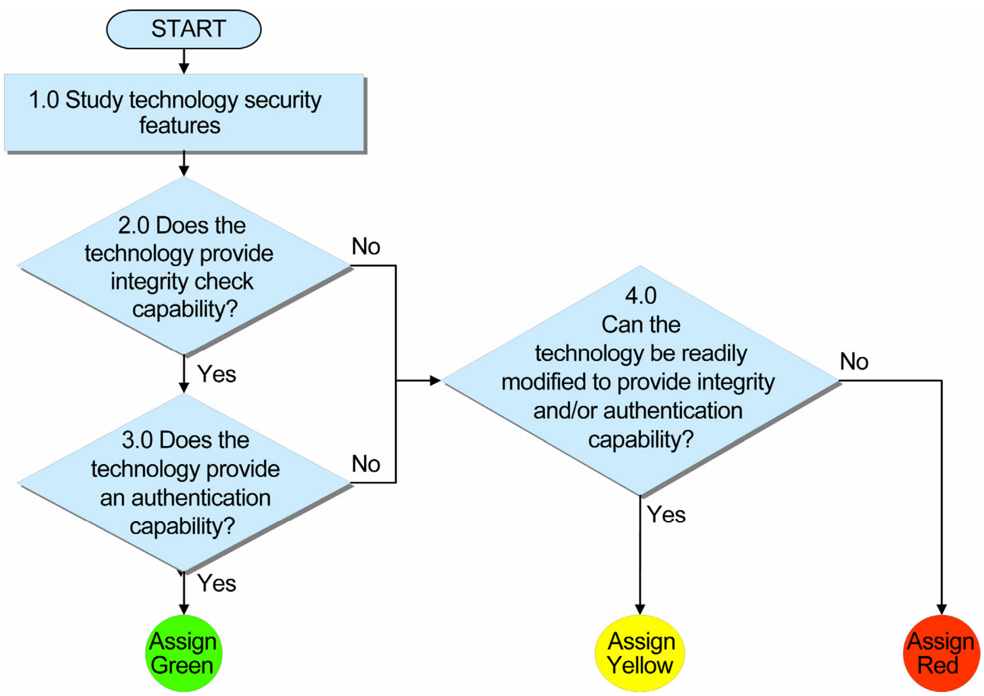


Figure 49.—Process flow diagram for Criterion 9.

TABLE 37.—EVALUATION INPUTS FOR CRITERION 9

Process step	Step name	Required input	Source(s)
1.0	Study Technology Security Features	• Technology protocol description/specifications	• Technology specifications • Technology technical description documents

A.10 Criterion 10

Criterion 10	Security—Robustness to Interference
Criterion definition	• This criterion provides a relative assessment of technology robustness to interference • COCR security requirements indicate need for FCI to provide “reliability and robustness to mitigate denial of service attacks” • Inherent technology capability (e.g., frequency hopping multiple access techniques) may address these requirements • Excess link margin in technology deployment can also support these requirements
Assumptions	Technology implementation as defined in the FCS Concept of Use is used for the evaluation
Metrics	• GREEN: Technology provides significant robustness to interference (e.g., technology uses specific techniques for interference protection (such as frequency hopping) or can be viably deployed with significant excess margin (e.g., ≥12 dB)) • YELLOW: Technology provides moderate robustness to interference (e.g., technology does not provide specific techniques for interference protection, but can be viably deployed with excess margin (3 to 11 dB)) • RED: Technology does provide specific techniques for interference protection nor can it viably be deployed with excess link margin (e.g., margin is less than 3 dB)

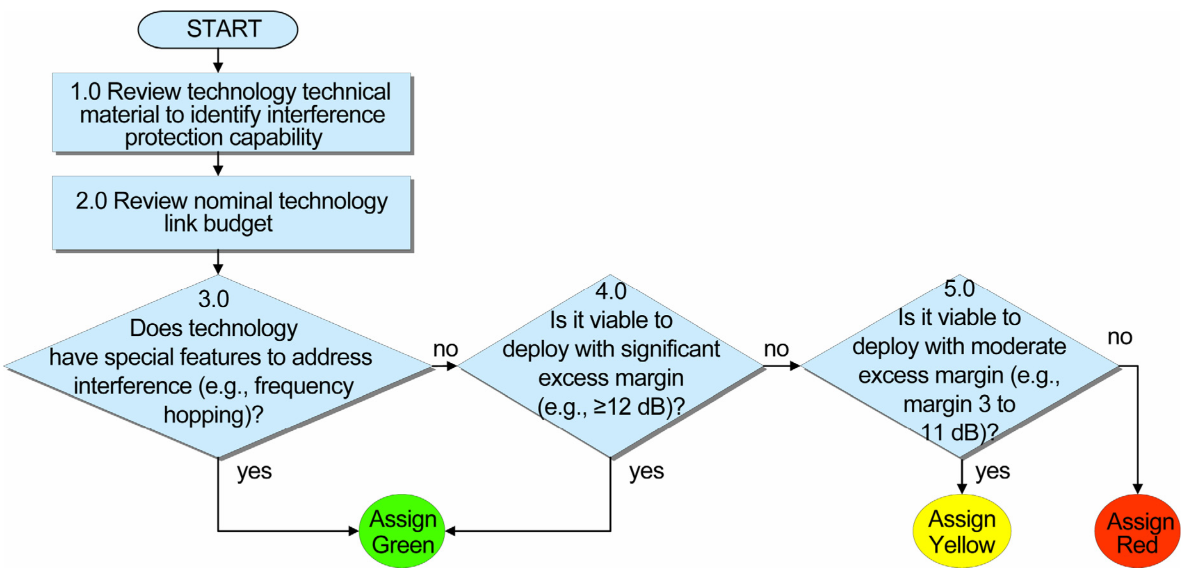


Figure 50.—Process flow diagram for Criterion 10.

TABLE 38.—EVALUATION INPUTS FOR CRITERION 10

Process step	Step name	Required input	Source(s)
1.0	Review Technology Technical Material to Identify Interference Protection Capability	• Technology protocol description and specifications	• Technology specifications • Technology technical description documents
2.0	Review Technology Link Budget	• FCS technology link budget	• FCS Technology Concept of Use (representative ink budget)

A.11 Criterion 11

Criterion 11	Transition
Criterion definition	• This criterion assesses acceptable transition characteristics, including • Partial return on investment (ROI) • Ease of technical migration (spectral and physical) • Ease of operational migration (air and ground users)
Assumptions	NA

Metrics	• GREEN: Technology meets all of the following conditions:
	  • Can be deployed to achieve ROI (i.e., service provision and benefit) without requiring full investment/deployment
	  • Can be operated simultaneously (in adjacent airspace) with legacy A/G communications systems (i.e., you can bring the new system up incrementally while bringing down the legacy system incrementally)
	  • Initial transition can be nearly operationally transparent (i.e., initially users do not have to significantly alter procedures) or features that drive changes in operational procedures can be employed incrementally
	• YELLOW: Cases other than defined in green or red
	• RED: Technology meets all of the following conditions:
	  • Provides little or no ROI without full investment and/or deployment
	  • Requires operation of legacy A/G communications to be widely discontinued in order to operate
	  • Initial transition requires significant changes to operational procedures

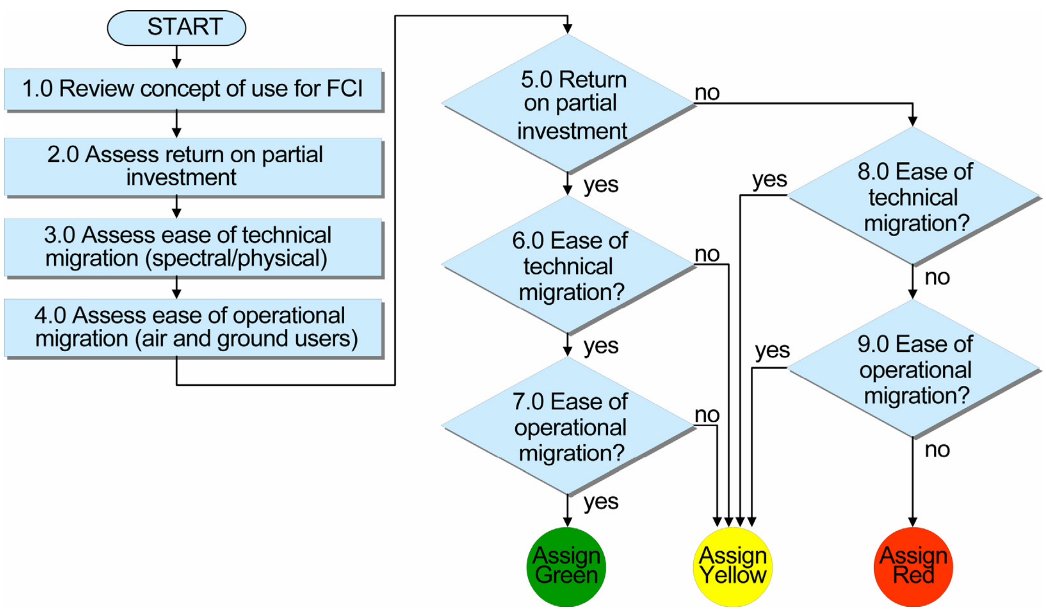


Figure 51.—Process flow diagram for Criterion 11.

TABLE 39.—EVALUATION INPUTS FOR CRITERION 11

Process step	Step name	Required input	Source(s)
1.0	Review Concept of Use for FCI	Technology concept of use	FCS Technology Concept of Use
2.0, 3.0, 4.0	Assess Return on Partial Investment; Assess Ease of Technical Migration; Assess Ease of Operational Migration	• Technology concept of use • Technology technical descriptions/designs (technology and functional protocols, physical architecture, etc.) • Transition plans	• Technology specifications • Technology technical description documents • Technology design documents • Implementation concepts/transition plans

Appendix B—Technology Inventory Description

The following sections provide a brief introduction to the technologies defined in the technology inventory. For the most part, this material is a replication of material provided in the interim FCS Phase II report (ref. 6) (Section 3.3.1) and summarizes technology descriptive information included in the FCS Phase I technology report (ref. 7).

B.1 Cellular Telephony Derivative Technologies

The technologies in this family encompass the existing and evolving standards relating to cellular telephony. This family has seen a fast-paced evolution and implementation in the past 20 years characterized in terms of cellular "generations." The first generation (1G) systems appeared in the early 1980s. These systems were followed by second generation (2G), 2.5G, and currently third-generation (3G) systems, which now offer high data rate services, Internet access, location-based services, and multimedia applications. This evolution is expected to continue with the implementation of fourth-generation (4G) systems, which offer high data rates, greater bandwidth efficiency, and advanced antennas and coding. The 4G systems are currently under development.

Seven cellular technologies were considered for this study. A summary of these candidates with key discriminating parameters is provided in table 42. Additional descriptive information on these technologies can be found in Section 3.2 of the initial technology prescreening report (ref. 6).

TABLE 40.—OVERVIEW OF CELLULAR TELEPHONY TECHNOLOGIES[a]

No.	Standard	Description	Peak data rate	Max. range	Duplexing approach	Channel bandwidth
1	WCDMA/ UMTS FDD	3G evolution of the European Global System for Mobile Communication (GSM); a direct spread, wideband frequency division duplex CDMA standard developed by GPP.	2 Mbps	No explicit limitation	FDD	2 by 5 MHz
2	TD–CDMA/ UMTS TDD	Time division counterpart to WCDMA. Uses a combined TDMA and CDMA scheme and designed for hot spots for dual-mode handsets that support WCDMA and TD–CDMA.	2 Mbps	30 km	TDD	5 MHz
3	CDMA2000 3x	This technology is a combination of multiple CDMA2000 1xEV components; it is a multicarrier, frequency duplex CDMA standard.	4 Mbps	100 km	FDD	5 MHz
4	CDMA2000 1xEV	This is an evolution of the first CDMA standards (IS–95A/IS–95B); it provides a data-only mode and a data and voice mode; this technology includes synchronous cells utilizing a time-phased spreading code on the forward link.	2 Mbps	100 km	FDD	2 by 1.25 MHz
5	GSM/GPRS/ EDGE	GSM is a frequency division duplex TDMA 2G standard; general packet radio services (GPRS) is an extension to GMS providing higher data rate packet service; Enhanced Data Rates for GMS Evolution (EDGE) is a technology that gives GSM the capacity to handle 3G services for mobile telephony (3x data capacity of GPRS).	400 kbps	35 km	FDD	2 by 200 KHz
6	TD–SCDMA	This is a time division duplex CDMA standard similar to TD–CDMA; it is being developed by the TD–SCDMA Forum for use in China.	2 Mbps	40 km	TDD	1.6 MHz
7	DECT	This is a European TDD standard incorporating TDMA and FDMA for Digital Enhanced Cordless Telecommunications (DECT).	552 kbps	300 m	TDD	1.728 MHz

[a]A majority of the values specified in this table are based on information documented in ref. 7; additional references have been provided as applicable.

B.2 IEEE 802 Wireless Derivatives Technologies

This technology family encompasses the hierarchy of cellular wireless network standards. They range from small personal area networks (PANs), which correspond to operations within about 30 ft to wide area networks (WANs) that operate over large regions (e.g., one or more cities and extended suburbs). The technologies in this family offer unicast and broadcast and multicast data services. Operations are organized into two basic topologies. The basic service set (BSS) is a set of stations controlled by a single access point; and the independent basic service set (IBSS) is a self-contained network without a dedicated access point, with a mesh network with peer-to-peer communications.

Four IEEE 802 wireless technologies were considered for this study. A summary of these candidates with key discriminating parameters is provided in table 43. Additional descriptive information on these technologies can be found in Section 3.3 of the initial technology prescreening report (ref. 7).

TABLE 41.—OVERVIEW OF IEEE 802 WIRELESS TECHNOLOGIES[a]

	Standard	Description	Peak data rate	Max. range	Duplexing approach	Channel bandwidth
1	IEEE 802.11	This is an evolving set of standards for local area networks (LANs). 802.11(b) is a direct sequence spread spectrum waveform similar to CDMA in cellular telephony. 802.11(a) and (g) use OFDM, similar to the modulation used for wireline digital subscriber line and for digital TV and radio broadcasts.	Up to 54 Mbps	~100 m	FDD	A/G: 20 MHz b: 25 MHz
2	IEEE 802.15	This is an evolving set of standards for personal area networks (PANs) that use a variety of modulation and access techniques	Up to 55 Mbps	~few m	FDD	~20 MHz
3	IEEE 802.16	This is an evolving set of standards for metropolitan area networks (MANs). It uses 256 subcarrier OFDM and includes an option for 2048 subcarrier OFDM. A subset of the carriers are used for pilot signals to provide phase reference across the frequency band	Up to 63 Mbps	~10 km (> with multiple cells)	FDD, TDD	1.75 to 20 MHz
4	IEEE 802.20	This is an evolving set of standards for wide area networks (WANs). It aims to provide better mobility management and wider area coverage as compared to 801.16.	Approx. 2 Mbps	~15 km (> with multiple cells)	FDD	1.25N MHz for N = 1, 4, 8, 16

[a]A majority of the values specified in this table are based on information documented in ref. 7; additional references have been provided as applicable.

B.3 Public Safety and Specialized Mobile Radio Technologies

Public safety and specialized mobile radio technologies are standards and systems in use for public safety and service communications. They are a subset of a larger standard family called land mobile radio systems. There are both open and proprietary technologies within this family. The open standards have been developed in various forums including

- APCO standards—standards developed by the TR–8 Private Radio Technical Standards Committee, under sponsorship by TIA
- TETRA standards—standards produced by Project Terrestrial Trunked Radio (TETRA), a technical body of ETSI
- TETRAPOL—standards developed publicly by manufacturers of the TETRAPOL Forum and the TETRAPOL Users' Club
- IDRA—standards developed by the Association of Radio Industries and Businesses (ARIB)

Proprietary standards have been developed by radio manufacturers, including Motorola (iDEN) and Ericsson (EDACS).

Eight public safety and specialized mobile radio technologies were considered for this study. A summary of these candidates with key discriminating parameters is provided in table 44. Additional descriptive information on these technologies can be found in Section 3.4 of the initial technology prescreening report (ref. 7).

TABLE 42.—OVERVIEW OF PUBLIC SAFETY AND SPECIALIZED MOBILE RADIO TECHNOLOGIES[a]

	Standard	Description	Peak data rate, kbps	Max. range, km	Duplexing approach	Channel bandwidth, kHz
1	APCO P25	A narrowband (12.5-kHz) digital voice and data system that can operate in either a trunked or conventional radio mode. It provides direct mobile-to-mobile communications as well as full duplex base-station repeater mode.	9.6	7.6 to 35	FDM	12.5
2	TETRA Release 1	This is a narrowband system (25-kHz) using four-slot TDMA to provide digital voice and data services to up to four simultaneous users.	36	3.8 to 17.5	FDM	25
3	TETRAPOL	This standard provides voice and data capability over frequency division multiplexed narrowband channels (10- and 12.5-kHz).	8	8 to 28	FDM	10, 12.5
4	IDRA	This is a six-slot TDMA voice and data system providing up to 64 kbps data rate in 25-kHz channels. It is an evolution of Japan's first digital dispatch standard (RCR STD–32).	64	20 to 40	FDM	25
5	iDEN	This is a proprietary Motorola narrowband TDMA voice and data system that is functionally equivalent to IDRA. The system uses six-slot TDMA.	64	5 to 40	FDM	25
6	EDACS	EDACS is a proprietary system that utilizes a standardized air interface (Electronic Industries Alliance (EIA) TSB 69 series). It operates in 25- or 12.5-kHz channels providing 4.8 to 9.6 kbps (using GFSK modulation)	9.6	Power limited	FDM	12.5, 25
7	APCO P34	A wideband (50-, 100-, and 150-kHz channels) digital voice and data system that provides high data rate IP services. It provides direct mobile to mobile communications as well as full duplex base-station repeater mode.	76.8 to 691.2 (SAM) (ref. 41); 88 to 864 (IOTA) (ref. 20)	150 to 187.5	FDM	50, 100, 150
8	TETRA Release 2 (TAPS)	This is a wideband evolution of TETRA that is an adaptation of the enhanced GPRS standard (cellular GPRS operating over EDGE) intended to be a TETRA 1 overlay network	473	<5	FDM	50, 100, 150
9	TETRA Release 2 (TEDS)	This is a wideband evolution of TETRA incorporating multicarrier modulation over a time division multiple access structure intended to be fully compatible with TETRA 1	36 to 691	<5	FDM	50, 100, 150

[a]A majority of the values specified in this table are based on information documented in refs. 7 and 19; additional references have been provided as applicable.

B.4 Satellite and Other Over-Horizon Communication Technologies

Traditionally, satellite systems have provided communication services to remote areas or areas that cannot accommodate a ground infrastructure (e.g., oceanic regions). Currently, there are hundreds of functional satellites providing communication services including broadcast and mobile telephony.

Because of similarity in the extent of geographic coverage, non-satellite-over-the-horizon communications were included in this technology family.

Nine satellite and over-horizon communication technologies were considered for this study. A summary of these candidates with key discriminating parameters is provided in table 45. Additional descriptive information on these technologies can be found in Section 3.5 of the initial technology prescreening report (ref. 7).

TABLE 43.—OVERVIEW OF SATELLITE AND OVER-HORIZON TECHNOLOGIES[a]

	Standard	Description	Peak data rate	Max. range	Duplexing approach	Channel bandwidth
1	Custom Satellite System/SDLS	This candidate addresses custom satellite solutions specifically designed to address the needs of aviation. An example system concept is the SDLS, a European Space Agency-funded effort for a satellite-based system for safety services. This concept utilizes bent-pipe geostationary satellites and CDMA at L-band.	As needed (one defined SDLS service provides 6.4 to 30 kbps per user)	NA	FDD	NA
2	Connexion by Boeing	This was a high data rate system targeted at APC and AAC communications. Services were offered in Ku-band on geostationary satellites. On Aug. 17, 2006, the service was to be discontinued; the technology therefore was removed from the candidate set.	Up to 1 Mbps (forward); Up to 5 Mbps (return)	NA	FDD	NA
3	Inmarsat SBB	Inmarsat was initiated as an intergovernmental agency providing global safety and communication services for the maritime community. In 1999, the organization was transformed into a private company, and focus of the service offerings expanded beyond the maritime community. Basic low data rate aeronautical services are offered while planned high data rate offerings (e.g., Swift Broadband) are in roll-out.	Up to 432 per channel	NA	FDD	NA
4	Iridium	Iridium is a constellation of 66 satellites in low Earth orbit (LEO) providing global telephony services. Both voice and low data rate services are offered.	2.4 kbps full-duplex channels per user	NA	FDD	NA
5	GlobalStar	GlobalStar consists of 48 satellites in LEO/MEO orbit. Bent-pipe telephony (voice and data) services are offered in CDMA sub-bands.	Up to 9.6 kbps per user	NA	FDD	NA
6	Thuraya	This is a regional mobile satellite system that provides telephony services. It is operated as a private company by the United Arab Emirates with two satellites currently in orbit.	9.6 kbps (per user)	NA	FDD	NA
7	IGSAGS	This is a proposed custom satellite concept providing integrated CNS services using geostationary satellites. Voice and data would be provided by dividing the DME band into narrow band channels.	30 kbps (per user)	NA	FDD	NA
8	HF Data Link	HFDL is a certified data link used to transfer messages between HF (3 to 30 MHz) ground stations and avionics systems on aircraft. Services provided include AOC data link communications.	300 to 1800 bps (ref. 42)	NA	TDD	2.7 kHz (ref. 42)

TABLE 43.—CONCLUDED. [a]

	Standard	Description	Peak data rate	Max. range	Duplexing approach	Channel bandwidth
9	Digital Audio Broadcast	This technology includes proprietary satellite services (such as XM radio and Sirius) providing broadcast services. The systems offer approximately 100 channels with data rages of 48 kbps.	48 kbps	NA	Broadcast only	NA

[a]A majority of the values specified in this table are based on information documented in ref. 7; additional references have been provided as applicable.

B.5 Custom Narrowband VHF Technologies

This technology family includes standard narrowband VHF systems already developed for AOC, ATS, and/or ATC services and some proposed variants for application to AOC, ATC, and automatic dependent surveillance–broadcast (ADS–B) services. Three systems are approved as VHF subnetworks through ICAO including

- VDL2: an AOC and ATS data-only system
- VDL3: an ATC system capable of providing both voice and data
- VDL4: a surveillance data-only system being developed for point-to-point data

Other additional technology candidates in this family are proposed variations to the candidates noted above that incorporate changes in channel spacing or combine select features of the technologies.

A total of five custom narrowband VHF technologies were considered for this study. A summary of these candidates with key discriminating parameters is provided in table 46. Additional descriptive information on these technologies can be found in Section 3.6 of the initial technology prescreening report (ref. 7).

TABLE 44.—OVERVIEW OF CUSTOM NARROWBAND VHF TECHNOLOGIES[a]

	Standard	Description	Peak data rate	Max. range	Duplexing approach	Channel bandwidth
1	VDL Mode 2 (VDL2)	This technology is the evolution the ARINC Airborne Communications and Reporting System. It is a digital bit-oriented data system that uses a carrier sense multiple access shared data channel. Its primary use is AOC traffic although use for ATC message sets has been proposed.	31.5 kbps (raw); throughput is approx. 10 kbps	195 nmi[b]	TDD	25 kHz
2	VDL Mode 3 (VDL3)	Based on a physical layer similar to VDL2, VDL3 is a TDMA system designed to support ATC voice and data communications. The scheme guarantees controller access through the channel, by use of a management channel carrier control information along with a data channel	31.5 kbps (raw); throughput is 4.8 kbps to approx. 12 kbps	185.1 nmi[c]	TDD	25 kHz

TABLE 44.—CONCLUDED. [a]

	Standard	Description	Peak data rate	Max. range	Duplexing approach	Channel bandwidth
3	VDL Mode E	This is an adaptation of the VDL3 standard that reduces the bandwidth and use of framing for insertion into airspace with 8.33-kHz channel spacing. This provides six Mode E channels per 25-kHz DSB–AM channel.	15.75 kbps (raw); throughput is 4.8 kbps	185.1 nmi[d]	TDD	8.33 kHz
4	VDL Mode 4 (VDL4)	This technology is based on a data-only broadcast system developed for maritime harbor surveillance applications. The application was adapted for aviation usage, employing a self-organizing TDMA layer, through which requested time slots are set by a ground scheduler. Although approved for a surveillance broadcast application, standards are under development for an adaptation providing point-to-point data-only communications.	19.2 kbps (raw)	202.5 nmi[e]	TDD	25 kHz
5	E–TDMA	This is a technology that builds on the VDL3 and VDL4 concepts, based on a cellular ground architecture configuration. A primary focus is the provision of managed QoS throughout the service volumes, employing the use of global signaling channels.	Not explicitly defined; assume on the order of 10 to 12 kbps (similar to Mode 3)	200 nmi[f]	TDD	Not explicitly defined; assume 25 kHz (similar to Modes 3/4)

[a]A majority of the values specified in this table are based on information documented in ref. 7; additional references have been provided as applicable.

[b]As per ref. 24, the maximum range was (uplink) above FL 350, and the value was taken from "RC trials."

[c]This assumes that the smallest guard time is between an uplink M-Burst and a downlink V/D Burst, or about 65 symbol periods between LBACS, minus the length of an uplink M-Burst (53 symbols) or about 12 symbols. At a rate of 10 500 symbols/s, this gives a maximum communications slant range of 185 nmi. See ref. 25 for more details.

[d]Assume same assumptions as used for VDL3 apply.

[e]Per ref. 27, segment E is the guard interval of duration of about 1250 μs (equivalent to about 205 nmi guard range), which includes segment D.

[f]Ref. 7; The use of statistical self synchronization and a small guard band seems to indicate that the technology might become unstable at very large distances. Regardless, RLOS was used.

B.6 Custom Broadband Technologies

Several proposals have been and continue to be developed to provide wideband solutions for ATS and AOC communication requirements. The candidates considered include those broadband technologies proposed to ICAO ACO WG–C (B–AMC, LDL, AMACS, and airport data link (ADL)); those proposed in response to the NASA RFIs (Flash-OFDM) or suggested by the FAA (UAT and Mode S). These seven candidates are the custom broadband technologies considered for this study. A summary of these candidates with key discriminating parameters is provided in table 47. Additional descriptive information on these technologies can be found in Section 3.7 of the initial technology prescreening report (ref. 9).

TABLE 45.—OVERVIEW OF CUSTOM BROADBAND TECHNOLOGIES[a]

	Standard	Description	Peak data rate	Max. range	Duplexing approach	Channel bandwidth
1	ADL	The advanced airport data link (ADL) is a system for the APT environment and includes a data rate of at least 120 kbps per user; large user capacity; APT coverage area, and QoS capability. The system definition includes a multicarrier CDMA system in C-band.	2048 kbps	30 nmi[b]	TDD	8192 kHz
2	Flash-OFDM	This technology has been developed for IP services between networks and personal computers, focusing on mobility and data communications	3.2 Mbps (ref. 29)	4 km (ref. 29)	FDD (ref. 29)	
3	UAT	This technology was specifically designed for ADS–B application, with simplicity and robustness as design objectives. It operates on a single common wideband channel. Aircraft transmitters transmit one message every second on one of 3200 message start opportunities.	1 Mbps (raw)	200 nmi[c]	TDD	1.17 MHz[d]
4	Mode S	Mode S is a multifunctional surveillance and communication system that was originally designed as a surveillance improvement for Mode A/C secondary surveillance radar. The 1090 (extended squitter (ES)) operation includes the aircraft broadcast of a data message once per second.	1 Mbps (raw)	100 nmi[e]	TDD	2.6 to 14 MHz[f]
5	B–AMC	This is a technology that has evolved from the B–VHF concept (based on the MC–CDMA providing voice and data dedicated and party-line and broadcast services). The system, based on multicarrier (OFDM) technology, was initially envisioned as an overlay in the VHF band, but more recently considered as a candidate in L-band	To be defined	200 nmi[g]	FDD	500 to 2 MHz (to be defined)
6	LDL	This technology is the VDL3 standard with a redesigned physical layer for operation in L-band. The new physical layer has been developed based on the UAT physical layer. Similar to VDL3, a TDMA structure accommodating data (and potentially voice) has been defined.	37.5 to 100 kbps (draft proposal)	268 nmi (ref. 44)	TDD	83.33 kHz (proposed)
7	AMACS	This technology is the evolution of the E–TDMA and VDL–4 standards with a redesigned physical layer to address operation in L-band; the technology definition may also apply elements of the UAT and LDL technologies as well.	100 kbps (assumed, not yet defined)	200 nmi (assumed)	TDD	To be defined

[a]A majority of the values specified in this table are based on information documented in ref. 7; additional references have been provided as applicable.
[b]Reference is ADL Technology Description in ref. 28.
[c]Maximum range supported is similar to VHF (200 nmi at 30 000 ft and 80 nmi at 5000 ft); the UAT proposal is to establish a series of ground stations to provide coverage over the U.S. at low (1000 ft) altitude; Assumed that the UAT maximum range is limited by LOS conditions.
[d]Estimated based on information in RTCA DO-282 (estimated 3 dB bandwidth).
[e]Maximum range assuming LOS exists, range performance depends on traffic density and the 1090-MHz interference environment (i.e., ADS–B uses the same frequency as ATC transponder-based surveillance). In low density environments (e.g., oceanic) range performance is typically 100+ nmi, while in a high-traffic density and 1090 interference environments (e.g., LAX terminal area) the range performance is on the order of 50 to 60 nmi with current receiver techniques (improved processing techniques have been identified that are expected to provide range performance to 90 nmi in dense environments).
[f]Estimated based on information in ref. 43.
[g]Assumed (range value was defined for B–VHF in ICAO ACP Working paper, ref. 28); need to update when B–AMC details become available.

B.7 Military Technologies

The military services employ a variety of communication technologies for command and control, situational awareness, and air traffic control. Functionality that is provided by military technologies includes pilot-to-controller dialog; pilot-to-pilot dialog; flight information services; ATM data exchanges; information downlink; and A/A surveillance. Because of their similarity to functional needs of the FRS, military communications were reviewed to identify potential candidates.

Three military technologies were considered for this study. A summary of these candidates with key discriminating parameters is provided in table 48. Additional descriptive information on these technologies can be found in Section 3.8 of the initial technology prescreening report (ref. 7).

TABLE 46.—OVERVIEW OF MILITARY TECHNOLOGIES[a]

	Standard	Description	Peak data rate, kbps	Max. range	Duplexing approach	Channel bandwidth
1	Link 16	Link 16 is a UHF, frequency-hopping (51 frequencies) standard initially designed as a Tactical Data Link system for NATO. The primary mission of the technology is to provide a situational awareness, and command and control voice and data capability.	115	Up to 300 miles	TDD	3.75 MHz at 3-dB points on hopped frequency
2	SINCGARS	SINCGARS is a 2320 25-kHz channel frequency-hopped VHF voice and data technology. The technology provides line of sight communications, including data communications in variable message format.	16	40 km	TDD	25 kHz
3	HAVEQUICK	Initially designed as a voice-only system, but HAVEQUICK has evolved to include a data capability. It is a 7000, 25-kHz channel, frequency-hopped VHF voice and data system. Data communications is accomplished with a modem.	16	Up to 300 miles	TDD	175 MHz

[a]A majority of the values specified in this table are based on information documented in ref. 7; additional references have been provided as applicable.

B.8 Other Technologies

The final category of technologies denoted "other" includes a single candidate accounting for airline passenger communications. As its name implies, this technology was designed with the goal of accommodating the telephony communication needs of airline passengers. Specific system implementations include Airphone (Airphone Telecom), Aircell (Aircell), and SkyWay (SkyWay West). A summary of key discriminating parameters associated with this candidate technology is provided in table 49. Additional descriptive information on these technologies can be found in Section 3.9 of the initial technology prescreening report (ref. 7).

TABLE 47.—OVERVIEW OF APC TELEPHONY TECHNOLOGY

	Standard	Description	Peak data rate	Max. range	Duplexing approach	Channel bandwidth
1	APC Telephony	This technology is a FDD circuit voice and data system operating in the 849-to-851 and 894-to-896 MHz spectrum.	2.4 Mbps[a]	NA	FDD	4 kHz (ref. 7)

[a]Reference representative APC information provided at http://www.airfax.com/airfax/features/viewstory.asp?filepath=sep2005%5Caircell.htm.

Appendix C—Concepts of Use Details

This appendix provides detailed concept of use material for candidate general solution (continental airspace) FRS technologies that have been brought forward from the technology screening process. They include

- TIA–902 (P34)
- WCDMA
- LDL
- AMACS
- B–AMC

The information included in the concepts of use included in this appendix complements technology information provided in the FCS Phases I and II reports. This appendix provides additional detail on the envisioned services, architecture, and provisioning of services specific to evaluation scenarios that support the evaluation of the technologies.

C.1 TIA–902 (P34) Concept of Use Details

The TIA–902 (P34) is a standardized technology of Telecommunications Industry Association (TIA). It was developed by TR–8 Private Radio Technical Standards Committee, under sponsorship of the TIA in accordance with a memorandum of understanding between TIA and the Association of Public-Safety Communication Officials/National Association of State Telecommunications Directors/Federal Government) (APCO/NASTD/FED), also a joint standard with Electronic Industries Alliance (EIA).

TIA–902 (P34) is the TIA 902 series of standards that define a wideband technology defined for provisioning of wireless packet data services in a dispatch-oriented topology for public safety service providers. The technology was developed as part of a government-industry partnership formed to address issues that restrict the use of commercial services for mission-critical public safety wireless applications. The Development of a Statement of Requirements document for a wideband aeronautical and terrestrial mobile digital radio technology standard for wireless transport of rate-intensive information initiated the TIA–902 (P34) standardization activities.

C.1.1 Technology Overview

C.1.1.1 Standardization Status and Technical Readiness for Deployment

TIA–902 (P34) is a layered protocol technology organized in a set of published standards. This technology is fully standardized, with predominately mature standards. Some standards have been updated in the past 2 years. Standards are published and available for purchase through EIA/TIA. The standards numbers correspond to different protocols are shown in figure 52.

TIA–902 (P34) builds on concepts, standardized in APCO P25, with similar functional architecture elements including mobile radio; mobile routing and control; mobile data peripheral; base radio; base routing and control; and RF gateway. See reference 44, a related document.

The TIA–902 (P34) system is specified to provide IP version 4 (IPv4) and IP version 6 (IPv6) bearer services for the transport of packet data using the IP suite of protocols. The wideband IPv4 (and IPv6) delivery service is required to directly support standard IP transport layers, including user datagram protocol (UDP), terminal control protocol (TCP), and real-time transit protocol (RTP). It may optionally transport other protocols via standard Internet Engineering Task Force (IETF) encapsulation methods. Unicast service is required, and broadcast and multicast services are standard options. Utilization of mobile IP and IP security (IPsec) services may be optionally implemented.

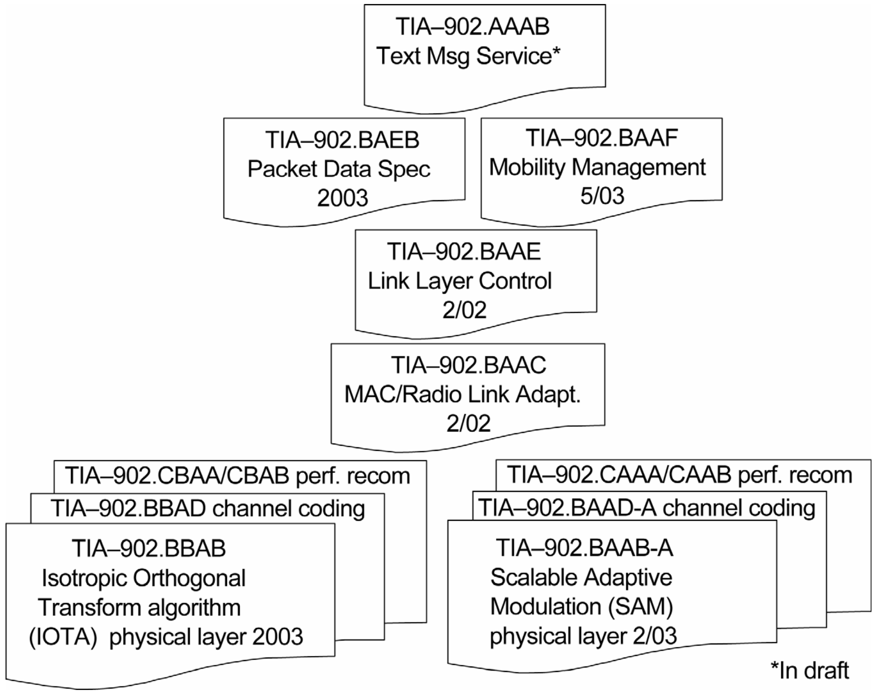


Figure 52.—TIA–902 (P34) standards.

TIA–902 (P34)-related validation and deployment activities include

- A demonstration and validation TIA–902 (P34) system has been deployed in Pinellas County, Florida, which provides wideband data at 700 MHz.
- Larger scale deployment is planned for 700-MHz public safety frequencies when they open up (vacated by test volume (TV) in 2009). Part of the spectrum (60 MHz) will be auctioned per Federal Communications Commission (FCC) announcement on April 23, 2007, and perhaps it will be an incentive to help build public safety network. The effects of this announcement on public safety implementation plans are uncertain (current FCC plan seems to reserve 12 MHz (24 for FDD system) for public safety broadband network).

C.1.1.2 Technology Services and Architecture

TIA–902 (P34) is a wideband public safety digital radio system that provides high-speed packet data services using the IP on 50-, 100-, and 150-kHz channels in the 700-MHz band. The TIA–902 (P34) network can interoperate with other TIA–902 (P34) networks with endsystems (Ew interface), with mobile data peripheral (Aw interface), and with mobile users over the AI (Uw). It provides connectivity between mobiles and also between mobiles and fixed equipment and repeater for extending range to distant stations. A depiction of the TIA–902 (P34) open system architecture is shown in figure 53.

TIA–902 (P34) Services: Basic TIA–902 (P34) configuration modes include

- Mobile-to-fixed host service (FNE data)
- Mobile-to-mobile data service (repeated data)
- Mobile-to-mobile data service (direct data)

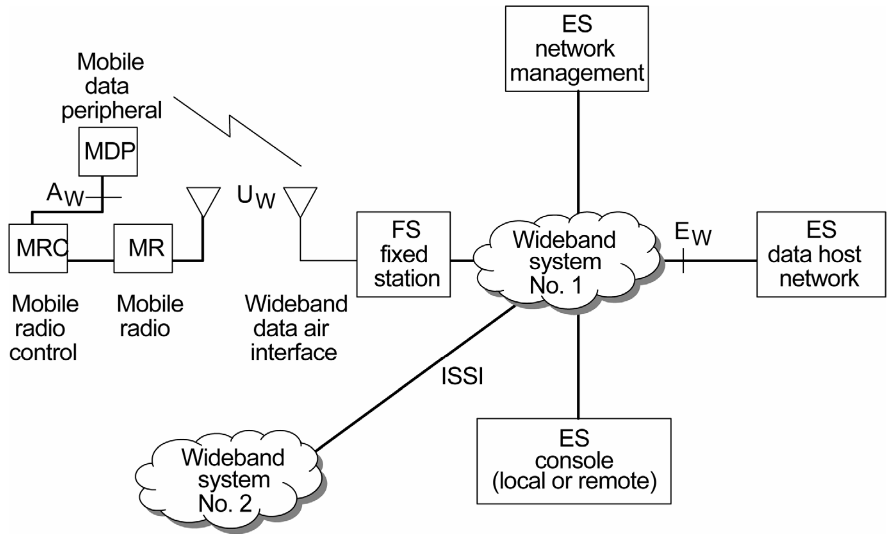


Figure 53.—TIA–902 (P34) functional components and interfaces.

TABLE 48.—TIA–902 (P34) SERVICE CONFIGURATION OPTIONS

	Radio-to-FNE configuration	Radio-to-radio configuration
Unicast IPv4 or Unicast IPv6	Mandatory	Mandatory
ICMP support	Mandatory	Mandatory
Reliable wideband air interface (WAI) delivery	Mandatory	Mandatory
Wideband text messaging	Mandatory	Mandatory
WAI registration	Standard option	NA
WAI authorization	Standard option	NA
WAI location updating	Standard option	NA
Subnetwork dependent convergence protocol (SNDCP)	Standard option	NA
Broadcast IPv4 or IPv6	Standard option	Standard option
Multicast IPv4 or IPv6	Standard option	Standard option
Unreliable WAI delivery	Standard option	Standard option
WAI service class support	Standard option	Standard option
Security services support	Standard option	Standard option
Mobile radio application	Standard option	Standard option

Service requirements vary with configurations as shown in table 50.

As shown in figure 54, TIA–902 (P34) protocol stack is layered, and assumes a point of attachment to an IP network. The TIA–902 (P34) system is specified to provide IPv4 and IPv6 bearer services for the transport of packet data using the IP suite of protocols. List of services are shown as follows:

- Subnetwork standardized for IP network point of attachment
- Bearer services include IPv4/IPv6 for packet data transfer (UDP, TCP, and RTP)
- Accommodates unicast, broadcast, and multicast services for IPv4/IPv6
- Mobility management is part of standardized services
- Supplemental services offered include
- Security
- Data compression
- Streaming audio transport
- Streaming video transport

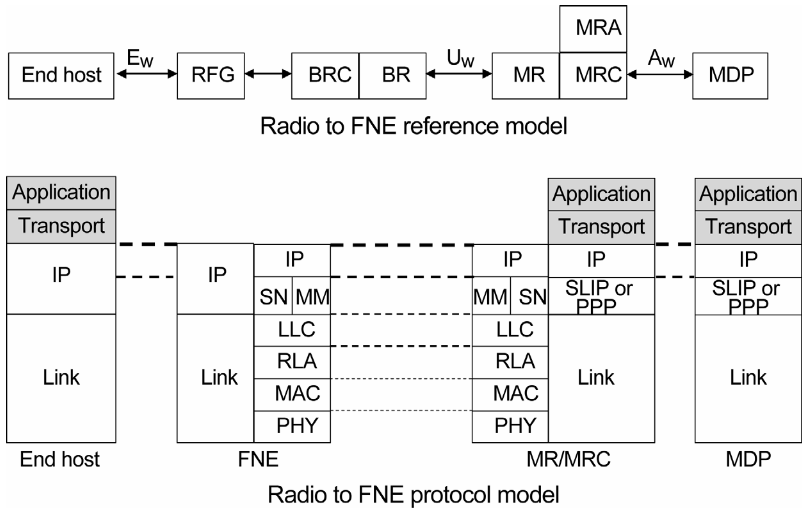


Figure 54.—TIA–902 (P34) radio to FNE reference and protocol models.

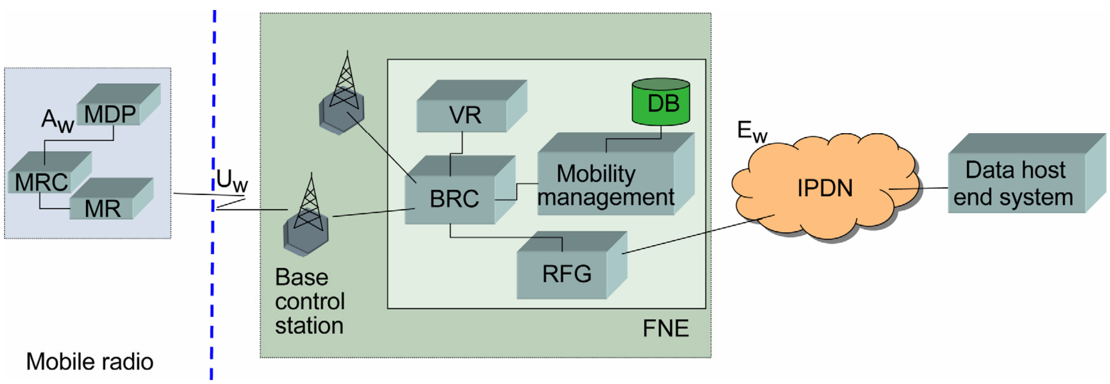


Figure 55.—TIA–902 (P34) network architecture.

Figure 55 shows a representative network architecture for TIA–902 (P34). The network contains the following functional elements: mobile radio with mobile routing and control (MRC) and mobile data peripheral (MDP). Mobile radio mobility management is included in the MRC function. The fixed network equipment (FNE) has the base station, the base routing and control (BRC), radiofrequency gateway (RFG), vehicular repeater (VR), and mobility management (MM); the RFG interfaces to the external network and data host end system.

To provide a user's view of both the CNS/ATM and TIA–902 (P34) network systems and elements, a logical mapping of the two systems is provided as shown in figure 56, where TIA–902 (P34) network elements mobile radio, FNE, Internet packet data network (IPDN), and data host end system are mapped to aircraft system element, interface to air traffic service provider (ATSP) communication services, ATSP communication services, and air traffic services unit (ATSU), respectively. An air traffic context is also shown to reflect the potential application of TIA–902 (P34) in CNS/ATM context.

The notional avionics integration of TIA–902 (P34) elements is shown in figure 57.

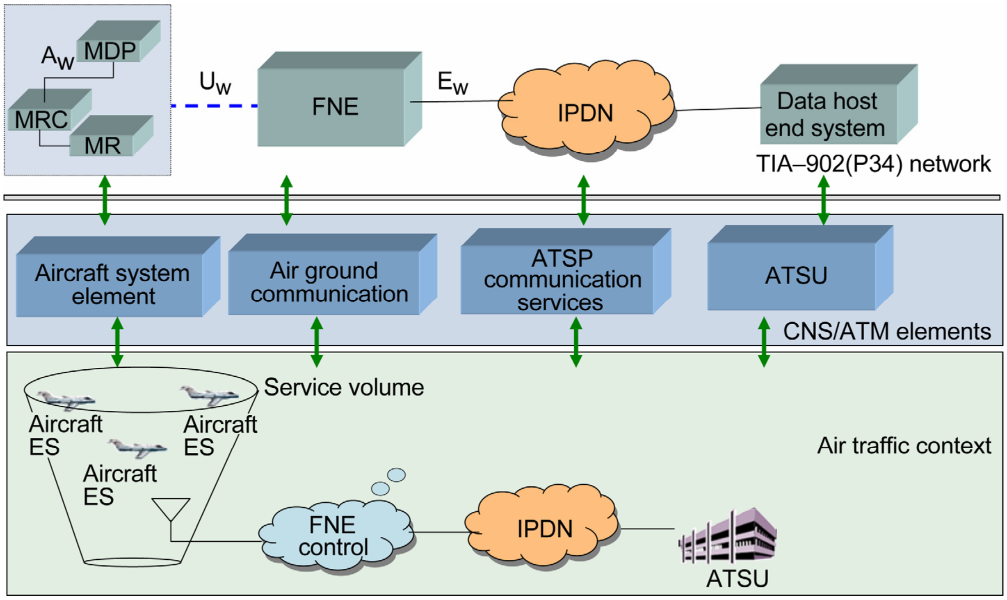


Figure 56.—Logical mapping of TIA–902 (P34) elements to CNS/ATM context.

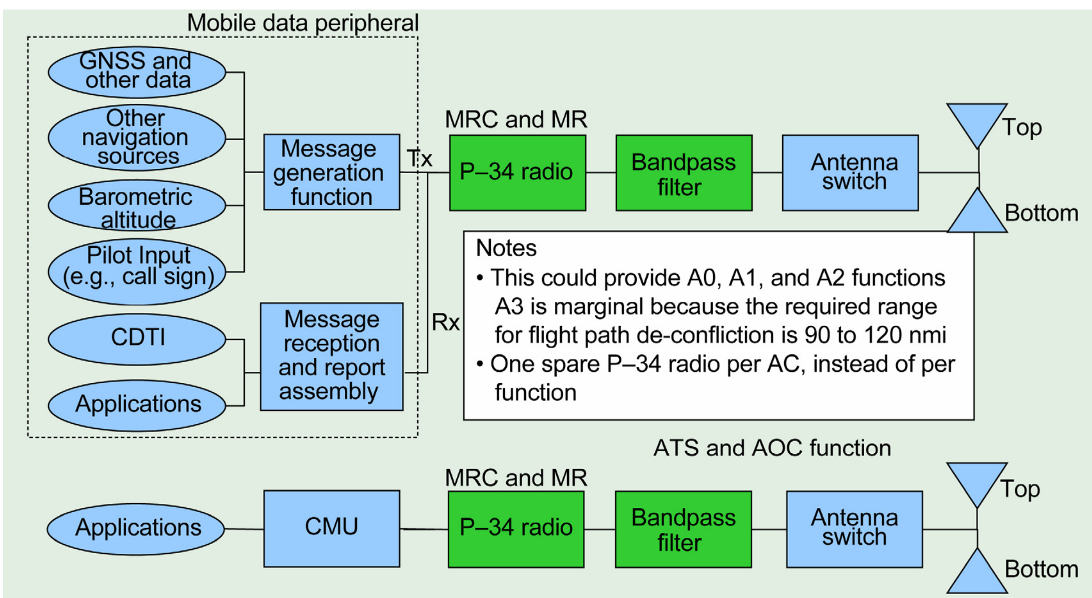


Figure 57.—Logical mapping to CNS/ATM context (notional avionics integration).

C.1.2 Concept for the Future Aeronautical Environment

This section describes how the TIA–902 (P34) technology can be applied in the future aeronautical environment in terms of technology details; COCR service provisioning; evaluation scenario assessment (including target deployment band; channelization, and deployment in ER, TMA, and surface domains); and finally some cost considerations.

C.1.2.1 Technology Details

TIA–902 (P34) Physical Layer Options: TIA–902 (P34) offers two physical layer formats, one is required implementation, and the other one is optional. Specifically, they are

- **Scalable adaptive modulation (SAM)** (required implementation). SAM defines adaptive signal constellations on an OFDM set of carriers that can be applied to 50-, 100-, and 150-kHz channels (scalable). This concept accommodates different modulation and coding rate combinations that can dynamically be applied to adapt to channel conditions (modulation options include QPSK, QAM–16, and QAM–64). Both physical layers define adaptive signal constellations on an OFDM set of carriers.
- **Isotropic orthogonal transform algorithm (IOTA)** (optional). IOTA is an OFDM concept that can be applied to 50-, 100-, and 150-kHz channels (scalable). IOTA is defined for increased capacity, it uses amplitude shift keyed modulation that can be applied to 50-, 100-, and 150-kHz channels.

The expected performance of the defined TIA–902 (P34) modulation in the A/G channel is quite good. Rather than using the typical cyclic prefix that is common to most OFDM systems, both SAM and IOTA implement coherent detection by transmitting a number of pilot symbols in every frame. Each pilot symbol transmits a known phase and amplitude value to the receiver. From this, the receiver can determine the amplitude and phase distortion of the channel, and apply the inverse function to reconstruct the symbol. This technique provides immunity to delay spread as long as the coherence time of the channel is long compared to the symbol duration.

TIA–902 (P34) Physical Layer for the FRS: This study recommends use of TIA–902 (P34) SAM physical layer because it provides sufficient capacity with less complex implementation than the IOTA implementation; also because it is the standard feature. The SAM configuration parameters are shown in table 51. Specific SAM parameters for the FRS implementation will be selected based on COCR-based scenario evaluations.

TABLE 49.—SAM PARAMETERS

Parameter	Channel Configuration		
	50 kHz	100 kHz	150 kHz
RF subchannels	8	16	24
Subchannel spacing, kHz	5.4	5.4	5.4
Symbol rate, k	4.8	4.8	4.8
Symbol filter	Root raised cosine (α=0.2)	Root raised cosine (α=0.2)	Root raised cosine (α=0.2)
Modulation type 1	QPSK (2 bits/symbol)	QPSK (2 bits/symbol)	QPSK (2 bits/symbol)
Modulation type 2	16QAM (4 bits/symbol)	16QAM (4 bits/symbol)	16QAM (4 bits/symbol)
Modulation type 3	64QAM (6 bits/symbol)	64QAM (6 bits/symbol)	64QAM (6 bits/symbol)
Modulation rate 1, kbps	76.8	153.6	230.4
Modulation rate 2, kbps	153.6	307.2	460.8
Modulation rate 3, kbps	230.4	460.8	691.2
Demodulation	Coherent (pilot symbol assisted)	Coherent (pilot symbol assisted)	Coherent (pilot symbol assisted)
TDM slot time, ms	10	10	10

TIA–902 (P34) MAC Layer Functions: The TIA–902 (P34) MAC layer has the following functions:

- Logical channel management and synchronization
- Random access channel
- Broadcast control channel
- Slot signaling channel
- Packet data channel
- Channel access, allocation of bandwidth, and contention resolution
- Priority queuing
- Slotted Aloha reservation requests
- Carrier sense multiple access for direct mode (mobile-to-mobile)

- Dynamic radio link adaptation control
- Radio power management
- Uses both closed- and open-loop power control
- Radio channel encryption and scrambling

The TIA–902 (P34) MAC layer priority queuing and slotted Aloha reservation request functions are accommodated via inbound random access slot structures. This standard slot structure (see below) limits the design range of a TIA–902 (P34) system to 187.5 km for SAM (about 100 nmi). The FCS Phase I reported noted however that the design range would appear to be easy to modify by requiring that only the even (or odd) reservation slots be used when making reservation requests for data. The TIA–902 (P34) standard defines three slot structures:

- Outbound: Continuous stream of 10-ms slots; includes combination of control and management information and outbound data
- Random access inbound: Two opportunities per 10-ms slot; frame structure includes 625-µs guard and 208.33-µs ramp-down for SAM
- Scheduled inbound: Frame structures include 208.33-µs guard and 208.33-µs ramp-down for SAM; includes combination of control and management information and inbound data

Note that scheduled inbound slot structure has tighter propagation delay allocations; however, the lookahead feature (i.e., mobile user knows a priori structure and allocation of next inbound random access frame (as managed by fixed (ground) equipment)) is a timing advance that assures propagation delays are not seen at the radio receiver except for the initial random access slot. Specific frame formats vary depending on end user (mobile for FNE) and configuration (FNE-to-mobile and mobile-to-mobile).

C.1.2.2 COCR Service Provisioning

Applicable domains: TIA–902 (P34) is a terrestrial-based technology that can be applied to the ER, TMA, and surface (APT) flight domains, but it is not applicable to oceanic/remote/polar domains.

Applicable services: FCS technology evaluation applies an evaluation scenario that includes both ATS and AOC on a shared communication connection. This is a conservative approach that includes most stringent communication requirements. Services to be provided include all except A–EXEC, WAKE, and ASAS (air-to-air broadcast). Associated communication functional needs are A/G addressed data, ground broadcast data, and A/A addressed.

C.1.2.3 Evaluation Scenario Assessment

C.1.2.3.1 Target Aeronautical Spectrum

TIA–902 (P34) is a wideband technology with channel bandwidths scalable from 50 to 100 to 150 kHz.

- Practical collocation with voice in VHF aeronautical spectrum not a viable implementation
- Target allocation is aeronautical L-band: 960 to 1024 MHz
- Utilize lower part of the DME band where there are ground DME allocations (and no allocations at the lowest part of the band)
- Allocation is subject to interference compatibility
- Implementation configuration is mobile to FNE using FDD (same as public safety deployment concept for 700 MHz using 18-MHz separation between uplink/downlink)

C.1.2.3.2 High-Level Deployment Concept

Deployment concepts for ER, surface, and TMA domains have been considered and evaluated.

- For ER environment, TIA–902 (P34) coverage range and capacity make it suited for implementation in a regular grid (cellular) fashion for ER domain, where users typically evenly distributed across this domain.
- In surface domains, individual surface channels are used, and because the surface environment is such that each implementation is beyond the radio horizon, surface frequencies can be reused between sites.
- For the TMA environment, locations are typically grouped in a nonuniform manner; in some locations, there can be a number of TMA environments close together while in other areas, TMA domains can be isolated from other TMA airspace. A cellular approach can be employed as needed in large TMA areas or where TMA areas are grouped together; alternatively, a set of TMA channels can be assigned channels and reused such that unique channels are deployed within the same radio horizon.

In the grid concept as shown in figure 58, each ground station provides data link connections to all sectors or partial sectors within their service volume, data is routed to appropriate ATSU, and mobility management functions are used for seamless connectivity.

C.1.2.3.3 TIA–902 (P34) Link Budgets

TIA–902 (P34) link budgets are calculated for forward and reverse links. The link budgets assumptions are shown in figure 59 and link budgets results for forward and reverse links are shown in figure 60.

In the calculations of figure 60, a coverage range of 150 nmi can be achieved with positive margin. However, because of standard use of MAC framing structures and propagation delay allocations, the maximum cell size would be on the order of 100 nmi. As noted above, this range could be expanded by implementing rules requiring that only the even (or odd) reservation slots be used when making reservation requests for data. However, for this analysis, a conservative service volume size (maximum) of 100 nmi was assumed.

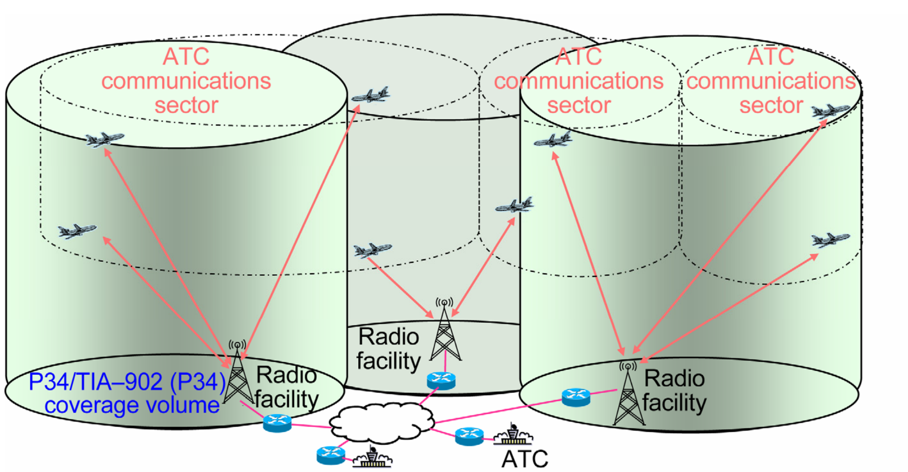


Figure 58.—The grid concept.

Parameter	Assumed value	Source
Physical Layer Spec	SAM–QPSK	
Bandwidth	50 kHz	Assumed
Forward Link (Gnd to A/C) Center Frequency	1000 MHz	Reference: ITT FCS Phase I report, pg 32, F
Reverse Link (A/C to Gnd) Center Frequency	960 MHz	Reference: ITT FCS Phase I report, pg 32, F
Base Station Transmit Power	15 Watts	DO-224B Table L-3
Base Station Cable Loss	2 dB	DO-224B Table L-3
Base Station Antenna Gain	6 dBi	DO-224B Table L-3
Aircraft Transmit Power	15 Watts	DO-224B Table L-3
Aircraft Cable Loss	3 dB	DO-224B Table L-3
Aircraft Antenna Gain	–4 dBi	DO-224B Table L-3
Ground Station Receiver Noise Figure	10 dB	DO-224B Table L-3
Aircraft Reciever Noise Figure	14 dB	DO-224B Table L-3
External System Noise Figure	10 dB	DO-224B Table L-3
Modulation		
Forward Link (Gnd to A/C) data rate	153 kbps	
Reverse Link (A/C to Gnd) data rate	153 kbps	

Figure 59.—TIA–902 (P34) link budgets assumptions.

Coverage volume size is 150 nmi diameter (diameter approx. = max. slant range)

Forward Link Budget

Air to Ground Slant Range (nmi)	ρ	150	Variable 277.8 km
Ground Antenna Height (ft)	h_T	50	Assumed (DO-224B assumes 33 - 50 ft)
Transmitter Power (dBm)	P_T	41.76091	Convert Watts above to dBm
Transmit Antenna Gain (dBi)	G_T	6	From assumptions above
Transmit Line Loss (dB)	L_T	2	From assumptions above
Transmit EIRP (dBm)	$P_T x(G_T/L_T)$	45.76091	Calculated
Free Space Path Loss (dB)	L_{FS}	141.3218	Calculated - 37.8 + 20log10(ρ)+20log10(*f*) for ρ in nmi and *f* in MHz
Excess Path Loss (dB)	L_{GR}	4	Reference FCS Phase II Cost Analysis Link Budget (Tony Boci)
Receive Antenna Gain (dBi)	G_R	-4	From assumptions above
Receiver Line Loss (dB)	L_R	3	From assumptions above
Received Signal Level (dBm)	P_R	–106.5609	Calculated: EIRP - Free Space PL - Excess PL + Antenna Gain - Receiver Line
Receiver Noise Figure (dB)	NF	5	Warren Wilson White Paper on LDL
Receiver Noise Power Density (dBm/Hz)		–168.98	Calculated: 10log(K*To*1000)+NF
Data Rate		51.85	
Receiver Noise Power in Data Rate (dBm)		–117.13	
Coding Gain		0.00	ASSUMED (need to examine P34 specs)
Available Eb/No		10.57	
Required Eb/No		10.00	Assumed (8 dB (verify) theoretical for QPSK at 10-3 BER plus 2 dB implementa
Margin		0.57	

Forward Link Budget

Air to Ground Slant Range (nmi)	ρ	150	Variable 277.8 km
Transmitter Power (dBm)	P_T	41.76091	Convert Watts above to dBm
Transmit Antenna Gain (dBi)	G_T	-4	From assumptions above
Transmit Line Loss (dB)	L_T	3	From assumptions above
Transmit EIRP (dBm)	$P_T x(G_T/L_T)$	34.76091	Calculated
Free Space Path Loss (dB)	L_{FS}	140.9672	Calculated: 37.8 + 20log10(ρ)+20log10(*f*) for ρ in nmi and *f* in MHz
Excess Path Loss (dB)	L_{GR}	4	Reference FCS Phase II Cost Analysis Link Budget (Tony Boci)
Receive Antenna Gain (dBi)	G_R	6	From assumptions above
Receiver Line Loss (dB)	L_R	2	From assumptions above
Received Signal Level (dBm)	P_R	–106.2063	Calculated: EIRP - Free Space PL - Excess PL + Antenna Gain - Receiver Line
Receiver Noise Figure (dB)	NF	5	Warren Wilson White Paper on LDL
Receiver Noise Power Density (dBm/Hz)		–168.98	Calculated: 10log(K*To*1000)+NF
Data Rate		51.85	
Receiver Noise Power in Data Rate (dBm)		–117.13	
Coding Gain		0.00	ASSUMED (need to examine P34 specs)
Available Eb/No		10.92	
Required Eb/No		10.00	Assumed (8 dB (verify) theoretical for QPSK at 10-3 BER plus 2 dB implementat
Margin		0.92	

Figure 60.—TIA–902 (P34) link budgets.

C.1.2.3.4 En Route Evaluation

The common evaluation scenario document (ref. 45) describes several en route (ENR (European acronym)) test volumes.

- Small ENR (test volume 3.1 (TV3.1)): 55 nmi cube/45 PIAC/80.4 kbps
- Medium ENR (TV3.2): 100 nmi cube/62 PIAC/94.3 kbps
- Large ENR (TV3.3): 200 nmi cube/204 PIAC/226.9 kbps
- Super large ENR (TV3.4): 400 nmi cube/522 PIAC/528.4 kbps

An OPNET simulation of an ENR scenario with PIAC of 95 on a single 50-kHz QPSK channel indicated that required QoS can be achieved (throughput around 63 percent). As noted above, a service volume size of 100 nmi was defined for the TIA–902 (P34) implementation. This corresponds closely with the medium ENR test volume size (TV3.2) that has a PIAC of 62 and capacity requirement of 94.3 kbps. As noted above, a previous OPNET simulation of up to 95 users performed and COCR performance requirements were met in the simulation model using a single ground channel. Therefore, a single ground channel is estimated for provision of services is TV3.2 (and smaller) service volumes.

To provision services in larger service volumes, a cellular approach was considered. The TIA–902 (P34) SAM physical layer protocol was designed to accommodate seven cell reuses (there are seven pilot and synchronization code sets). This factor was applied for the scenarios in the analysis (e.g., for large service volumes, seven frequencies are reused to provide regular-grid cellular services). To conservatively estimate the required number of channels within the various ENR service volumes, it was assumed that a fully redundant set of channels would be needed to address availability requirements (similar to current deployment scenarios). Thus, the resulting estimates of ground station sites and channels for accommodating the ENR test volumes include

- TV3.1 and TV3.2
  - One ground station site
  - Two 50-kHz channels each (one primary and one backup)
- TV3.3
  - Seven ground station sites
  - Fourteen 50-kHz channels (seven for primary and seven for backup)
- TV3.4
  - Twenty-two ground stations
  - Seven 50-kHz channels

A representative illustration of ground station sites and/or channels is provided in figure 61.

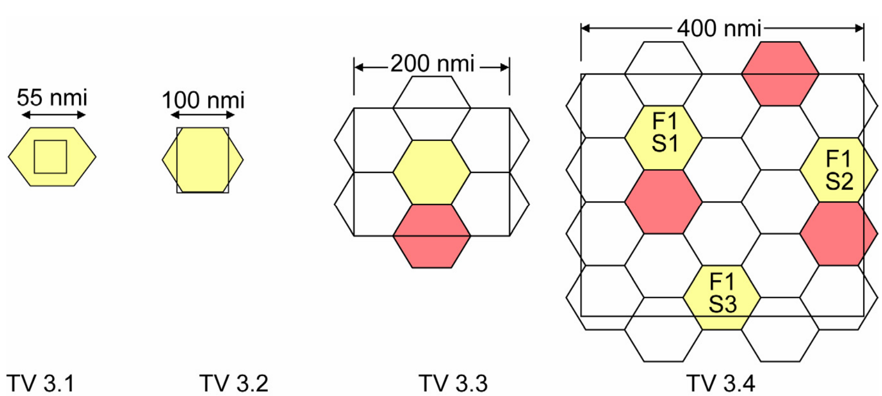


Figure 61.—Representative TIA–902 (P34) ENR coverage (notional illustration of concept, not drawn to scale).

C.1.2.3.5 TMA Evaluation

Two TMA test volumes are defined in the common evaluation scenario document (ref. 45) including:

- Small TMA (TV2.1): 49 nmi cube/44 users/17.4 kbps
- Large TMA (TV2.2) : 75 nmi cube/53 users/20 kbps

As noted above, an irregular pattern of TMA volumes is anticipated because of location of population centers; some areas may have several nearby large TMAs, and some large TMAs may be isolated. The same scenario may hold true for small TMA service areas. As a result, a regular grid of TMA ground stations is neither required nor practical. Instead, it is assumed that a set of frequencies will be applied and reused to provision TMA services.

Dense TMA airspace areas are assumed to drive TMA channel requirements. In a recent VDL2/3 bandwidth assessment (ref. 46), a terminal coverage volume of 60 nmi coverage volume was assumed and, iteratively stepping through required channel assignments across a large geographic area with varying organizations of TMA service volumes (i.e., the U.S. National Airspace System) such that no frequency was applied twice within radio line of sight (RLOS) (assumed 420 nmi) and hidden transmitter problem is tolerable, 23 channels were found to be required. A TIA–902 (P34) TMA deployment concept could be assumed to have a similar organization and similar constraints; however, reuse gains may be achieved because of the large number of synchronization sequences defined for the technology.

Recall that TIA–902 (P34) 50-kHz channels can be deployed with QPSK (76.8 kbps), QAM–16 (153.6 kbps), and QAM–64 (230.4 kbps). Contention-based reservation packet data network assessments identify the range of factors that impact performance, but many conservatively estimate that achievable throughput is typically high (50 to 80+ percent) (refs. 47 and 48). Considering a conservative throughput efficiency (50 percent) and the requirements of the large TMA service volume, it can reasonably be assumed that a single 50-kHz TIA–902 (P34) channel can accommodate the required capacity (with one of the three offered modulations). A single ground channel could also provision services to the small TMA service volume as well. Thus, the resulting nominal estimates of ground station sites and channels for accommodating the TMA test volumes include:

- TV2.1 and TV2.2
  - One ground station site
  - One 50-kHz channel

A representative illustration of ground station sites/channels is provided in figure 62.

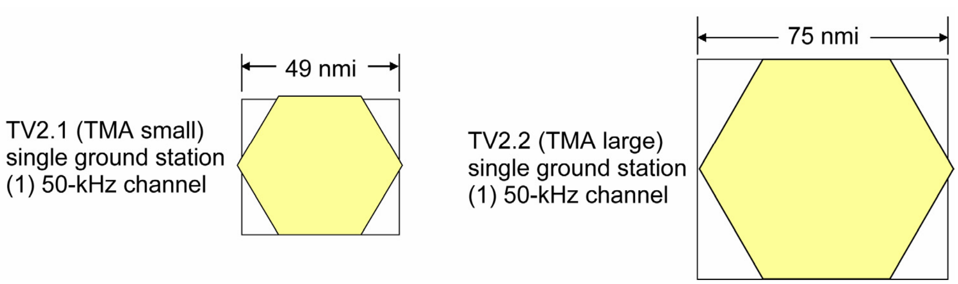


Figure 62.—Representative TIA–902 (P34) TMA coverage (notional illustration of concept, not drawn to scale).

C.1.2.3.6 Surface Domain Evaluation

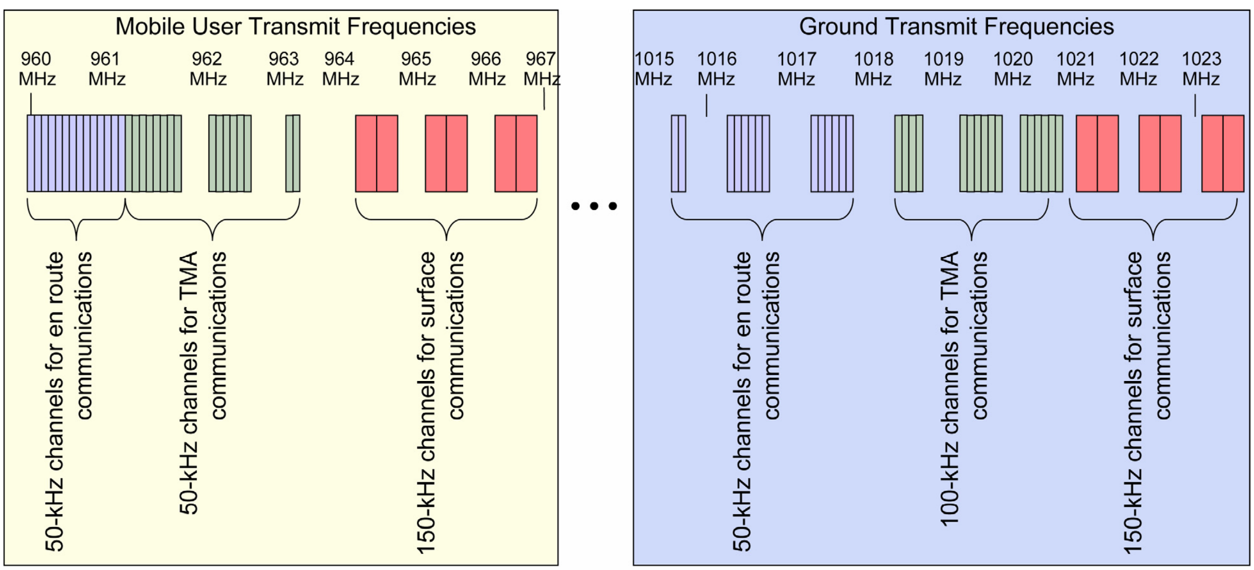
The surface domain is addressed by two evaluation scenarios (as defined in the common evaluation scenario document, ref. 45) including

- Airport zone, TV1.1 (PIAC = 26), 10.22 kbps
- Surface, TV1.2 (PIAC = 264), 142 kbps

TIA–902 (P34) 50-kHz, QPSK data rate (76.8 kbps) is less than the offered load, so alternative channel sizes and/or modulation schemes are considered. Specifically, the 150-kHz channel size, which offers 230.4 kbps (QPSK) and 461 (QAM–16), is used in the representative surface assessment scenario. In this case, applying a conservative estimate of 50 percent throughput (described previously), the technology (single channel) will have sufficient capacity to provision COCR services. As surface channels can be heavily reused due to location of the service volumes and radio horizon effects, an estimate of five to ten times per-APT channel requirements is assumed to accommodate the surface domain (thus 5 to 10 channels).

C.1.2.3.7 Notional Channelization Plan

Figure 63 shows the notional deployment concept, incorporating 50-kHz channels for the ER and TMA domains and using 150-kHz channels to provide surface communications.



Note: Specific channelization plan is subject to full interference assessment and/or modifications to the physical layer waveform; provided concept assumes inlay of TIA–902 (P34) channels is possible between DME allocations (300 kHz between allocations)

Figure 63.—Notional channelization plan.

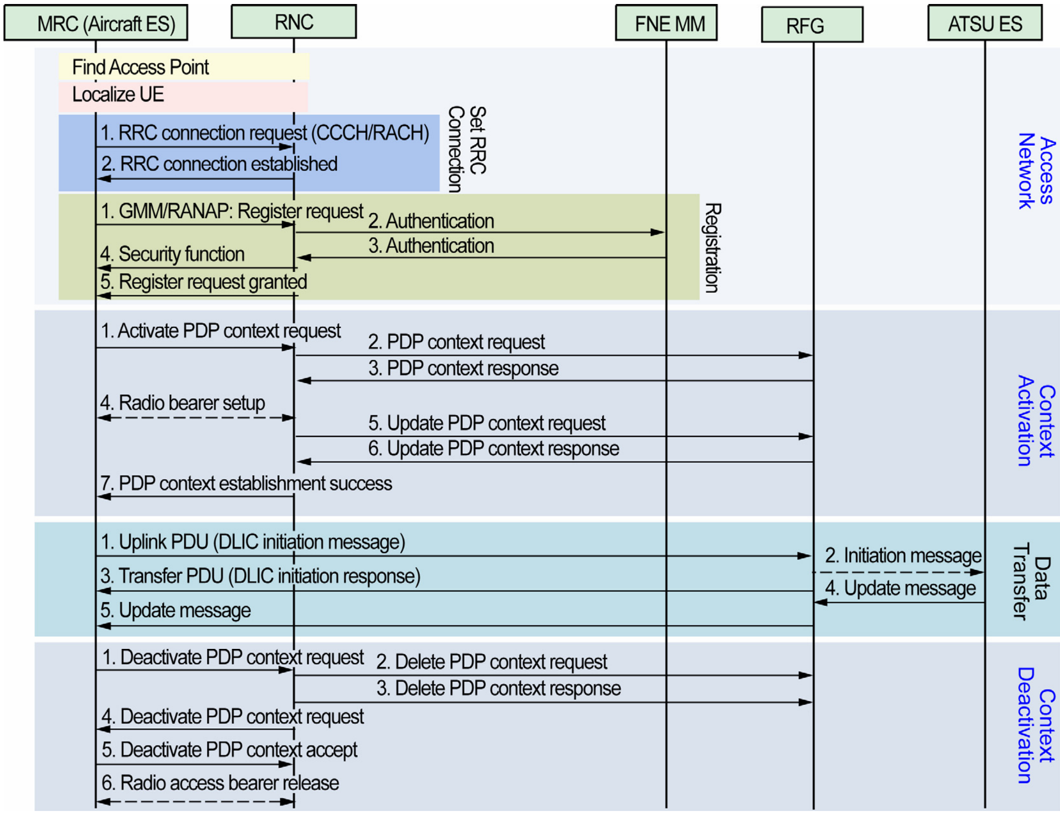


Figure 64.—DLIC to TIA–902 (P34).

C.1.2.4 Cost Considerations

The applied cost assessment accounts for required functional elements to support technology implementation; relative number of ground stations for deployment in large areas (consider deployment in combined super large/large ENR and large TMA); and specialized equipment/component required for provisioning of COCR services with this technology.

To gain an understanding of the functional elements of the technology that are needed to provision COCR services, a notional service mapping of COCR data link services to the technology was created. A representative DLIC (data link initiation capability) service was used for this assessment. DLIC exchanges information between an aircraft and an ATSU; DLIC provides version and address information for all data link services; DLIC service is executed prior to any other data link services; three DLIC subfunctions are Initiation, Update, and Contact. The mapping of DLIC to TIA–902 (P34) functions is shown in figure 64.

Figure 64 shows that the mobile radio interacts with the ground radio site (base radio and radio control equipment), ground mobility management functionality and ground network gateway for communications with an ATSU end system. No specialized equipment has been identified for a TIA–902 (P34) aeronautical implementation.

C.1.3 Additional Notes

TIA–902 (P34) can provide both an air-to-ground communication connection as well as an A/A communication connection. Communications between the aircraft (mobile radios) and the ground (base stations, or more precisely fixed network equipment) would follow the TIA–902 (P34) “Mobile Radio to Fixed Network Equipment” process. Communications between aircraft would be in accordance with the TIA–902 (P34) “Radio to Radio” configuration. This is the most basic of TIA–902 (P34) configurations, and is frequently called “talk-around” in the literature. Both modes would be supported by the same avionics radio.

Provisioning ADS–B with TIA–902 (P34) would be somewhat problematic because of the size of the TIA–902 (P34) random access slot (5-ms duration). This means that a 50-kHz TIA–902 (P34) system could provide no more than 200 random access opportunities for broadcast of ADS–B position reports a second. Each slot provides 262 bits of useable (payload) data, as the specification requires that the random access slots use the lowest modulation symbol constellation (the IOTA physical layer would thus use 2–ASK (amplitude shift keying) and provide 262 bits; SAM uses QPSK and provides somewhat less, roughly 164 bits). When compared with the UAT, which offers 3200 message-start opportunities every second, each providing the ability to send either a 16- or 32-byte ADS–B message, the following observations can be made:

1. IOTA physical layer looks like a better match than the SAM physical layer for transfer of ADS–B message (provides the same data message transport size as UAT)
2. In order to provide the same number of message opportunities, the TIA–902 (P34) system would have to be scaled sixteen-fold. This represents a system with a signal bandwidth of (16×50 kHz) 800 kHz, which compares favorably with the UAT

As the modulation is defined to scale linearly, this seems to be achievable. However, this signal would require a large number of subcarriers (roughly 397 for IOTA and 128 for SAM), and its performance in the A/G channel needs to be evaluated carefully.

TIA–902 (P34) is a packet data protocol, but can support voice transport using the voice over Internet protocol (VoIP). Talk groups would be set up using multicast IP services, and individual voice calls would be set up using unicast IP services.

C.2 WCDMA Concept of Use

WCDMA is a wideband spread-spectrum mobile telecommunication AI that uses CDMA. As a standardized technology of 3GPP (Third Generation Partnership Project), WCDMA is one of the main technologies for 3G cellular systems based on the radio access technique proposed by ETSI Alpha group and the specifications were finalized in 1999. WCDMA was submitted to the International Telecommunications Union (ITU) as a candidate for the international 3G standard known as IMT–2000; the ITU eventually accepted WCDMA as part of the IMT–2000 family of 3G standards. Later, WCDMA was selected as the AI for UMTS, the 3G data part of GSM. ETSI was responsible for the UMTS standardization process. In 1998 the 3GPP was formed to continue the technical specification work.

WCDMA is a direct sequence, wideband frequency division duplex CDMA with a signal bandwidth of 5 MHz. WCDMA, also referred to as UMTS FDD or UTRA FDD, is proposed as a candidate solution by the ICAO ACP.

C.2.1 Technology Overview

C.2.1.1 Standardization Status and Technical Readiness for Deployment

WCDMA is a mature set of commercial/industrial standards (3GPP). Validations of UMTS for commercial cellular applications are vast; and deployments of UMTS have occurred in many parts of the world (Europe, Asia, Australia, Africa, etc.).

As this is a cellular standard, it was designed to support mobile speeds of at most 250 km/h, and the channel and its capacity degrades at such speeds. However, a GSM extension for the European rail system (GSM–R) supports mobile speeds up to 500 km/h. Clearly, this is still well below the cruise speed of a jet airplane, but it is important to note that typically the cited speeds for the cellular standards are applicable to the non-line-of-sight (NLOS) channel, which imposes more severe constraints than a line-of-sight (LOS) channel, where there is a clear, direct path between ground and aircraft antennas. Accordingly, in a LOS channel, one would expect that much higher speeds could be supported. This has been at least partially demonstrated in field tests with both WCDMA and TD–CDMA that have been conducted by EUROCONTROL. In these tests Doppler effects generated by aircraft speeds of up to 400 knots (740.8 km/h) were compensated without any noticeable bit error (ref. 49).

C.2.1.2 Technology Services and Architecture

Because the ITU accepted WCDMA as part of the IMT–2000 family of 3G standards in 2000 and WCDMA was later selected as the AI for UMTS, the 3G successor to GSM, this study used the UMTS architecture for the assessment. The UMTS protocol architecture is shown in figure 65.

WCDMA services: There are a wide range of WCDMA services, including

- Bearer services
  - Packet-switched (PS) data
- Point-to-point (PTP) services
- Point-to-multipoint (PTM) services
  - Circuit switched data
- Teleservices
  - Speech
  - Short messaging service (SMS)
  - Cell broadcast service (CBS)
  - Various data applications
- Supplementary services
  - Calling line identification (CLI)
  - Call waiting
  - Call hold
  - Multiparty (up to five)
  - Unstructured supplementary service data (USSD)
  - Call forward
  - Call barring
  - Location-based services

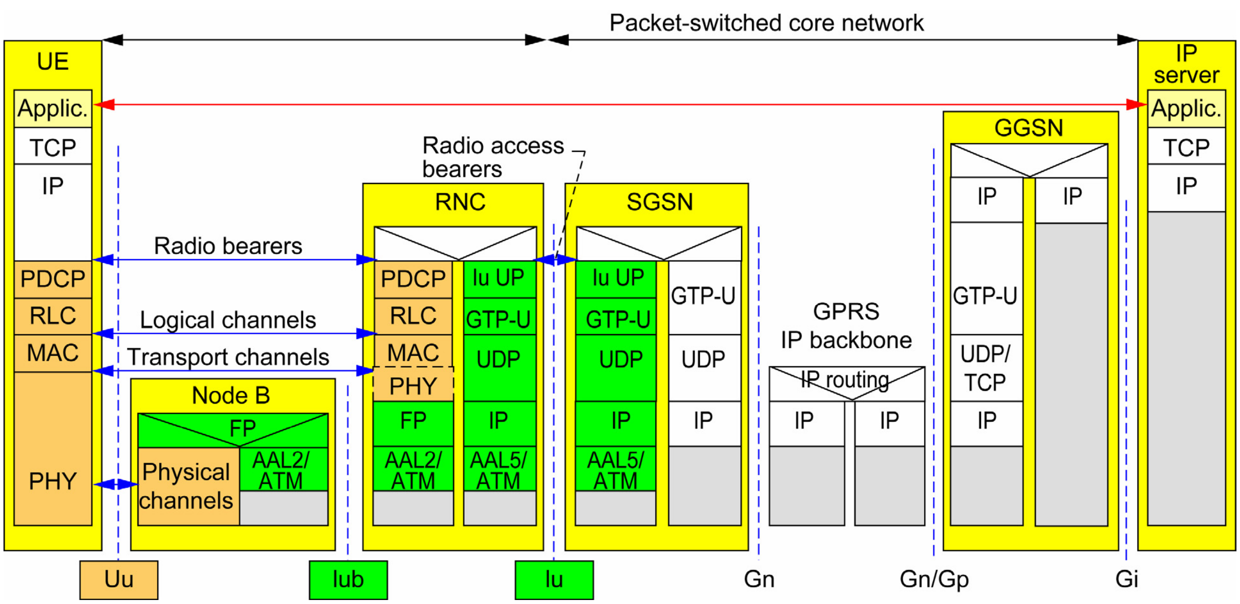


Figure 65.—UMTS/WCDMA protocol architecture (ref. 50)

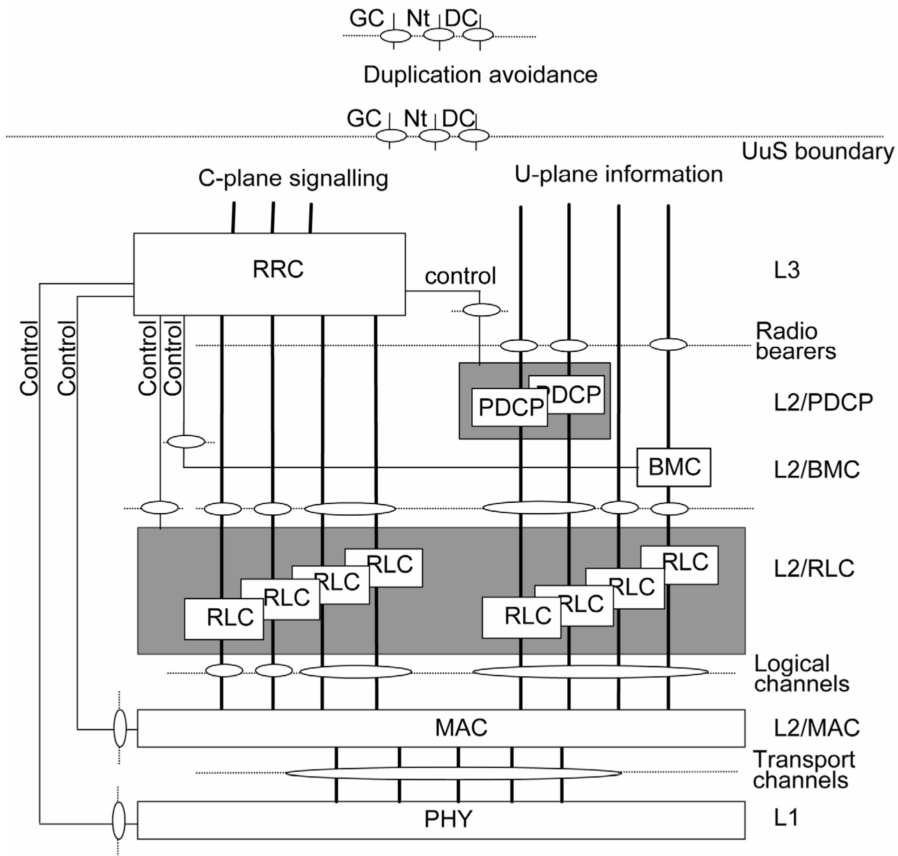


Figure 66.—WCDMA radio interface protocol architecture (ref. 51).

WCDMA Protocol Stack: The WCDMA protocol stack is layered and assumes a point of attachment to an IP network. Details of the radio link protocol are shown in figure 66.

Three separate channels correspond to different protocol layers. The physical channel forms the physical existence of the Uu interface between the user equipment (UE) domain and access domain. The transport channels carry different information flows over the Uu interface and the physical elements. The logical channels determine and manage different tasks the network and the terminal should perform at different times.

Figure 67 illustrates a representative network architecture for WCDMA. This network consists of three interacting domains: core network (CN), WCDMA UMTS Terrestrial Radio Access Network (UTRAN), and UE. The UTRAN provides the AI access method for the UE. The base station is referred to as Node-B, and the control equipment for Node–Bs is called radio network controller (RNC). The main functions of the CN are to provide switching, routing, and transit for user traffic. The CN also contains the databases and network management functions. The core network is divided into circuit-switched (CS) and packet-switched (PS) domains. Some of the CS elements are mobile services switching centre (MSC), visitor location register (VLR) and gateway MSC. PS elements are serving GPRS support node (SGSN) and gateway GPRS support node (GGSN). Some network elements, like EIR, home location register (HLR), VLR, and AUC are shared by both domains. The PS domain can connect to an Internet and/or packet data network (PDN).

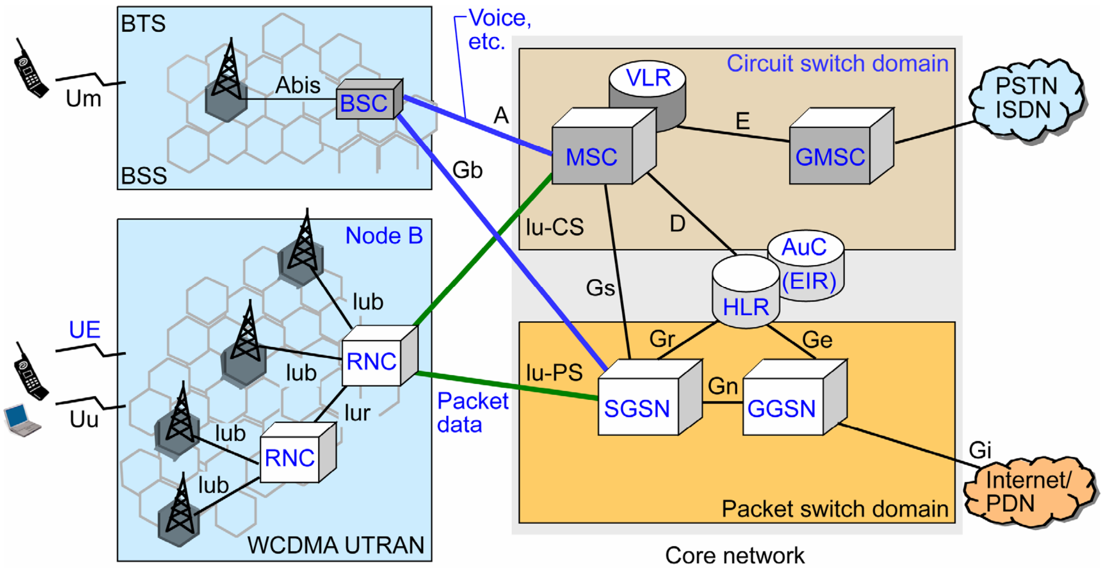


Figure 67.—WCDMA network architecture.

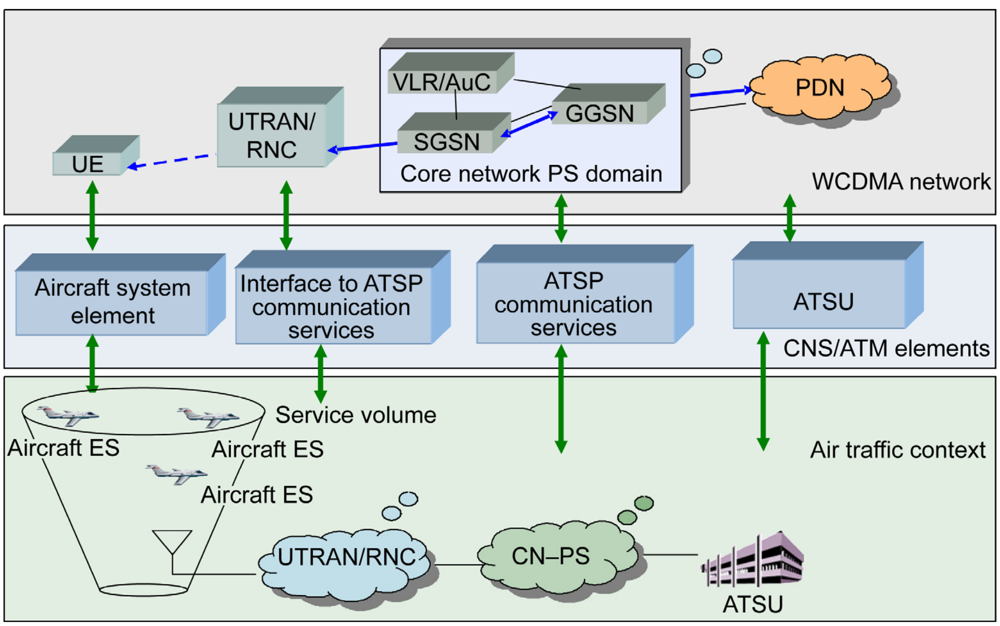


Figure 68.—Logical mapping of WCDMA elements to CNS/ATM context.

UMTS mobile station can operate in one of three modes of operation.

- PS/CS mode of operation: The MS is attached to both the PS domain and CS domain; and the MS is capable of simultaneously operating PS services and CS services.
- PS mode of operation: The MS is attached to the PS domain only and may only operate services of the PS domain. However, this does not prevent CS-like services to be offered over the PS domain (like VoIP).
- CS mode of operation: The MS is attached to the CS domain only and may only operate services of the CS domain.

To provide a user's view of both the CNS/ATM system and WCDMA network system and elements, a logical mapping of the two systems is provided as shown in figure 68, where WCDMA network

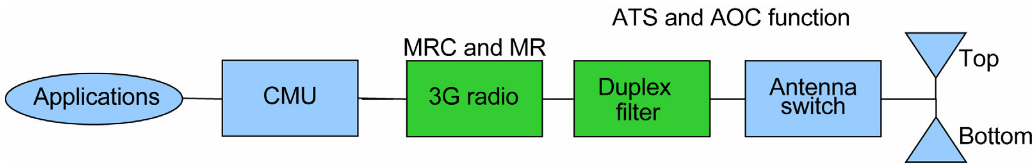


Figure 69.—Logical mapping to CNS/ATM context (notional avionics integration).

elements UE, UTRAN/RNC, core network PS domain and PDN are mapped to aircraft system element, A/G communication services, ATSP communication services and ATSU, respectively. An air traffic context is also shown to reflect the potential application of WCDMA in CNS/ATM context.

The notional avionics integration of WCDMA elements is shown in figure 69.

C.2.2 Concept for the Future Aeronautical Environment

This section describes how the TIA–902 (P34) technology could be applied in the future aeronautical environment in terms of technology details; COCR service provisioning; evaluation scenario assessment (including target deployment band; channelization, and deployment in ER, TMA, and surface domains); and finally some cost considerations.

C.2.2.1 Technology Details

WCDMA Physical Layer Options: WCDMA has two basic modes of operation:

- Frequency division duplex (FDD) mode. Here separate frequencies are used for uplink and downlink. FDD is currently being deployed and is usually referred to as WCDMA.
- Time division duplex (TDD) mode. In this mode, the uplink and downlink are carried in alternating bursts on a single frequency.

In a previous study (ref. 16), a comparison of these two modes was performed while checking the feasibility of UMTS to ATC. Example results from this study are shown in table 52.

TABLE 50.—FDD MODE AND TDD MODE COMPARISON

FDD mode	TDD mode
Large cell size High mobility Symmetric link	Small cell size Low mobility Asymmetric link

As seen in table 52, FDD standards tend to support the larger cell sizes applicable to aeronautical communications. However, they require a pair of frequency bands separated by a large guard band. They transmit and receive on different frequency bands and thus are not amenable to reengineering to support direct mobile-to-mobile communications required in the aeronautical environment. TDD standards do not support very large cell sizes, but like current aeronautical communications, they require only a single frequency band that is used for both transmit and receive. The assessed mode of WCDMA is the FDD mode. Key WCDMA physical layer parameters are shown in table 53.

The WCDMA specification offers multiple physical layer modulations and associated coding rate configurations for both uplink (mobile to ground station) and downlink (ground station to mobile) connections. The uplink uses BPSK modulation and the downlink uses QPSK modulation. However, multiple coding rate options are included in the specification. Within WCDMA, data is transmitted in frames (10 ms) consisting of 15 slots. Slots consist of data channels (designated dedicated physical data channel or DPDCH) or control channels. Scrambling and spreading codes can be both long and short

TABLE 51.—KEY WDCMA PARAMETERS

Frequency band, MHz	1920 to 1980 and 2110 to 2170 (FDD WCDMA_ Paired UL and DL, channel spacing is 5 MHz and raster is 200 kHz. Needs 3 to 4 channels (2 by 15 MHz or 2 by 20 MHz) to build a high-speed, high-capacity network.
Minimum frequency band, MHz	2 by 5
Frequency reuse	1
Carrier spacing, MHz	4.4 MHz to 5.2
Channel coding	Convolutional coding. Turbo code for high-rate data. Duplexer need (190-MHz separation)
Tx/Rx isolation, dB	MS: 55, BS: 80
Data type	Packet and circuit switch
Modulation	QPSK on the downlink, BPSK on the uplink
Chip rate, Mcps	3.84
Data rate (physical channel)	~2.3 Mbps (spreading factor 4, parallel codes (3 DL/6 UL), ½ rate coding)
Maximum user data rate, kbps	384 (year 2002)
Channel bit rate, Mbps	5.76
Frame length, ms	10 (38 400 chips)
Number of slots per frame	15
Number of chips per slot	2560
PHY spreading factors	4 to 256 uplink and 4 to 512 downlink

TABLE 52.—WCDMA SLOT FORMAT AND CHANNEL BIT RATE

Slot format, No. i	Channel bit rate, kbps	Channel symbol rate, kbps	SF	Bits/frame	Bits/slot	N_{data}
0	15	15	256	150	10	10
1	30	30	128	300	20	20
2	60	60	64	600	40	40
3	120	120	32	1200	80	80
4	240	240	16	2400	160	160
5	480	480	8	4800	320	320
6	960	960	4	9600	640	640

scrambling codes. Codes are mobile specific in the uplink and ground station specific in the downlink. Spreading codes are orthogonal variable spreading factor (OVSF) codes. Channelization codes (OVSF) are the same in each cell whereas scrambling codes are different among adjacent cells. Channel spreading codes partition capacity of each transmission slot: High spreading factor creates many partitions (e.g., 128) at low data rate, and low spreading factor creates few partitions (e.g., 4) at a high data rate. Table 54 shows the relation of different spreading factors to different channel bit rates.

Physical Layer for the FRS: The evaluation scenario for WCDMA focuses on UMTS–FDD/WCDMA only and the wideband direct sequence code division multiple access, which does not assign a specific frequency to each user. Instead every channel uses the full available spectrum. Individual conversations are encoded with a pseudorandom digital sequence. Configuration parameters will be selected based on COCR-based scenario evaluations. Given stakeholder direction within the FCS to focus on a data-only capability, the ability to use the WCDMA packet mode was considered (this included the FDD and thus supports a larger cell size).

The packet service supports all data communications and PTT over cellular (PoC) (a service that can be used to create and maintain a group voice conference and supports access via PTT). As noted above, the focus of the implementation for this analysis is data communications. Table 55 shows notional WCDMA parameters for the FRS.

TABLE 53.—WCDMA PARAMETERS FOR FRS

Parameter	Value
Frequency band, MHz	960 to 1024 (FDD WCDMA paired UL and DL)
Minimum frequency band, MHz	2 by 5
Frequency reuse	1
Carrier spacing, MHz	4.4 to 5.2
Channel coding	Convolutional coding, turbo code for high rate data; Duplexer needed 190 MHz separation
Tx/Rx isolation, dB	MS: 55 and BS: 80
Data type	Packet
Modulation	QPSK on the downlink and BPSK on uplink
Chip rate, Mcps	3.84
Data rate (physical channel)	Varies based on COCR
Maximum user data rate, kbps	384 (year 2002)
Channel bit rate, Mbps	5.76
Frame length, ms	10 (38,400 chips)
Number of slots per frame	15
Number of chips per slot	2560
PHY spreading factors	4 to 256 uplink and 4 to 512 downlink

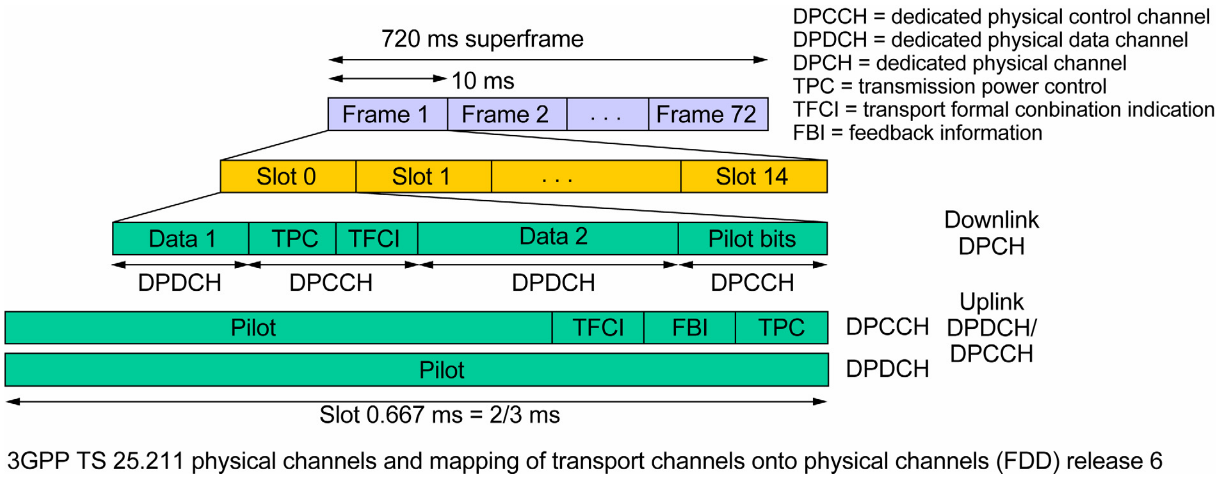


Figure 70.—Time slot configuration example.

WCDMA MAC Layer Functions: The WCDMA MAC layer performs the following functions:

- Mapping between logical channels and transport channels
- Selection of appropriate TF (basically bit rate), within a predefined set, per information unit delivered to the physical layer
- Service multiplexing on RACH, FACH, and dedicated channels
- Priority handling between data flows of one user as well as dynamic scheduling between data flows
- Access control on RACH
- Address control on RACH and FACH
- Contention resolution on RACH
- Transport channel type switching

An example of the WCDMA time slot configuration is shown in figure 70.

C.2.2.2 COCR Service Provisioning

Applicable domains: WCDMA is a terrestrial-based technology, which can be applied to the ER, TMA, and surface (APT) flight domains, but it is not applicable to oceanic/remote/polar domains.

Applicable services: The FCS technology evaluation applies an evaluation scenario that includes both ATS and AOC on a shared communication connection. This is a conservative approach, which includes most stringent communication requirements. Services to be provided include all except A–EXEC, WAKE, and ASAS (air-to-air broadcast). Associated communication functional needs are A/G addressed data, ground broadcast data, and A/A addressed.

C.2.2.3 Evaluation Scenario Assessment

C.2.2.3.1 Target Aeronautical Spectrum

A notional allocation of channels in 960 to 1024 MHz is proposed for WCDMA deployment. Coverage of airspace may be used in a number of ways.

- Single channel covering all airspace
- Dedicated channels allocated to airspace tiers:
  - Channel A for ultra-high ER; channel B for high ER; and other channels for lower altitude airspace
- Dedicated channels for specific airspace domains (e.g., TMA)

A EUROCONTROL WCDMA evaluation report (ref. 16) indicates that each WCDMA channel requires 5-MHz channel bandwidth and two 5-MHz guard bands. The report proposes a single channel covering all airspace. The report also suggests a forward link (ground-to-mobile) center frequency at 968 MHz and a reverse link (mobile-to-ground) center and downlink at 1149 MHz. Note that the downlink center frequency is beyond the band proposed for aeronautical coprimary use in WRC–2007 recommendations (ref. 7); therefore, the concept of use here assumes implementation of the reverse link at the upper part 960 to 1024 band (specifically, a reverse link center frequency of 1016 MHz is used). Sufficient separation between the forward and reverse channels requires validation. A notional WCDMA L-band deployment concept is shown in figure 71.

At the eighth meeting of the ICAO ACP/Working Group C (WGC8) in September 2004, the FAA presented its initial WRC–2007 recommendations regarding such opportunities. These were as follows:

- Pursue AM(R)S allocation (in DME band) should be limited to 960 to 1024 MHz
- Pursue AM(R)S allocation for 5091- to 5150-MHz band for APT local area systems

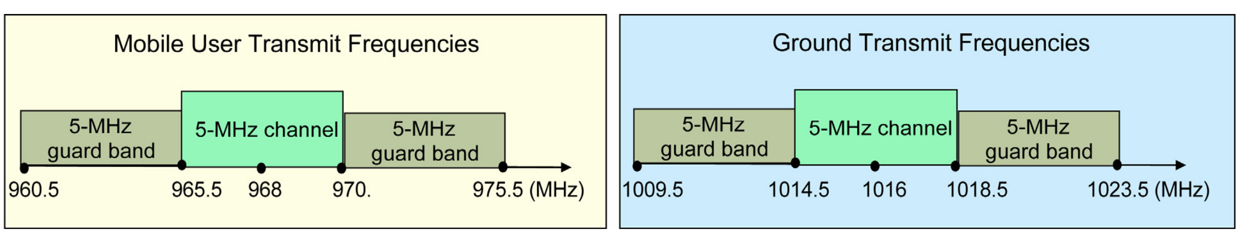


Figure 71.—Notional WCDMA L-band deployment concept.

C.2.2.3.2 High-Level Deployment Concept

Deployment concepts for ER, surface, and TMA domains have been considered and evaluated. WCDMA has been defined for implementation in a cellular (regular grid) fashion, where cells can be defined to provide ER, TMA, or surface coverage. A cellular grid concept is shown in figure 58. Here, each ground station provides data link connections to all sectors or partial sectors within their service volume, data is routed to appropriate ATSU, and mobility management functions are used for seamless connectivity.

C.2.2.3.3 WCDMA Link Budgets

The WCDMA link budget analysis applied in this study is based on available WCDMA link budgets from EUROCONTROL CDMA Simulation Results (ref. 52) (see table 56). Other WCDMA studies indicate that the ground transmitter power considered may be higher than the numbers provided in these link budgets (48 dBm identified in the Roke Manor WDMA analysis report, ref. 53). Considering this increase in ground transmitter power from ground, the cell size calculation identified in table 56 for ground-to-air communications can be increased to about 175 km. Considering this range as well as the air-to-ground link budget, cell sizes between 80 and 100 nmi can be achieved with positive link margin.

To conduct a conservative assessment, cell sizes proposed in the CDMA simulation assessment (ref. 52) were considered, namely 80 km (TMA) and 50 km (ER); this is equivalent to approximately 45 and 30 nmi, respectively.

TABLE 54.—LINK BUDGETS FROM EUROCONTROL CDMA SIMULATION PAPER

Parameter	CDMA 2000	UMTS
Forward link mean frequency, MHz	960.0	960.0
Base station transmit power, dBm	43.0	43.0
Aircraft cable loss, dB	1.0	1.0
Base station cable loss, dB	1.0	1.0
Base station antenna gain, dB	6.0	6.0
Sector edge antenna attenuation, dB	6.0	6.0
Aircraft antenna gain, dB	1.5	1.5
Free space loss at 1 km, dB	92.1	92.1
Required E_b/N_0, dB	4.5	4.5
Aircraft Rx noise figure, dB	6.0	6.0
Max. traffic relative power, dB	–13.0	–18.2
Data rate, bps	9600.0	9600.0
On code Tx power, dBm	30.0	24.8
Sensitivity, dBm	–123.5	–123.7
Edge of cell noise rise, dB	10.0	10.0
Path loss capability, dB	142.9	138.0
Excess path loss (over 1 km), dB	50.8	45.9
Gaseous plus rain and fog losses, dB	0.067	0.067
Range, km	128.9	94.9

Parameter	CDMA 2000	UMTS
Reverse link mean frequency, MHz	1325.0	1325.0
Aircraft transmit power, dBm	33.0	33.0
Aircraft transmit cable loss, dB	1.0	1.0
Base station cable loss, dB	1.0	1.0
Base station antenna gain, dB	6.0	6.0
Sector edge antenna attenuation, dB	6.0	6.0
Aircraft antenna gain, dB	1.5	1.5
Free space loss at 1 km, dB	92.2	92.2
Required E_b/N_0, dB	4.7	2.7
BTS Rx noise figure, dB	6.0	6.0
Data rate, bps	9600.0	9600.0
Sensitivity, dBm	–123.5	–125.7
Loading noise rise, dB	10.0	10.0
Path loss capability, dB	146.0	148.0
Excess path loss, dB	51.1	53.1
Gaseous plus rain and fog losses, dB	0.067	0.067
Range, km	130.2	146.1

C.2.2.3.4 En Route Evaluation

The common evaluation scenario document (ref. 45) describes several en route (ER) (ENR is European acronym) test volumes.

- Small ENR (test volume 3.1 (TV3.1)): 55 nmi cube/45 PIAC/80.4 kbps
- Medium ENR (TV3.2): 100 nmi cube/62 PIAC/94.3 kbps
- Large ENR (TV3.3): 200 nmi cube/204 PIAC/226.9 kbps
- Super large ENR (TV3.4): 400 nmi cube/522 PIAC/528.4 kbps

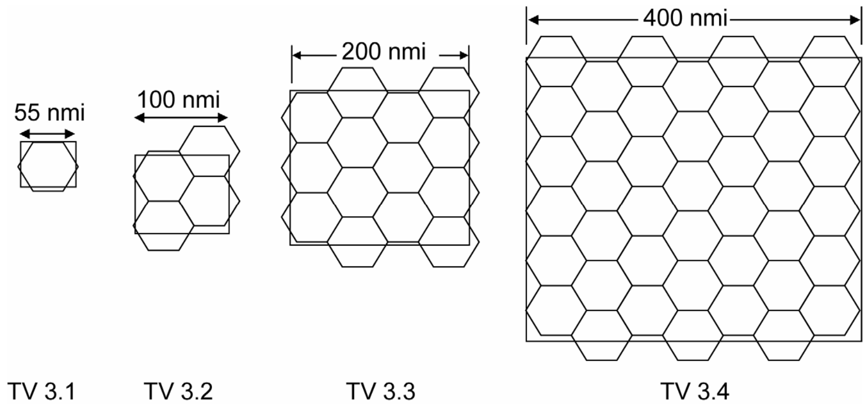


Figure 72.—Representative WCDMA ENR coverage (notional illustration of concept, not drawn to scale).

A single WCDMA cell/service volume will line up with the small ENR test volume. Initial simulation results of a cellular layout of WCDMA service volumes to provision services in a large ENR area found that UMTS can meet requirements (with cell radius of 50 nmi; per aircraft data rate = 9600 bps and activity factor of 10 percent) (ref. 52). Additional simulations should be conducted to validate that a single ground channel can provision services to TV3.1 and a regular grid of ground stations can be used in the other test volume sizes. Due to the flexibility in WCDMA specification to provide high-capacity services, the WCDMA technology is assumed to meet requirements (may require adjustment in cell size). Assuming (as in the TIA–902 (P34) assessment) that a full redundant set of channels may be needed to address availability requirements, the following nominal estimates of ground station sites and channels are made for the ENR test volumes:

- TV3.1
  - One ground station site
  - Two 2- by 5-MHz channels (one set primary and one set backup)
- TV3.2
  - Approximately four ground station sites
  - Two 2- by 5-MHz channels (one set primary and one set backup)
- TV3.3
  - Approximately 14 ground station sites
  - Two 2- by 5-MHz channels (one set primary and one set backup)
- TV3.4
  - Approximately 42 ground station sites
  - Two 2- by 5-MHz channels (one set primary and one set backup)

A representative illustration of ground station sites and channels is provided in figure 72.

C.2.2.3.5 TMA and Surface Evaluation

Two TMA test volumes are defined in the common evaluation scenario document (ref. 45) including

- Small TMA (TV2.1): 49 nmi cube/44 users/17.4 kbps
- Large TMA (TV2.2): 75 nmi cube/53 users/20 kbps

As noted previously, an irregular pattern of TMA volumes is anticipated because of location of population centers; some areas may have several nearby large TMAs, and some large TMAs may be isolated. The same scenario may hold true for small TMA service areas. As a result, a WCDMA cell size can be adjusted to accommodate the anticipated traffic in the coverage volume. Based on initial simulations in the TMA domain, applying a cell size of approximately 45 nmi, COCR service requirements could be met. As noted in the ENR evaluation, additional simulations should be conducted to validate that a single ground channel can provision services to TV2.1 and a regular grid of ground stations can be used in the large TMA test volume size. Due to the flexibility in WCDMA specification to provide high-capacity services, the WCDMA technology is assumed to meet requirements (may require adjustment in cell size). A nominal estimate of ground station sites and channels for accommodating the TMA test volumes include

- TV2.1
  - One ground station site
  - One 2- by 5-MHz channel
- TV2.2
  - Approximately four ground station sites (assuming cell size of 45 nmi)
  - One 2- by 5-MHz channel

Note that the WCDMA concept is to use a single 5-MHz channel to provision all aeronautical services; actual deployment may require adjustment in cell size (or other capacity gaining techniques such as sectorization) in high user density areas or use of overlay cells. These concepts are introduced in reference 52.

C.2.2.3.6 Surface Domain Evaluation

Surface domain is addressed by two evaluation scenarios (as defined in the common evaluation scenario document (ref. 45)) including

- Airport zone, TV1.1 (PIAC = 26), 10.22 kbps
- Surface, TV1.2 (PIAC = 264), 142 kbps

No explicit simulation of WCDMA for the APT surface was identified. Because of the high capacity capability of WCDMA, it is thought that this technology could be configured and deployed to meet APT surface requirements. Simulation of technical parameters and architecture configurations is needed to test WCDMA performance to services needs and requirements. The APT surface is assumed to be accommodated by a single ground channel (one 2- by 5-MHz channel, with cells sized appropriately). Note that the WCDMA concept is to use a single 5-MHz channel to provision all aeronautical services; actual deployment may require adjustment in cell size (or other capacity gaining techniques such as sectorization) in high user density areas or use of overlay cells. These concepts are introduced in ref. 52.

C.2.2.4 Cost Considerations

The applied cost assessment accounts for required functional elements to support technology implementation; relative number of ground stations for deployment in large areas (consider deployment in combined super large/large ENR and large TMA); and specialized equipment/components required for provisioning of COCR services with this technology.

To gain an understanding of the functional elements of the technology that are needed to provision COCR services, a notional service mapping of COCR data link services to the technology was created. A representative DLIC service was used for this assessment. DLIC exchanges information between an aircraft and an ATSU; DLIC provides version and address information for all data link services; DLIC service is executed prior to any other data link services; and the three DLIC subfunctions are Initiation, Update, and Contact. The mapping of DLIC to TIA–902 (P34) functions is shown in figure 73.

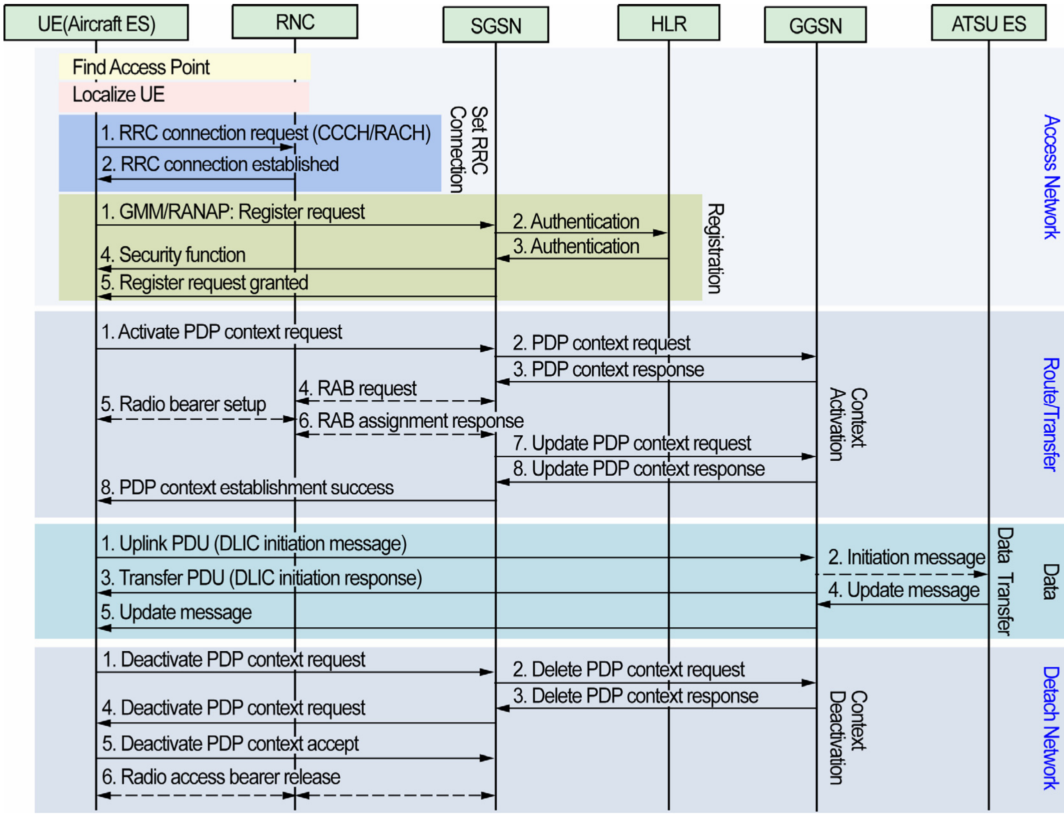


Figure 73.—DLIC to WCDMA.

Figure 73 shows that mobile radio interacts with the ground radio site (base radio (BR) and radio control equipment); core network gateway function (SGSN); ground mobility management functionality (HLR); and gateway to external systems/networks (GGSN) for communications with an ATSU end system. In other words, in addition to base radio equipment (base stations), the regular grid concept defined for WCDMA requires the following:

- Radio network controllers (radio control and switching)
- Core network
  - SGSN
  - GGSN
  - HLR
  - VLR

Initial EUROCONTROL CDMA analysis efforts identify potential specialized equipment required for a WCDMA implementation. This includes dual antenna radio sites (recommended by the EUROCONTROL CDMA simulation report for diversity gain) and sectorized antennas.

C.2.3 Additional Notes

Cellular telephony standards offer a wealth of capabilities and underlying technology that could be applied to aeronautical communications. There are obstacles to this application, however. It is unclear if clearing of DME frequencies, which is likely to be required for L-band implementation based on early interference assessments, is a viable option. With respect to technical performance, additional work needs to be done to provide a high level of assurance that aeronautical applications, which are well outside the 3G design envelopes for range and Doppler, can be reliably served. With respect to infrastructure cost, insertion of 3G technology could drive changes to much of the A/G infrastructure (e.g., voice switches, automation, antennas, radios, etc.) and with respect to certification, 3G systems are among the most complex and feature-rich communications systems.

C.3 LDL Concept of Use

The LDL protocol is not a standardized technology, but an evolution of the ICAO standardized narrowband VDL3 technology with a redesigned physical layer for operation in L-band. LDL was proposed by MITRE Corporation in 2006 to support the new civilian air-to-ground communication systems. The new physical layer is based on the ICAO standardized UAT standard, but with a lower data rate. The upper layers are almost identical as those proposed for VDL3.

C.3.1 Technology Overview

C.3.1.1 Standardization Status and Technical Readiness for Deployment

No specific standards exist for the LDL technology; however, LDL has been documented in several technical description documents brought forward into ICAO ACP. As noted previously, LDL incorporates much of the VDL3 upper layer specifications, with some modifications (e.g., MAC) to support higher-capacity operations. Some of the VDL3 upper layers may be applicable with minimal modifications. The LDL physical layer proposal has been defined and brought forward in several aeronautical forums for review and comment (e.g., ICNS and ICAO ACP); but details are not completely defined and are subject to fine-tuning. Based on the VDL3 protocol structure, the assumed set of LDL standards is provided in figure 74.

Specific LDL validation and deployment has not taken place. Related validation and deployment activities include

- As noted above, LDL reuses VDL3 and UAT (marriage of VDL3 upper layers and UAT physical layer) standards. VDL3 has been standardized by ICAO and was developed specifically for providing ATC communications in the VHF band (VDL3 SARPs, VDL3 technical manual, and VDL3 implementation aspects). ICAO standards are being developed for UAT for provision of air-air broadcast communications (UAT SARPs). Thus, these can be considered related validation activities.
- Although LDL has not been specifically demonstrated or validated, parts of its component specifications (e.g., upper layer VDL3 demonstrations and validations are applicable).

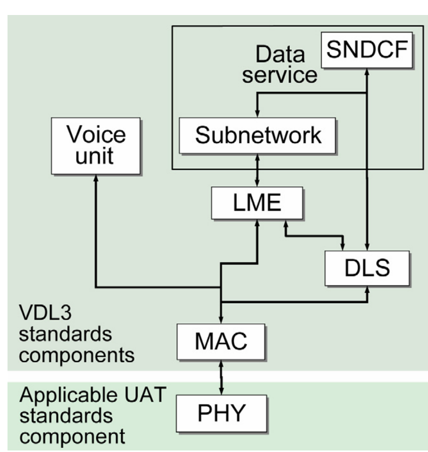


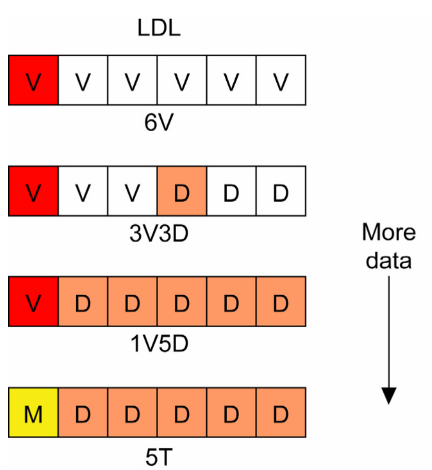
Figure 74.—LDL protocol elements.

C.3.1.2 Technology Services and Architecture

LDL is a custom aeronautical technology evolving from the VDL3 standards with a redesigned physical layer and slight modifications to the link layer to facilitate operations in L-band (960 to 1024 MHz). VDL3 was designed for ATC voice and data messages, and the critical nature of ATC usage, in some cases, requires additional latency and integrity mechanisms to achieve reliable and available data link performance designed into VDL3 and hence LDL. For example, VDL3 was based on an acknowledged, connectionless data link services (A–CLDL) layer where acknowledgments are placed in reserved time slots, including a connectionless broadcast feature. At the subnetwork layer, it uses either a connection-oriented ISO 8208 protocol or a connectionless network protocol (CLNP). It also provides a reservation-based ground-air data link with four-level grouped priority. The use of priority grouping and transmission of priority frames and use of reserved timeslots for acknowledgements contributes to the integrity of the data link. The use of dedicated timeslots for voice with the added features of controller override, next channel uplink automation, among others adds to the availability of the safety-critical voice function for ATC.

The services for LDL (as for VDL3) are distinguished by the configuration mode of the ground station. These configurations are classified according to the mix of voice and data services provided as well as the number of user groups supported. User groups may be assigned to groups of aircraft based on a particular sector of airspace and, consequently, may get a reserved timeslot or timeslots for either or both voice and data. Six timeslots define a frame. As an example, a 6V (voice) configuration will support six voice circuits (timeslots) labeled A, B, C, D, E, and F. Timeslot A would be used by all aircraft in an area of airspace, most likely a single sector, and the other three slots would be assigned similarly. It is in this manner that a single 83.3-kHz channel may be split into a total of six groups.

When data services are desired, a mixed mode may be configured. For example, a 3V3D mode can support three user groups with each user group possessing a voice slot as well as an associated 4800 bps data timeslot. The 5T mode provides, in effect, one large user group with 5 data timeslots and 1 shared voice circuit. This is useful where the traffic is essentially data. The main user group is further logically divided into three separate user groups (timeslots B, C, D, E, and F) for traffic and timeslot A carries the management channel information for all three user groups. The VDL3 addressing bit field restrictions limit the number of aircraft per each of the groups to 60 aircraft, but this may be modified when tailoring for LDL. Figure 75 shows the vice and data composition of the framing structures.



Used with permission from Warren J. Wilson.

Figure 75.—Overview of LDL operational modes.

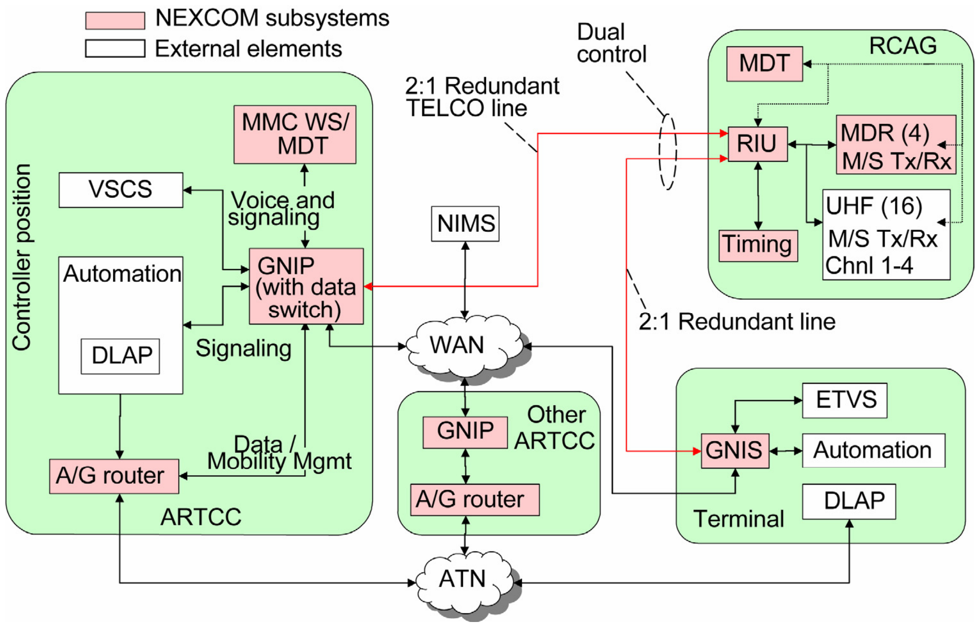


Figure 76.—Proposed architecture for LDL (based on NEXCOM VDL3 network).

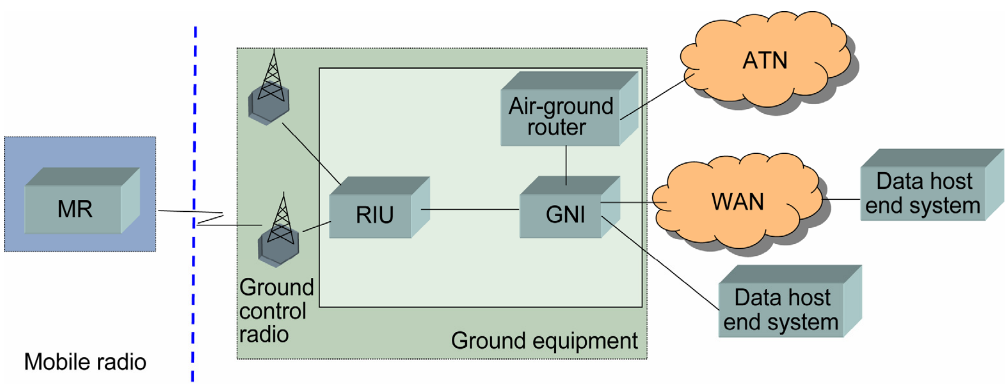


Figure 77.—LDL network architecture.

In figure 75, the M represents a management time slot used to accommodate management traffic, while V/D time slots accommodate voice or data, accordingly. Channel access requests for LDL 5T are random access requests processed as part of the management traffic (similar to VDL3 3T mode).

The notional network architecture and elements for LDL are based on NEXCOM proposed architecture for VDL3 network as shown in figure 76. Elements include a radio, radio interface unit (RIU), ground network interface (GNI), and air/ground router (AGR). The RIU manages radio operations at the radio site and provides the radio interface to the ground communication network. The GNI provides the interface to the RIU and to external users that may interface directly to the LDL subnetwork. Where applicable, GNI also provides the voice coding function. The AGR is needed to provide the SNDCP conversion function, including conversion of aeronautical telecommunications network (ATN) service data packets into LDL/VDL3 data frames and conversion of service priority into LDL/VDL3 data frame priority.

Another, more simplified view of the major LDL network elements and interfaces is provided in figure 77.

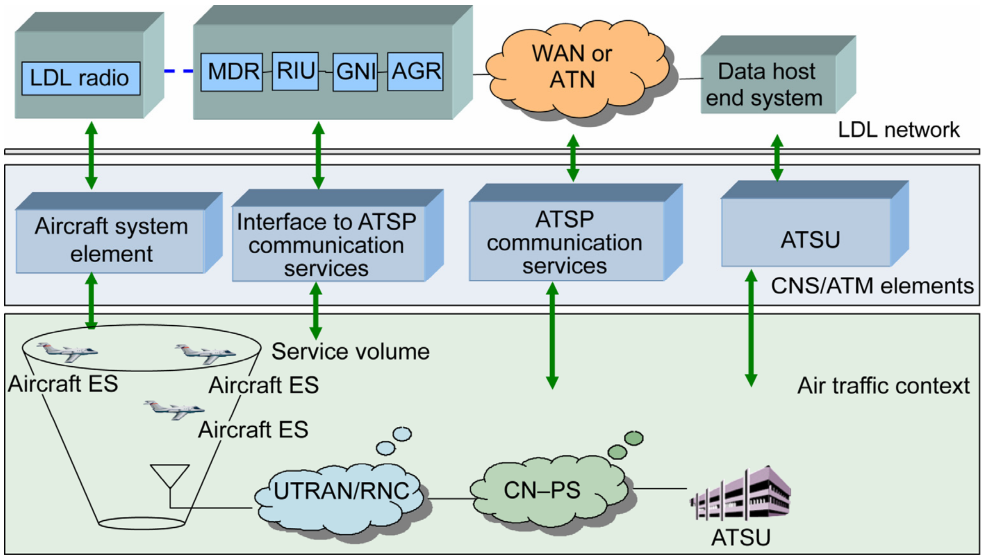


Figure 78.—Logical mapping of LDL elements to CNS/ATM context.

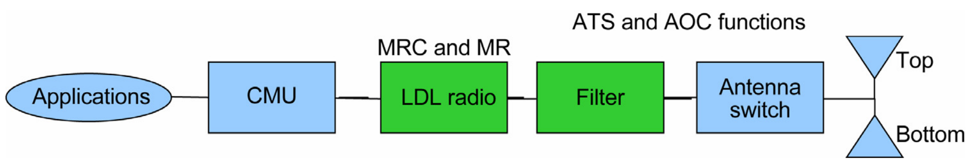


Figure 79.—Logical mapping to CNS/ATM context (notional avionics integration).

To provide a user's view of both the CNS/ATM system and LDL network system and elements, a logical mapping of the two systems is provided as shown in figure 78, where LDL network elements, LDL mobile radio, ground equipment including the MDR, RIU, GNI, AGR, WANATN, and data host end system are mapped to aircraft system element, A/G communication, ATSP communication services and ATSU, respectively. An air traffic context is also shown to reflect the potential application of LDL in CNS/ATM context.

The notional avionics integration of LDL elements is shown in figure 79.

C.3.2 Concept for the Future Aeronautical Environment

This section describes how the LDL technology can be applied in the future aeronautical environment in terms of technology details; COCR service provisioning; evaluation scenario assessment (including target deployment band; channelization, and deployment in ER, TMA, and surface domains); and finally some cost considerations.

C.3.2.1 Technology Details

LDL Physical Layer Options: LDL uses the frequency band 960 to 1024 MHz. The LDL-proposed signaling technique is binary frequency shift keying (BFSK) with spectral shaping. This modulation has excellent co-channel rejection properties and experience with UAT has shown that a desired-to-undesired ratio (D/U) can be tolerated as low as 3 dB. This would allow a high degree of frequency reuse and a high degree of system-wide efficiency. The required E_b/N_0 for a BER of 0.001 is about 9 dB. LDL has a number of transmission rates including 62.5, 83.3, and 100 kbps. A summary of key LDL characteristics is provided in table 57.

TABLE 55.—INITIAL PROPOSED LDL PARAMETERS

Parameter	Value
Frequency range, MHz	960 to 1024
Bandwidth, kHz	62.5 to 100
Bit rate, bps	62 500, 83 300, 100 000
Modulation	BFSK
E_b/N_0 (for 0.001 BER), dB/Hz	9
Noise figure, dB	~11.3
D/U, dB	3
Output power, W	50
Receiver sensitivity, dBm	–105.7
Channel separation (proposed), kHz	416
Data type	Voice/Data

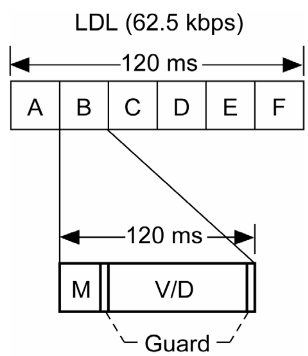


Figure 80.—LDL time slot structure.

The highest channel and data rate noted above have been used in this concept of use (so that the technology may be best able to provision COCR services with high capacity requirements). These values are subject to optimization.

LDL MAC/Link Layer Features: For the LDL link layer, very few VDL3 link layer changes were made.

- The LDL time slot remains at 20 ms so that there would be six nets per frequency channel.
- The frame time remains at 120 ms, and the MAC cycle remains at 240 ms, because the bit rate of LDL is twice that of VDL3, the burst lengths are about half as long.
- The guard time between frames is about 4.424 ms. This allows a sector radius (the largest ground/air slant range) of 358 nmi.

An example of LDL time slot structure is shown in figure 80.

C.3.2.2 COCR Service Provisioning

Applicable domains: LDL is a terrestrial-based technology that can be applied to the ER, TMA, and surface (APT) flight domains, but it is not applicable to oceanic/remote/polar domains.

Applicable services: The FCS technology evaluation applies an evaluation scenario that includes both ATS and AOC on a shared communication connection. This is a conservative approach, which includes most stringent communication requirements. Services to be provided include all except A–EXEC, WAKE, and ASAS (air-to-air broadcast). Associated communication functional needs are A/G addressed data, ground broadcast data, and air-to-air (A/A) addressed.

C.3.2.3 Evaluation Scenario Assessment

C.3.2.3.1 Target Aeronautical Spectrum

LDL can be considered a narrow-band technology with channel bandwidth of 83.33 kHz. Practical collocation with voice in VHF aeronautical spectrum is not a viable implementation. A target allocation for LDL is aeronautical L-band (960 to 1024 MHz), using the lower part of the DME band. This allocation is subject to interference compatibility.

C.3.2.3.2 High-Level Deployment Concept

Deployment concepts for ER, surface, and TMA domains have been considered and evaluated.

- For the ER environment, the LDL coverage range and capacity can be considered suited for implementation in a regular grid (cellular) fashion for ER domain, where users typically evenly distributed across this domain; this would incorporate mobility management functions not currently part of the LDL (VDL3) technology definition.
- In surface domains, individual surface channels would be used, and because the surface environment is such that each adjacent ground station is beyond the radio horizon, surface frequencies can be reused between sites.
- For the TMA environment, locations are typically grouped in a nonuniform manner; in some locations, there can be a number of TMA environments close together while in other areas, TMA domains can be isolated from other TMA airspace. Similar to the surface domain approach, a set of TMA channels can be assigned channels and reused such that unique channels are deployed within the same radio horizon.

C.3.2.3.3 LDL Link Budgets

LDL link budgets applied in this study leverage link budget estimates and related assumptions provided in previous studies and standards including

- Dr. Wilson, W., June 2005, “An L-band Digital Communications Link Concept for Air Traffic Control” The MITRE Corporation, McLean Virginia (MP05B0000018)
- RTCA, Inc. DO–224B, August 3, 2005, “Signal In Space Minimum Aviation System Performance Standards (MASPS) for Advanced VHF Digital Data Communications Including Compatibility With Digital Voice Techniques” (APPENDIX L Preparation of Link Budgets for VHF Data Link)
- RTCA, Inc. DO–282A, July 29, 2004, “Minimum Operational Performance Standards for Universal Access Transceiver (UAT) Automatic Dependent Surveillance–Broadcast (ADS–B)”

Using the information in the references above, two LDL link budgets were calculated and evaluated as shown in figure 81. One link budget closes at 160 nmi (0 margin); the second, with a smaller data rate (62.5 kbps) and larger margin (10 dB), closes at 120 nmi.

The more conservative link budget was used for further consideration; the service volume size is addressed further in the subsections below.

v05	L-Band link budget	L-Band link budget Gr = 6.0 dBi
1	Slant range, nmi	160.0
2	Ground antenna height, ft	50.0
3	Frequency, MHz	1024.0
4	Transmitter power, watts	25.0
5	Transmitter power, dBm	44.0
6	Transmit antenna gain, dBi	-4.0
7	Transmit line losses, dB	3.0
8	Transmit EIRP, dBm	37.0
9	Free space loss, dB	142.1
10	Excess path loss, dB	4.0
11	Receive antenna gain, dBi	6.0
12	Receiver line loss, dB	2.0
13	Receiver signal level, dBm	–105.1
14	Receiver noise figure, dB	5.3
15	Receiver noise power density, dBm/Hz	–168.7
16	Total system noise power in specified data rate, dBm	–118.7
17	Data rate, kHz	100.0
18	Theory E_b/N_0 for a BER of 0.001	9.0
19	Raised cosine filter loss, dB	1.8
20	Transmitter implementation Loss, dB	1.0
21	Receiver implementation Loss, dB	1.2
22	Required E_b/N_0, dB	13.0
23	Required receiver sensitivity, dBm	–105.7
24	E_b/N_0 available, dB	13.6
25	Residual system margin, dB	0.6

LINK BUDGET 1

Calculated from statistics derived from multiple iterations of the IF–77 Electromagnetic Wave Propagation Model (Gierhart-Johnson) model for slightly rolling plains terrain.

The LDL description document proposes several data rates for LDL. 100 kHz was selected based on analysis of capacity requirements in United States in the 2020 to 2025 timeframe.

	VDL Mode 3	LDL
Power, 15 Watts, dBm	42	42
Cable loss, dB	–2	–2
Antenna gain, dBi	6	6
EIRP, dBm	46	46
FSPL, 120 NM, dB	–122	–139
Antenna gain, dB	–4	–4
Cable loss, dB	–3	–3
Received power, dBm	–83	–100
Bit rate, dBHz	45	48
Eb, dBm	–128	–148
External NF, dB	20	N/A
Internal NF, dB	14	5
Total NF, dB	19	5
No, dBm/Hz	–155	–169
Received E_b/N_0, dB	27	21
Theoretical E_b/N_0, dB	13	9
Implementation losses, dB	4	2
Required E_b/N_0, dB	17	11
Margin, dB	10	10

LINK BUDGET 2

*Used with permission from Warren J. Wilson.

Figure 81.—LDL link budgets.

C.3.2.3.4 En Route Evaluation

The common evaluation scenario document (ref. 45) describes several ENR test volumes.

- Small ENR (test volume 3.1 (TV3.1)): 55 nmi cube/45 PIAC/80.4 kbps
- Medium ENR (TV3.2): 100 nmi cube/62 PIAC/94.3 kbps
- Large ENR (TV3.3): 200 nmi cube/204 PIAC/226.9 kbps
- Super large ENR (TV3.4): 400 nmi cube/522 PIAC/528.4 kbps

Modeling and simulation of the LDL technology ability to provision the full complement of COCR services has not been performed (no studies have been identified); therefore only a high-level consideration is given to LDL capacity performance. As noted previously, contention-based reservation packet data network assessments identify the range of factors that impact performance, but many conservatively estimate that achievable throughput is typically high (50 to 80+ percent) (refs. 47 and 48). Also, the link budget estimates result in a range that maps closest to the Medium ENR scenario. It can be seen, however, that the data rate associated with this test volume is larger than most of the defined data rates for the LDL channel (94.3 kbps vs. 62.5/83.3/100 kbps). Additionally, considering a conservative throughput efficiency, it can reasonably be assumed that a configuration with two LDL radio channels would be required to provision services to this service volume. An alternative implementation would be to implement LDL channels on a per sector basis. Per COCR V2, the maximum ATC-only service data rate requirement (per sector) is 50 kbps, while the ATS and AOC service data rate requirements is 150 kbps; here a single LDL channel may meet the ATS-only requirement, but more than one channel would be needed to meet ATS and AOC requirements.. Although simulation of LDL performance is required to further explore exact capacity calculations, it is assumed that up to two ground channels are estimated for provision of services to TV3.2 (and smaller) service volumes.

In reference 11, it is noted that if assigning LDL channels by sector, 2688 orthogonal nets may be possible in L-band, but that the real capacity increase with LDL comes from its co-channel performance. Because required D/U is on the order of 3 dB, and even if a more conservative value of 9 dB is applied, there is the potential of much greater reuse as compared to system like DSB–AM or VDL3.

With changes to the M-burst structure (to accommodate more aircraft IDs) as proposed in the referenced paper, and making use of the ground station code parameter, a cellular approach may also be possible. If implementing a cellular approach, considerations of another reference study could be applied. A reference study (ref. 46) indicates that a reasonable estimate of frequency reuse factor that can be applied in the ER demand is nine. This factor was assumed for the scenarios in the analysis (e.g., for large service volumes, nine frequencies are reused to provide regular-grid cellular services). To conservatively estimate the required number of channels within the various ENR service volumes, it was assumed that a fully redundant set of channels would be needed to address availability requirements (similar to current deployment scenarios). Thus, the resulting estimates of ground station sites and channels for accommodating the ENR test volumes include

- TV3.1 and TV3.2
  - One ground station site
  - Four channels each (two primary and two backup)
- TV3.3
  - Seven ground station sites
  - Eighteen channels (nine for primary and nine for backup)
- TV3.4
  - Twenty-two ground stations
  - Eighteen channels (nine for primary and nine for backup)

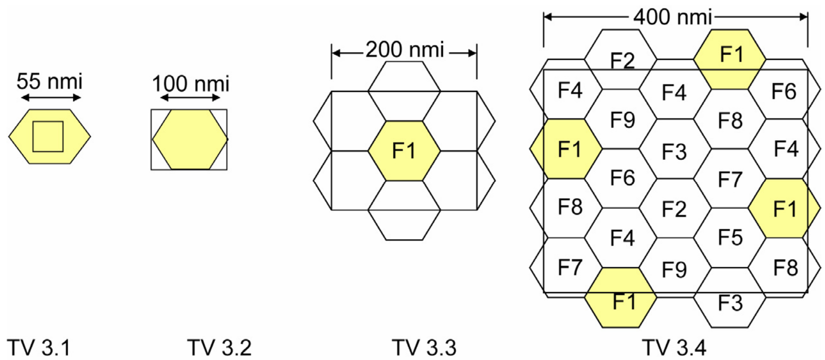


Figure 82.—Representative LDL ENR coverage (notional illustration of concept, not drawn to scale).

A representative illustration of ground station sites and channels is provided in figure 82.

C.3.2.3.5 TMA Evaluation

Two TMA test volumes are defined in the common evaluation scenario document (ref. 45) including

- Small TMA (TV2.1): 49 nmi cube/44 users/17.4 kbps
- Large TMA (TV2.2): 75 nmi cube/53 users/20 kbps

As noted above, an irregular pattern of TMA volumes is anticipated because of location of population centers; some areas may have several nearby large TMAs and some large TMAs may be isolated. The same scenario may hold true for small TMA service areas. As a result, a regular grid of TMA ground stations is neither required nor practical. Instead, it is assumed that a set of frequencies will be applied and reused to provision TMA services.

Dense TMA airspace areas are assumed to drive TMA channel requirements. In a recent VDL2/3 bandwidth assessment (ref. 46), a terminal coverage volume of 60 nmi was assumed, and iteratively stepping through required channel assignments across a large geographic area with varying organizations of TMA service volumes (i.e., the U.S. National Airspace System) such that no frequency is applied twice within RLOS (assumed 420 nmi) and hidden transmitter problem is tolerable, 23 channels were found to be required. A LDL TMA deployment concept can be assumed to have a similar organization and similar constraints; however, reuse gains may be achieved as the hidden transmitter problem will not be as severe as for VDL2 (driver for 23 channel estimation).

Considering the same conservative throughput efficiency as introduced above and the requirements of the Large TMA service volume, it can reasonably be assumed that a single LDL channel can accommodate the required capacity. A single ground channel could also provision services to the small TMA service volume as well. Thus, the resulting nominal estimates of ground station sites and channels for accommodating the TMA test volumes include

- TV2.1 and TV2.2
    - One ground station site
    - One channel

A representative illustration of ground station sites and channels is provided in figure 83.

C.3.2.3.6 Surface Domain Evaluation

The surface domain is addressed by two evaluation scenarios (as defined in the common evaluation scenario document, ref. 45) including

- Airport zone, TV1.1 (PIAC = 26), 10.22 kbps
- Surface, TV1.2 (PIAC = 264), 142 kbps

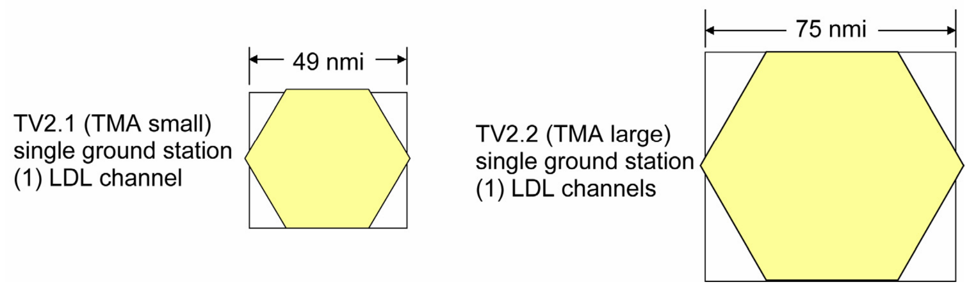
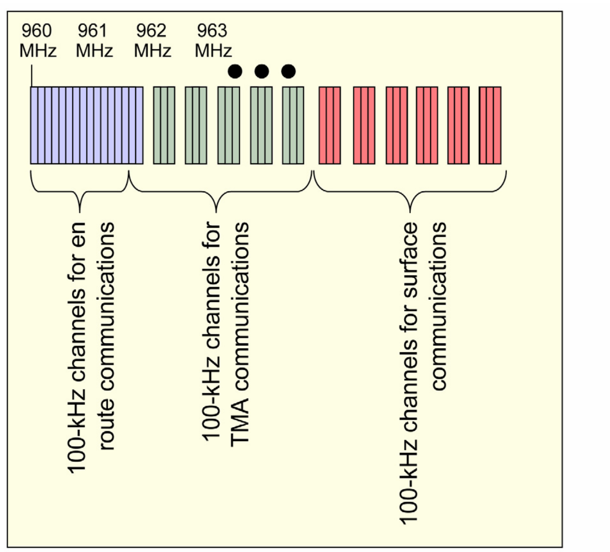


Figure 83.—Representative LDL TMA coverage (notional illustration of concept, not drawn to scale).



Note: Specific channelization plan is subject to full interference assessment; provided concept assumes inlay of LDL channels is possible between DME allocations (300 kHz between allocations).

Figure 84.—Notional channelization plan.

The LDL data rate (100 kbps) is less than the offered load, so multiple channels will be required to provision channels in the surface environment. Applying a conservative estimate of throughput (described previously), up to three channels may be needed to provide sufficient capacity to provision COCR services (ATS and AOC); for ATS-only services, a single channel could be sufficient. As surface channels can be heavily reused due to location of the service volumes and radio horizon effects, an estimate of 5 to 10times per-APT channel requirements was assumed to accommodate the surface domain (thus 15 to 50 for ATS and AOC; 5 to 10 for ATS-only).

C.3.2.3.7 Notional Channelization Plan

Figure 84 shows the notional deployment concept using 100-kHz channels.

C.3.2.4 Cost Considerations

The cost assessment applied for this evaluation accounts for required functional elements to support the technology implementation; the appropriate number of ground stations for deployment in large areas (consider deployment in combined super large/large ENR and large TMA); and specialized equipment and components required for provisioning of COCR services with this technology.

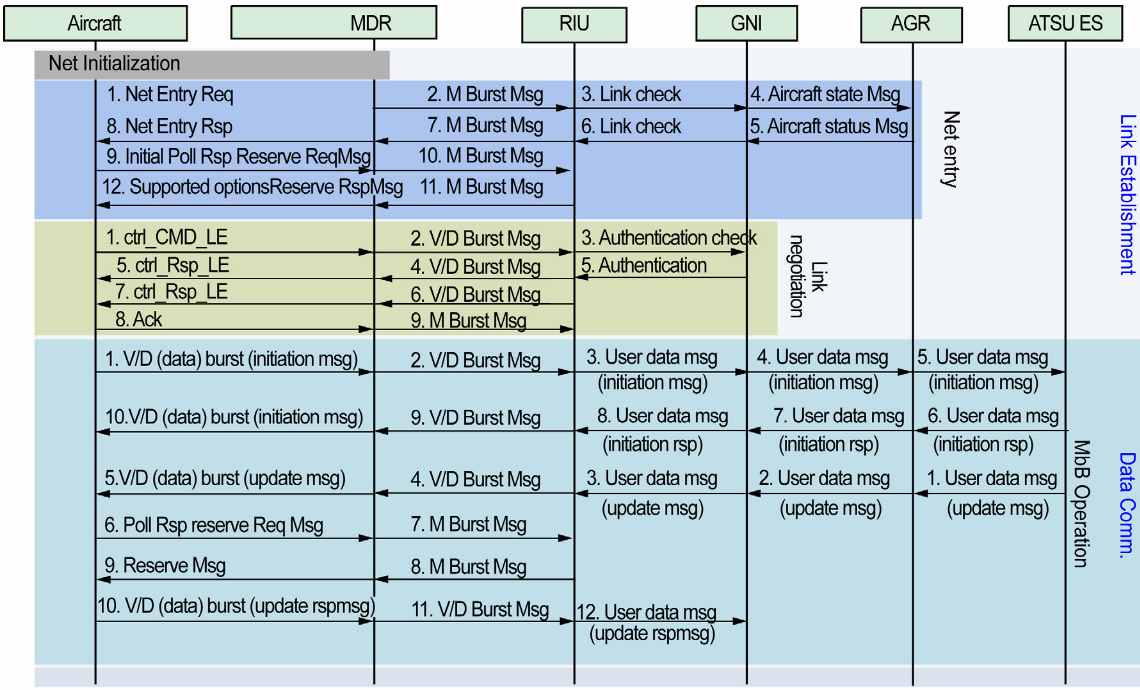


Figure 85.—DLIC to LDL.

To gain an understanding of the functional elements of the technology that are needed to provision COCR services, a notional service mapping of COCR data link services to the technology was created. A representative DLIC service was used for this assessment. DLIC exchanges information between an aircraft and an ATSU; DLIC provides version and address information for all data link services; DLIC service is executed prior to any other data link services; and the three DLIC subfunctions are Initiation, Update, and Contact. The mapping of DLIC to LDL functions is shown in figure 85.

Figure 85 shows that mobile radio interacts with the ground radio site (MDR and RIU), GNI for communications with an ATSU end system; additionally, to accommodate specific deployment concepts (e.g., cellular layout) and network concepts (network connectivity via ATN), the AGR is included in the communication interactions. No specialized equipment has been identified for a LDL aeronautical implementation.

C.3.3 Additional Notes

Although not a focus of the current study, LDL could provide both air-to-ground voice and data connectivity on a single channel. This mode of operation for VDL3 has been standardized and validated.

C.4 AMACS Concept of Use

AMACS is a multipurpose communication system, with narrowband (50 to 400 kHz) channels, operating in the lower aeronautical L-band (960 to 975 MHz). AMACS is not a standardized technology, but has been developed from a baseline of the existing UAT/GSM and VDL4 systems to operate in the aeronautical L-band. The AMACS physical layer reuses appropriate UAT and GSM specifications; the MAC layer is based on the existing E–TDMA MAC layer concept; and AMACS uses existing VDL4 broadcast and reservation protocols.

C.4.1 Technology Overview

C.4.1.1 Standardization Status and Technical Readiness for Deployment

No fully integrated standards exist for the AMACS technology; however, AMACS has been documented in reference 40. AMACS can be characterized as follows:

- The design of AMACS has been finalized at the physical and MAC layer levels with complete definitions of the frame, slot, and message structures.
- The error correction coding definition is completed.
- The channel structure, cellular deployment and network architecture are specified.
- All of the AMACS message types have been defined and the definition of services has been provided.
- Specific AMACS validation and deployment has not taken place. Related validation and deployment activities are not defined yet.
- The protocols and system operations are defined for both point-to-point and broadcast communications.

The protocol stack of the AMACS interface (interface with ATN case) is shown in figure 86.

C.4.1.2 Technology Services and Architecture

As noted above, AMACS is a custom aeronautical technology evolved from the GSM/UAT and VDL4 standards with a redesigned physical layer and modifications to the link layer to facilitate operations in L-band. The already-validated modulation family CPFSK used by GSM and UAT is used in AMACS physical layer. Deterministic slot scheduling and potentially statistical self-synchronization (S3) and deterministic slot scheduling for remote area applications (without ground stations) is employed for the AMACS high-integrity deterministic MAC layer.

AMACS provides reliable data transfer ensuring delivery on a per-frame basis. Acknowledged connectionless services are expected to be used in an ATN or IP context. In terms of communication services, AMACS proves both unicast as well as multicast. The following communication types are provided by AMACS:

- Air-to-ground point-to-point
- Ground-to-air point-to-point
- Air-to-air point-to-point
- Ground-to-air broadcast

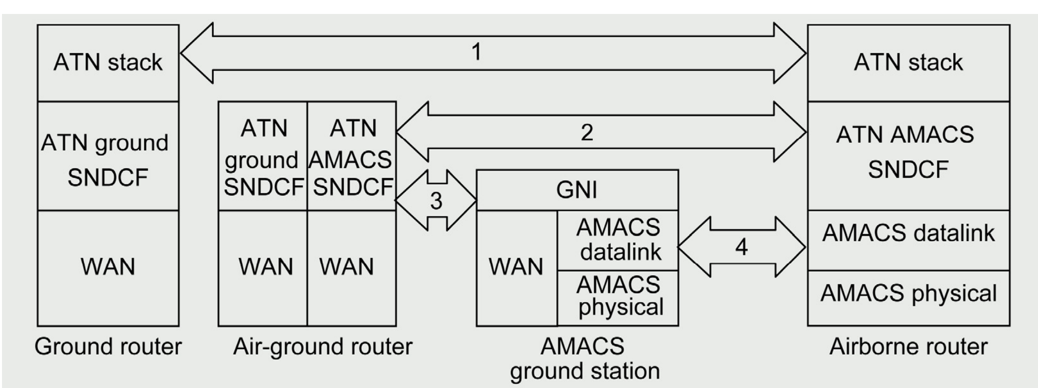


Figure 86.—AMACS protocol elements (ATN case).

In addition, the following service types could be supported by AMACS:

- Mobile broadcast
- Ground station broadcast
- Autonomous mobile broadcast

Flexibility and configurability are designed into AMACS. An aircraft can use AMACS to communicate both with other aircraft and with the ground station (using the appropriate channels), and the ground station can communicate with individual aircraft or all aircraft selectively.

According the description of AMACS document, the notional network architecture for AMACS is shown in figure 87. The ground AMACS infrastructure has a number of AMACS ground radio stations organized into clusters. The ground radio stations in a cluster may be geographically adjacent, or may have overlapping areas of coverage (using different frequencies). Each ground radio station in a cluster is connected to the GNI, which helps to interface to the transport network via an ATN AGR or to other types of router (e.g., an IP router). The AGRs supporting each cluster would be interconnected by a ground transport network, using ground and ground routers for interconnection with endusers.

Another view of the AMACS network elements and interfaces is provided in figure 88.

To provide a user's view of both the CNS/ATM system and AMACS network system and elements, a logical mapping of the two systems is provided as shown in figure 89.

Notional avionics integration views of an AMACS implementation of ADS–B functions, and AOC and ATS functions are shown previously in figure 57.

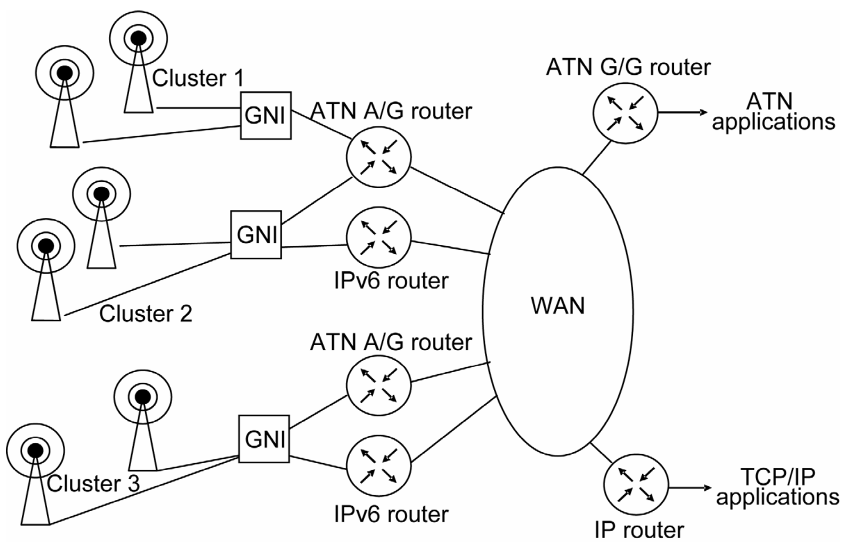


Figure 87.—Expected network architecture in support of AMACS.

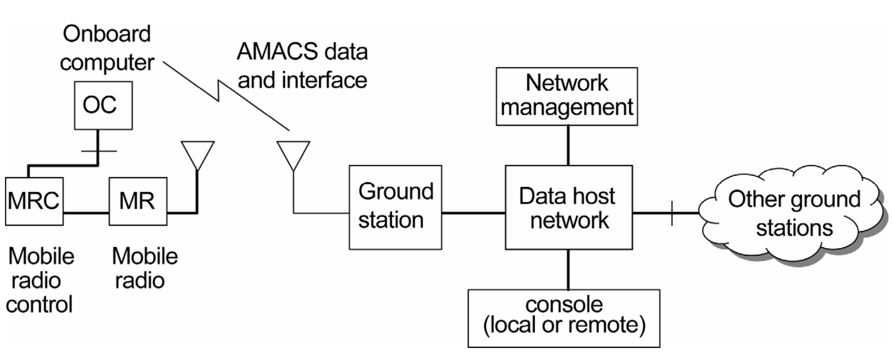


Figure 88.—AMACS network architecture.

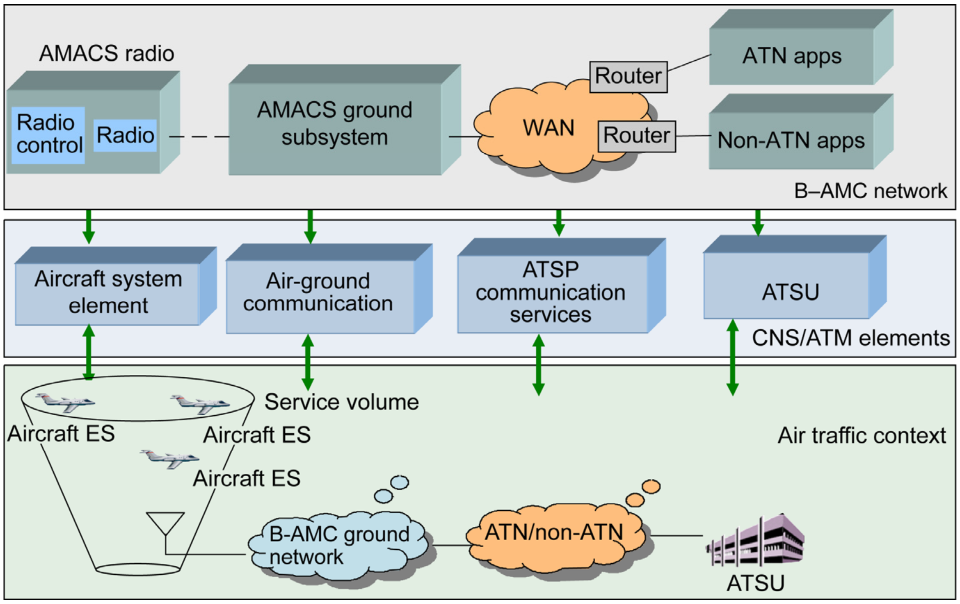


Figure 89.—Logical mapping of AMACS elements to CNS/ATM context.

TABLE 56.—AMACS PHYSICAL LAYER CHARACTERISTICS

Parameter	Value
Frequency range, MHz	960 to 975
Bandwidth, kHz	400
Gross bit rate, kbps	~540
Modulation	GMSK (h=0.5 and BT = 0.3)
Expected C/I, dB	~9
Data type	Data

TABLE 57.—AMACS SLOT STRUCTURE

Parameter	Value
Channel bandwidth, kHz	500
Length of FFT	64
Number of used subcarriers	48
Number of CC	2×2= 4
Subcarrier spacing, kHz	10.416
Overall OFDM symbol duration, µs	120
Guard interval duration, µs	24
Number of OFDM symbols per OFDM FL/RL data frame	54
FL/RL OFDM frame duration, ms	6.48
Pilot spacing in time direction	1
Pilot spacing in frequency direction	12

C.4.2 Concept for the Future Aeronautical Environment

This section describes how the AMACS technology could be applied in the future aeronautical environment in terms of technology details; COCR service provisioning; evaluation scenario assessment (including target deployment band; channelization and deployment in ER, TMA, and surface domains); and finally some cost considerations.

C.4.2.1 Technology Details

AMACS Physical Layer Options: AMACS uses the frequency band 960 to 975 MHz, and features the physical layer characteristics as shown in table 58.

AMACS MAC/Link Layer Features: The AMACS link layer slot structure characteristics are listed in table 59; and an example of the AMACS time slot structure is shown in figure 90.

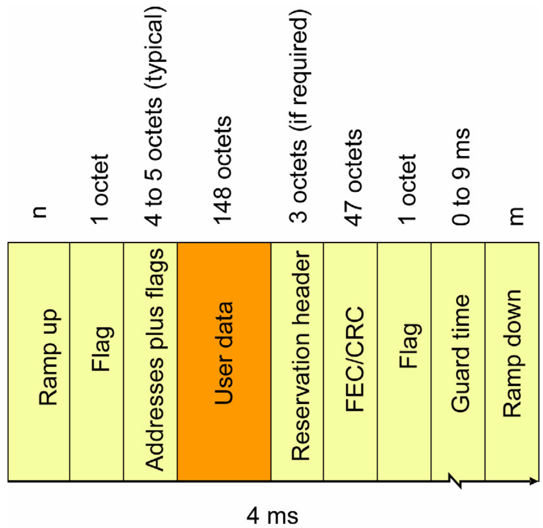


Figure 90.—AMACS time slot structure.

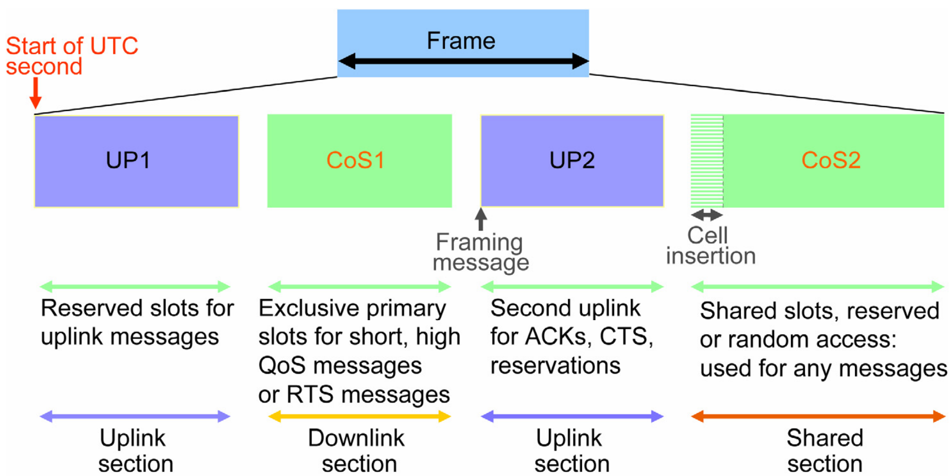


Figure 91.—AMACS frame structure.

The AMACS frame structure is shown in figure 91. AMACS will have a frame repeating every 2 seconds, with uplink and downlink sections having the following features:

- The use of the uplink sections in the frame is configurable by the ground station.
- These sections are ground-reserved areas for uplinks and ground-directed signaling.
- The two downlink sections are separated for different classes of service (CoS).
- CoS1 is intended for a high QoS and each aircraft is allocated one exclusive downlink slot in CoS1 for high QoS messages.
- More downlink slots are available on request in the lower QoS section (CoS2).

C.4.2.2 COCR Service Provisioning

Applicable domains: AMACS systems could provide A/G communications in continental airspace (core area as well as periphery), including ER and terminal areas. It is assumed that the surface (APT) area would be covered by another terrestrial-based system (such as WiMAX 802.16e); and oceanic and polar (ORP) communications would be supported by a satellite-based system.

Applicable services: The FCS technology evaluation applies an evaluation scenario that includes both ATS and AOC on a shared communication connection. This is a conservative approach that includes most stringent communication requirements. The services to be provided include all except A–EXEC, WAKE, and ASAS (air-to-air broadcast). The associated communication functional needs are:A/G addressed data, ground broadcast data, and A/A addressed.

The applicable services of AMACS are

- Air-ground and ground-air point-to-point communications (as required today by AOC and also by emerging ATS applications such as COTRAC, ADS, and CPDLC)
- Air-air, air-ground, and ground-air multicast (i.e., locally broadcast) communications (as proposed for ADS–B, FIS–B, and TIS–B)
- Air-air point-to-point communications (as envisaged for supporting autonomous separation assurance applications)

Also, AMACS is designed to support two distinct modes of operation: the ground-supported mode where the aircraft fly within the range of ground datalink stations (these stations may be interconnected via ground links or not), and the autonomous mode where the aircraft fly without any ground datalink infrastructure to support them.

C.4.2.3 Evaluation Scenario Assessment

C.4.2.3.1 Target Aeronautical Spectrum

AMACS can be considered a narrow-band technology with channel bandwidths ranging from 50 to 400 kHz. A target allocation for AMACS is the lower aeronautical L-band from 960 to 975 MHz. The use of this band is subject to WRC approval of co-prime allocation to Aeronautical Mobile (Route) Service (AM(R)S). A new channelization scheme will have to be provided in the band, to accommodate the AMACS system's use of channels ranging from 50 kHz to 400 kHz.

C.4.2.3.2 High-Level Deployment Concept

AMACS deployment concepts for ER, surface, and TMA domains have been considered and evaluated and include the following.

- For ER environment, AMACS coverage range and capacity can be considered suited for implementation in a regular grid (cellular) fashion for the ER domain, with users typically evenly distributed across this domain. This would incorporate the AMACS mobility management functions.
- The AMACS description document (ref. 40) suggests that the surface area be covered by another terrestrial-based system (such as 802.16).
- For the TMA environment, locations are typically grouped in a nonuniform manner. In some locations, there can be a number of TMA environments close together while in other areas, TMA domains can be isolated from other TMA airspace. A set of TMA channels could be assigned and reused such that different channels are deployed within the same radio horizon.

C.4.2.3.3 AMACS Link Budgets

According to the AMACS description document, the AMACS link budgets yield the following information:

> A BER of 10^{-3} after demodulation is enough for operations. This BER, for a minimum shift keying (MSK), corresponds to a SNR value of 10 dB. The results will be different for a prefiltered GMSK, but we start with this approximation.
>
> We assume our system uses a 400-kHz channel bandwidth. Its noise floor is
>
> N = FkTB = 6 –174 dBm + 20 log(400kHz) = –112 dBm
>
> Assuming the C/N at the receiver is close to the SNR (E_b/N_0) when the spectral efficiency is close to one, the operational receiving threshold is:
>
> S = N + C/N = –102 dBm
>
> For an aircraft in high altitude and large cells (~110 nmi), the free space propagation model is relevant. Considering antennae with 0 dB gain
>
> S = EIRP –34 –20 log (970 MHz) –20 log (110 nmi)
> This leads to
>
> EIRP = –102 + 32 + 60 + 46 = 36 dBm
>
> An EIRP of 4W could be enough to set up an operational transmission.

Based on the link budget information quoted above, a conservative cell range of 110 nmi could be expected, though the AMACS system has been evaluated for larger service volumes, as described in the following sections.

C.4.2.3.4 En Route Evaluation

The common evaluation scenario document (ref. 45) describes several ENR test volumes:

- Small ENR (test volume 3.1 (TV3.1)): 55 nmi cube/45 PIAC/80.4 kbps
- Medium ENR (TV3.2): 100 nmi cube/62 PIAC/94.3 kbps
- Large ENR (TV3.3): 200 nmi cube/204 PIAC/226.9 kbps
- Super large ENR (TV3.4): 400 nmi cube/522 PIAC/528.4 kbps

Modeling and simulation of the AMACS ability to provide the full complement of COCR services was not available for this study (planned modeling work has been identified, but no description of the work nor results are available); therefore only a high-level consideration is given to AMACS capacity performance.

The link budget estimates result in a range that maps closest to the Medium ENR scenario. The data rate associated with this test volume is within the expected data rates for the AMACS channel (540 kbps). Considering a conservative throughput efficiency, a configuration where one AMACS radio channel would provide services to this service volume could be assumed. An alternative implementation would be to implement AMACS channels on a per sector basis. Per COCR–V2, the maximum ATC-only service data rate requirement (per sector) is 50 kbps, while for ATS and AOC services, it is 150 kbps. Therefore a single AMACS channel could meet the ATS-only, ATS, and AOC requirements. Although simulation of AMACS performance is required to further explore exact capacity calculations, it is assumed that one ground channel is necessary for provision of services to TV3.2 (and smaller) service volumes.

A VDL reference study (ref. 46) indicates that a reasonable estimate of a frequency reuse factor to be applied in the ER demand is nine. This factor was assumed for the scenarios in the analysis (e.g., for large service volumes, nine frequencies are reused to provide regular-grid cellular services). To conservatively estimate the required number of channels within the various ENR service volumes, it is assumed that a

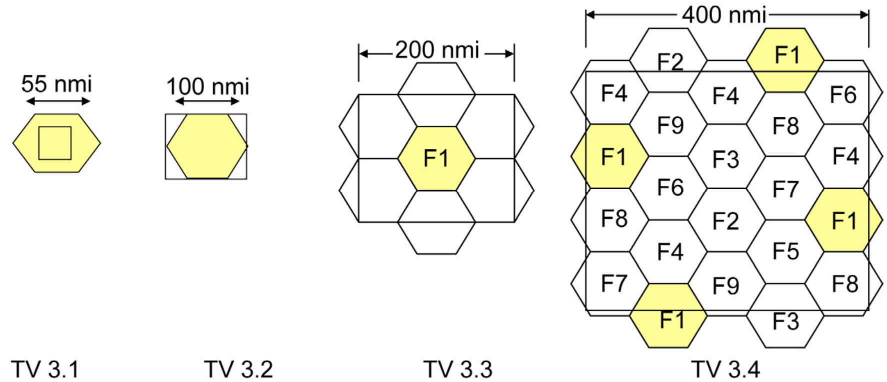


Figure 92.—Representative AMACS ENR coverage (notional illustration of concept, not drawn to scale).

fully redundant set of channels would be needed to address availability requirements (similar to current deployment scenarios). Thus, the resulting estimates of ground station sites and channels for accommodating the ENR test volumes include

- TV3.1 and TV3.2
  - One ground station site
  - Two channels per site (one primary and one backup)
- TV3.3
  - Seven ground station sites
  - Eighteen channels (nine for primary and nine for backup)
- TV3.4
  - Twenty-two ground stations
  - Eighteen channels (nine for primary and nine for backup)

A representative illustration of ground station sites and channels is provided in figure 92.

C.4.2.3.5 TMA Evaluation

Two TMA test volumes are defined in the common evaluation scenario document (ref. 45) including

- Small TMA (TV2.1): 49 nmi cube/44 users/17.4 kbps
- Large TMA (TV2.2): 75 nmi cube/53 users/20 kbps

As noted, an irregular pattern of TMA volumes is anticipated due to location of population centers; some areas may have several nearby large TMAs and some large TMAs may be isolated. The same scenario may hold true for small TMA service areas. As a result, a regular grid of TMA ground stations is neither required nor practical. Instead, it is assumed that a set of frequencies will be applied and reused to provide TMA services.

Dense TMA airspace areas are assumed to drive TMA channel requirements. In the VDL2/3 bandwidth assessment (ref. 46), a terminal coverage volume of 60 nmi coverage volume is assumed and, iteratively stepping through required channel assignments across a large geographic area with varying organizations of TMA service volumes (i.e., the U.S. National Airspace System) such that no frequency is applied twice within RLOS; 23 channels were found to be required. An AMACS TMA deployment concept can be assumed to have a similar organization and similar constraints.

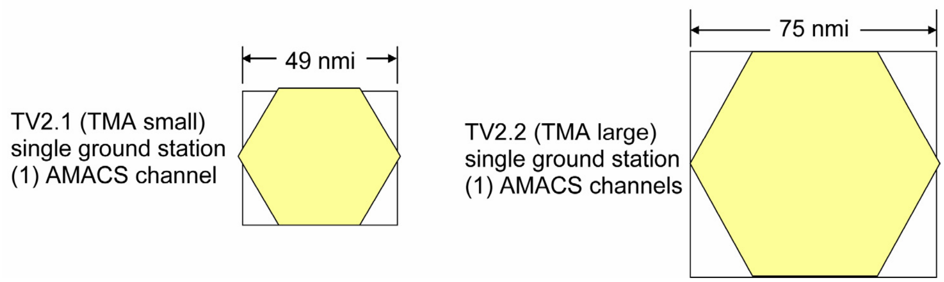


Figure 93.—Representative AMACS TMA coverage (notional illustration of concept, not drawn to scale).

Considering the same conservative throughput efficiency as introduced above and the requirements of the Large TMA service volume, it can reasonably be assumed that a single AMACS channel can accommodate the required capacity. A single ground channel could also provision services to the small TMA service volume as well. Thus, the resulting nominal estimates of ground station sites and channels for accommodating the TMA test volumes include

- TV2.1 and TV2.2
  - One ground station site
  - One channel

A representative illustration of ground station sites/channels is provided in figure 93.

C.4.2.3.6 Surface Domain Evaluation

The surface domain is addressed by two evaluation scenarios (as defined in the common evaluation scenario document, ref. 45) including

- Airport zone, TV1.1 (PIAC = 26), 10.22 kbps
- Surface, TV1.2 (PIAC = 264), 142 kbps

The AMACS data rate (540 kbps) is greater than the offered load, so a single channel will have sufficient capacity to provide COCR services (ATS and AOC); for ATS-only services, a single channel would also be sufficient. As surface channels can be heavily reused due to the locations of the service volumes and radio horizon effects, an estimate of 5 to 10 times per-airport channel requirements is assumed to accommodate the surface domain (thus 15 to 50 channels for ATS and AOC; 5 to 10 channels for ATS-only).

C.4.2.4 Cost Considerations

The cost assessment applied for this evaluation accounts for the required functional elements to support the technology implementation; the appropriate number of ground stations for deployment in large areas (e.g., combined super large/large ENR and large TMA sectors); and the specialized equipment and components required to provide COCR services with this technology.

To gain an understanding of the functional elements of the technology needed to provide COCR services, a notional service mapping of COCR data link services to the technology was created for the other selected technologies (e.g., WCDMA, LDL, and TIA–902 (P34)) in the study. A representative DLIC service was used for the assessment. Because of a lack of protocol interaction level information, the functional mapping of a representative DLIC service to AMACS network elements was not provided in this evaluation.

C.5 B–AMC Concept of Use

B–AMC (broadband aeronautical multicarrier communications system) is based on the B–VHF system concepts to operate in the aeronautical L-band. B–VHF, cofunded by the European Commission, is a multicarrier-based wideband communication system that supports aeronautical communications. The B–VHF system showed some potential for satisfying the needs of future aeronautical communications; however, due to current spectrum congestion, there is no spectrum available in the VHF band for a dedicated B–VHF implementation. In the mean time, the FAA and EUROCONTROL share a common view that a new datalink system for the year 2020 and beyond should preferably be implemented in the aeronautical L-band. Therefore the objective of the B–AMC study is to design a system similar to B–VHF capable of operating in the L-band. The L-band B–AMC A/G system specification reuses B–VHF system concepts to the maximum possible extent; adjustments at the physical layer and data link layer were made because of special L-band conditions. The main physical layer changes include the duplex scheme, the forward link access-scheme, the OFDM parameter set and the framing structure. B–AMC offers a large coexistence potential in L-band as it reuses B–VHF sidelobe suppression concepts, tailors coding, and uses interleaving to combat L-band interference. B–AMC allows systematic adjustments to L-band use by optimizing link efficiency and robustness and minimizing interference to legacy systems.

C.5.1 Technology Overview

C.5.1.1 Standardization Status and Technical Readiness for Deployment

The B–AMC system has a layered protocol stack as shown in figure 94. The ongoing B–AMC study is adapting the B–VHF physical layer protocol functions and optimizations. The suite of B–VHF protocols and functions above the physical layer (data link layer and up) has been adapted. Computer modeling and simulations are being carried out to support physical layer adaptation and protocol optimizations. Yet the B–AMC system prototypes and full scope of the required standardization materials are not available. Much additional work is needed to establish B–AMC as a fully validated, mature, and deployable technology for the aeronautical communications. The B–AMC project deliverables, such as the B–AMC System High Level Description, B–AMC Technology Operational Concept and Deployment Scenarios, and B–AMC System Specification and Standardization and Certification Considerations, provide an initial basis for producing appropriate aeronautical standards.

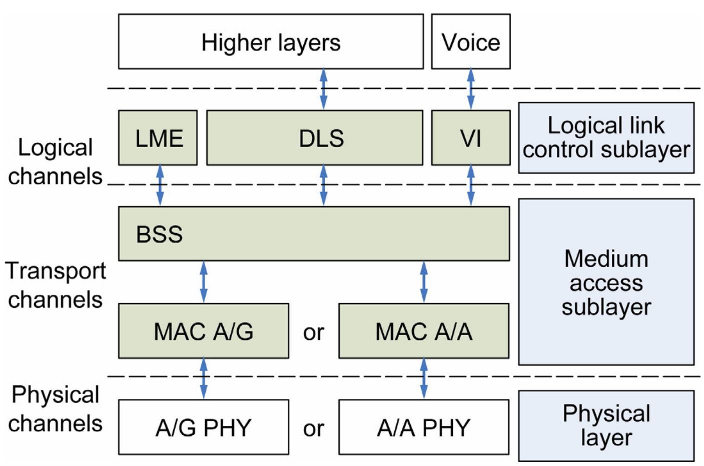


Figure 94.—B–AMC protocol elements.

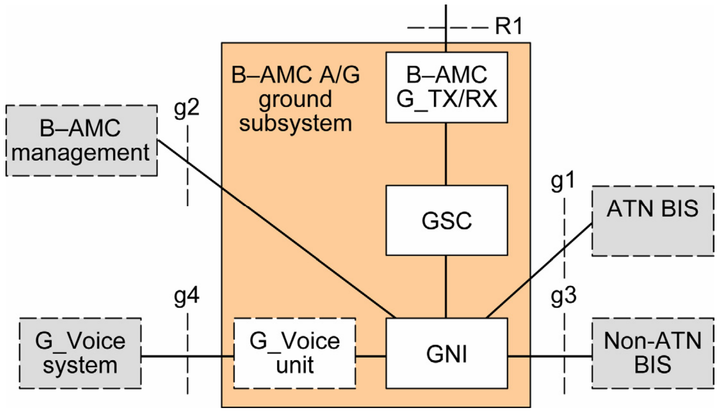


Figure 95.—B–AMC ground subsystem (A/G mode).

C.5.1.2 Technology Services and Architecture

The airborne B–AMC design provides two modes of operation, one is for A/G communications and the other one is for A/A communications. The two modes use different radio channels with different physical layer and data link layer approaches. This use-concept document focuses on A/G datalink communications only.

B–AMC focuses on the two lowest layers of the open systems interconnection (OSI) model: layer 1 (physical layer) and layer 2 (data link layer). In addition, a concept for the lowest sublayer (subnetwork access protocol, SNAcP) of layer 3 has been developed to support both ATN and future IP traffic. The B–AMC system protocol stack is shown in figure 95. More specifically

- The physical layer provides TX/RX radio and/or modulation functions, frequency control, bit exchanges over radio media and notification functions. It creates OFDM frames and maps them to physical channels.
- The data link layer contains three entities: BSS (B–AMC Special Services), MAC, and LLC (logical link control) sublayer. The BSS entity provides data transfer to the LLC sublayer on logical channels, provides a buffer for transport channel, and injects and extracts DLL–PDUs from transport channels. The MAC entity provides the framing structure, controls access to time slots, and maps transport channels to physical channels for the A/G and A/A modes. The LLC sublayer contains the data link service (DLS) that supports connectionless communication with different QoS classes, the voice interface (VI) and the link management entity (LME). The LLC manages the radio link and offers higher layer connectionless transport services with different levels of QoS by using ARQ (automatic repeat request for A/G mode) and checksums to support priorities between QoS classes by providing mapping of higher layer packet logical channels. All B–AMC traffic (voice, data, and management) is routed through the BSS entity. The aircraft BSS entity additionally supports resource allocation by indicating the length of the BSS queues.
- The subnetwork layer supports both ATN and IP traffic. It provides packet exchanges, header compression, subnetwork connection management function, error recovery, flow control, and packet fragmentation.

B–AMC A/G Services: The B–AMC A/G mode proposes a star-topology where aircraft are connected to a controlling ground station. Each ground station provides multiple logical data/voice channels to users by using a dedicated broadband A/G channel. A ground station can support several bidirectional data links to multiple aircraft at the same time. B–AMC's cellular concept is that cell coverage is decoupled from service operational coverage with each cell operating in the FDD mode using dedicated forward link/reverse link (FL/RL) channel pairs. Wide-area coverage is provided at several adjacent B–AMC cells. The handover between cells is seamless, automatic, and transparent to the users. Data link services provided by the B–AMC are ground station to aircraft broadcast/multicast, unicast (point-to-point) data links and aircraft to ground station unicast point-to-point data links. The B–AMC A/G mode also supports ATS voice channels (with retransmission over the ground station to rebuild the party-line functionality) and selective AOC voice communications. B–AMC provides communication services with an envisioned capacity and QoS capability adequate to support existing and future ATS and AOC services. The B–AMC subsystem can be integrated as an ATN subnetwork, it also supports future bidirectional non-ATN point-to-point and non-ATN broadcast/multicast (FL) data links.

Shown in figure 95, ground B–AMC infrastructure provides regional coverage by multiple B–AMC ground stations that include physical B–AMC radio units (transmitters and receivers) and ground station controller (GSC) that connects to the GNI. The GNI implements the B–AMC subnetwork functions and interfaces with external ATN routers such as an ATN BIS (ground boundary router) and optionally interfaces to non-ATN data link systems. The GNI interfaces with an external voice system and accepts both PTT (push to talk) and extended voice signaling. Also, the GNI provides an interface that implements B–AMC management functions that provide access to all B–AMC resources (GSC and B–AMC radios) within an entire region. The timing interface is considered to be a local implementation issue. Either a precise local timing source or an interface to external timing source (e.g., GPS) can be implemented. The GSC implements the DLL layer components above the MAC sublayer and provides local support of voice operation. The GNI implements functions involving managing handovers between B–AMC cells. The GNI also implements the B–AMC subnetwork layer functions and interfaces with an external ATN router. The GNI interfaces with the external VCS and accepts both PTT and extended voice signaling. The GNI also provides an interface to and implements functions for B–AMC management, providing access to all B–AMC resources (e.g., GSC and B–AMC radios) within an entire region.

The B–AMC airborne subsystem operation in the A/G mode as shown in figure 96 contains an airborne B–AMC transmitter and receiver, airborne network interface (ANI) and optional airborne voice unit containing the vocoder. The TX/RX interfaces with the radio control and airborne voice systems (option), and the ANI interfaces with ATN and non-ATN data link systems.

Another view of the B–AMC network elements and interfaces is provided in figure 97.

To provide a user's view of both the CNS/ATM system and B–AMC network system and elements, a logical mapping of the two systems is provided as shown in figure 98.

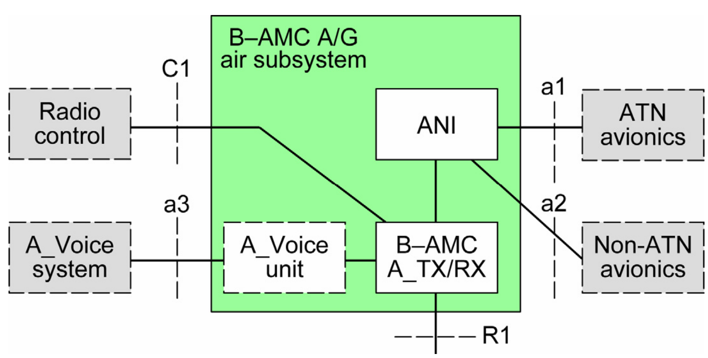


Figure 96.—Airborne Subsystem (A/G mode).

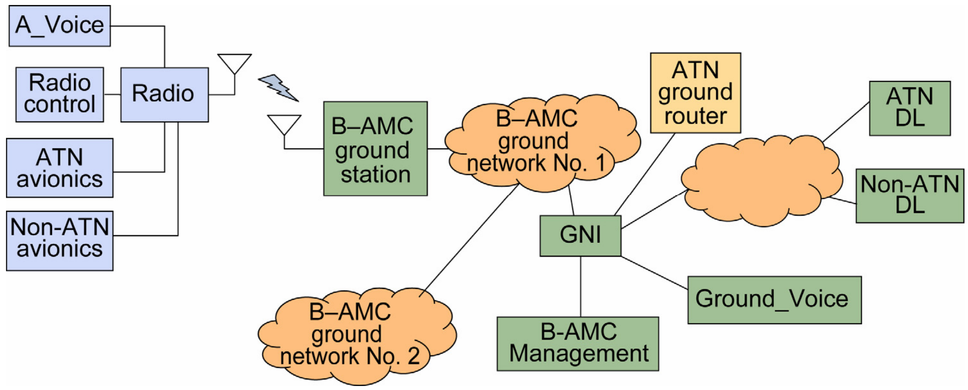


Figure 97.—B–AMC network architecture.

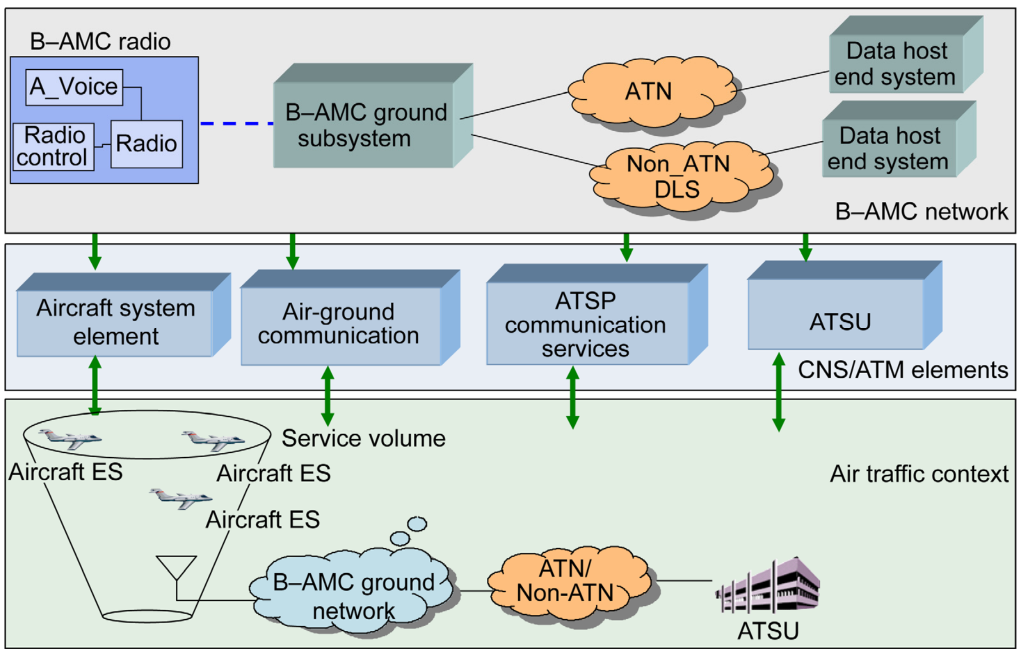


Figure 98.—Logical mapping of B–AMC elements to CNS/ATM context.

Notional B–AMC Avionics Integration: The A/G mode is shown in figure 99, in which a B–AMC radio is connected to the airborne audio management unit (AMU) to be able to operate in the voice mode. To be able to support ATN functionality, the B–AMC radio is connected to the communications management unit (CMU)/ATSU. The CMU interfaces with many systems such as the FMS (flight management system), the CMC (central maintenance computer), the ACMS (aircraft condition and monitoring system), and the MCDU (multipurpose control and display units). The CMU itself contains an ATN A/G BIS router and hosts higher sublayers of different data link subnetwork protocols. The CMU acts as an endsystem for ATS and AOC data link services and as an airborne router for other onboard endsystems like the FMS.

It is recommended that the existing CMU and the B–AMC multimode transceiver be used to provide all functions required for the B–AMC operations. Part of the B–AMC data link protocol stack may be delegated to the CMU.

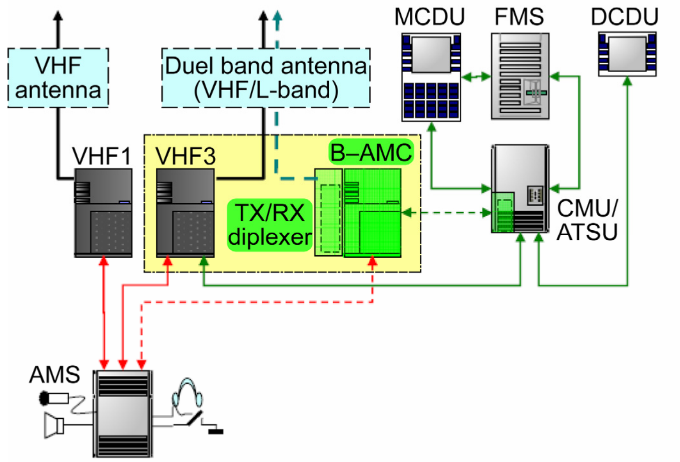


Figure 99.—Airborne B–AMC integration (A/G mode).

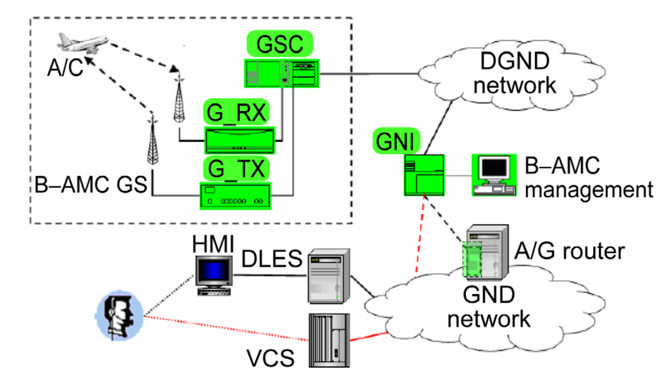


Figure 100.—Ground B–AMC integration (A/G mode).

The airborne B–AMC radio in A/G mode operates as a full-duplex unit. When B–AMC TX and RX front ends use one single L-band antenna then a RF diplexer is required to provide the required TX/RX decoupling. The diplexer is part of the B–AMC radio functionally, but can be installed as a separate antenna or a switchable antenna pair that has to be installed for the B–AMC system; additionally, an antenna switch would be required. If two separate L-band antennas are used for the B–AMC TX and RX, respectively, then a combination of TX and RX band-pass filters will be used. To provide undisturbed operation of the B–AMC RX when TX transmits, the B–AMC airborne system operating in the A/G mode should be attached to the suppression bus.

Ground B–AMC Integration: The ground B–AMC integration in A/G mode is shown in figure 100. The required ground components include the physical B–AMC TX and RX, GSC, and the GNI. The GNI manages the connectivity changes within the B–AMC subnetwork due to aircraft mobility and provides an interface to the B–AMC management system. The GNI is expected to be deployed at the ATS facility. When the voice option is used, the GNI must be connected to the ground voice system (VCS) of the corresponding ATS facility. If only the basic voice functions are used, voice units could be implemented within the GNI with no changes required at the VCS side. If more advanced voice features are needed, moderate VCS modifications would be required. To provide A/G data link service, the GNI will be attached to an A/G ATN router. The router should support the new B–AMC subnetwork protocol together with existing ones. This may require modification of the subnetwork dependent convergence facility (SNDCF). For the GSC component that manages time-critical functions such as resource reservation and management, the GSC should be placed onsite to be physically close to the B–AMC ground TX and RX. The ground B–AMC radios are single-channel equipment. No need is identified of the integration of ground B–AMC radios with existing ground radios, but the cost of the ground infrastructure would be reduced if the B–AMC ground radios were deployed at existing VHF radio sites. In the case where additional B–AMC TX/TX are needed, some could be placed at existing DME sites (additional filtering equipment would be installed onsite).

C.5.2 Concept for the Future Aeronautical Environment

This section describes how the B–AMC technology could be applied in the future aeronautical environment in terms of technology details; COCR service provisioning; evaluation scenario assessment (including target deployment band; channelization and deployment in ER, TMA, and surface domains); and finally some cost considerations.

C.5.2.1 Technology Details

B–AMC Physical Layer: The B–AMC system offers two modes of operation, one for A/G communications and the other one for A/A communications. Because the requirements for A/G and A/A communications are completely different, separating A/G and A/A communication modes can lead to more spectrally efficient implementation. Two RF branches are expected for A/G and A/A mode, together with an appropriate frequency diplexer. This section focuses only on the physical layer for the A/G communications mode.

The B–AMC physical layer is based on B–VHF design but is adapted due to special L-band conditions. Several changes are relevant to the physical layer design. First, interference situations are different. B–AMC is designed to be “inlaid.” B–AMC RF channels are to be inserted and operated between adjacent DME channels considered to be the main interference source in the L-band. Also, the characteristic of the DME interference is more noise-like and bursty. It is not clear how much bandwidth will be available between successive DME channels. The current working hypothesis is based on the assumption that around 500 kHz is available for B–AMC transmissions. Second, the Carrier Frequency is different. The L-band carrier frequency is about 7 to 8 times higher than in the VHF band. This has an effect on the free space propagation loss and on Doppler shifts due to the moving airborne transmitter and/or receiver. Third, the voice option is different. Use of L-band within the FCI is mostly for a new data link subsystem of FRS. Voice remains an option. This affects the B–AMC system design on the DLL protocol aspects as well as the physical layer framing structure. Due to these special L-band conditions, the following required physical layer adjustments are made:

- Duplex Scheme for A/G: FDD for B–AMC: B–AMC uses FDD instead of TDD and thus avoids large guard times as required for TDD because of propagation delays. B–AMC bandwidth between successive DME channels is small, which leads to a restricted transmission capacity of the B–AMC cell, further division of the B–AMC into FL and RL that would arise from TDD should be avoided to have a reasonable capacity amount. FDD puts RL and FL on two different B–AMC channels and thus offers doubled B–AMC capacity.
- Forward Link Access Scheme: OFDM is a special case of OFDMA where a single user transmits over all available OFDM subcarriers. B–AMC uses pure OFDM in the Forward link, which enables establishment of packet-switched communications. Packet-switched communication cannot be established using MC–CDMA as used in B–VHF. Also, OFDMA (OFDM) is much simpler and achieves performance comparable to MC–CDMA, taking into account L-band propagation and interference conditions.
- OFDM Parameters: The most important changes concern the RF bandwidth and the subcarrier spacing that influences other OFDM parameters. The largest bandwidth is 500 kHz, which enables B–AMC to be inlaid between DME channels. The subcarrier spacing is about 10.4 kHz and 48 subcarriers are used for B–AMC transmission. The OFDM parameter setting is optimized with respect to the channel condition and interference conditions in the L-band. To combat interference from DME and other

legacy systems in the L-band, special attention is paid to the B–AMC code design. A convolutional code adapted to the expected error patterns introduced by L-band interferers concatenated with a Reed-Solomon (RS) code has been applied. Simulations show this code design can almost completely combat the influence of the interference. To achieve the highest possible data throughput, adaptive coding and modulation is proposed to adapt to current channel and interference conditions. The data rate ranges from 272 kbps to 1.4 Mbps. Sidelobe suppression techniques developed for B–VHF are applied to B–AMC. This minimizes the out-of-band radiation of the B–AMC system, therefore minimizing the impact of B–AMC on the legacy L-band systems. Two powerful suppression techniques are retained for B–AMC: a cancellation carriers technique and transmit signal windowing.

- Framing Structure: The B–AMC FL and RL channels separated by FDD are structured in almost equally spaced time slots that have a length of either 6.72 or 6.48 ms and are managed by the MAC sublayer. These slots carry either user information such as data or voice, or carry B–AMC system data.

The main OFDM parameters for B–AMC are shown in table 60.

The B–AMC physical layer framing structure is hierarchically arranged from the super-frame down to the OFDM frames as shown in figure 101.

TABLE 58.—B–AMC SLOT STRUCTURE

Parameter	Value
Active slot length	4 ms – (ramp + guard times) = 3 ms
Bits per slot	Active slot length × BER = 1620 bits
Bits for FEC/CRC	~30% of bits per slot = 376 bits
Remainder	Bits per slot – CRC = 1244 bit = 155.5 octets
ISO flags plus reservation header	3 octets
Addresses plus administrative flags (typical)	4.5 octets
User data space	148 octets

OFDM symbol	120 μs
OFDM frame (54*120 μs)	6.48 ms
RA slot/BC frame (56*120 μs)	6.72 ms
Multiframe, 9 OFDM frames	58.32 ms
Superframe, 1*6,72 + 4*58,32 ms	240 ms
Hyperframe, 25*240 ms	6 s

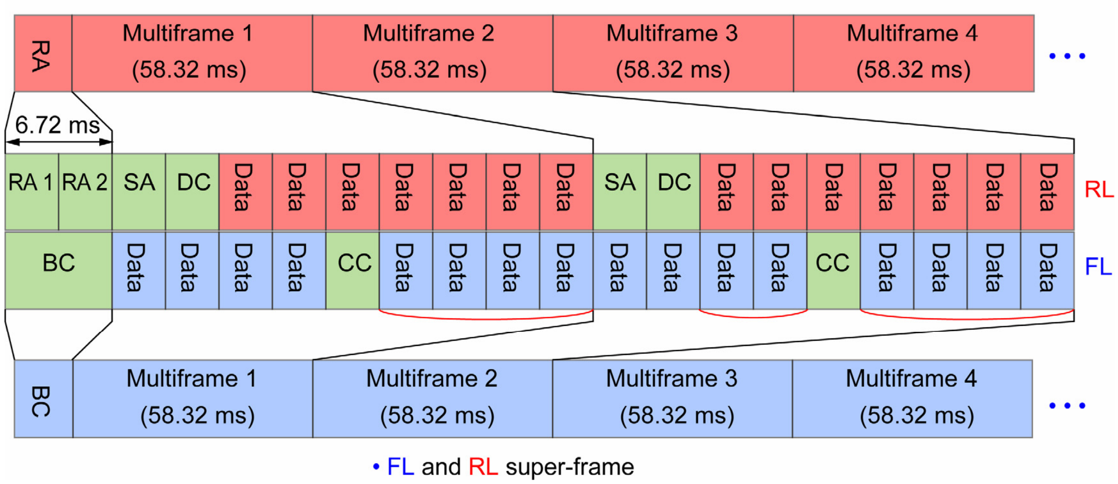


Figure 101.—B–AMC frame structure.

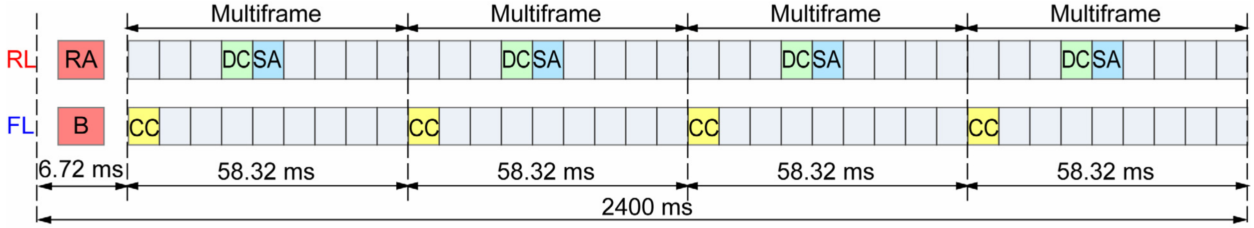


Figure 102.—The B–AMC signaling frame.

B–AMC has five types of dedicated OFDM signaling frames (fig. 102).

- Broadcast (BC) frame—broadcast control information to all users (FL)
- Random access (RA) frame—for all users to send their net entry requests (RL) BC and RA signaling frames have a specific internal structure
- Dedicated control (DC) slot—control information is sent by a specific user (RL)
- Common control (CC) slot—control information is sent to a specific user (FL)
- Synchronized access (SA) slot—all users send their reservation requests (RL)

The B–AMC physical channels consist of selections of OFDM subcarriers in a layered structure of OFDM frames that normally appear within specific time slots. On the FL, except for the broadcast slot, the ground station always uses all OFDM carriers; different channels corresponding to different bandwidth are realized by assigning different numbers of OFDM subcarriers. The RL channels of different users are separated by OFDM, except for the random access slot that may be used by one aircraft user at a time. The RL channel capacity is requested by the aircraft MAC entity and is allocated by the ground station.

B–AMC MAC/Link Layer: The B–AMC data link layer is derived from the B–VHF data link layer. It has two sublayers and six major entities. The MAC layer contains the BSS (B–AMC special service) entity and the MSC A/G or MAC A/A entity. BSS maps logical channels to transport channels, provides a sending and a receiving buffer for each transport channel, and injects or extracts DLL–PDUs from the transport channels. The A/G mode MAC entity maps transport channels to physical channels of the A/G radio link. The A/A protocol is based on TDMA and is distributed and self-organized. The B–AMC operating in the A/A mode assumes a dedicated global common control channel. The link layer contains three entities: the DLS (data link services) entity, the LME, and the VI (voice interface). DLS supports connectionless communication with different traffic classes (QoS). DLS uses the logical data channel DCH for the transmission of user data and the DCCH channel for signaling. B–AMC DLS dropped the support for connection-oriented communication so that B–AMC offers a simple connectionless interface. The LME function is similar to the B–VHF LME function except the resource management subfunction is moved to the MAC sublayer. The B–AMC VI is identical to the B–VHF VI. The VI uses logical channel VCH. Figures 103 and 104 present the high-level B–AMC data link layer and channel mapping methods.

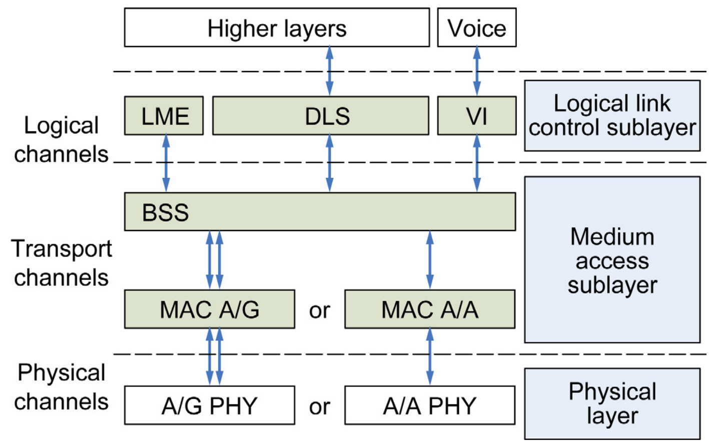


Figure 103.—High-level B–AMC data link layer.

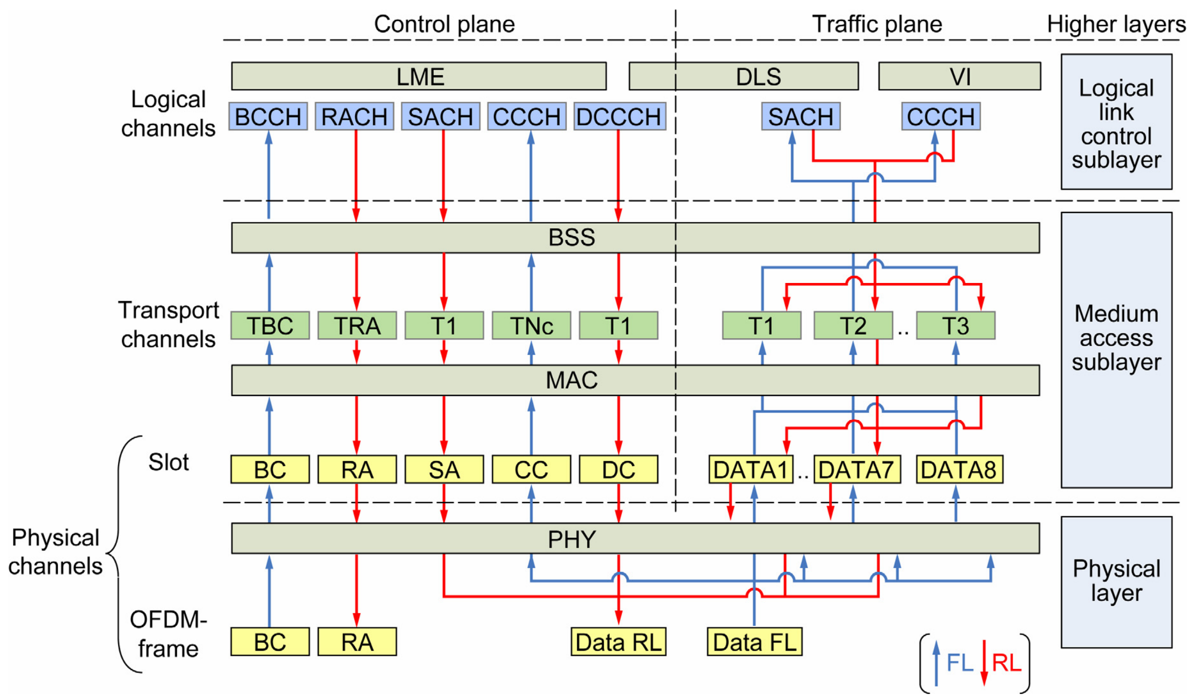


Figure 104.—B–AMC channel mapping (aircraft perspective).

C.5.2.2 COCR Service Provisioning

Applicable domains: The B–AMC A/G mode supports APT, TMA, and ENR service volumes, but cannot provide A/G service in ORP domains, except for entry/exit areas where the ground infrastructure is available. In the A/A mode, B–AMC provides direct A/A broadcast and addressed A/A data link. B–AMC is not applicable to the oceanic/remote/polar domains.

Applicable services: The FCS technology evaluation applies an evaluation scenario that includes both ATS and AOC on a shared communication connection. This is a conservative approach that includes most stringent communication requirements. Services to be provided include all except A–EXEC, WAKE, and ASAS (air-to-air broadcast). Associated communication functional needs are A/G addressed data, ground broadcast data, and A/A addressed.

Applicable services of B–AMC A/G mode are

- B–AMC A/G, which supports ATS traffic (with A–EXEC) in all investigated scenarios
- B–AMC A/G, which supports combined ATS and AOC traffic (with A–EXEC) in all investigated scenarios except ENR large and ENR super large
- In these scenarios the required throughput lies above the theoretical maximum throughput of B–AMC

Because of the throughput restrictions, the ENR large scenario with combined ATS and AOC traffic can be supported only without A–EXEC.

C.5.2.3 Evaluation Scenario Assessment

C.5.2.3.1 Target Aeronautical Spectrum

B–AMC is a wideband technology. In A/G mode, it uses RF channels with 0.5-MHz occupied bandwidth. This bandwidth is independent of the airspace type or B–AMC cell size. Each B–AMC cell operates in the FDD mode, using its assigned FL/RL channel pair. Both FL and RL channels lie on a 1-MHz grid with an offset of 500 kHz to the center frequencies of the adjacent DME channels. With the proposed deployment option (OPTN2), B–AMC channels are

- FL channels: 962 to 1024 MHz range
- RL channels: 1025 to 1087 MHz range

Assuming the maximum pool of 24 B–AMC FL/RL channels, the FL B–AMC sub-band channels are

- FL channels: 985 to 1009 MHz range
- RL channels: 1048 to 1072 MHz range

Not all of these 24 channels would be effectively required for A/G. A minimum number of required channels depends on the co-channel rejection performance of the B–AMC receiver. The B–AMC system in the A/G mode uses FDD with fixed duplex spacing between B–AMC FL and RL channels. The B–AMC duplex spacing is the same as for the DME (63 MHz).

C.5.2.3.2 High-Level Deployment Concept

The B–AMC Project investigated three deployment options.

- OPTN1—Utilizing spectrum between successive DME channels for B–AMC. This would allow for B–AMC frequency planning that is "independent" from DME planning. Preliminary results of interference simulations have shown that OPTN1 will not provide sufficient isolation between systems both because of limited selectivity of the involved receivers and relatively broad spectrum of the transmitted signals (Report D2.2 Draft A)
- OPTN2—Assigning DME frequencies to B–AMC channels in areas where they are not used locally by DME. This is the preferred deployment concept (per Report D2.2 Draft A). Required FL and RL channels would be allocated such that the existing DME frequency planning criteria are expected and supplemented.
- OPTN3—Utilizing the lower part of the L-band (960 to 978 MHz) as a dedicated sub-band for B–AMC. In this case interference with GSM (and UMTS), which are operated in the frequency band below, would need to be considered. Should the development of supplementary rules for B–AMC deployment along with DME channels prove to be not

feasible, the system could be deployed by following the OPTN3 where DME operations on/around a minimum number of required B–AMC FL/RL channel pairs would cease and these channels made exclusively available for B–AMC A/G operations (Report D2.2 Draft A).

Deployment concepts for ER, surface, and TMA domains have been considered and evaluated.

- For the ER environment, B–AMC coverage range and capacity can be considered suited for implementation in a regular grid (cellular) fashion for ER domain, where users typically are evenly distributed across this domain.
- In surface domains, individual surface channels are used. Because the surface environment is such that each ground station is beyond the radio horizon of the next ground station, surface frequencies can be reused between sites.
- For the TMA environment, locations are typically grouped in a nonuniform manner. In some locations, there can be a number of TMA environments close together while in other areas, TMA domains can be isolated from other TMA airspace. Similar to the surface domain approach, a set of TMA channels can be assigned channels and reused such that unique channels are deployed within the same radio horizon.

C.5.2.3.3 B–AMC Link Budgets

Table 61 shows some example B–AMC FL/RL link budgets (ref. 39) for the B–AMC A/G system operating in the ENR, TMA, and APT environments under noise-only conditions with no external interference and with a full 500-kHz bandwidth.

TABLE 59.—EXAMPLE B–AMC LINK BUDGETS

		ENR_0	ENR	TMA	APT
Thermal noise density at 300 K, dBm/Hz	No	–174	–174	–174	–174
B–AMC RX BW, Hz	BW	500 000	500 000	500 000	500 000
B–AMC RX BW, dBHz	BW	57	57	57	57
Thermal noise power at BW, dBm	Nt	–117	–117	–117	–117
RX NF, dB	NF	9	9	9	9
Total RX noise power (BW), dBm	N	–108	–108	–108	–108
E_b/N_0 at BER = 10^{-4}, dB	E_b/N_0	3	3	3.6	15.6
B–AMC bit rate R, bps	R	355 000	355 000	355 000	355 000
Required C/N = $E_b/N_0 \times$ R/BW, dB	C/N	1.5	1.5	2.1	14.1
B–AMC_A RX sensitivity, dBm	C	–106.5	–106.5	–105.9	–93.9
Safety margin (SM = S–C), dB	SM	6	18.6	26.5	32.0
B–AMC_A available signal, dBm	S	–100.5	–87.9	–79.4	–61.9
RX cable loss, dB	LcR	2.0	2.0	2.0	2.0
Peak RX antenna gain, dB	GaR	8.0	8.0	8.0	8.0
TX-RX antenna distance, nm	D	200.0	200.0	75.0	10.0
Free space loss at 1024 MHz, dB	Lfs	144.0	144.0	135.5	118.0
Peak TX antenna gain, dB	GaT	5.4	5.4	5.4	5.4
TX cable loss, dB	LcT	3.0	3.0	3.0	3.0
B–AMC TX power, dBm	P	35.1	47.7	47.7	47.7

Computer modeling and simulation of the B–AMC ability to provide the full complement of COCR services has been performed (ref. 36). Results of these modeling and simulation activities concluded that assuming the deployment option with frequency planning (Option 2), the B–AMC A/G subsystem operating under specified DME interference scenarios can support cell sizes with radii up to 200 nmi. The data rate associated with this test volume is 355 kbps.

Two A/G ENR deployment scenarios are listed in the B–AMC operating concept and deployment scenarios report (ref. 39)

- Scenario 1: Combined ATS and AOC services (without A–EXEC service) could be provided by using B–AMC cells with up to 100 nmi coverage. Because of the shorter antenna size in L-band, beam-forming techniques may be used as a means to increase the required operational coverage such as off-shore operations.
- Scenario 2: Assuming proper site engineering, ANSPs could also deploy B–AMC ground stations at existing VHF voice radio sites. Coverage of 100 nmi would be possible from each ground station (excluding A–EXEC). The RL simulation result shows a potential to achieve a 200 nmi range with this scenario.

For this analysis, a conservative service volume size of 100 nmi was assumed.

C.5.2.3.4 En Route Evaluation

The common evaluation scenario document (ref. 45) describes several ENR test volumes.

- Small ENR (test volume 3.1 (TV3.1)): 55 nmi cube/45 PIAC/80.4 kbps
- Medium ENR (TV3.2): 100 nmi cube/62 PIAC/94.3 kbps
- Large ENR (TV3.3): 200 nmi cube/204 PIAC/226.9 kbps
- Super large ENR (TV3.4): 400 nmi cube/522 PIAC/528.4 kbps

An implementation option would be to implement B–AMC channels on a per-sector basis. Per COCR–V2, the maximum ATC-only service data rate requirement (per sector) is 50 kbps while for ATS and AOC services it is 150 kbps. Thus a single B–AMC channel could meet ATS-only requirement and ATS and AOC requirements. It is assumed that one ground channel is estimated for provision of services to TV3.1 and TV3.2 service volumes.

To provide services in larger service volumes, a cellular approach is considered.

A reference study (ref. 46) indicates that a reasonable estimate of frequency reuse factor that can be applied in the ER demand is nine. This factor was assumed for the scenarios in the analysis (e.g., for large service volumes, nine frequencies are reused to provide regular-grid cellular services). To conservatively estimate the required number of channels within the various ENR service volumes, it is assumed that a full redundant set of channels would be needed to address availability requirements (similar to current deployment scenarios). Thus, the resulting estimates of ground station sites and channels for accommodating the ENR test volumes include

- TV3.1 and TV3.2
  - One ground station site
  - Two FL/RL channel pairs (one pair for primary and one pair for backup)
- TV3.3
  - Seven ground station sites
  - Fourteen FL/RL channel pairs (seven pairs for primary and seven pairs for backup)
- TV3.4
  - Twenty-two ground stations
  - Fourteen FL/RL channel pairs (seven pairs for primary and seven pairs for backup)

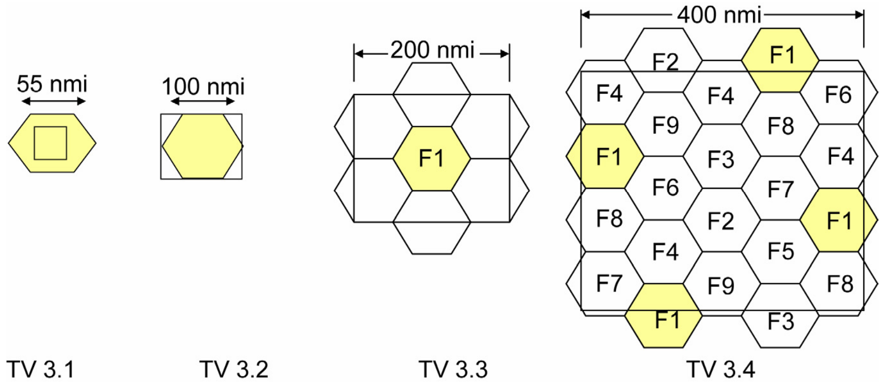


Figure 105.—Representative B–AMC en route coverage (notional illustration of concept, not drawn to scale).

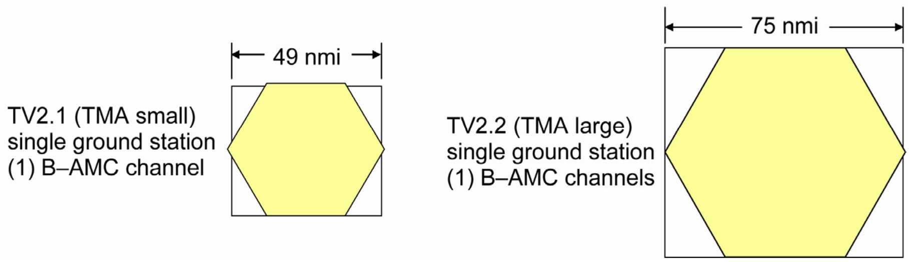


Figure 106.—Representative B–AMC TMA coverage (notional illustration of concept, not drawn to scale).

A representative illustration of ground station sites and channels is provided in figure 105.

C.5.2.3.5 TMA Evaluation

Two TMA test volumes are defined in the common evaluation scenario document (ref. 45) including

- Small TMA (TV2.1): 49 nmi cube/44 users/17.4 kbps
- Large TMA (TV2.2): 75 nmi cube/53 users/20 kbps

As noted above, an irregular pattern of TMA volumes is anticipated due to the location of population centers. Some areas may have several nearby large TMAs and some large TMAs may be isolated. The same scenario may hold true for small TMA service areas. As a result, a regular grid of TMA ground stations is neither required nor practical. Instead, it is assumed that a set of frequencies will be applied and reused to provide TMA services.

B–AMC computer modeling and simulation results concluded that B–AMC cells can provide combined ATS and AOC services without A–EXEC service for up to 100 nmi coverage. TMA operational coverage could be provided from a single B–AMC ground station, operating on the single FL/RL channel pair to cover small or large TMA service volumes. Very large TMAs with complicated terrain topology might require several ground stations at different locations to provide seamless coverage at TMA FLs. In some cases it may be possible to provide both ENR and TMA services by sharing the same infrastructure (GNI and ground stations).

Thus, the resulting nominal estimates of ground station sites and channels for accommodating the TMA test volumes include

- TV2.1 and TV2.2
  - One ground station site
  - Two FL/RL channel pairs (one pair for primary and one pair for backup)

A representative illustration of ground station sites and/or channels is provided in figure 106.

C.5.2.3.6 Surface Domain Evaluation

The surface domain is addressed by two evaluation scenarios (as defined in the common evaluation scenario document (ref. 45)) including

- Airport zone, TV1.1 (PIAC = 26), 10.22 kbps
- Surface, TV1.2 (PIAC = 264), 142 kbps

The B–AMC data rate (FL 270 kbps/ RL 236 kbps) is more than the offered load, so a single channel will have sufficient capacity to provision COCR services (ATS and AOC); for ATS-only services, a single channel would be sufficient. As surface channels can be heavily reused due to location of the service volumes and radio horizon effects, an estimate of 5 to 10 times per-airport channel requirements is assumed to accommodate the surface domain (thus 15 to 50 channels for ATS and AOC services and 5 to 10 channels for ATS-only services).

C.5.2.3.7 Notional Channelization Plan

Figure 107 shows the L-band usage for B–AMC A/G and A/A communications proposed in the EUROCONTROL report (ref. 53).

C.5.2.4 Cost Considerations

The cost assessment applied for this evaluation accounts for the required functional elements to support the technology implementation; the appropriate number of ground stations for deployment in large areas (e.g., combined super large/large ENR and large TMA sectors); and the specialized equipment and components required to provide COCR services with this technology.

To gain an understanding of the functional elements of the technology needed to provide COCR services, a notional service mapping of COCR data link services to the technology was created for the other selected technologies (e.g., WCDMA, LDL, and TIA–902 (P34)) in the study. A representative DLIC service was used for the assessment. Because of a lack of protocol interaction level information, the functional mapping of a representative DLIC service to B–AMC network elements was not provided in this evaluation.

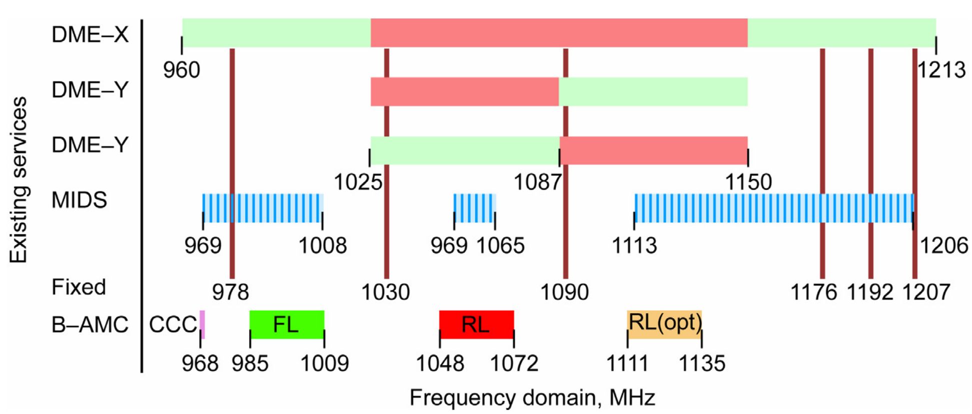


Figure 107.—Proposed L-band usage for B–AMC (ref. 39).

Appendix D—Summary of Indepth Assessments

Many of indepth technical assessments supporting the FCS technology assessment were performed during the FCS Phase II summary. An overview of the work performed and results is provided in the following subsections:

- Section D.1: L-Band Air/Ground (A/G) Channel Characterization
- Section D.2: TIA–902 (P34) Performance Assessment
- Section D.3: TIA–902 (P34) Technology Intellectual Property Assessment
- Section D.4: LDL Performance Assessment
- Section D.5: WCDMA Functional Assessment
- Section D.6: L-Band Technology Cost Assessment for Ground Infrastructure
- Section D.7: L-Band Interference Analysis and Testing
- Section D.7.1: DME Interference Assessment
- Section D.7.2: UAT Interference Modeling
- Section D.7.3: Mode S Interference Modeling
- Section D.7.4: L-Band Interference Measurements
- Section D.8: Satellite Technology Availability Performance
- Section D.9: C-Band Technology (IEEE 802.16e) Performance

D.1 L-Band Air/Ground (A/G) Channel Characterization

To support the assessment of technology performance in the L-band A/G channel, a literature search revealed that while many channel models exist for the terrestrial channel in close proximity to L-band, there had been no previous activity to develop a channel model that characterizes the L-band A/G channel for radio communications. As most standardization bodies consider it a best practice to test candidate waveform designs against carefully crafted channel models that are representative of the intended user environment, a channel model was developed that could be used for common characterization of communications waveform performance in this A/G channel.

Characterization of the delay spread and the Doppler power spectrum is essential for generating a useful model for waveform simulation and evaluation of candidate FRS technologies in L-band. In order to form estimates of the delay spread and associated statistics, a ray-tracing simulation was developed. This simulation models both diffuse and specular reflections from the Earth's surface. The developed simulation used a method of concentric oblate spheroids to model multipath contributions. The desired product was the set of points on the terrain that were intersected by the oblate spheroids. When plotted, each set of intersection points appears as a distorted annulus, approximating the cross section of the spheroid when sliced by the Earth's surface. Each set of intersection points is mutually exclusive from any other set because any intersection point can only be accounted for once. Each set of intersection points contributes to multipath for a particular delay. Figure 108 illustrates the method of concentric oblate spheroids used to model multipath contributions.

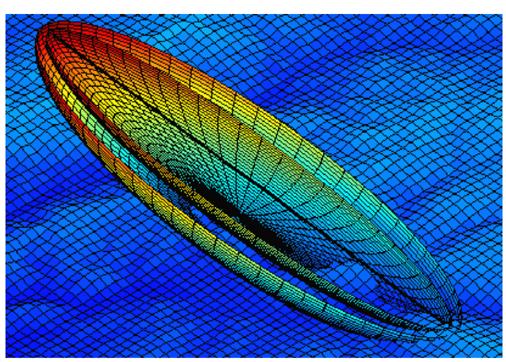


Figure 108.—Two concentric oblate spheroids intersecting the underlying terrain.

TABLE 60.—DATA RATES OF LDL AND TIA–902 (P34)

Waveform	Data rate, kbps	Symbol duration, µs	1/10th of the symbol duration, µs
	R	$T_b = \frac{1}{R}$	$t_0 = \frac{T_b}{10}$
LDL	62.5	16.0	1.60
TIA–902 (P34)	[a] 4.8	208.3	20.83

[a]TIA–902 (P34) is an OFDM system. The tabulated data rate is per carrier and is the symbol rate. Overall TIA–902 (P34) data rates range from 76.8 to 691.

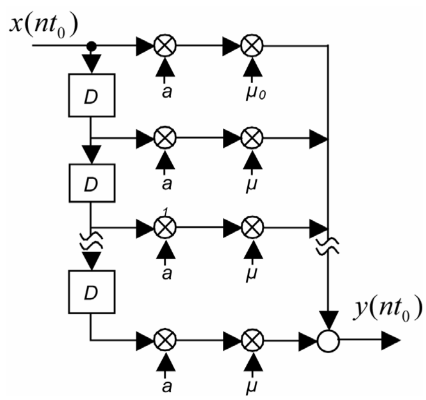


Figure 109.—Block diagram for frequency-selective channel model.

Implementing the methodology to apply ray tracing to determine specific specular and diffuse multipath components and employing data reduction and analysis techniques, the mean RMS delay spread was calculated to be 1.4 µs. It is instructive to consider representative technologies at this point since the technology data rate will drive channel-model parameter estimation. A rule of thumb frequently applied is that if the mean RMS delay spread is at least one-tenth of the symbol duration, then the channel is frequency-selective. In order to illustrate this, two technologies emerging from the FCS Phase I study were considered: LDL and TIA–902 (P34). Table 62 exhibits the corresponding data rates and symbol durations for LDL and TIA–902 (P34).

Using our rule of thumb, TIA–902 (P34) should undergo flat fading, and LDL presents a borderline case because the mean RMS delay spread is very close to one-tenth of the symbol duration. It is important to note that frequency-selective channel models differ in structure from flat-fading channel models. For this reason, it was decided to develop a frequency-nonselective fading model for TIA–902 (P34) and a frequency-selective fading model for LDL.

First the channel model for LDL is described. Figure 109 shows the block diagram representation for a deterministic simulation model for a frequency-selective mobile radio channel (Pätzold 270).

The parameters that define the LDL channel model are as follows:

- Number of taps (N)
- Tap spacing (a_0, a_1, ..., a_N)
- Tap weights (D_1, D_2, ..., D_N)
- Tap fading processes (μ_0, μ_1, ..., μ_N)

Table 63 defines the LDL channel model parameters that were derived in the Phase II study.

The TIA–902 (P34) channel model is much less complex than the LDL channel model because the channel is frequency-nonselective. Figure 110 illustrates the TIA–902 (P34) channel model.

TABLE 61.—LDL CHANNEL MODEL PARAMETERS

Tap no.	Delay, μs	Power, lin	Power, dB	Fading process	Doppler category[a]
1	0.0	1.0000	0.0	Ricean	Jakes
2	1.6	0.0359	–14.5	Rayleigh	Jakes
3	3.2	.0451	–13.5	Rayleigh	Jakes
4	4.8	.0689	–11.6	Rayleigh	Jakes
5	6.4	.0815	–10.9	Rayleigh	Jakes
6	8.0	.0594	–12.2	Rayleigh	Jakes
7	9.6	.0766	–11.2	Rayleigh	Jakes

[a]Note that the assumptions used in the development of the Jakes model are not applicable for the anticipated Ricean A/G channel, but this model has been incorporated to provide a conservative estimate of Doppler effects.

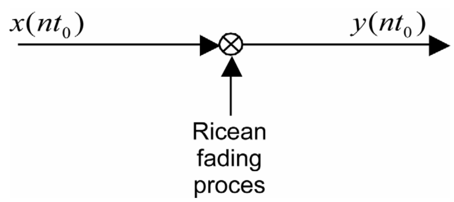


Figure 110.—TIA–902 (P34) channel model.

The Ricean fading process is derived in the complex baseband by creating two colored gaussian processes. The Rice method is used to generate the gaussian processes as a summation of sinusoids whose coefficients and frequencies are determined by the Doppler power spectrum of the channel. As the process is Ricean, a time-variant mean is summed with the colored gaussian process (LOS component). The magnitude of the complex gaussian colored processes yields the Ricean process with fade durations and amplitudes determined by the channel.

One of the primary results reported is the simulated RMS delay spread. It should be noted that this delay spread can be modeled as a function of the average distance from the transmitter, with increasing delay spreads reported for increasing distances. Because of this phenomenon, our simulated positions were constrained to be in an area with dimensions that were small compared to the average distance from the transmitter. For these simulations, an RMS delay spread of 1.4 μs was predicted for a certain distance (average distance = 40 miles) from the transmitter in mountainous terrain. A generalized model, using the method cited in Greenstein, has the form

$$\overline{\sigma}_\tau = \overline{\sigma}_{\tau 0} d^{\varepsilon} A$$

where

- d is the distance in km
- σ_0 is the median value of the RMS delay spread at d = 1 km
- ε is an exponent that lies between 0.5 and 1.0, based on the terrain type
- A is a lognormal variate

To determine the parameters that are appropriate for a generalized L-band A/G model in mountainous terrain, RMS delay spreads were predicted for a reference distance of 1 km as well as for the previously mentioned values at 64.37 km (40 mi). The two predicted values that resulted from the simulation work are

$$\sigma_{RMS}(1\text{ km}) = 0.1\ \mu\text{s}$$

$$\sigma_{RMS}(64.37\text{ km}) = 1.4\ \mu\text{s}$$

Fitting the Greenstein model to the reference data provides a generalized expression for RMS delay spread, which is found to be

$$\overline{\sigma}_{\tau} = 0.1 \times d^{0.6337} \quad \mu s \quad (A = 6dB)$$

A full description of the L-band A/G channel characterization work is provided in the interim FCS Phase II report, Section E.1.

D.2 TIA–902 (P34) Performance Assessment

In addition to L-band channel characterization, L-band technology performance studies specific to individual technologies were also conducted. An indepth analysis of TIA–902 (P34) net entry, data transfer and BER performance in the L-band channel was performed. The simulation of TIA–902 (P34) included evaluation of a ground station and 95 mobile nodes (COCR-defined National Airspace System super sector) employing TIA–902 (P34) SAM physical layer properties associated with 50-kHz channelization and QPSK modulation. Simulation model results are shown in figure 111. These figures show the response time of the TIA–902 (P34) simulation to the offered load for each of transmitted message. Note that the subnetwork latencies over TIA–902 (P34) protocols (SNDCP, LLC CP, LLC UP, and MAC) meet COCR latency requirements. Specifically, although there are some startup outliers, 95 percent of delay measurements are under 0.7 s. Reference the interim FCS Phase II report, Section E.1.2.2.

In addition to simulation of TIA–902 (P34) net entry and data transfer performance, TIA–902 (P34) performance in the defined L-band A/G channel was also evaluated. As part of this effort, TIA–902 (P34) transmitter and receiver models were generated. Specifically, the TIA–902 (P34) SAM physical layer interface was modeled by developing a custom application using C code. The transmitter was implemented as detailed in the specification for the 50-kHz channel using QPSK modulation. The receiver implementation was tested against published results for standardized channel models. Additionally, TIA–902 (P34) coding gain (for specified concatenated Hamming codes) was investigated. It was found that a 3×10^{-3} raw BER is approximately equal to 10^{-5} coded BER for P34.

The developed TIA–902 (P34) transmitter and receiver models were combined with a model of the expected L-band channel based on analysis work previously described. Specifically, a two-tap channel model was simulated where Tap 1 was modeled as Ricean, with a K-factor of 18 dB, unity gain, and Jakes Doppler Spectrum; and Tap 2 was modeled as Rayleigh, with a 4.8 μs delay, –18 dB average energy, and Jakes Doppler Spectrum (conservative estimate). In this model, the mobile velocity was taken to be 0.88 mach. This is the maximum domestic airspeed given in the COCR based on Boeing 777 maximum speed. Additionally, in the model the TIA–902 (P34) tuned frequency was taken to be 1024 MHz, with maximum Doppler shift of 1022 Hz.

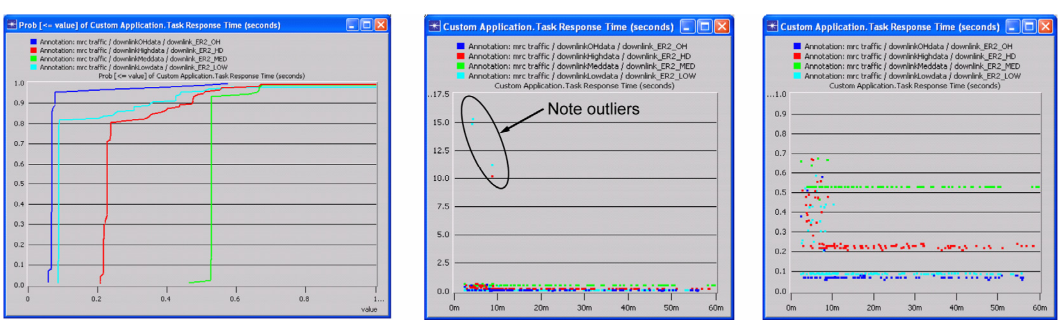


Figure 111.—TIA–902 (P34) OPNET modeling results.

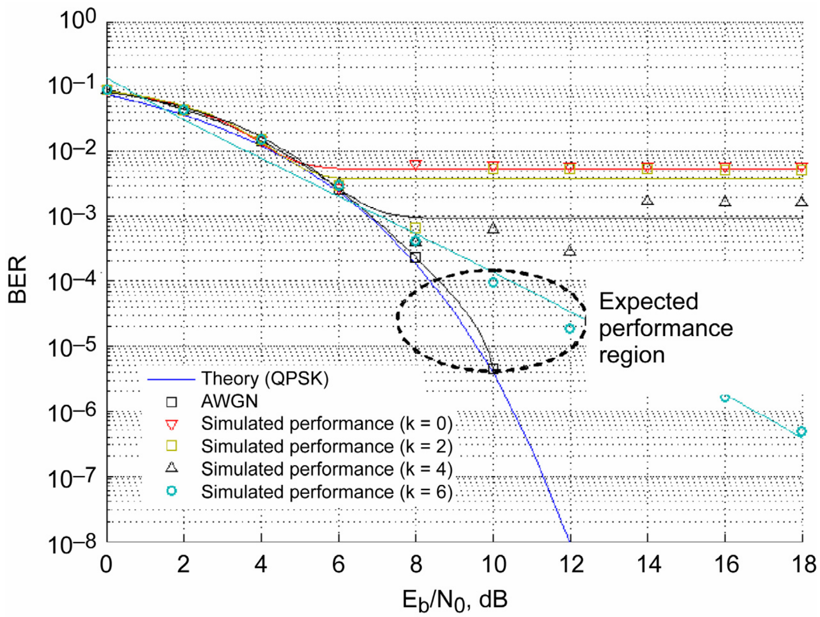


Figure 112.—TIA–902 (P34) predicted performance in the L-band aeronautical channel.

Initial simulations indicate good performance can be achieved in the aeronautical channel (e.g., flat channel effects), primarily a consequence of the strong LOS component of the received signal (with K factors greater than four). Figure 112 shows initial performance results and a complete description of the TIA–902 (P34) performance assessment including simulation block diagrams, receiver implementation details (channel estimation using interpolation weighting), model validation results, and details on the simulation A/G channel are provided in Section E.1.2.3 of the interim FCS Phase II study report.

D.3 TIA–902 (P34) Technology Intellectual Property Assessment

One of the indepth analyses conducted during Phase III of the FCS technology investigation was the TIA–902 (P34) Intellectual Property assessment. This study evaluated the potential impact of the TIA–902 (P34) standard intellectual property in the context of an FRS implementation.

There are eight patents associated with TIA–902 (P34) standards, two of which are associated with Media Access Control/Radio Link Adaptation (MAC/RLA) layer specifications; six are in the physical (PHY) layer (SAM, Channel Coding (CHC), or IOTA). In the process of proposing recommendations for the patents, certain terms and assumptions were found to be applicable. They are

- All eight patents will all expire prior to FCS equipment deployment (assuming 2020 roll-out). The term of a new patent is 20 years from the date on which the application for the patent was filed in the United States and is not renewable.
- U.S. patents are not applicable to companies outside the United States. U.S. patents are not effective to implementations outside the United States.
- TIA–902 (P34) physical layer modifications have been identified as needed for the application of this technology in the L-band aeronautical channel; six out of eight patents address features of the physical layer.
- TIA–902 (P34) has more flexibility than FRS applications may need; sometimes only a subset of the TIA–902 (P34) characteristics is needed. Partial implementation of a patent is considered an “alternative solution” case (as the patent would not be applicable).

- FRS ground infrastructure will likely be optimized for one modulation type, not for multiple modulation types, this reflects feedback received in FCS Phase I interim results in which the TIA–902 (P34) concept of use included multiple modulation features was noted to adding unnecessary complexity and is not desirable.
- Current analysis results suggest that QPSK is likely sufficient to meet COCR requirements (QAM is not likely to be necessary).

Team study and review of the impacts of patents to potential TIA–902 (P34) application to FRS were conducted; a corporate-level patent counsel was invited to review and address issues. As the result of the analysis, recommendations based on the desirability and criticality of the patents were proposed and documented. Recommendations specific to reviewed patents took the form of three implementation options including bypass the patent, find an alternative solution, or implement the patent.

Thorough review of the patents and consultation with a patent counsel helped to develop the following conclusions:

- The concept of use defined for TIA–902 (P34) makes some patents not applicable (for example IOTA physical layer not used in the FCS application and associated patents do not apply); also recommended tailoring of physical layer standard for the FCS application results in bypassing of most physical layer patents
- Only one patent is assessed as desirable to implement, it is a methodology proposed for power amplifier linearization, modification of which would influence definition of MAC framing structure
- Most if not all patents will expire before timeframe of FCS
- These patents are not applicable to companies outside the United States

Intellectual property associated with TIA–902 (P34) standard is deemed to have little or no impact on the FRS if it is an implementation based on this standard (table 64).

A detailed description of this analysis, including detail evaluation results of each patent, can be found in FCS Phase III interim Report, Section 4.

D.4 LDL Performance Assessment

A second technology investigated for performance in the L-band aeronautical channel was LDL. As with TIA–902 (P34), LDL transmitter and receiver models were generated and the receiver model validated against known results. After validation, investigation of LDL coding, RS(72, 62), provides a coding gain of 3 to 4 dB in the expected region of operation. LDL performance was simulated in the L-band aeronautical channel environment. The LDL channel model is a conservative model that introduces an irreducible error floor to system performance (reference Section D.1). The plot shown in figure 113 shows the system performance of LDL in the presence of both AWGN and the L-band aeronautical channel model. Based on the results of this simulation, LDL may require channel equalization to mitigate the effects of the A/G aeronautical channel model in L-band.

A complete description of the LDL performance assessment including simulation block diagrams, receiver implementation details, model validation results, and details on the simulation A/G channel are provided in Section E.1.3.2 of the interim FCS Phase II study report.

TABLE 62.—PATENT EVALUATION SUMMARY

No.	Patent name	Patent number	Protocol layer	Decision	Comment
1	Encryption Synchronization Combined With Encryption Key Identification	US 5,185,796 Feb. 1993 Motorola Filed May 1991	MAC/RLA	Bypass	Implementation could be achieved by driving requirements to upper layers
2	Power Amplifier Linearization in a TDMA Mobile Radio System	US 5,559,807 Sept. 1996 Motorola Filed 1994	MAC/RLA	Implement patent desirable (expires 2014)	Alternative implementation could be achieved, but requires modification to MAC layer
3	Method for Providing and Selecting Amongst Multiple Data Rates in a Time Division Multiplexed System	US 5,533,004 July 1996 Motorola, Inc. Filed 1994	SAM Channel Coding	Alternative solution	Adaptive data rate not a desirable feature
4	Communication Signal Having a Time Domain Pilot Component	US 5,519,739 May 1996 Jasper Filed 1991	SAM and IOTA PHY	Bypass	Develop new PHY
5	Peak to Average Power Ratio Reduction Methodology for QAM Communications Systems	US 5,381,449 Jan. 1995 Motorola Filed 1991	SAM PHY	Bypass	Develop new PHY, and QAM is not identified modulation in CONUSE
6	Quadrature Amplitude Modulation Synchronization Method	US 5,343,499 Aug. 1994 Motorola, Inc.	SAM PHY	Bypass	Develop new PHY, and QAM is not identified modulation in CONUSE
7	Scalable Patter Methodology for Multicarrier Communication Systems	US 6,424,678 July 2002 Motorola Filed 2000	SAM PHY	Bypass	Develop new PHY
8	Construction of a Multicarrier Signal	US 6,278,686 Aug. 2001 France Telecom & Télédiffusion De France Filed 1996	IOTA PHY	Bypass	Develop new PHY

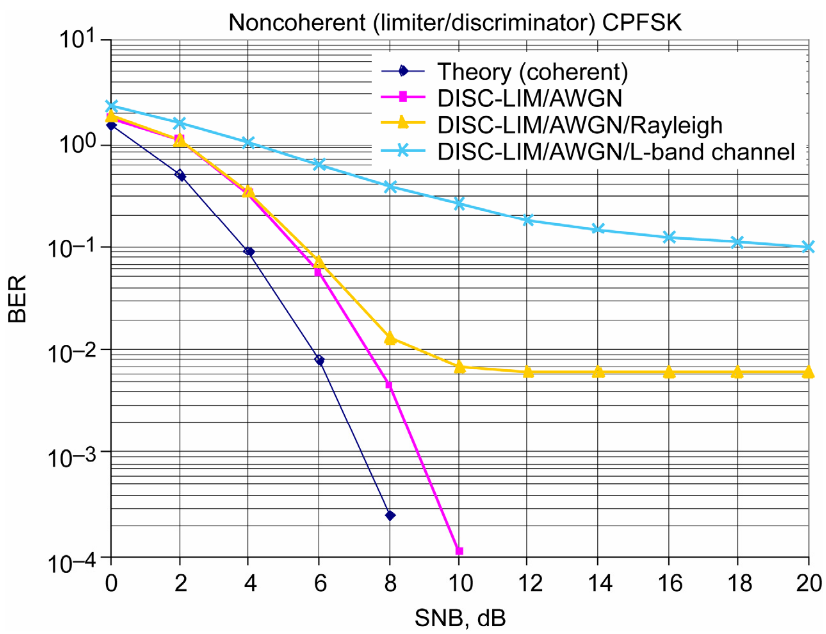


Figure 113.—LDL predicted performance in AWGN and the L-band aeronautical channel.

D.5 WCDMA Functional Analysis

WCDMA functional analysis conducted as part of the FCS Phase III effort to identify how WCDMA can be used to support COCR services. Results of this analysis were used to determine the necessary elements of the architecture and protocol stack required to provision COCR services, which further supports the assessment of cost, certification, and standardization impact for applying WCDMA in aeronautical applications.

WCDMA network architecture, protocols, and functions based on UMTS WCDMA network architectures and 3GPP technical specifications were examined. Data link services support the implementation of aeronautical communications air traffic that are documented in the COCR and RTCA/DO–290 (ref. 54) documents were selected and mapped WCDMA network functions. The COCR includes a complete set of FRS data link service definitions including service descriptions and operational context. RTCA/DO–290 provides service transaction details beyond what is provided in the COCR such as operational methods, sequence diagrams, abnormal events, safety, performance, etc.

A logical mapping from CNS/ATM elements to WCDMA network elements is provided as shown in figure 114.

The example DLIC service exchanges information between an aircraft and an ATSU to support other data link services. The DLIC provides version and address information for all data link services including itself and this service is executed prior to any other data link services. Mapping of DLIC to WCDMA functions is shown in figure 115 in which columns represent the necessary WCDMA elements, and rows represent the three high-level network functions exercised and sequence shows the DLIC data exchange sequences.

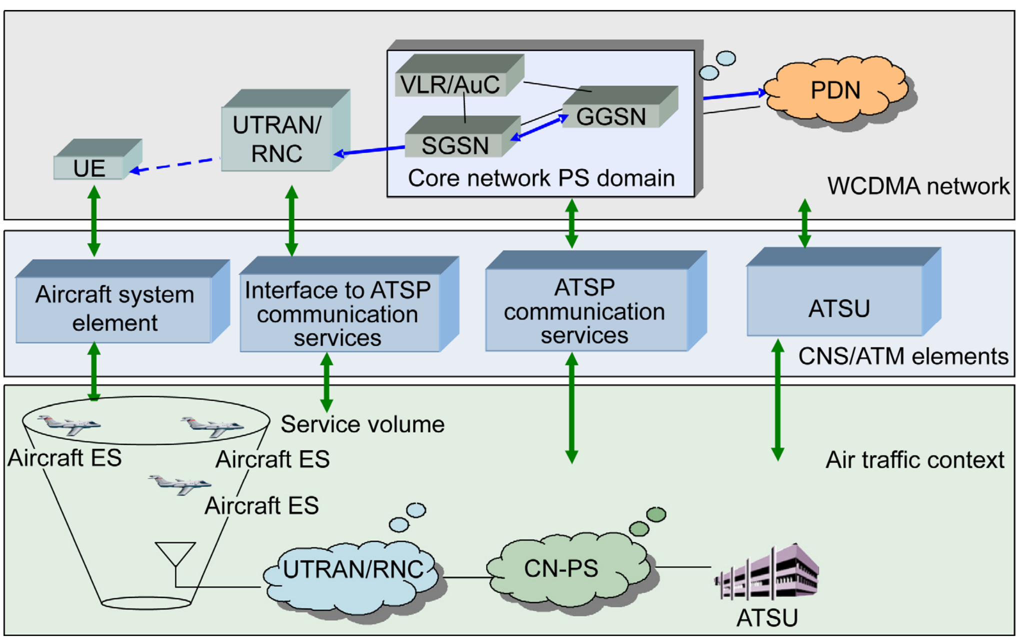


Figure 114.—Logical mapping.

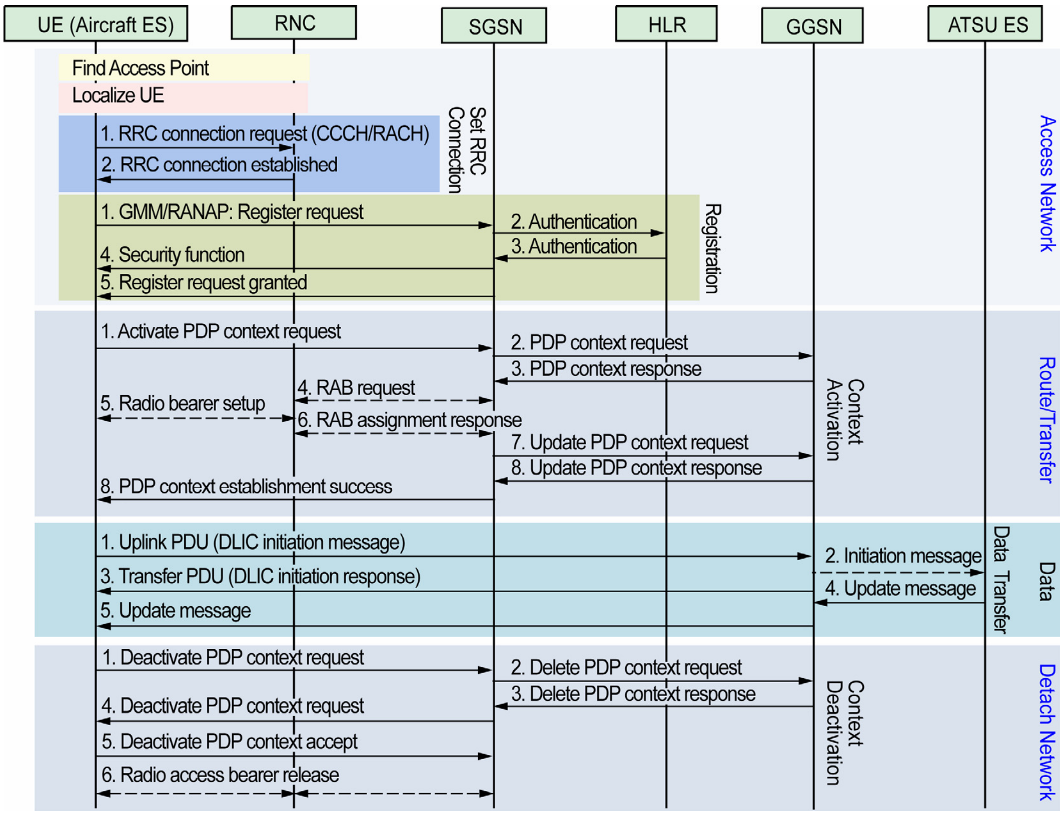


Figure 115.—Map DLIC Contact+Update functions to WCDMA service.

WCDMA specific services that support aircraft movement through the ATC system have also been examined. Four operational scenarios were identified and mapped to aircraft movement scenarios.

Applying the WCDMA standards as defined, the study indicates that a full complement of WCDMA functional elements is required to provision COCR services. Not only the AI and elements of the radio network controller are needed, but also elements of the core network such as HLR, SGSN, and GGSN. Required implementation of a full complement of WCDMA functionally elements and protocols has impact on cost, certification, and standardization because of the anticipated correlations between number of ground elements and cost, required number of functional elements and complexity/risk of certification, number of ground and/or protocol elements, and standardization complexity and/or risk. A complete description of the WCDMA functional analysis can be found in FCS Phase III interim Report, Section 3.

D.6 L-Band Technology Cost Assessment for Ground Infrastructure

L-band technology cost was another focus area of indepth analysis. In this work, the economic feasibility from the perspective of the ground infrastructure provider was evaluated. This analysis was responsive to feedback received on the technology prescreening results (FCS Phase I) that indicated that due to cost constraints, an L-band solution is only considered should VHF spectrum prove insufficient to provide total required data link capability. The L-band business case analysis provided a first order of magnitude estimate of required investment for an L-band aeronautical ground infrastructure. The technical approach for accomplishing this objective included

- Through detailed analysis, develop a notional ground L-band architecture that can meet FCI requirements as defined in the COCR document for ATC communications
    - Derive number of radio sites required for total U.S. coverage

- Perform L-band link budget analysis
    - Develop L-band link budget spreadsheet and derive the parameters to close the link
    - Excess path loss derivation
- Perform L-band coverage analysis
- Derive radio site redundancy to meet system availability requirements
- Develop an architecture to meet availability required

- Determine if the business case can close
    - Develop cost elements and estimates for initial development and O&M
    - Determine required revenue flow to close the business case

An overview of the technical approach workflow is shown on figure 116.

Details of the work performed to develop a link budget, determine radio site redundancy, and defined the radio site equipment is provided in the interim FCS Phase II study report (Sections E.1.8.1 and E.1.8.2). The details of the cost-estimating approach are shown in figure 117.

Applying the approach above for the L-band cost-modeling work, several assumptions were considered including

- L-band provides coverage to a large continental region (e.g., United States or Core Europe)
- Coverage is above FL180
- System Availability of Provision (A_p) meets COCR requirements for COCR Phase II ER services (sans Auto-Execute service)
- Cost elements considered include research and development (including system design and engineering); investment (including facilities and equipment); and operations and maintenance (including telecommunications, personnel, and utility costs)

The first order of magnitude cost estimate for implementing an L-band aeronautical ground infrastructure, considering life cycle costs and applying the present worth simple payback method (with minimum attractive rate of return = 5 percent), indicates that a positive business case can be achieved (payback period of 4 years). While the first order of magnitude cost estimate yielded positive results, the important aspect of the study to bring forward was the framework of the analysis, which can be considered a generic framework specifying infrastructure costs associated with an L-band system. Additional details specific to the L-band cost assessment are in the FCS Phase II report, Section E.1.8.

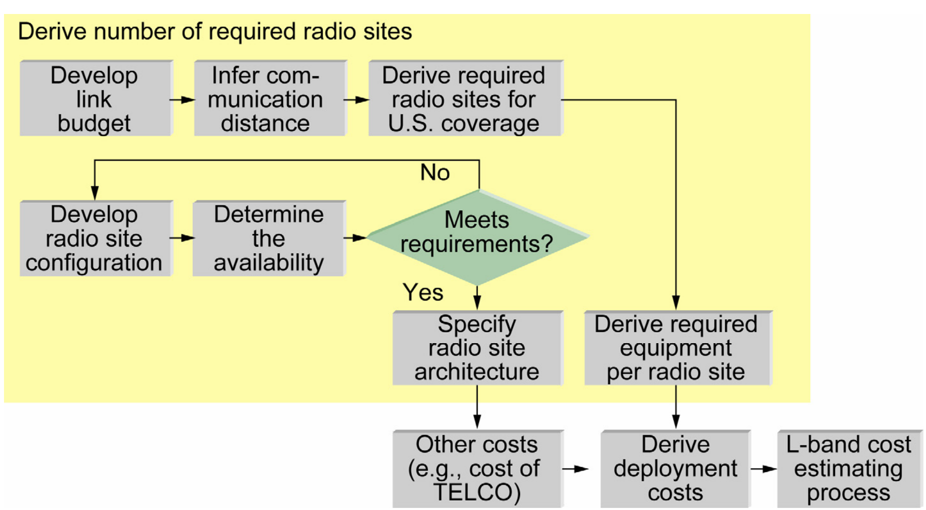
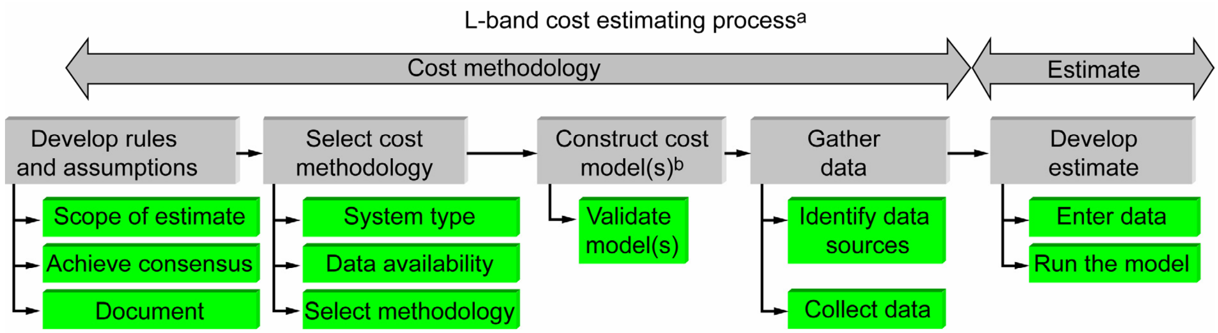


Figure 116.—Process for determining service provider cost.



[a] Based on NASA Cost Estimating Handbook.
[b] William G. Sullivan, James A. Bontadelli, Elin M. Wicks: "Engineering Economy," 11th Ed., 2000.

Figure 117.—L-band cost estimating process.

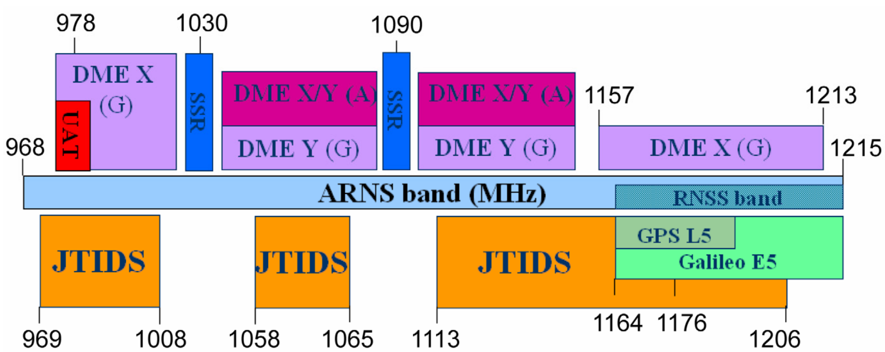


Figure 118.—Current and Planned L-band utilization (ref. 55).

D.7 L-Band Interference Analysis and Testing

Work on this topic was addressed in two ways. First, a modeling effort was performed to assess the interference effects of two candidate technologies on existing L-band aeronautical systems. This work was conducted as part of the FCS Phase II study. Next, as a result of the Phase II findings, an interference measurement campaign was conducted as part of the FCS Phase III study. A summary of the results relating to the analytical assessment are provided here, with details provided in the FCS Phase II report, Section E.1.4. A full description of the objectives, methodology and results relating to the interference measurement work conducted during FCS Phase III is provided in FCS Phase III interim report.

A candidate spectrum band for the future aeronautical communication radio system is the aeronautical L-band spectrum. This band, 960 to 1215 MHz, has a primary allocation for ARNS. There are currently several system implementations that occupy the band. ICAO systems that use spectrum in this band include the UAT, secondary surveillance radars (including ATCRBS, Modes A, C, and S), and DME. A majority of the spectrum allocations for these systems are standardized by ICAO. There are, however, some exceptions such as DME allocations defined on a national basis between 962 and 977 MHz in the United States.

Additional systems operating in the aeronautical L-band spectrum include military systems. These include TACAN and JTIDS/MIDS (Link-16). The use of military systems in this band is subject to national coordination between military and civil authorities. Global navigation satellite systems also occupy this band. Specifically, the upper part of the band has been designed for radio-navigation satellite service (RNSS). A visual depiction of the current and planned L-band utilization is shown in figure 118.

As part of the consideration of new future communication system technology implementations in this band, the need to analyze the interference potential of proposed technologies to systems current operating the aeronautical L-band spectrum has been identified. A generic process for interference analysis would have the following elements:

- Describe the source of interference and the interference mechanism
- Description is usually in the form of power spectrum and time characteristics (e.g., transmit (TX) power, transmission bandwidth, and duty cycle)
- Quantify the isolation between transmitter output and receiver input
- This isolation includes the effects of antenna gains, cabling losses, and propagation
- Determine the ratio of undesired to desired signal power at the input of the receiver decision process (detector)
- Quantify receiver performance as a function of this D/U ratio, ascribe a required performance, and assess compatibility

The last item noted above is the most difficult element of the process and was the focus of the interference simulation work defined for this study. Specifically, during consensus FAA, NASA, and ITT deliberations at the beginning of the Phase II study, two technologies were selected for detailed analysis, LDL and TIA–902 (P34). At that time, it was determined that the compatibility of those two proposed systems with existing ICAO standardized civil aviation systems would be included in the detailed analysis. Thus, the objective of the interference analysis task was to determine the compatibility of TIA–902 (P34) and LDL with standardized civil aviation systems. The approach for the interference analysis included (for each system being analyzed) the following:

- Selection of an appropriate measure of interference degradation
- Collection of information about the system (known susceptibilities and system technical parameters)
- Development of a physical layer system model and validation with known results
- Introduction of the interference source and prediction of victim performance

In an effort to prioritize analysis resources, a list of individual candidate interference analyses was defined. This list is provided in table 65.

In table 65, it can be noted that some of the vulnerabilities have previously been characterized. Therefore, the focus of this study was on the vulnerabilities shaded in red, that is, those vulnerabilities that have not previously been addressed.

TABLE 63.—CANDIDATE INTERFERENCE ANALYSES

Interference source	Victim receiver	Interference mechanisms	Source characterization	Has vulnerability been characterized?
FRS 960 to 1024 MHz 960 to 977 MHz	GNSS 1176.45 MHz	Broadband noise Spurious emissions Desensitization	Noise (WB) NB or CW	Yes Yes
	Mode S 1030 MHz 1090 MHz	Broadband noise Spurious emissions Desensitization	Noise (WB) NB or CW	Yes Unknown
	UAT 978 MHz	Adjacent signal Broadband noise Spurious emissions	FRS dependent Noise (WB) NB or CW	No Yes Yes
	DME 962 to 1019 MHz	Co-channel Adjacent signal Broadband noise Spurious emissions	FRS dependent FRS dependent Noise (WB) NB or CW	No No Yes Yes

D.7.1 DME Interference Assessment

The DME system is an ICAO standardized navigational aid used to determine the aircraft location. It consists of an interrogator located onboard the aircraft and a transponder located at a ground station. At regularly spaced intervals, the interrogator transmits a coded pulse to the transponder. Reception of this pulse triggers a coded reply from the interrogator at a different frequency. The DME system uses the principle of elapses time measurement between these two messages as the basis for determining the distance between the aircraft and the ground station, also called the slant range distance. DME frequencies are spaced in 1-MHz increments throughout the 962 to 1213 MHz band, providing potential for interference to and from FRS in L-band. A list of known susceptibilities and previous DME susceptibility test were reviewed.

With the knowledge gained from review of existing DME tests, a first step in the FCS/DME interference analysis was the development of a DME receiver model. To perform this work, published data on DME interference from GPS signals was obtained. The data indicated that interference from P(Y) and from C/A signals does not differ much, even though the P(Y) signal has 10 times larger bandwidth. Thus a hypothesis was developed, which assumes that pulse detection in DME is performed over a short window, on the order of one P(Y) chip length. A receiver window length, which would have yielded a match with the published data, was then computed.

This hypothesis and associated DME architecture assumptions were applied and a mathematical model, which describes this architecture, was built. The model was run for different values of parameters to determine sets of parameters that matched published results. The implemented model was then tested using a UAT interfering signal to test results. The developed model and associated UAT test results are shown in figure 119.

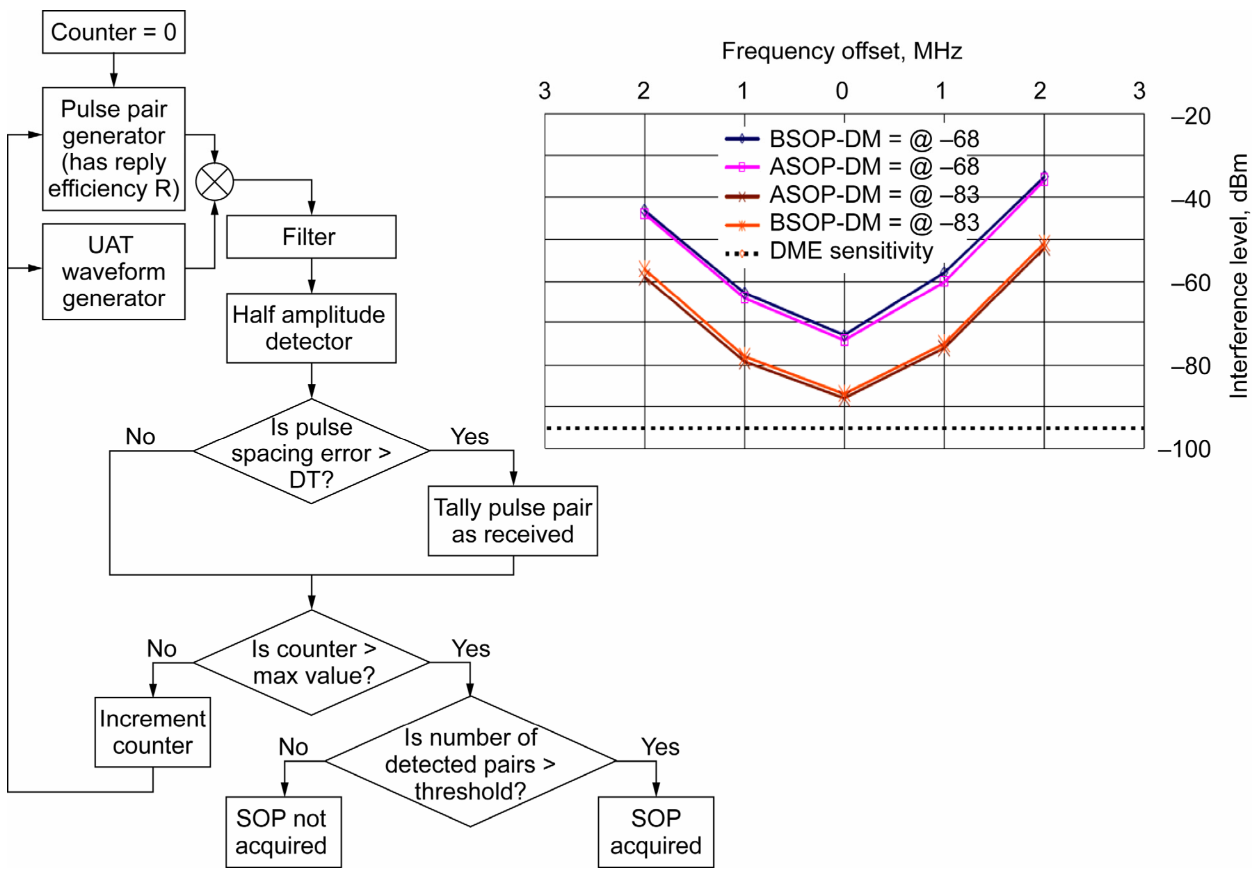


Figure 119.—Implemented DME model and UAT interference results.

For the model in figure 119, DME pulses were modeled as gaussian. UAT was modeled as a frequency-shift keying, constant amplitude signal. Here, the DME pulses and interference were superimposed in the time domain. The resulting signal was filtered using a filter with gaussian response function; the width of the filter response is computed to match a measured decrease of interference effect as a frequency offset of 1 MHz as compared to no offset.

Results captured were compared with published data and despite the seemingly good correlation of results of the developed model and measurements, several problems with the developed model were noted during validation testing. Specifically,

- The measured results are extremely flat over the reply efficiency range of the test
- Indicative of an AGC circuit (perhaps) or some second order effect that is not immediately obvious
- To create a range of "Acquire Locks" for various reply efficiencies, the interference power for our model had to be varied over a 10- to 12-dB range
- This was deemed to be sufficiently far from measured results as to be a nonreliable indicator (for use in predicting interference from FRS sources)
- Several requests for information and assistance were made by NASA, but the information that was needed (detailed algorithm descriptions from radio manufacturers) was not made available

As a result of the observations above, a decision was made to not further use the developed model. Rather, measurements were recommended to more substantively characterize the DME to communication waveforms in the final phase of the FCS technology assessment.

D.7.2 UAT Interference Modeling

UAT is a wideband data link that enhances pilot situation awareness and increases safety by allowing general aviation pilots to process navigational signals from the global positioning system (GPS), receive traffic information, broadcast their position, and perform other functions. It is a technology that is standardized through ICAO for ADS–B, Traffic Information Services–Broadcast (TIS–B), and Flight Information Services–Broadcast (FIS–B). UAT operates at 978 MHz, providing potential for interference to and from a FRS in L-band.

UAT has several known susceptibilities. These include

- DME signal interference (basic and high-performance receivers)
- 99 percent successful message reception of long messages in presence of DME pulse pairs at a nominal rate of 3600 ppps at either 12 or 30 µs spacing at a level of –30 dBm for any 1-MHz channel frequency between 980 MHz and 1215 MHz (desired signal ≥ –90 dBm)
- DME signal interference (basic receivers only)
- 90 percent successful message reception of long messages in presence of DME pulse pairs at a nominal rate of 3600 ppps at either 12 or 30 µs spacing at a level of –56 dBm for any 1-MHz channel frequency between 979 MHz (desired signal ≥ –87 dBm)
- DME signal interference (high-performance receivers only)
- 90 percent successful message reception of long messages in presence of DME pulse pairs at a nominal rate of 3600 ppps at either 12 or 30 µs spacing at a level of –43 dBm for any 1-MHz channel frequency between 979 MHz (desired signal ≥ –87 dBm)

For this study, the objective was to characterize the impact of LDL and TIA–902 (P34) interference on UAT performance. To perform the analysis, several assumptions were employed. For UAT, the basic ADS–B message code RS(30,18) has been modeled. The analysis did not include long ADS–B message

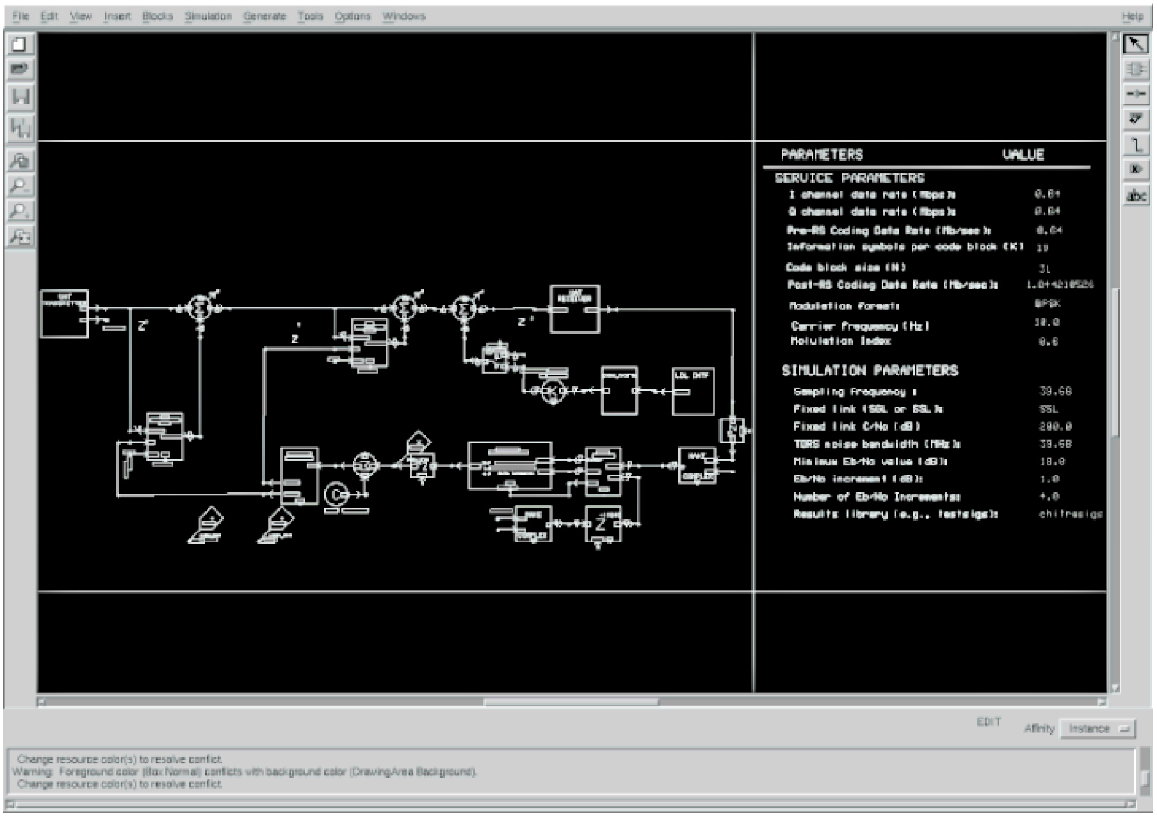


Figure 120.—UAT end-to-end simulation model.

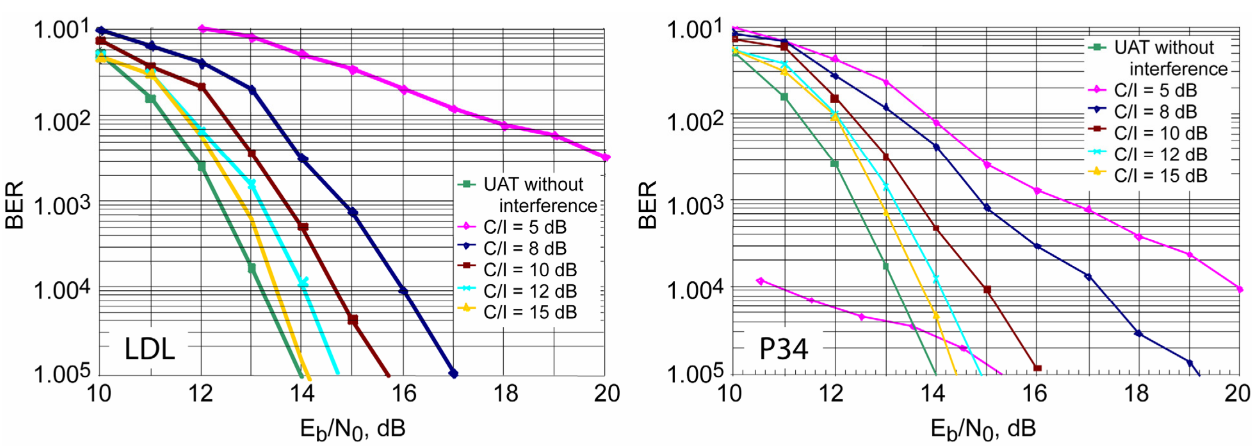


Figure 121.—UAT interference assessment results.

codes RS(48,34) or ground uplink message codes RS(92,72). For LDL, the transmitter model used a data rate of 62.5 kbps. The analysis did not consider other possible LDL data rates. Finally, for TIA–902 (P34), the 50-kHz channelization configuration of TIA–902 (P34) was modeled. The analysis did not consider the 100- or 150-kHz configurations.

Details of the UAT/LDL/TIA–902 (P34) transmitter block diagrams; analysis parameters and SPW tool transmitter implementations are described in Section E.1.4.2 of the FCS Phase II report. The end-to-end simulation model is shown in figure 120.

The model was validated using the AWGN environment and good correlation with published results achieved. A summary of simulation results, which include a collection of BER curves for varying degrees of LDL/TIA–902 (P34) interference into the UAT signal, are shown in figure 121.

From the curves in figure 121, it would appear that a carrier to interference (C/I) ratio between 12 and 15 dB is required for minimum degradation to the UAT receiver. LDL has slightly better performance than TIA–902 (P34) in terms of not interfering with UAT receivers.

D.7.3 Mode S Interference Modeling

Mode Select (Mode S) is a system developed to phase out the Air Traffic Control Radar Beacon System (ATCRBS) by providing enhanced surveillance information for use by ATC automation Mode S provides more accurate position information and minimizes interference by discreet interrogation of each aircraft. Each aircraft has its own unique Mode S address, providing a mechanism by which an aircraft can be selected and/or interrogated such that no other aircraft reply. Mode S also provides a digital data link to exchange information between aircraft and various ATC functions and weather databases. The system operates at 1030 and 1090 MHz providing a potential for interference to and from a FRS in L-band.

The developed Mode S transmitter simulation model exactly met the rise-time, decay-time, and PSD mask requirements given in the Mode S MOPS. The developed simulation modeled the Mode S preamble detection circuit, making a hard decision on every 0.5 microsecond symbol. Selectable sensitivity is also included in the model. Using the developed Mode S transmitter and preamble detection models, an end-to-end simulation was created. This end-to-end model included integrated LDL and TIA–902 (P34) interferer models. Details on the simulation block diagrams and SPW transmitter implementations are described in Section E.1.4.3 of the FCS Phase II report.

For both LDL and TIA–902 (P34) interferences, Mode S probability of correct preamble detection and probability of false preamble detection were measured for several interference levels and several assumptions of required correlation to achieve preamble detection. To compare the interfering effects of TIA–902 (P34) and LDL, a probability of correct preamble detection based on varying C/I values (for 94 percent correlation and 100 percent correlation for declaring detection) for both TIA–902 (P34) and LDL interferers are shown in figure 122.

A similar comparison of interfering effects for Mode S probability of false preamble detection is shown in figure 123.

The modeling results would seem to indicate that a C/I ratio of 15 dB or better is required to not substantially degrade the Mode S preamble detection performance. The behavior of “false preamble detection” would appear to be somewhat worse than the behavior of “missed preamble detection.” As in the UAT case, the performance of LDL is better than that of TIA–902 (P34); that is, TIA–902 (P34) acts as more of an interference source than LDL to both Mode S and UAT receivers. It should be noted that all simulations were made “on-tune.” Actual deployment scenarios should be far off-tune, especially for the Mode S case (proposed band for the FRS is 960 to 1024 MHz, and the Mode S Extended Squitter equipment is at 1090 MHz). Additionally, measurements should be made that further

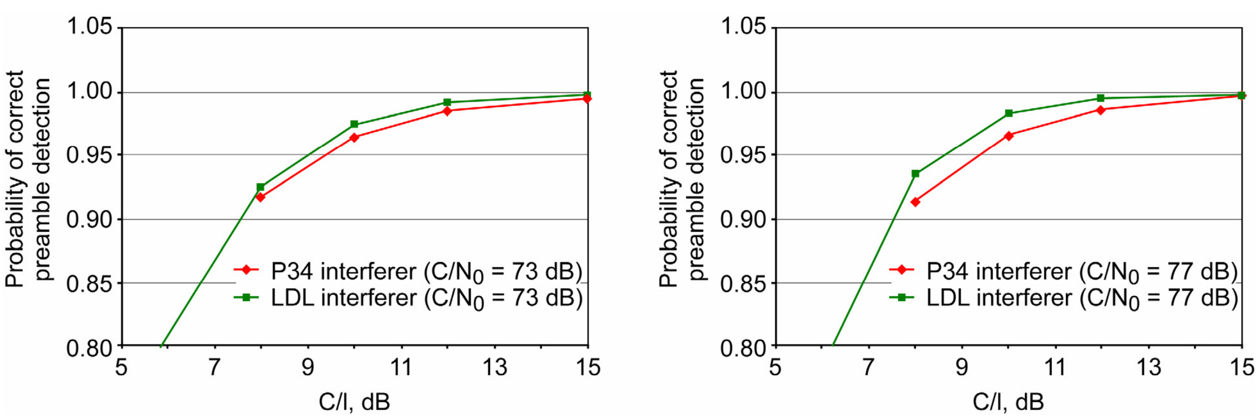


Figure 122.—Comparing effects of TIA–902 (P34) and LDL interference on Mode S—preamble detection.

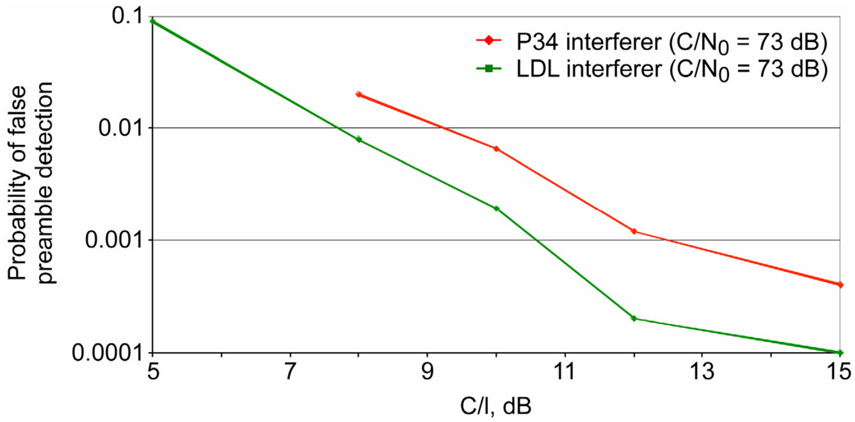


Figure 123.—Comparing effects of TIA–902 (P34) and LDL interference on Mode S—false preamble detection.

characterize Mode S behavior as there are other metrics to investigate besides preamble detection. Finally, the preamble detection modeled here is hardly sophisticated, and better performance from actual equipment is predicted.

D.7.4 L-Band Interference Measurements

In order to assess the viability of proposed communication systems in aeronautical L-band (960 to 1024 MHz), the potential for interference from FRS candidates to systems already utilizing this spectrum must be characterized. ITT, with the help of the Ohio University Avionics Engineering Department, conducted interference measurements against DME for three FRS candidate technologies: WCDMA, LDL, and P34.

Compatibility analysis of candidate technologies with DME in L-band involves many interference scenarios; the cosite interference scenario was the focus of the measurement study. The cosite interference scenario serves as a guide for specifying the bounds of interference power used when taking measurements. This study focuses only on the susceptibility of interference to existing airborne avionics. This study does not focus on interference from DME to FRS airborne avionics as L-band FRS receivers do not yet exist.

The overall approach for the interference measurements study consists of six interrelated tasks: generating a test plan and procedure, specifying interference sources to evaluate; procuring test equipment to emulate FRS transmitters; conducting bench tests against the DME receivers; analyzing and reducing the measurement data; and finally documenting the results.

The basic methodology for characterizing interference susceptibility is to observe the response of the DME interrogator in the presence of the interfering signals. The interfering waveforms are injected into the system at various frequency separations and the signal levels are incrementally adjusted in order to determine the power thresholds that induce a standard response from the device under test.

The test setup for the interference measurements is illustrated in figure 124. Interrogations are sent from the DME interrogator to the DME test set. The DME test set replies to interrogations with a DME reply signal. The DME reply signal is coupled with the interference signal and the DUT is observed. The interference signal undergoes bandpass filtering before it is coupled with the DME reply signal. This is performed to reduce transmitter broadband noise that produced by the vector signal generator. The spectrum analyzer allows test engineers to observe spectrums of the signals in the system.

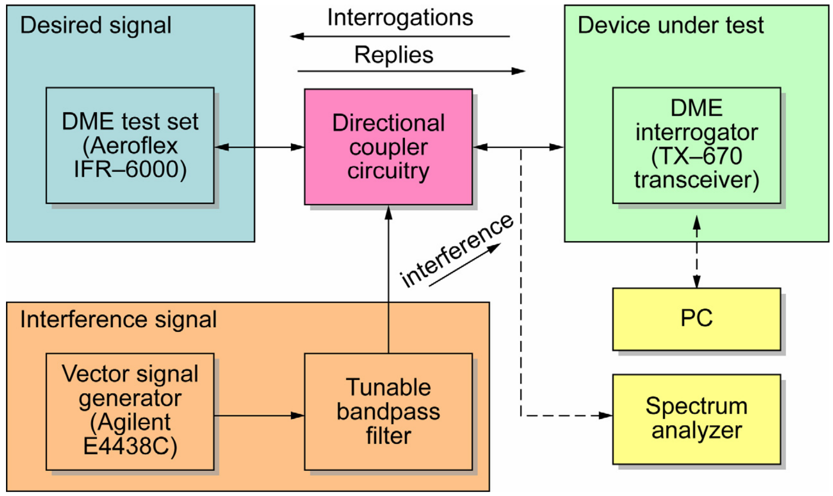


Figure 124.—Test setup for DME interference measurements.

L-band interference measurements results are summarized as follows:

- The power levels expected from continuously transmitting FRS equipment onboard the aircraft may be sufficiently high as to cause desensitization in the DME interrogator. This phenomenon was evident for all of the FRS candidates, even at large frequency separations for the DME that was tested. This finding is not favorable for FRS candidate technologies whose concept of use assumes continuous transmissions (e.g., WCDMA).
- The data also indicates that the DME interrogator is more tolerant to gated transmissions (i.e., there is potential for implementation of a technology with a gated waveform; but offset channels may still be required (to be investigated)). A majority of the measurements used 100 percent duty cycles, which results in a conservative analysis. Lesser duty cycles may be expected in practice. It is expected that low-to-moderate duty cycles will interfere less with DME compared to FRSs with high duty cycles. This finding may be favorable for FRS candidate technologies whose concept of use assumes noncontinuous transmissions (i.e., LDL and TIA–902 (P34) (partial)).
- It is recommended that further analysis be conducted to characterize the relationship between FRS duty-cycle and interference susceptibility (the duty cycle investigation should include more variables than just overall duty cycle; there may be some combination of specific time-scales of on/off pulses and overall duty cycle that results a seemingly “invisible” waveform from the DME interrogator’s perspective). In the context of this investigation, identification of collocation constraints can also be investigated. It is also recommended that different models of DME interrogators be tested to provide a range of performance.

A detailed description of this L-band interference measurements task, including approach, methodology, test setup, test results, and conclusions, can be found in the FCS Phase III interim report, Section 2.

D.8 Satellite Technology Availability Performance

For the satellite and over-horizon technology family, two technology inventory candidates have emerged from the technology screening: Inmarsat SBB and Custom Satellite Solution. For satellite aeronautical communication solutions, availability typically arises as an important issue to address. In order to provide required availability, a highly redundant custom satellite system architecture is needed. As this issue is similar for both Inmarsat and Custom Satellite Solutions, it was considered instructive to estimate the availability of two existing, operational satellite systems, Inmarsat SBB and Iridium, which provide services in protected aeronautical spectrum (AMS(R)S).

The approach used for satellite communications (SATCOM) availability modeling was the analysis model described in RTCA DO–270. This document defines an availability fault tree to permit characterization and evaluation of multiple availability elements. The fault tree is organized into two major categories, system component failures and fault-free rare events. This model, shown in figure 125, was useful for comparing architectures and was applied in this study.

Details of the evaluation of each component failure (see fig. 125) are documented in the FCS Phase II report, Section E.2. Figure 126 shows a summary of availability modeling results. For SATCOM systems, limiting factors for availability include satellite equipment failures and RF link effects (Inmarsat and Iridium), capacity overload (Iridium), and interference (Iridium). For the VHF terrestrial reference architecture, the limiting factors for availability include RF link events and capacity overload. Overall, the detailed evaluation of satellite communication systems (with a focus on provision of required availability) indicated that both Inmarsat SBB and Iridium would not meet availability requirements. Also, Custom Satellite Solution designed to meet COCR availability requirements would, in fact, require a highly redundant and costly architecture. Although availability concerns may limit the use of satellites as cost-effective solutions for continental airspace domains, this does not preclude their effective role in providing communication capability in remote and oceanic airspace.

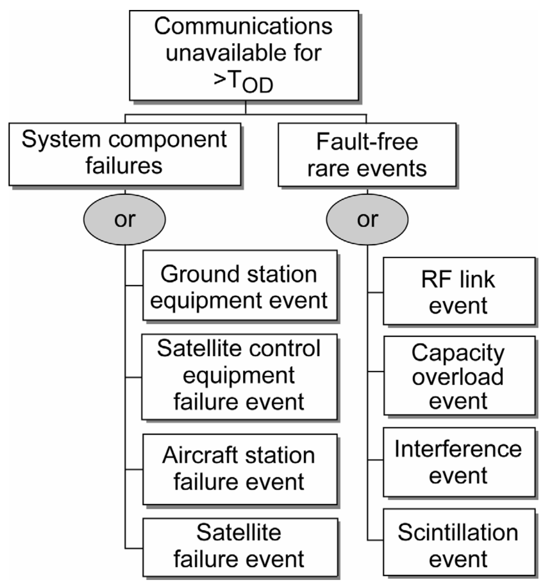


Figure 125.—SATCOM availability modeling approach—Fault tree.

	System component failures				Fault-free rare events			
	Ground station	Control station	Aircraft station	Satellite	RF link	Capacity overload	Interference	Scintillation
Inmarsat	~ 1	~ 1	~ 1	0.9999	0.95	~ 1	~ 1	~ 1
Iridium	0.99997	~ 1	~ 1	0.99	0.995	–1	0.996	~ 1
VHF Terrestrial	0.99999	N/A	~ 1	N/A	0.999	–2	~ 1	N/A

Notes:

1 NASA Technology Investigations for the Future Communications Study. Iridium Capacity Overload availability of AES to SATCOM traffic is essentially one (1) (for both ATS only and ATS and AOC). No steady-state can be achieved for SATCOM to AES traffic.

2 Terrestrial Capacity Overload availability is for VHF-Band reference architecture business case; for L-Band Terrestrial Capacity Overload availability would be essentially one (1).

Figure 126.—Summary of availability modeling results.

D.9 C-Band Technology (IEEE 802.16e) Performance

C-band modeling activities were conducted to investigate the utility of an industry standard system in the APT surface environment. The system that was chosen for analysis was the IEEE 802.16e metropolitan area network (MAN) interface standard. The IEEE 802.16e standard (referred to as simply the 802.16e standard, or 802.16e henceforth) was chosen as it scored well during the initial phase (technology prescreening) of the FCS technology investigations.

As the 802.16e standard supports a range of physical layers, prior to the modeling process, a specific physical layer needed to be selected. Of the possible candidates, better mobility performance is expected from OFDMA than OFDM, and the leading commercial 802.16 forum (the WiMAX Forum) has defined "Mobile" WiMAX profiles, which are all expected to adopt the OFDMA physical layer. In this study, however, the OFDM physical layer was selected for analysis, as it seems that if good performance can be predicted for OFDM then by inference the OFDMA physical layer would also work well. Further, there are commercially available chipsets for the 802.16 OFDM physical layer currently available. Since a logical next step to this research would be prototype implementations and trials in the band, and noting that OFDM (due to the aforementioned chipset) is more amenable to prototype equipment development, this seemed to be a reasonable decision.

Implementing the methodology defined above, 802.16e transmitter and receiver functions were modeled in the MATLAB Simulink environment. The next step in the C-band modeling work was to validate the developed model, as depicted in figure 127. Specifically, the simulation was executed in an AWGN environment and corresponding results compared to published results. Good correlation was achieved. Details related to the developed models and validation results can be found in the FCS Phase II report, Section E.3.2.1.

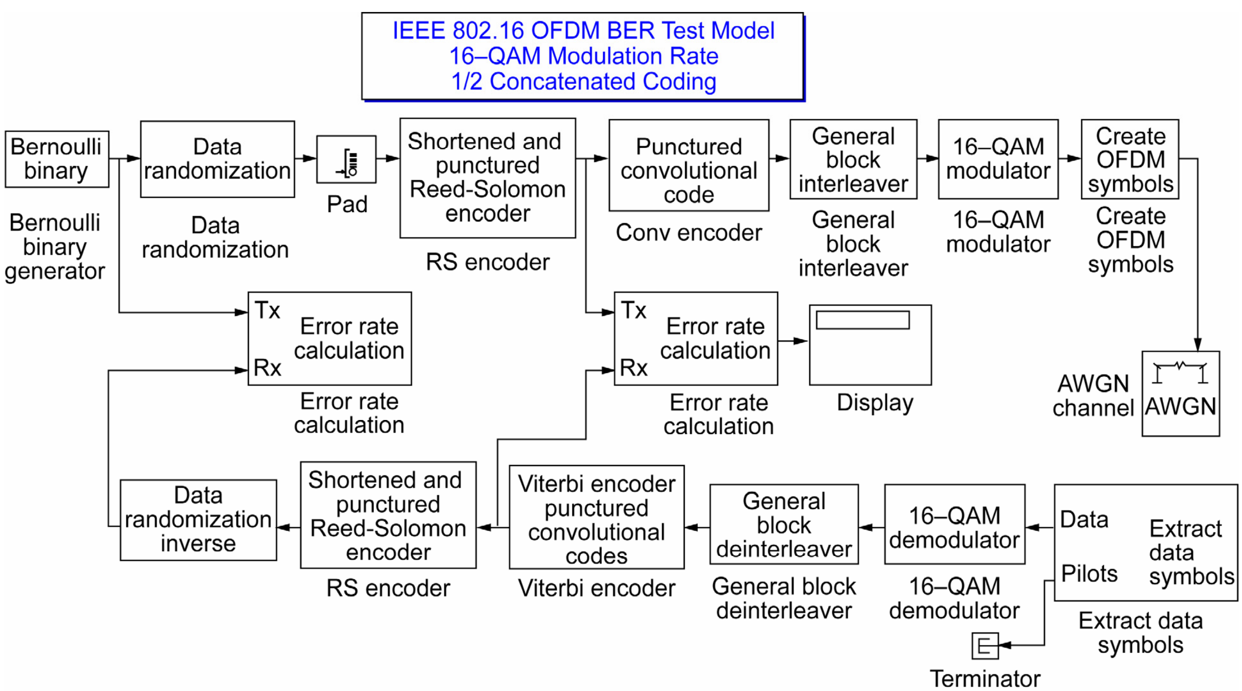


Figure 127.—802.16e end-to-end model.

Using a channel model adapted from a detailed model developed by Ohio University (described in detail in Section E.3.3 of the FCS Phase II report), the performance of 802.16e in the aeronautical APT environment was simulated as shown in figure 128. Here performance was found to be quite good for most of the movement area (incorporating equalization techniques). While this technology has good potential applicability for this domain, additional analysis to look at features to enhance performance (e.g., hybrid automatic repeat request, fast feedback channel, and diversity subcarrier permutations) is warranted.

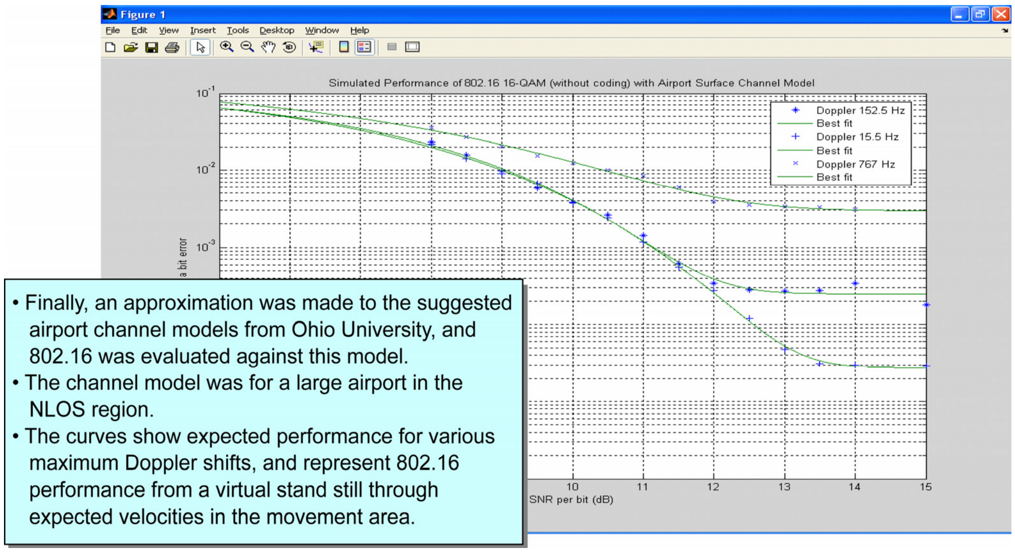


Figure 128.—The 802.16e simulation results for the aeronautical C-band surface channel model.

Appendix E—List of Acronyms and Abbreviations

The following list identifies acronyms and abbreviations used throughout this report.

1G	1st generation cellular
1x	single carrier
2G	2nd generation cellular
3G	3rd generation cellular
3GPP	Third Generation Partnership Project
3GPP2	Third Generation Partnership Project 2
4G	4th generation cellular
A/A	air-to-air
A–CLDL	acknowledged, connectionless data link
ACMS	aircraft condition and monitoring system
ACP	Aeronautical Communications Panel
ADL	airport data link
ADS–B	Automatic Dependent Surveillance–Broadcast
A/G	air/ground
AGR	air/ground router
AHP	analytical hierarchy process
AI	air interface
AMCP	Aeronautical mobile communications panel
AMACS	all-purpose multichannel aviation communication system
AM(R)S	Aeronautical Mobile (Route) Service
AMU	airborne audio management unit
ANI	airborne network interface
AOC	aeronautical operational control
AOPA	Aircraft Owners and Pilots Association
AP–17	action plan–17
APC	airline passenger communications
APCO	Association of Public-Safety Communications Officers
APT	airport
ARIB	Association of Radio Industries and Businesses
ARNS	aeronautical radio navigation services
ARQ	automatic repeat request
ASAS	air-to-air broadcast
ASK	amplitude shift keying
A–SMGCS	Advanced Surface Movement and Guidance System
ATA	Air Traffic Association
ATCRBS	air traffic control radio beacon system
ATM	air traffic management
ATMAC	air traffic management advisory committee

ATN	aeronautical telecommunications network
ATS	air traffic services
ATSP	air traffic service provider
ATSU	air traffic services unit
AUC	authentication center
AVLC	aviation VHF link control
AWGN	additive white gaussian noise
BA	base audio
B–AMC	broadband aeronautical multicarrier communications
BC	broadcast
BE	best effort service
BER	bit error rate
BGAN	Broadband Global Area Network
BLOS	beyond line of sight
BOC	billing operations center
BFSK	binary frequency shift keying
BPSK	binary phase shift keying
BR	base radio
BRC	base routing and control
BSC	base station controller
BSOP	break stable operating point
BSS	basic service set
BTS	base transceiver station
B–VHF	broadband VHF
CBS	cell broadcast service
CC	common control
C/I	carrier to interference
C/N	carrier/noise power ratio measured in db
CDMA	code division multiple access
CLI	calling line identification
CLNO	connectionless network protocol
CLNS	connectionless network service
CM	configuration management
CMC	central maintenance computer
CMU	communications management unit
CN	core network
CNS	communication, navigation, surveillance
COCR	communications operating concept and requirements
CODEC	combined coder and decoder
CoS	class of service
COTS	commercial off-the-shelf
CPDLC	controller pilot data link communications
CPFSK	continuous phase frequency shift keying\

CS	circuit-switched
DC	dedicated control
DCN	data core network
DECT	digital enhanced (formerly "European") cordless telecommunications
DLE	data link entity
DLIC	data link initiation capability
DLS	data link services
DME	distance measuring equipment
DMO	direct mode operation
DPCCH	dedicated physical control channel
DPCH	dedicated physical channel
DPDCH	dedicated physical data channel
DQPSK	differential quaternary phase shift keying
DSB–AM	double sideband amplitude modulation
D/U	desired-to-undesired
EDACS	enhanced digital access communications system
EDGE	enhanced data rates for GSM evolution
EIA	Electronic Industries Alliance
EPLRS	enhanced position location reporting system
ER	en route
ESA	European Space Agency
E–TDMA	enhanced time division multiple access
ETSI	European Telecommunications Standards Institute
EU	European Union
FAA	Federal Aviation Administration
FBI	feedback information
FCI	future communications infrastructure
FCC	Federal Communications Commission
FDD	frequency division duplex
FDM	frequency division multiplexing
FDMA	frequency division multiple access
FEC	forward error correction
FED	Federal Government
FIS–B	flight information service—broadcast
FL	forward link
FMS	flight management system
FNE	fixed network equipment
FRC	forward reference carrier
FRS	future radio system
GFSK	gaussian frequency shift keying
GGSN	gateway GPRS support node
GNI	ground network interface
GPRS	general packet radio services

GPS	global positioning satellite
GSC	ground station controller
GSM	global system for mobile communications
GSM–R	global system for mobile communications rail extension
HLR	home location register
IATA	International Air Transport Association
IBSS	independent basic service set
ICAO	International Civil Aviation Organization
iDEN	integrated dispatch enhanced network
IEEE	Institute of Electrical and Electronics Engineering
IETF	Internet Engineering Task Force
IOTA	isotropic orthogonal transform algorithm
IP	internet protocol
IPDN	internet packed data network
IPsec	IP security
IPv4	IP version 4
IPv6	IP version 6
IRL	implementation readiness level
ISO	International Standards Organization
ITU	International Telecommunications Union
JTIDS	joint tactical information distribution system
JTRS	joint tactical radio system
LAN	local area network
L–DACS	L-band digital aeronautical communications system
LDL	L-band digital link
LEO	low Earth orbit
LME	link management entity
LOS	line of sight
MAC	media access control
MAN	metropolitan area network
MASPS	minimum aviation system performance standards
MCDU	multipurpose control and display unit
MC–CDMA	multicarrier code division multiple access
MC–TDMA	multicarrier time division multiple access
MDP	mobile data peripheral
MDR	multimode digital radio
MESA	mobility for emergency and safety applications
MHz	megahertz
MIDS	multifunctional information distribution system
MLS	microwave landing system
MM	mobility management
MOPS	minimum operational performance standards
MPDS	mobile packet data service

MR	mobile radio
MRC	mobile router and control
MSC	mobile switching center
MSK	minimum shift keying
MTSAT	multifunctional transport satellite
NASTD	National Association of State Telecommunications Directors
NBAA	National Business Aviation Association
NLOS	non-line-of sight
OFDM	orthogonal frequency division multiplexing
ORP	oceanic and polar
OSI	open systems interconnection
OVSF	orthogonal variable spreading factor
PAN	personal area networks
PIAC	peak instantaneous aircraft count
PDN	packet data network
PoC	PTT over cellular
PS	packet-switched
PTM	point-to-multipoint
PTP	point-to-point
PTT	push to talk
QAM	quadrature amplitude modulation
QoS	quality of service
QPSK	quadrature phase shift keying
RCTP	required communication technical performance
RA	random access
RF	radiofrequency
RFI	request for information
RFG	radio frequency gateway
RIU	radio interface unit
RL	reverse link
RLOS	radio line of sight
RMS	root mean square
RNSS	radio-navigation satellite service
ROI	return on investment
RTCA	Radio Technical Commission for Aeronautics
RTP	real-time transit protocol
RTT	radio transmission technology
SA	synchronized access
SAIC	single antenna interference cancellation
SAM	scalable adaptive modulation
SARP	autonomous pulse record system
SATCOM	satellite communications
SBB	swift broadband

SCC	satellite control center
SCDMA	see CDMA
SDLS	satellite data link system
SDS	short data service
SGSN	serving GPRS support node
SINCGARS	single channel ground and airborne radio system
SMS	short messaging service
SNDCF	subnetwork dependent convergence facility
SNDCP	subnetwork dependent convergence protocol
TCP	terminal control protocol
TDD	time division duplex
TDL	tactical data link
TDMA	time division multiple access
TD–SCDMA	time duplex-synchronous code division multiple access
TEDS	TETRA enhanced data service
TELCO	telephone company
TETRA	terrestrial trunked radio
TETRA MoU	terrestrial trunked radio memorandum of understanding
TIS–B	traffic information service—broadcast
TFCI	transport formal combination indication
TIA	Telecommunications Industry Association
TMA	terminal maneuvering area
TOC	tactical operations center
TRL	technology readiness level
TV	test volume
UAT	universal access transceiver
UDP	user datagram protocol
UE	user equipment
UMTS	universal mobile telecommunications service/3G technology
USSD	unstructured supplementary service data
UTRA	UMTS terrestrial radio air interface
VCS	ground voice system
V+D	voice plus data
VI	voice interface
VDL	very high frequency digital link
VHF	very high frequency
VLR	Visitor Location Register
VoIP	voice over internet protocol
VR	vehicular repeater
WAI	wideband air interface
WAN	wide area network
WAP	wireless application protocol
WCDMA	Wideband Code Division Multiple Access

WG	working group
WiMAX	Worldwide Interoperability Microwave Access
WRC	World Radiocommunications Conference

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REPORT DOCUMENTATION PAGE						*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*
01-04-2008

2. REPORT TYPE
Final Contractor Report

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Future Aeronautical Communication Infrastructure Technology Investigation

5a. CONTRACT NUMBER
NNC-05CA85C

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Gilbert, Tricia; Jin, Jenny; Berger, Jason; Henriksen, Steven

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
WBS 561581.02.08.03.11.01

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
ITT Corporation
12975 Worldgate Drive
Herndon, Virginia 20170-6008

8. PERFORMING ORGANIZATION REPORT NUMBER
E-16306

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORS ACRONYM(S)
NASA

11. SPONSORING/MONITORING REPORT NUMBER
NASA/CR-2008-215144; TR07040

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Category: 32
Available electronically at http://gltrs.grc.nasa.gov
This publication is available from the NASA Center for AeroSpace Information, 301-621-0390

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This National Aeronautics and Space Administration (NASA) Contractor Report summarizes and documents the work performed to investigate technologies that could support long-term aeronautical mobile communications operating concepts for air traffic management (ATM) in the timeframe of 2020 and beyond, and includes the associated findings and recommendations made by ITT Corporation and NASA Glenn Research Center to the Federal Aviation Administration (FAA). The work was completed as the final phase of a multiyear NASA contract in support of the Future Communication Study (FCS), a cooperative research and development program of the United States FAA, NASA, and EUROCONTROL. This final report focuses on an assessment of final five candidate technologies, and also provides an overview of the entire technology assessment process, including final recommendations.

15. SUBJECT TERMS
Ground-air-ground communication; Aircraft communication; Radio communication; Air traffic control

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			STI Help Desk (email:help@sti.nasa.gov)
U	U	U	UU	217	**19b. TELEPHONE NUMBER** *(include area code)* 301-621-0390