TECHNICAL MEMORANDUM
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ALTERNATE COMMUNICATIONS SPECTRUM STUDY (ACSS) FOR AVIATION DATA LINKS (ADL)

Project Final Report

for

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ADL	Aviation Data Link
ADS-B	Automatic Dependent Surveillance-Broadcast
AMPS	Advanced Mobile Phone System
AIC	Airborne Internet Consortium
AOC	Airline Operations Control
ARINC	Aeronautical Radio, Inc.
ATC	Air Traffic Control
ATM	Air Traffic Management
CDMA	Code Division Multiple Access
CNS	Communications, Navigation, Surveillance
DAMPS	Digital Advanced Mobile Phone System
DASC	Digital Avionics Systems Conference
DLL	Data Link Layer
DME	Distance Measuring Equipment
DS	Direct Sequence
FAA	Federal Aviation Administration
FCC	Federal Communications Commission
FDMA	Frequency Division Multiple Access
FEC	Forward Error Correction
FH	Frequency Hopped
FIS	Flight Information Services
GPS	Global Positioning System
GRC	Glenn Research Center
GSM	Global System for Mobile communication
ICAO	International Civil Aviation Organization
ICNS	Integrated Communications, Navigation, Surveillance
IEEE	Institute of Electrical and Electronics Engineers
ILS	Instrument Landing System
LAAS	Local Area Augmentation System
LAN	Local Area Network
MAC	Medium Access Control
MC	Multicarrier
MLS	Microwave Landing System
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NEXCOM	Next Generation Air-Ground Communications
NTIA	National Telecommunications & Information Administration

OFDM	Orthogonal Frequency Division Multiplexing
PHY	Physical Layer
QoS	Quality of Service
RCAG	Remote Communications Air Ground
RF	Radio Frequency
RTCA	Radio Technical Commission for Aeronautics
SATS	Small Aircraft Transportation System
SHF	Super High Frequency
SNIR	Signal to Noise Plus Interference Ratio
SNR	Signal to Noise Ratio
SS	Spread Spectrum
TDMA	Time Division Multiple Access
UAT	Universal Access Transceiver
UHF	Ultra High Frequency
VDL	VHF Digital Link
VHF	Very High Frequency
WINCOMM	Weather Information Communications program
WRC	World Radio Conference

EXECUTIVE SUMMARY

This report describes work conducted under NASA grant NAG3-2815, entitled "Airborne Internet: Alternate Spectrum Feasibility Study" during the period from January 2003 to July 2003. The aim of the work was to identify the key factors involved in the use of alternate spectrum in various bands for a future integrated CNS data link. The study focused on systems and spectral bands that can deliver VDL-or-higher data rates in a two-way communication setting (including air-ground, ground-air, and air-air modes of operation), with multiple platforms (aircraft) operating in the same local environment.

We begin with a review of the initial task list, and the final task list. The final task list contained a focus upon spectral availability and related systems that could be affected by the deployment of a new aviation data link (ADL) system. Most of this addresses the lower few layers of the communications protocol stack.

A brief review of current related efforts in the aeronautical community is then provided, in which we describe several systems and programs of interest. Participation in some of these efforts is recommended. We also delineate several of the advantages and disadvantages of these systems/efforts, in view of anticipated requirements of a new ADL.

Desired attributes of a new ADL system are then discussed, and a connection with existing systems is made. The need to consider a wider set of alternative systems and technologies is described, and the beneficial aspects of a particular transmission technique—spread spectrum—are discussed.

We then discuss in more detail several potential spectral regions, in terms of propagation conditions, available technology, spectrum availability, and waveform selection. Some comments on the need for standardization are also provided. We note that none of the existing systems described will likely meet the full range of desired features of a new ADL, but that several systems and spectral regions offer promise in terms of one or more characteristics.

A system design and analysis approach is then provided. In this, we again focus on the lower few layers of the protocol stack, and aim to capture the main features and parameters that must be selected in the design. Two appendices show example versions and initial results of the first few technical steps in the design approach.

Some conclusions are then drawn, and in the final section, recommendations are provided, the most important of which are repeated here:

1. Continue the effort begun here. As detailed in this report, we have only uncovered much of the work that needs to be done in order to provide the foundation for a flexible, high-performance, robust ADL.

2. Seize the opportunity to begin testing in the MLS band. The wide bandwidths and low level of usage of this band make it an ideal one for proof-of-concept type testing. Other (non-aeronautical) organizations are likely to make claims on the band if it is not being used.

The primary conclusion is that there is a real and pressing need for a new aviation data link.

1. INTRODUCTION

1.1 Background

The need for additional communication capabilities in civilian aviation is well documented. To support this claim, one can cite the Federal Aviation Administration's (FAA) National Airspace System (NAS) "modernization blueprint," [1], any one of numerous papers from recent professional conferences in the field, such as the Digital Avionics Systems Conferences (DASC), e.g., [2], [3], or recent Integrated Communications, Navigation, and Surveillance (ICNS) workshops, e.g., [4], [5]. The growth of passenger communications is also expected [6]. We thus begin with the premise that new capabilities are unquestionably in need, for the benefit of the aviation community.

Additional communication capabilities, along with additional navigation and surveillance capabilities, will require not only new technologies, but careful planning. The aim toward integration of these three functions (hence: ICNS) has initiated many studies on technology options, e.g., [7], [8], and many on planning efforts; this report is in fact one such effort, aimed at exploring potential requirements and means to achieve new CNS capabilities.

Until now, each component of the NAS has traditionally occupied and operated, independently, in its own reserved frequency spectrum. For example, VHF communications is allocated the 118.0-137.0 MHz frequency spectrum, navigation is allocated 108–118 MHz, 330 MHz and 900-1020 MHz, and surveillance is allocated 1030/1090 MHz. Next generation Air Traffic Control/Air Traffic Management (ATC/ATM) infrastructure development and systems, such as proposed by the NASA Small Aircraft Transportation System (SATS), are driving towards an "integrated" CNS system solution that can operate in a single "swath" of spectrum to gain efficiency in bandwidth usage and economy from integration of services.

Also, given that current services cannot be eliminated (at least not without a careful transition plan, over a potentially very long time period), additional frequency spectrum allocations appear essential to support any successful new aviation data link (ADL). The FAA's NEXCOM program [10] is an initial attempt to meet the burgeoning need for additional communications capability, but it is likely that this program and the systems it provides will be inadequate to meet these needs. This need for datalink bandwidth, beyond the currently used allocations dedicated to existing services, requires that the FAA examine spectrum usage across and beyond the traditional aeronautical spectrum. NASA Glenn Research Center's (GRC) continuing research into advanced communication systems has made significant contributions to the efforts of the FAA to enhance and improve the state of ATC/ATM communications. The recently formed Airborne Internet Consortium [9] will also contribute to these efforts.

This report examines the feasibility of using alternate spectrum that may be available for enhancing ATC/ATM communications in future operations of the NAS. Some of these alternative spectral bands include the portion of C-band that has been reserved for the Microwave Landing System (MLS) (5000-5250 MHz), unpaired Distance Measuring Equipment (DME) channels at 966, 971, and 981 MHz, and aeronautical spectrum at 330 MHz currently used for glideslope.

1.2 Report Scope

We first provide a brief discussion of the original set of tasks proposed for this work, and a description of how these tasks were focused. The original set of tasks partly illustrates the breadth of topics that should be considered for investigation for a thorough alternative communications spectrum study. The scope of the remainder of the report is then described.

As proposed, this work was to be a "feasibility study" for application of new communications technologies in several spectral bands. As such, we began with the aim of a first characterization of the key factors involved in the use of alternate spectrum in the 330 MHz, 970 MHz, and 5 GHz bands for a future integrated CNS data link. The study was to focus on systems that can deliver data rates that are at least as high as those planned for the new VHF data link (VDL) systems, in a 2-way communication setting (including air-ground, ground-air, and air-air modes of operation), with multiple platforms (aircraft) operating in the same local environment. We subsequently both broadened and deepened the study, but these candidate spectral bands are still of interest, both as potential spectrum, and as "case studies" to illustrate planning and methods of analysis.

1.2.1 Original Tasks

The initial areas of investigation, directed at the physical and data link layers, were as follows:

1. Spectrum availability: in addition to existing allocations per the FCC and NTIA, future systems such as the next-generation wireless LAN (IEEE standard 802.11a and 802.16) must be considered.

Study Goal: determine amount of "free" spectrum, and any potential CNS spectrum that could be allocated to ATC/ATM communications on either a shared or dedicated basis accommodating both non-time-critical messages and more critical pilot-controller communications. "Shared" spectrum incorporating AOC and APC services will be considered if sufficient synergy can be gained to justify economic goals.

2. Co-existence: related to spectrum availability, any new system must co-exist with current deployments and planned future system deployments.

Study Goal: based upon existing and planned systems, assess "intersystem" interference issues in both directions, i.e., from new CNS on existing, and from existing on new CNS. In future work, this could include study of simultaneous "overlay" of spread spectrum onto existing bands for mutual coexistence among systems in the same or adjacent bands.

3. Hardware: depending upon application, various transmission schemes currently used (e.g., 330 MHz, 970 MHz, MLS, or WLAN) require significantly different hardware components (e.g., power amplifiers), hence the impact of employing available hardware of a given type on system performance is critical to feasibility.

Study Goal: translate specifications on typical hardware for the various applications into communication link performance parameter estimates (range, margin, QoS, etc.) and physical installation feasibility. (size, weight, power, etc.)

4. Waveform: waveform selection has significant effect upon communication system performance in the presence of non-idealities (e.g., channel dispersion, nonlinear distortion, interference), and also upon hardware cost.

Study Goal: assess link performance (e.g., as described in #3 Goal) for several existing waveform types, and their suitability for any CNS-required modifications. Also consider potential new waveforms and their benefits/drawbacks.

5. Multiple Access: the new CNS system would require access to/from multiple platforms over time in a given spatial area, and total system throughput is a direct function of the chosen multiple access scheme.

Study Goal: assess existing multiple access approaches with regard to complexity, dependence upon ground/satellite infrastructure, and estimate system capacity. Also consider potential new multiple access schemes and their benefits/drawbacks.

Additional goals, to be pursued to the extent possible given the project funding and timeline, were as follows:

6. Identify potential ground networks, or suggest a notional network based on new spectrum allocation that can provide air-ground connectivity to support a national Airborne Internet ATC/ATM infrastructure that minimizes communication link coverage "holes." Options to begin a national grid-based system include SATS airports and existing RCAG sites.

7. Identify potential satellite communication systems that could supplement a national air/ground integrated CNS system to enable continuous ("seamless") connectivity for "remote" and "over-water" flight operations.

8. Identify potential technical solutions, in conjunction with ground network development (task 6), that could be used to provide an "autonomous navigation solution" for meeting GPS risk mitigation issues.

After the initial conference with FAA and GRC personnel, it was decided that some of the tasks as outlined would need to be conducted in follow-on studies, and that the effort for this project should focus on Task 1, Spectrum Availability. Most of the tasks as described are not independent, hence some of the work reported here can be viewed as fitting within Tasks 2-8. The majority of the effort falls under Task 1, of which Task 2 can be considered a subset.

1.2.2 Revised Tasks

For the revised task (essentially Task 1), the specific goals are to identify the key technical considerations and constraints involved with deploying any new ADL system in a given spectral band (or bands) and proceed, as appropriate, with more in-depth study and recommendations. In this project, we thus have worked to assess the feasibility of candidate spectral bands in terms of the following:

- Propagation
- Technology
- Spectrum Availability (Regulatory + Coexistence)

This has also required us to evaluate candidate technologies, in terms of

- Waveforms
- Aeronautical systems
- Alternatives, e.g., Cellular Standards

As is clear from most of the above points, the focus for this work is on the two or three lowest layers of the communications protocol stack: the physical layer (PHY), the data link layer (DLL), and the medium access control (MAC) layer.

Because of increased concern regarding communications security, the use of spread spectrum was identified as being very promising, and worthy of some detailed consideration. Hence, some analytical and simulation studies (described in the Appendices) were initiated. We have also kept apprised of the ongoing work in the Airborne Internet Consortium (AIC) [9]. This forum will be of use for gathering information on any proposed requirements for new ADL systems, and for enabling input to these requirements. We have attended several AIC meetings, and will likely attend additional meetings in the future. In particular, the relationship of the AIC to the Small Aircraft Transportation System (SATS) program is of interest, as the SATS program may be a useful area of application for a new ADL system.

1.2.3 Report Scope

In order to make this report as useful as possible to as wide an audience as practical, we provide some background, or overview material, on a few key pertinent topics. Section 2 of the report discusses several related efforts in terms of aviation communications. In Section 3 we discuss some of the desired attributes of a new ADL system. We also briefly note some of the steps and efforts that would be required to standardize any new ADL. This section also describes the attractive features of spread spectrum, and some of the unique characteristics regarding its implementation.

Section 4 discusses the potential spectral regions of interest. Focus is upon those already used for aeronautical purposes. In Section 5 we describe a general method useful for evaluating potential spectral regions. From the technical perspective, the focus is on the physical layer, but we also discuss additional related items such as technology re-use, cost and complexity concerns, and multiple band operation. Finally, Section 6 provides conclusions, and Section 7 provides a summary of our recommendations.

2. RELATED EFFORT REVIEW

2.1 Next Generation Air Ground Communications (NEXCOM)

The Next Generation Air Ground Communications (NEXCOM) program has been underway for several years in terms of R&D [10]. As described on the website, it is

> ...the Federal Aviation Administration's (FAA) radio system of the 21st century. It is an analog/digital system incorporating the latest technological advances in radio communications. NEXCOM will provide capability to accommodate additional sectors and services; reduce logistical costs; replace expensive to maintain VHF and UHF radios; provide data link communications capability; reduce A/G RF Interference and provide security mechanisms. When completed over 46,000 radios will be installed throughout the FAA system.

The NEXCOM program has several phases of implementation and refers several potential radio modes; the radios will operate in the VHF aeronautical spectrum, from 118.0-137.0 MHz, using the existing 25 kHz channels. The preferred radio mode is denoted VHF digital link (VDL) mode 3, offering both digital voice and data. The International Civil Aviation Organization (ICAO) has developed VDL Standards and Recommended Practices (SARPs) that define two additional VDL modes:

> Mode 1 using an MSK-AM modulation scheme providing a 2.4 kb/s data rate;
> Mode 2 using a D8PSK modulation scheme providing a 31.5 kb/s data rate.

The VDL2 system is a carrier sense-multiple access (CSMA) system that employs the same modulation as VDL3, differential 8-ary phase shift keying (D8PSK). The VDL2 system is not part of NEXCOM [11]. The VDL3 system is designed for time division multiple access (TDMA) operation, for both voice and data, ultimately as a replacement for the current analog AM system that is used for pilot-controller two-way communications. The VDL2 applications are generally classified under the following general categories:

- Air Traffic Control (ATC)
- Flight Information Services (FIS)
- Aeronautical Operational Control (AOC).

In addition, VDL2 is planned to be deployed and operated primarily by Aeronautical Radio, Incorporated (ARINC), whereas VDL3 will be operated by federal entities (e.g., the FAA). Also, VDL2 is planned to support only non-time-critical messages. A brief summary table of some of the attributes of the VDL3 system is given in Table 1.

As noted in [11], NEXCOM is being designed to work within existing channel configurations, and will not result in the establishment of any new radio sites. This implies that radio coverage will not be extended. Hence, untowered-uncontrolled airports are not likely to obtain any new NEXCOM services. Explicit in [11] is the requirement for backward compatibility of NEXCOM, which means that the VDL3 radios will be multi-mode radios, capable of offering digital VDL3, or 25 kHz or 8.33 kHz analog services.

The data rates available for digital data with VDL3 are modest. Per *all four* timeslots, 19.2 kbps can be attained. In the current configuration, a maximum of three timeslots can be used for data.

Table 1. Summary of some VDL3 characteristics.

Parameter or Characteristic	VDL3 Parameter Value
Frequency Band	118-137 MHz
# Channels	~ 760
Radio Range Limits (due to timing/delay)	200 nmi, for 4-slot mode 600 nmi, for 3-slot mode
Approximate Channel Bandwidth (90% power)	$B_{90} \cong 16.8$ kHz
Multiple Access (MA)	TDMA (polling & random access)
Channel Data Rate R_b (kbps)	31.5
Minimum total frequency band for operation	25 kHz
Duplex method	Time: dedicated uplink/downlink slots
Minimum up/downlink frequency separation	0
Frequency planning requirements (re-use)	Unknown: likely a re-use factor of > 7
RF channel spacing Δf	25 kHz
Spectral Efficiency (bps/Hz)	31.5 kbps/16.8 kHz = 1.875
Max. User R_b (kbps) per timeslot	4.8 (192 symbols/30ms burst/4)
Multi-User Capacity: contention effect on overall R_b	With assigned channels, full R_b
Modulation	D8PSK, w/RRC pulse shaping, $\alpha = 0.6$
Frame time	120 ms
# Timeslots/frame	3 or 4
Synchronization Sequence	Two 16-symbol words/slot
User services	Voice and Data Point-to-point: Ground↔Air Broadcast: Ground-to-air
Addressing capability	Two-way

2.2 Small Aircraft Transportation System (SATS)

The Small Aircraft Transportation System (SATS) program is a joint FAA/NASA program to explore future means of air transportation with small aircraft. The initial work is focused on research and development of some of the technologies needed for SATS [12]: "the project's initial focus is to prove that four new operating capabilities will enable safe and affordable access to virtually any runway in the nation in most weather conditions. These new operating capabilities rely on on-board computing, advanced flight controls, Highway in the Sky displays, and automated air traffic separation and sequencing technologies."

The technologies referred to are actually composed of multiple subsystems beneath. We consider only the last one—automated air traffic separation and sequencing technologies. Clearly these must include communication systems, navigation systems, and surveillance systems (CNS), all of which must work together to ensure safety of all phases of flight. Recently, NASA (Glenn and Langley) reported successful demonstration of some "airborne internet" capabilities [13]. This demonstration was also presented at the most recent ICNS conference, May 2003, in Annapolis, MD. The demonstration showed the feasibility of some of the required features of "airborne internet," related to SATS. Yet it was still only a demonstration, and used VDL mode 4 radio technology "research purposes" in developing for the physical and lower layers. This was primarily because of the readily available and simple interface between the radio and common internet connections. The VDL mode 4 radios are not planned to be used in the US for any communication system.

As noted in [13], the next stage planned for this capability will be transfer of the demonstration system to one of the SATSLabs and the Airborne Internet Consortium (see below) for experimental evaluations and commercialization. These two steps (evaluation and commercialization) may require substantial changes to the demonstration system in terms of its components, capabilities, and modes of operation. That is, a final SATS airborne internet communication system (even the lowest few layers) will likely be substantially different from the demonstration system. A few items of interest in this study that could, or will likely change, include the following

- frequency band of operation,
- available data rates and channel bandwidths,
- number of simultaneous users,
- range and spatial discrimination.

Nevertheless, the SATS program may in fact be one of the best "vehicles" for development of a true production-quality airborne internet communication system. This is discussed below in Section 2.4.

2.3 Universal Access Transceiver (UAT)

The Universal Access Transceiver (UAT) system is, like NEXCOM, a set of technologies applicable to the lower few layers of the communications protocol stack. The UAT has been mostly applied to surveillance applications, in particular Automatic Dependent Surveillance—Broadcast (ADS-B). In this application, it has been successfully deployed on a trial basis in Alaska. Plans for its use in the contiguous US may be underway.

The UAT system uses a fairly simple binary modulation, to enable reduction of aircraft radio costs. Like NEXCOM's VDL3, it also uses time slotting, and burst transmissions, although the aircraft transmissions are not assigned to slots, but are randomly accessed [14] (this is also known as "Slotted ALOHA" random access).

Multiple ground and airborne slots are available within each 1-second UAT frame period. The transmission rate is approximately 1 Mbps; with overhead and contention, the actual throughput is considerably less. For example, with ground transmission accounting for about

18% of each frame, with the Slotted ALOHA technique, the actual throughput (counting header and other overhead per each packet) would be approximately 0.36(0.82)1Mbps≅295 kbps. If more structured time slot allocations were imposed, the throughput could increase by approximately a factor of three (gaining back the Slotted ALOHA degradation). Clearly, the transmission technique of UAT itself is not as limiting in terms of data rate as is VDL3. In addition, the UAT transceivers do not (yet!) have to operate in more than a single mode, and hence can be less complex and less expensive. With their wider bandwidths, they are less spectrally efficient, but given their simpler design and more recent development, they could likely be more easily modified. The RTCA [15] is currently developing standards for UAT, and the FAA has a working group site for this [16]. The inability of the current UAT transceivers to provide individual message addressing and true peer-to-peer connectivity is one of the shortfalls of UAT for use in a new ADL system. In addition (like VDL3), no specific enhancements or features for robustness or strong security are provided in UAT. In Table 2 a set of summary UAT parameters is provided.

Table 2. Summary of some UAT characteristics.

Parameter or Characteristic	**UAT Parameter Value**
Frequency Band (currently unpaired DME channels)	(designable) In AK ~980 MHz
# Channels	1 (more if available)
Radio Range Limits (due to timing/delay)	Depends upon design
Approximate Channel Bandwidth (90% power)	$B_{90} \cong 1.4R_b$
Multiple Access (MA)	TD (Slotted ALOHA)
Channel Data Rate R_b (kbps)	1004.167
Minimum total frequency band for operation	~ 1 MHz
Duplex method	Time: dedicated uplink/downlink slots
Minimum up/downlink frequency separation	0
Frequency planning requirements (re-use)	Unknown: likely a re-use factor of > 7
RF channel spacing Δf	~2.8 MHz
Spectral Efficiency (bps/Hz)	0.714
Max. User R_b (kbps) per timeslot	Air: 701.75 Ground: 921.51 (Both counting user address as data)
Multi-User Capacity: contention effect on overall R_b	Degrade by 64% (multiply by 0.36) for MA (S-ALOHA)
Modulation	Binary CPFSK, h=0.6, $\Delta f = hR_b = 625$ kHz (900 kHz w/filtering)
Frame time	1 s
# Timeslots/frame	4000
Synchronization Sequence	36-bit preamble
User services	Data Point-to-point: Ground↔Air Broadcast: Ground-to-air
Addressing capability	One-way (broadcast)

2.4 Airborne Internet Consortium

The Airborne Internet Consortium (AIC) is recently formed group that has held several meetings in 2003 [9]. The group has also been termed the Airborne Internet Collaboration Forum. The group members come from the aviation industry, academia, and government organizations, and the purpose of the group is to:

- Encourage the development of an open systems architecture and standards for aviation digital communications
- Foster and promote internet protocols in aviation
- Develop intellectual content to guide and influence public and private investment.

Thus far, the group meetings have sought participation, discussed the group's aims, and outlined items for a workplan. As noted in the discussion on SATS above, there is a strong connection between this group and SATS. The nascent workplan items of direct relevance to our work are the following:

- Integrated CNS requirements
- Architectural candidates, trade-offs and evaluation
- AI system design
- Test and evaluation
- AI design and use of VDL, SAT, 802.11…
- Applicable technology assessment
- Applicable communication standards assessments.

Currently, our focus has been on the second, fifth-seventh items in this list. The above list is from a longer list compiled at the most recent AIC meeting on June 19, 2003, and is still a draft, or "working document" in form and function. Our participation in the AIC will continue as appropriate, depending upon future work we undertake.

3. DESIRED ATTRIBUTES OF ADL

In this section we discuss desirable attributes of a new ADL. As noted in other sections, our focus thus far is on the lower layers of the communications protocol stack: PHY, DLL, and MAC. In addition, as would be expected at this early stage, most of the attributes are qualitative. Turning these qualitative "desires" into quantitative requirements would be a future task, dependent upon a number of things such as transmission technology, available spectral bandwidth, expected geographic deployment, other aeronautical systems that could be affected, primary ADL system users and their "concept of operations," and the plan for the timing of actual deployment. Nevertheless, it is worth outlining these desired system attributes for the purpose of discussion, and completeness.

For widespread acceptance of any ADL system, the system must offer capabilities not present, or at least not fully supported by existing systems. Generally, this would mean that the new ADL system should offer higher data rates than existing systems. It should also be able to serve a large number of users "simultaneously" in any given geographic area. The geographic area, and hence range for air-ground, ground-air, or air-air communications should be as large as possible. Connectivity should be ideally peer-to-peer, so that any aircraft could transmit and receive data to/from any other aircraft or ground station in range.

The ADL system should be able to support asymmetric services, i.e., services that require different data rates in the different directions of transmission. This asymmetry is being designed into many new terrestrial wireless systems, and is based upon the asymmetric data rates common with Internet usage.

A new ADL system should also allow for a wide variety of data rates and data traffic types, with differing requirements on message latency (delay) and integrity. This variety is often cast in terms of Quality of Service (QoS) parameters: data rate (R_b), delay (τ), and error probability (e.g., P_b for bit error probability). A variety of message rates would enable the ADL system to be used for multiple purposes, which would enhance its acceptance.

Last, the system should be reliable, which implies redundancy, and it should be secure in several ways. The ADL system should be difficult to spoof (allow an unauthorized entity to masquerade as a system user or operator, thereby disrupting service). It should also be difficult to eavesdrop upon, for privacy reasons. It should also be difficult to disrupt or overload.

3.1 ADL Attributes in Relation to Existing Efforts

We discuss the desired ADL attributes as they relate to some existing efforts. Our main aim here is to identify both the beneficial aspects and the potential shortcomings of the existing efforts, for the benefit of any new ADL system design.

Regarding NEXCOM (i.e., VDL3), the main positive aspects are the highly structured and well-defined system timing, and the set of radio "states" and procedures. The radio "states" specify the logical modes of operation. For a new ADL, one of the biggest shortcomings of VDL3 is its low data rate—4.8 kbps per timeslot. In the current design, only up to two timeslots can be used for data, but this could be modified to allow all four timeslots to be used, yielding a data rate of 19.2 kbps.

Another key limitation of VDL3 is its fairly large required effective signal to noise ratio (SNR). This SNR is more accurately denoted the signal-to-noise-plus-interference ratio, or SNIR. An equivalent term in common usage is the co-channel protection ratio (CCPR). This CCPR is cited as 20 dB [17]. A large SNIR translates to a larger frequency-reuse value [18], which reduces overall system capacity. The difficulty of frequency planning for TDMA/FDMA systems is another drawback to these techniques. Part of the reason for the large SNIR requirement is simply margin—ensuring adequate performance under the most extreme conditions. Yet, the use of differential, instead of coherent, demodulation, and the relatively moderate-strength forward error correction (FEC) coding of VDL3 also contribute to the large SNIR requirement. In addition, it is not clear if any antenna diversity is applicable, nor are any signal processing subsystems in place to mitigate the effect of multipath distortion (this distortion will generally be minimal, except when the elevation angle of transmission is small). Finally, the VDL3 waveform is not designed for operation in the presence of interference, either unintentional or intentional; it has mechanisms to prevent spoofing and eavesdropping, but is not designed to withstand hostile interference (jamming).

For UAT, the available data rates are much higher, in particular if a structured (i.e., not random) access method could be applied. The simpler binary modulation scheme is also attractive. The required SNIR for UAT is considerably smaller than that for VDL3, on the order of 6 dB. This is due to the smaller modulation alphabet size, and the use of a generally stronger FEC code. Hence, in communications parlance, UAT is more energy efficient than VDL3, but VDL3 is more bandwidth efficient. Direct addressability of any platform in the current UAT design is not available, and like VDL3, the UAT design is not robust in the presence of interference.

While there are currently no precise requirements for a new ADL, designing any new system with low data rates (say, below 64 kbps) would prove severely limiting to future growth and widespread system acceptance. The data rates quoted in [19], an early airborne internet/SATS study, are surprisingly low. These are based upon

1. 100 aircraft within 50 miles of a SATS airfield
2. 250 aircraft within 50 miles of a SATS airfield

and include services such as Flight Information Services (FIS), Local Area Augmentation System (LAAS) data, etc. The data rates on average are only a few kbps, but did not consider any new services such as weather imagery. As a counterexample, the recent paper from the German Aerospace Center [8] describes plans for a system that supports data rates from 128 kbps to 2.048 Mbps. The early AI report [19] should though serve as a good baseline for future requirements studies, in particular its methodology. What could be called into question in [19] is the use of the "LA Basin" traffic model, which likely needs updating.

3.2 Attributes and System Design Parameters

Returning to some of the specific elements of our study, we now discuss what the desired attributes mean, or translate to, in terms of several general technical areas. As would be expected, these elements are intricately inter-related, and study of one generally leads into study of others.

3.2.1 Propagation

As is well known, propagation in the lower atmosphere undergoes a loss due to wavefront "spreading," which is proportional to carrier frequency. Hence for a given value of transmit power, range decreases as carrier frequency increases. Use of VHF, UHF, and SHF bands are most likely for any new ADL system. For maximum range, VHF is preferable, but the drawback is shortage of available aeronautical spectrum. In general, spectral bandwidths increase as carrier frequency increases. Depending upon concept of operations, the shorter range associated with the higher frequency bands may need to be addressed through the use of (adaptive) directive antenna systems, extraordinarily strong FEC (e.g., "turbo" codes), or relay techniques. Another possibility is the use of different frequency bands for different services and different phases of flight. For example, during takeoff and landing, when aircraft are relatively close to ground stations, higher-bandwidth shorter-range bands such as SHF could be used, and during "enroute" higher altitude phases of flight, lower data rate VHF bands could be used.

3.2.2 Technology

Generally, the term technology is quite broad in terms of interpretation. We restrict our attention here to its use to describe the circuits and subsystems that are either readily available, or "nearly available." An example of the latter is radio frequency components (e.g., amplifiers) being developed for nascent wireless local area networks (LANs) in the 5.8 GHz unlicensed band.

Clearly for reasons of economy, re-use of existing technologies is most attractive. For any new system design though, some modifications will be likely. Because of this, it makes much sense to consider technologies being developed for other applications (discussed below). Many of these technologies (e.g., wireless LANs) are planning to offer very high data rates, multiple levels of QoS, and strong security.

3.2.3 Spectrum Availability

This issue may prove to be one of the most significant for any new ADL system. With the aeronautical spectrum at VHF nearly full, obtaining any new bands at VHF will require significant administrative support. Currently, some of the SHF band reserved for aeronautical use, specifically the microwave landing system (MLS) band at 5 GHz, is being targeted by other (non-aeronautical) users in both Europe and the US. Hence, it is in the best interest of the aeronautical community to deploy even a prototype ADL system in the MLS band, simply for the sake of maintaining control over this portion of spectrum.

A second, more technical concern regards the coexistence of a new ADL system with any currently existing system. This will impact the ADL design in terms of out-of-band emissions, power levels, and spectral mask, and hence relates closely to the physical layer design.

3.2.4 Waveforms

The topic of waveforms is of course a physical layer one, and as noted above, cannot be considered in isolation. Yet with the fairly mature state of digital wireless communications, we have at our disposal a vast array of waveform choices, with mostly well-known (or estimate-able) characteristics. More will be said regarding waveforms in the subsection below on spread spectrum, and in the appendices.

3.2.5 Alternative Systems

As can be said of the topic of waveforms, it makes good sense to take advantage of the knowledge and techniques applicable to systems designed for other applications. One example is terrestrial cellular radio, for which at least three standards are currently in use worldwide: frequency division multiple access (FDMA) with analog FM modulation (the advanced mobile phone system, AMPS), time division multiple access (TDMA) with narrowband digital modulation (digital amps, DAMPS, or the Global System for Mobile communications, GSM), and code division multiple access (CDMA) with digital spread spectrum modulation (cdmaOne)

[18]. In addition, new upgrades to these standards are in current development (and some deployment, particularly in Japan). All of these upgrades are planning to employ CDMA.

Other commercial systems of interest include the wireless LAN standards, mostly overseen by the IEEE as their "802" set of standards. The 802.11b standard is currently in widespread use, with a direct-sequence spread spectrum (DS-SS) transmission scheme that uses the 2.4 GHz unlicensed band. It is capable of offering data rates up to 11 Mbps for short range applications. The 802.11a standard is currently nearly mature, with a form of spread spectrum (orthogonal frequency division multiplexing, OFDM) for the 5.8 GHz unlicensed band, with data rates up to approximately 50 Mbps, also for short range applications. A new 802 standard is also being developed, the 802.20 standard, aimed at data rates comparable to those of the 802.11a standard, but for high-speed mobile platforms.

Finally, systems and techniques used in military systems (both aeronautical and others) are also of interest, in particular for their very good security and robustness.

3.3 Use of Spread Spectrum

As alluded to earlier, the use of spread spectrum (SS) transmission offers several advantages over narrowband transmission schemes. This is certainly one of the reasons that ALL of the new terrestrial cellular standards will use SS [20], [21]. Generally, SS schemes are of two types: direct-sequence (DS) and frequency hopped (FH). Each has its own particular advantages and disadvantages with respect to the other, but both offer the following attractive properties:

- Security: SS transmissions are difficult to eavesdrop on because of their use of platform-unique spreading codes.
- Robustness: SS transmissions are resistant to interference, and can operate very well in distorting channel conditions
- Capacity: in the cellular context, SS schemes, used in CDMA fashion, have proven superior to narrowband schemes in terms of the number of simultaneous users they can support.
- Flexibility: in many ways, the use of strong and variable-rate FEC, and the use of advanced detection techniques is facilitated via SS transmission.

In addition, SS in various forms can be used simultaneously in the same spectrum with narrowband schemes. This is termed spectral overlay. Depending upon the actual bandwidth, SS transmissions can also be used for ranging (e.g., GPS is a spread spectrum system). During the development of SS CDMA for terrestrial cellular systems, it was initially presumed that the overall complexity of a CDMA system would prevent its deployment. This was proved incorrect, and the technologies required for effective SS transmission and reception are readily available. Also worthy of note is that the European aeronautical community is already conducting experiments with SS transmission [22]. Because of all the above qualities, SS is a good candidate for consideration in a new ADL system.

3.4 ADL Standardization

Ultimately, for any ADL system to succeed, it must be widely adopted. The development of an actual standard for ADL would be required to facilitate this adoption. This is currently outside the scope of this effort, but we make some brief comments on the subject.

If new spectrum is required, or if a case for a new use of existing spectrum must be made, this may require that ADL system developers and proponents participate in the periodic World Radio Conference (WRC) meetings. For domestic concerns, the RTCA would be the appropriate standards body, at which an initial working group would need to be formed. Subsequently, draft standards would need to be coordinated with the International Civil Aviation Organization (ICAO) for worldwide acceptance and implementation.

4. POTENTIAL SPECTRUM OPPORTUNITIES

In this section we provide a review of some of the potential spectral regions that could support a new ADL system. While in principle there exist vast amounts of unused spectrum, at frequencies above those in common use (e.g., the V band around 45 GHz), the technologies are not presently available to economically deploy communication systems in these bands. As noted in the previous section, propagation conditions favor the use of lower frequencies for transmission ranges of interest in the aeronautical case (tens of meters to a few hundred kilometers). Hence we claim that it is adequate to restrict our attention to frequency bands below Ku band (12 GHz), at least for ground-air and air-air communications. For satellite systems, it may be possible to use the higher frequency bands.

For the lower frequency limit, we select the upper limit of the HF band, equal to the lower limit of the VHF band, approximately 30 MHz. This is primarily because to support multiple users with data rates on the order of 100kbps or more requires more bandwidth than is available with channels in the HF band and below. Hence, we focus on the VHF, UHF, and SHF bands.

Because of the very high demand for spectrum in these bands, it is also most likely that any new ADL system will be deployed in spectrum already dedicated to aeronautical applications, either communications or otherwise. This may seem problematic, and it is likely that any current users of a band will need substantial experimental proof that their services will not be significantly degraded; yet, the actual duty cycle of usage of most spectral regions in most spatial areas is lower than one might expect [23]. As noted in [23], for many commercial and military spectral allocations, actual spectral occupancy by signals varies considerably in both time and space, with significant “gaps” available in both these dimensions. Even without exploitation of such gaps, more efficient use of spectrum is definitely possible. One method of some recent research interest (e.g., [24]) is spectral overlay of direct-sequence spread spectrum upon narrowband signal spectra. We briefly explore this for two spectral regions in the Appendices.

Thus far we have surveyed several candidate spectral bands, but more study is required to fully characterize all options. We have aimed at providing both some breadth, and some depth, the latter of which is exemplified by our analytical and computer simulation examples in the appendices. The key systems/spectral regions we have considered here are briefly described in Table 3.

Table 3. Example potential systems/spectra for a new ADL system.

System or Spectrum	Frequency Band	Comments
VDLM3	118-137 MHz	FAA choice for digital voice and data. Data rate limited. Keeping only 25 kHz channel bandwidths implies only moderate data rate achievable.
ILS Glideslope	329-335 MHz	Only approximately 5 MHz spectrum, but good propagation conditions. Coexistence with tone-modulated ILS signal is biggest challenge.
Universal Access Transceiver (UAT)	Two 1 MHz channels: 971 MHz (CONUS), 981 MHz (Alaska)	Developed in FAA Capstone (ADS-B) project. Only two channels currently; design modifications needed for increased data rates. Peer-peer user addressing not currently available.
Military UHF	225-328.6 MHz 335.4-399.9 MHz	Existing transceivers very high power, making coexistence very challenging. Commercial use of military spectrum is likely a large administrative and political challenge.
Microwave Landing System (MLS)	5-5.25 GHz	MLS not deployed widely. Technologies for this band less mature, but very wide bandwidth available. Propagation conditions may dictate use of directive antennas, and/or use in shorter range conditions.

The systems listed in Table 3 are very different in terms of communication parameters and application. In Table 4 we list more completely some of the lower layer communications protocol stack parameters for four of the systems of Table 3. The compilations are not exhaustive, but serve to present many of the lower-layer parameters of interest in one table; these parameters include data rates, channel bandwidths, and multiple access methods. Another type of listing, a comprehensive performance parameter listing, is useful to identify as many parameters as possible that need to be considered for evaluation in any system design. We provide in Appendix C an example of such a listing, taken from previous work under the NASA Glenn Weather Information Communications (WINCOMM) program. We next address individually four of the bands identified in Tables 3 and 4.

4.1 Instrument Landing System (ILS) Glideslope Band

The ILS Glideslope signal is used to aid in landing by providing a signal that enables aircraft to adjust their angle of descent upon approaching an airfield landing zone. The signal is thus required to be received over a limited range from an airport. Depending upon aircraft altitude and proximity to ILS transmitters at airports within range, multiple ILS signals could be received by an aircraft, yet only one signal is needed for landing.

In terms of propagation conditions, the ILS band at VHF is a good candidate for a new ADL system. Ranges achievable in this band would be essentially identical to those attained in the VHF communications band (118-137 MHz), with comparable transmit powers. The RF technology for radio systems in the ILS band is also readily available, mature, and relatively inexpensive. The digital processing technologies required for the baseband transceiver subsystems would also not be unreasonably expensive, since the clock rates required would be no more than a few tens of MHz, since the total available bandwidth in the ILS band is approximately 5 MHz. Depending upon the waveform selection, re-use of some digital processing subsystems (e.g., cellular) may be possible.

For the ADL spectral plan, either of two options would be possible: orthogonal allocations or spectral overlay. By orthogonal allocations, we mean that the ADL signal would adaptively locate its frequency content in a spectral region away from the ILS signal of interest (analogous to conventional FDM schemes, but adaptive). This could employ either multiple-carrier narrowband signals (e.g., OFDM or multicarrier (MC)-DS-SS), or FH-SS. Spectral overlay would use a single carrier or multicarrier DS-SS signal.

The most challenging aspect of the use of the ILS band for an ADL system is ensuring minimal degradation to the ILS system. This requires a careful study at the physical layer, along with analysis of tradeoff options. Adaptive power control of the ADL transmissions would be likely be required.

4.2 Microwave Landing System (MLS) Band

The MLS is not widely used in the US, but is used more in Europe. Depending upon the future of the European systems, use of this band for an ADL system could pose a problem in Europe. As with a design for the ILS band, any new ADL system deployed in the MLS band could be made adaptive in frequency to circumvent interference with MLS systems. Also, as with the ILS signals, the MLS signals do not need to be received at large distances from airfields.

In contrast to the ILS band, propagation at MLS is more constraining, in that, for the same transmit powers, signals incur approximately 25 dB more attenuation at 5 GHz than at 300 MHz, for the same distance traveled. The most effective way to counteract this attenuation is higher gain antennas, at the cost of directivity. This would then logically imply the use of an antenna array to enable omnidirectional coverage, if desired.

Technologies for the IEEE 802.11a wireless LAN standard (for the 5.8 GHz band) are becoming available, so there is some technology base from which to draw. The problem is that the wireless LANs operate only at short range, mostly indoor. Hence some technology development would be required.

The most attractive feature of the MLS band (other than its relatively low use) is its wide bandwidth. Also attractive and important is that it is currently exclusively dedicated to aeronautical services. The wide bandwidth would enable high data rate transmissions of many simultaneous users. Waveforms of choice could be similar to the 802.11a OFDM, or that in [8], or a scheme that uses either DS or FH SS. This relatively "open" band allows for the most innovative design since no (or at least few) restrictions would apply.

4.3 Universal Access Transceiver (UAT)

The UAT system is currently planned for use in surveillance (ADS-B) applications. It requires approximately 1MHz bandwidth for operation, and is currently allocated two channels in the 900 MHz band (see Table 3). Given that this band is used for other civilian aeronautical services (e.g., distance measuring equipment, DME), and is also used by the military for one of its tactical spread spectrum aeronautical data links, obtaining dedicated (or even time- or spatially-shared) spectrum could be a difficult administrative (and political) effort. Nonetheless, if desired, the UAT system could be applied to limited ADL applications.

The UHF band propagation conditions are not quite as good as those at VHF, but are comparable (signal attenuation is about 10 dB larger than at 300 MHz), and are better than at the 5 GHz MLS frequency. Alternatively, the UAT RF could be translated down to VHF, and used, for example, in the ILS band.

For use as an ADL system, modifications to the MAC layer protocol would be required, to enable higher per-user data rates and greater efficiency. At the physical layer, the waveform itself might not need many changes, as the binary CPFSK modulation is fairly robust, and the existing FEC is both flexible and strong.

4.4 VDL3

As with UAT, some radio equipment for VDL3 is currently available (or will soon be). There are a few channels in the current VHF band available for potential trial usage, and this means that early proof-of-concept testing and demonstrations (including flight tests) could be easier to initiate than in any of the other bands.

Propagation conditions are of course more favorable at VHF than at higher frequency bands. With VDL3, the waveform is determined, so little if any changes would be made at the physical layer. Another potential advantage to the use of VDL3 could be its mandated acceptance in the future, i.e., many aircraft would install VDL3 as a matter of course. Yet, because of the relatively low data rate though, VDL3 does not appear to be the system of choice for a new ADL system, and so its use would be primarily for proof-of-concept, and exploratory studies.

Table 4. Lower-layer characteristics and parameters of some of the candidate systems.

Parameter	MLS	ILS	UAT	VDLM3
Frequency Band	5.0 – 5.25 GHz	329-335 MHz	960 – 1215 MHz	118-137 MHz
# Channels	200 in 5.031-5.0907 GHz +198 more, up to 5.15 GHz	---	Currently 3 unpaired DME channels: 960, 971,983 MHz	---
Approx Chan BW (90% Power)	---	300 Hz	$1.4R_b$	$B_{90} \cong 16.8$ kHz
Multiple Access (MA)	NA	NA	TD (~S-ALOHA)	TDMA (polling & rand. acc.)
Channel R_b (kbps)	15.625	NA	1004.167	31.5
Minimum total frequency band for operation	~ 300 kHz?	300 Hz	~ 1.4 MHz (1 channel)	25 kHz
Duplex method	NA	NA	Time: dedicated uplink/downlink slots	Time: dedicated uplink/downlink slots
Minimum up/downlink Δf	Uplink transmission only	Uplink transmission only	0	0
Frequency planning requirements (re-use)	Since short range, full re-use possible; Δf spacing	Since short range, full re-use possible; Δf spacing	Unknown: likely re-use factor ≥ 7	Unknown: likely re-use factor ≥ 7
RF channel spacing Δf	300 kHz	---	~ 2.8 MHz	25 kHz
Spectral Eff. (bps/Hz)	≤ 1	NA	0.714	1.875
Max. User R_b (kbps) per timeslot	NA	NA	Air: 701.75; Ground: 921.51 (Counting user address data)	4.8 (192 sym/30ms burst/4) (NOT counting address info)
Multi-User Capacity: contention effect on R_b	NA	NA	Degrade by 64% (multiply by 0.36) for MA (S-ALOHA)	With assigned channels, full R_b available
Modulation	DBPSK	DSB AM tone mod: tones f_c ±90, ±150 Hz	h=0.6, $\Delta f = hR_b = 625$ kHz (900 kHz in practice)	D8PSK, with RRC pulse shaping, $\alpha = 0.6$
Frame time	---	NA	1 second	120 ms
# Timeslots/frame	variable	NA	4000	3 or 4
Synchronization Seq.	12 bit preamble	NA	36 bit preamble	Two 16-symbol words/slot

5. GENERAL ANALYSIS METHOD FOR SYSTEM SPECIFICATION AND DESIGN

In this section we provide a discussion of a general analysis and design method that could be used for development of a new ADL system. While flexibility would be highly desirable, no technology can have unlimited flexibility, and so ultimately some initial constraints need to be defined. Key among these are the total available amount of spectrum and how it is partitioned (contiguous or non-contiguous blocks), desired data rates, acceptable transmission ranges, transmission reliability and security requirements, and data traffic characteristics such as directional asymmetries in data rates, average and peak message rates and durations, and other QoS requirements.

Given at least the majority of these constraints, a design can begin. In the appendices we illustrate examples of some of the initial technical aspects of the study, given the choice of DS-SS with phase modulation for the waveform. Parts of steps 1-3 below are addressed in these appendices. If a significant number of these constraints are not provided, then more options are available. We describe the method in list form, and note that the order of some of the steps could change, and that the procedure would most certainly be iterative. We also note that this method would yield only major portions of a system design, and does not consider actual implementation and field experiments, which would of course be required.

1. Select waveform design: this would first amount to selection of conventional narrowband, or spread spectrum modulations. For spread spectrum the additional choice of DS or FH, or a combination would need to be made. For any of the options, the detection technique—either coherent or noncoherent—would follow. Coherent detection offers better performance, but noncoherent receivers can be simpler to implement, and possibly more robust in the presence of some channel impairments (e.g., fading). Applicable FEC code designs would then be determined. This would not mean selecting detailed FEC parameters, only ranges of parameters, and potential code types (e.g., block or trellis) suitable for the data rates and modulations chosen.

2. Select "conventional" transceiver design, and conduct analytical studies: all known modulation forms have associated transceiver designs, and the performance of the modulation scheme can be obtained either exactly or approximately. Bit and packet error probabilities would be derived. In addition, all known modulations have known or computable power spectra, at least for certain conditions (e.g., raised-cosine pulse shape). The effect of pulse shape filtering can be derived for various filter designs. Along with these waveform parameters, the multiple access capacity could be estimated. Based upon any frequency or spatial re-use models, wide-area capacity estimates could be obtained. The effect of both intra- and inter-system interference could also be assessed analytically. Finally, link budget parameters would be used to devise model scenarios of interest, for which transmission ranges, transmit powers, and antenna gains could be derived. Any methods for coverage extension could be incorporated into the link study.

3. Validate analyses via computer simulations: computer simulations can be conducted at several levels. The first level is the simplest, and assumes a number of ideal conditions, e.g., perfect phase coherence and symbol timing. This level of simulations is used to corroborate analyses, in particular validating any approximations or numerically-derived quantities. The next level of simulation typically extends the realism by introduction of non-idealities that are difficult or intractable to analyze. Examples of this include finite-impulse response filtering, and non-ideal channel conditions. Another potential level of simulation would include non-idealities

that are found in actual hardware implementations, including finite-precision signal processing. This level would likely not be considered until the waveform design is mature.

4. MA design: some of the modulation parameters dictate or at least affect, the MA scheme. In this step, based upon requirements, we would define system packet sizes, synchronization and control overhead blocks, and packet transmission rates. Also, if not explicitly determined by prior steps, the duplexing method for enabling two-way transmission would be devised. This would include definition of frequency guard bands and/or guard times. Methods for user ingress and egress to the system would also be defined, including definition of required access channels and access channel transmission formats. User authentication techniques would also be defined.

5. MA simulations: to assess the MA design, a "network" level simulation would be developed. This would simulate the transmissions of multiple users for both steady-state and transient conditions, for a wide variety of anticipated data traffic loads and profiles. Also, if deemed appropriate, the performance of the system in the presence of outside-system interference, either unintentional, or intentional, could be evaluated.

6. Enhancement proposal and test: from all the above, both expected and unanticipated shortcomings in system performance would likely be identified. Using known techniques, the impact of enhancements on the system would be quantified. Cost vs. performance studies would be conducted to evaluate the suitability of these enhancements. Examples include the use of multiple frequency bands, antenna diversity, improved FEC coding, and alternative signal acquisition approaches. The interaction and/or interworking with other systems, such as satellite systems, could also be addressed.

7. Evaluate performance and repeat: clearly, in any system of such complexity, iteration of the above procedure is required. Various steps could be revisited, and after a small number of times through this procedure, it is likely that a new procedure, which would provide more detailed focus as appropriate, would be required.

6. CONCLUSIONS

In this study we have considered a number of potential spectral bands for use in a new aviation data link system. We have also considered a number of existing aeronautical systems. From our research, one obvious conclusion is that existing aeronautical spectrum will be inadequate to satisfy currently-projected demand for the future, using existing systems. That is, there is a clear need for development of a new ADL system to provide SATS and/or other CNS services. These services would operate in conjunction with existing services, not as a replacement for existing services.

Data rates for all existing and proposed systems are inadequate for most new services, e.g., weather imagery. For moderate data rates and good range, the ILS band could be suitable for a new ADL system; for airport surface and terminal airspaces, the MLS band, with its capability for large data rates, is most attractive.

7. RECOMMENDATIONS

In this final section we provide recommendations based upon our work. We list them in arbitrary order.

1. Continue the effort begun here. It is clear that no existing system fits all the anticipated needs of a new ADL system, especially given the diverse range of future applications. Some of these needs include high data rate to support or enhance existing and new services such as weather imagery, peer-to-peer connectivity (and addressability), and providing greater spatial coverage than existing systems provide, in order to enable system usage at currently-uncovered (e.g., SATS) airspaces. Thus, there is a clear need for development of a new ADL system to provide SATS and/or other CNS services. We recommend that this effort continue in some form, minimally via participation in the Airborne Internet Consortium. The support and participation of other entities and organizations should also be encouraged.

2. Seize opportunity for some testing in VHF channels. Some VHF channels may currently be available for the purposes of testing, specifically channels recently vacated by VDL2 systems undergoing trials, or already allocated for VDL3 use. Although the 25 kHz VHF channels would not provide much room for high data rate experiments, the potential aggregation of two or more of these channels could provide a means for testing some upper-layer communications features and applications. We recommend that an effort be made to allow use of these VHF channels for such testing, and that appropriate personnel and equipment be obtained for such usage.

3. Get assistance with determination of civilian use of military UHF aeronautical bands. Because of time and personnel limitations, the full range of possible spectral opportunities has not yet been explored. In particular, the use of some of the military UHF aeronautical bands has not really been studied. In terms of propagation and technologies available, these bands are very suitable for an ADL system. As noted, the primary effort here is likely a political one: obtaining permission to use "military" bands for civilian applications. We recommend that some person or group of persons with the appropriate political credentials be "recruited" to begin the dialogue with the appropriate military organizations.

4. Seize any available portions of MLS band and begin testing. As noted, the spectrum in the 5 GHz MLS band could be at risk of being allocated to other (non-aeronautical) entities, so a concerted effort to begin use of this band in order to "lay claim" to it is strongly recommended. The primary drawback to this band is its less-than-ideal propagation conditions, but its wide bandwidth, and potential "openness" make it a very attractive spectral region. We plan to prepare a "white paper" to propose several means to begin exploration of this band for an ADL system.

5. Explore a multi-band ADL approach. For numerous reasons, allowing a system to operate in more than one distinct spectral region is attractive. One of these could be frequency diversity (improving reliability), but we envision more of a switching approach, in which for example the VHF band would be used for longer-range, lower data rate transmissions and the SHF band would be used for shorter range, higher data rate transmissions. Naturally this multi-band approach is more expensive than a single band approach, but it is much more flexible, and much more robust. We recommend at least a feasibility study of these techniques be conducted.

6. Extend the study to all the layers of the communications protocol stack. Currently, work in the Airborne Internet Consortium (AIC) appears to be focused upon only the upper layers of the stack; our work here by contrast focuses upon the lower layers. An effort to bridge these two areas must be undertaken, and should include both participants from the two efforts (ours and the AIC) and additional personnel conversant in the "middle" layers. We recommend supporting this position as an important element of the AIC workplan.

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APPENDIX A. Example Analysis for ILS Glideslope Band: DS-SS Spectral Overlay

In this appendix, we examine the effects of intentional spectral overlay between a direct-sequence spread spectrum (DS-SS) code-division, multiple-access (CDMA) system and the glide slope signal of the Instrument Landing System (ILS) currently employed by the Federal Aviation Administration (FAA). The purpose of the overlay system is to enable increased spectral efficiency (higher data throughput), for future potential aeronautical datalink communications. That is, this overlay would enable simultaneous use of the ILS band by the current glide slope systems and a new DS-SS CDMA digital communication system. We derive expressions for the performance of both the DS-SS and ILS signals in the presence of each other, for a range of transmit powers, DS-SS bandwidths and data rates, and typical ILS and CDMA system parameters. We use both analysis and computer simulations. Much of this appendix will appear as a paper in the upcoming Digital Avionics System Conference [25].

We employ classical analytical techniques, corroborated by computer simulation, to characterize the performance of both DS-SS and ILS systems in the presence of each other. In Section A.1 we describe the system model, assumptions, and introduce notation. The mathematical analysis of performance is in Section A.2, for both systems, and in Section A.3 we provide numerical results—both analytical and simulations. Section A.4 contains concluding remarks.

A.1 System and Signal Models

In establishing our model, several assumptions were made. To begin with, the distance between the Instrument Landing System (ILS) transmitter and the direct sequence spread spectrum (DS-SS) transmitter is assumed to be very small in relation to the distance between the aircraft and the runway. We also assume that the ILS signal is centered on the DS-SS carrier frequency. This is a worst case condition for the DS-SS receiver. In addition, multipath is neglected to simplify analysis. For most applications, the aircraft will have a line of sight to the ground transceivers, hence, our first order model for the channel is an additive white Gaussian noise (AWGN) channel. Figure A.1 shows a conceptual model of our system.

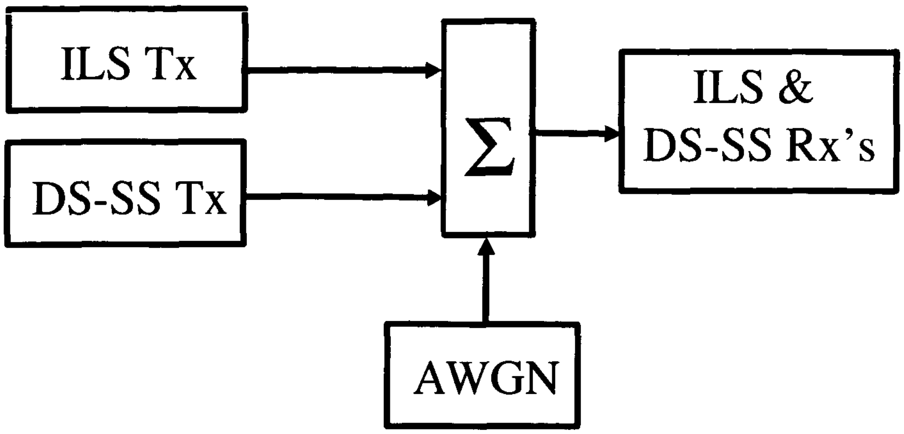

Figure A.1. Conceptual Model of DS-SS overlay system.

The ILS signal is an amplitude modulated signal. It consists of five tones: one at the center frequency, and two above and two below the center frequency. The ILS signal as seen by the DS-SS receiver can be defined as follows:

$$g(t) = A_c[1 + k_a m(t)]\cos(2\pi f_c t) \tag{A.1}$$

where A_c is the amplitude of the received signal, k_a is the amplitude modulator constant, f_c is the carrier frequency (329-335 MHz), and m(t) is the message signal. The worst-case effect on the DS-SS signal is obtained when the ILS signal center frequency is equal to the DS-SS carrier frequency [26], so we first analyze this case. The message signal, $m(t)$, is given as follows:

$$m(t) = A'\cos(2\pi 150t) + A'\cos(2\pi 90t) \tag{A.2}$$

where A' is the amplitude of the tones at 150 and 90 Hz from the carrier.

We expand $g(t)$ via trigonometric identities to obtain the following form:

$$g(t) = A_c\cos(2\pi f_c t) + \left(\frac{A_c A' k_a}{2}\right)[\cos(2\pi f_{c+90}t) + \cos(2\pi f_{c-90}t) + \cos(2\pi f_{c+150}t) + \cos(2\pi f_{c-150}t)] \tag{A.3}$$

where $f_{c+90} = f_c + 90$ Hz, $f_{c-90} = f_c - 90$ Hz, and likewise for the 150 Hz tones.

For simplicity, we assume that the DS-SS signal is binary phase modulated (BPSK). We also assume coherent detection. The DS-SS signal received by the aircraft can be defined as follows:

$$s(t) = \sqrt{2P}d(t)c_s(t)\cos(\omega_o t + \theta) \tag{A.4}$$

where P is the signal power, d(t) is the data modulation, $c_s(t)$ is the signal spreading code, ω_o is the radian carrier frequency, and θ is the signal phase, which is assumed to be zero for convenience in our coherent receiver. The data waveform is

$$d(t) = \sum_k d_k p_T(t - kT) \tag{A.5}$$

where d_k is the k^{th} bit, in $\{\pm 1\}$, T is the bit duration, and $p_x(t)$ is a unit amplitude rectangular pulse non-zero only in the interval $[0,x)$. The spreading signal is of a form similar to (A.5):

$$c_s(t) = \sum_{n=0}^{N-1} c_n p_{T_c}(t - nT_c) \tag{A.6}$$

with $c_n \in \{\pm 1\}$, T_c the chip duration, equal to $1/R_c$, with R_c the chip rate, and the processing gain is $N = T/T_c$. As in most cellular systems, we assume the use of "long" spreading codes—codes whose period is much longer than a single bit. Hence, (A.6) represents a length-N subsequence of a much longer pseudo-random sequence. These long codes are well-modeled by random Bernoulli sequences [26].

For the successful application of spectral overlay, the DS-SS bandwidth must be much larger than that of the ILS signal. This bandwidth is proportional to the chip rate R_c. In Figure A.2 we illustrate conceptually the power spectrum of both signals in an overlay mode. This figure is for a single-carrier DS-SS signal, described by (A.4)-(A.6). Multicarrier DS-SS signals may also be of interest; our work for the FAA and NASA is considering these signals, but for this paper we restrict attention to the single-carrier DS-SS case.

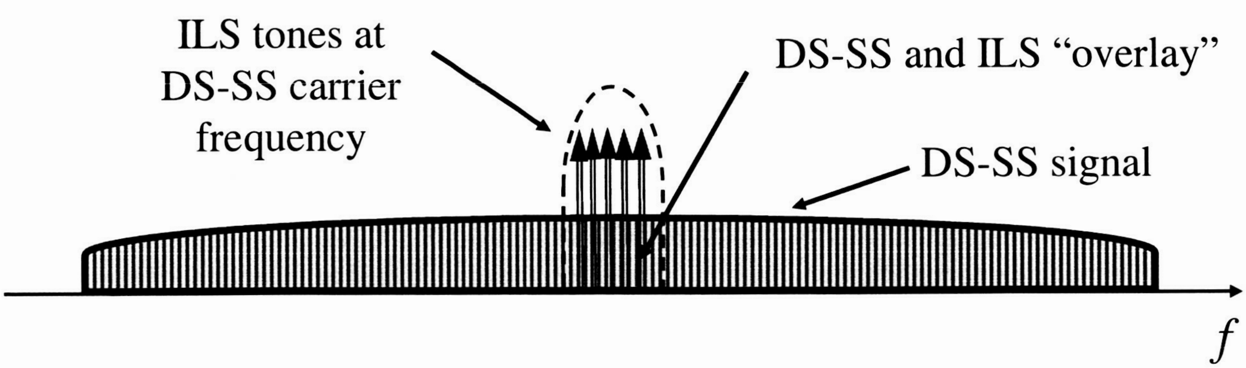

Figure A.2. Illustration of power spectrum of ILS with SC-DS-SS overlay.

A.2 Analysis

We are interested in quantifying the effect of the ILS signal on DS-SS performance, and also the effect of the DS-SS signal on ILS performance. For the digital DS-SS system, performance is measured by the bit error ratio (BER), and for the analog ILS signal, we estimate the effective signal-to-noise ratio (SNR), more precisely, the signal-to-noise-plus-interference ratio (SNIR).

In order to calculate the BER for the DS-SS system, it is necessary to first calculate the statistics of the output of the DS-SS receiver. Figure A.3 shows a block diagram of the DS-SS receiver. In Figure A.3, w(t) is the AWGN.

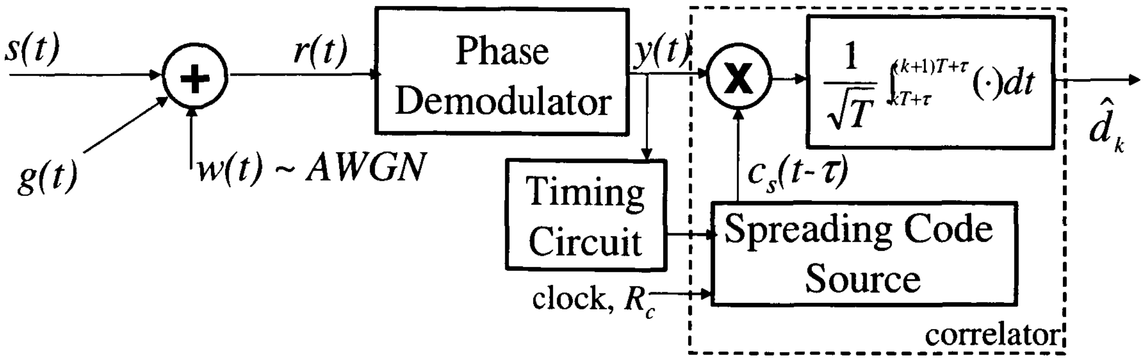

Figure A.3. Block diagram of a DS-SS receiver.

The statistics of interest are the mean and the variance. From these statistics, the SNIR can be obtained. When the processing gain of the DS-SS signal is large, the effect of the ILS signal can be modeled as an additive Gaussian disturbance to the desired signal. With this Gaussian approximation, we can obtain the BER in closed-form using standard functions.

This relationship is illustrated in the following equation:

$$BER = P_b = Q\left(\sqrt{SNIR}\right) = Q\left(\sqrt{\frac{S}{N+I}}\right) \tag{A.7}$$

where S is mean-square value of the desired DS-SS part of $\hat{d}_k$, N is the AWGN variance, and I is the ILS signal variance. The function $Q(x) = \int_x^\infty e^{-t^2/2} / \sqrt{2\pi}$ is the tail integral of the zero-mean, unit-variance Gaussian probability density function. For coherent BPSK in AWGN only, the BER for coherent BPSK is given by [26] :

$$BER = P_b = Q\left(\sqrt{SNR}\right) = Q\left(\sqrt{\frac{2E_b}{N_0}}\right) \tag{A.8}$$

where E_b is the received bit energy (equal to PT) and N_0 is the one-sided thermal noise power spectral density. Hence (A.8) must be modified to include the ILS signal variance. This entails inputting the ILS signal of (A.3) to the DS-SS receiver of Figure 3, and calculating the variance of the DS-SS receiver output. (The mean of the ILS part of $\hat{d}_k$ is zero when the spreading code is zero mean.)

The first process performed by the receiver is down converting the ILS signal and filtering the double frequency components. This yields the following expression:

$$I(t) = \frac{A_c}{2} + \left(\frac{A_c A' k_a}{2}\right)\left[\cos(2\pi 90t) + \cos(2\pi 150t)\right] \tag{A.9}$$

where $I(t)$ is the ILS part of $y(t)$ in Figure A.3. We next multiply $I(t)$ by the spreading code, and integrate, assuming the delay τ in Figure A.3 is zero, without loss of generality. This yields the ILS part of the decision statistic $\hat{d}_k$ as follows:

$$
\begin{aligned}
I = \sum_{n=0}^{N-1} c_n \Bigg[& \frac{A_c T_c}{2} + \frac{A''}{4\pi 150}\left[\sin(2\pi 150 T_c(n+1)) - \sin(2\pi 150 n T_c)\right] \\
& + \frac{A''}{4\pi 90}\left[\sin(2\pi 90 T_c(n+1)) - \sin(2\pi 90 n T_c)\right]\Bigg]
\end{aligned}
\tag{A.10}
$$

where $A''=A_cA'k_a/2$, and the variables in (A.10) are equivalent to those defined in the previous section. As noted, the mean of (A.10) is zero since the mean of the spreading code is assumed to be zero. To obtain the variance of (A.10), we square it and take the expected value of the resulting expression. This results in the following expression for the ILS signal variance:

$$
\begin{aligned}
\sigma_I^2 = & \sum_{n=0}^{N-1}\left[\alpha^2 + 2\alpha\beta\cos(\pi 150 T_c(2n+1)) + \beta^2\cos^2(\pi 150 T_c(2n+1))\right] \\
& + \sum_{n=0}^{N-1}\left[2\alpha\gamma\cos(\pi 90 T_c(2n+1)) + \gamma^2\cos^2(\pi 90 T_c(2n+1))\right] \\
& + \sum_{n=0}^{N-1}\left[2\beta\gamma\cos(\pi 150 T_c(2n+1))\cos(\pi 90 T_c(2n+1))\right]
\end{aligned}
\tag{A.11}
$$

where $\alpha=A_cT_c/2$, $\beta=\alpha\sin(\pi 150T_c)/(\pi 150T_c)$, and $\gamma=\alpha\sin(\pi 90T_c)/(\pi 90T_c)$.

Using (A.11), we can obtain the following expression for BER for the DS-SS system in the presence of the ILS signal:

$$
BER = Q\left(\sqrt{\frac{2E_b}{N_0 + 4\sigma_I^2/T}}\right). \tag{A.12}
$$

A.3 Numerical Results

We have computed the DS-SS BER according to (A.12) for several cases, to gain insight into the range of feasible values of several signal parameter values. We have also developed computer simulations to corroborate the analytical results of the previous section. These simulations were conducted in MATLAB. Parameters we vary are the DS-SS processing gain N, the signal-to-noise (only) ratio, expressed as E_b/N_0, and the ratio of the received ILS signal power to the received DS-SS signal power, expressed as the jamming-to-signal-ratio (JSR).

We show the effects of the ILS signal upon the DS-SS performance. In all cases we assume the ILS carrier signal amplitude and sideband amplitudes are equal ($A_c=A'$). Figure A.4 shows BER as a function of SNR for several different values of JSR. In Figure A.4, the chip rate of the DS-SS system is 5 MHz, and the bit rate of the DS-SS system is 5 kbps. These values result in a processing gain of 1000. If for example the DS-SS system requires an error probability of no greater than 10^{-3}, the acceptable JSR is between 20 dB and 25 dB—this can be translated, via link budget equations, into acceptable transmit power levels and ranges.

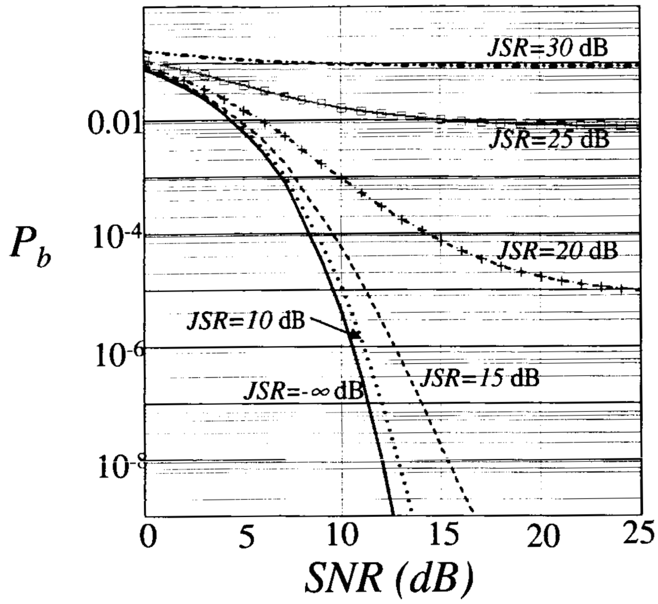

Figure A.4. DS-SS P_b vs. SNR (E_b/N_0) with a processing gain of R_c/R_b=5MHz/5kbps=1000.

In Figure A.5, a plot similar to Figure A.4 is shown. In this case, the chip rate of the DS-SS system remains 5 MHz, but the bit rate is increased to 50 kbps. This results in a reduction of the processing gain from 1000 to 100. Notice the performance degradation from Figure A.4 to Figure A.5 for identical JSR values. For example, for a DS-SS error probability of 10^{-3}, the maximum acceptable JSR is only between 10 dB and 15 dB.

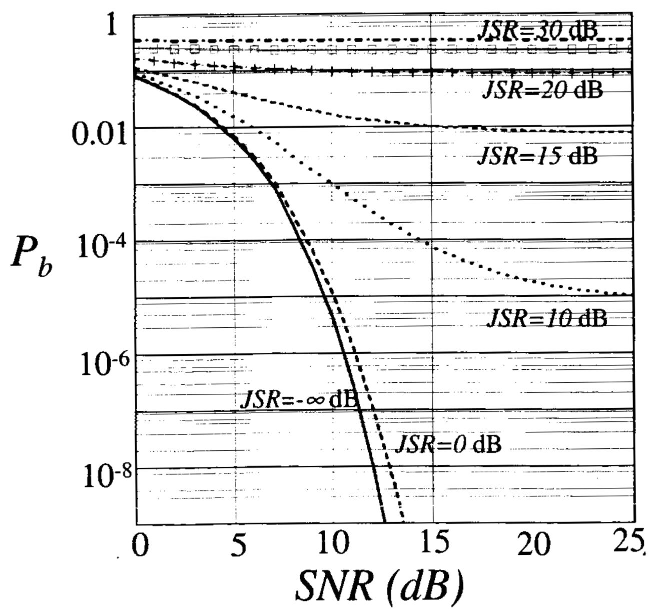

Figure A.5. DS-SS P_b vs. SNR (E_b/N_0) with a processing gain of R_c/R_b=5MHz/50kbps=100.

In Figure A.6, the achievable bit rate for two DS-SS systems in the presence of the ILS interference is plotted as a function of distance between the DS-SS receiver and DS-SS transmitter (i.e., communication link range). A desired value for BER is assumed for each system, which translates into a fixed value for the DS-SS SNIR of (A.12). It is also assumed that the distance between the DS-SS receiver and DS-SS transmitter is identical to that between the ILS transmitter and ILS receiver, or in other words, the DS-SS and ILS ground transmitters are close compared to the link range. In addition, we assume that both the ILS and DS-SS transmitters transmit one watt of power. Finally, a chip rate of 5 MHz is assumed for both systems. Figure A.6 was obtained numerically, based upon simple link equations, in which all antenna gains are zero dB, and the channel attenuation is modeled as that of free space. Worth noting is the fact that these results apply to uncoded modulation—actual error probabilities would be significantly lower with forward error correction, which would be used in any practical system.

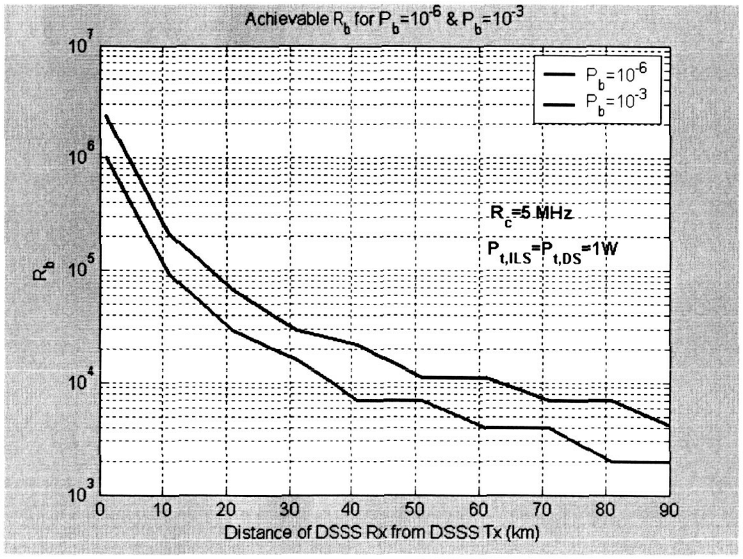

Figure A.6. Achievable DS-SS data rate R_b (bps) for given P_b vs. link range, in presence of ILS.

In Figure A.7, we compare the DS-SS analytical P_b results to those of our simulation. Excellent agreement is obtained.

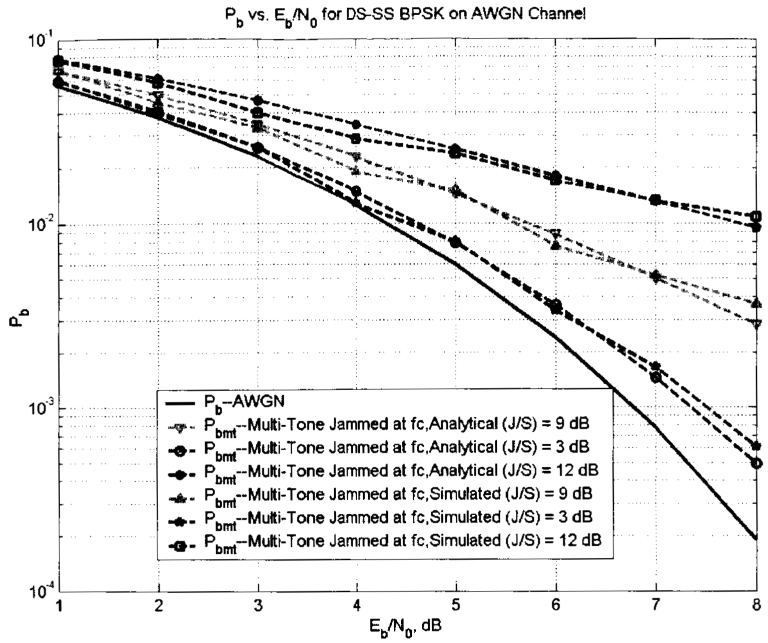

Figure A.7. P_b vs E_b/N_0 for DS-SS in presence of ILS; analytical and simulation results.

For assessing the degradation incurred by the ILS system in the presence of the DS-SS signal, we model the DS-SS interference as wideband, white Gaussian noise. Hence, the ILS SNR decreases from S_{ILS}/N, to $S_{ILS}/(N+I_{DS})$, where I_{DS} is the DS-SS signal power within the ILS receiver band. We have thus far been unable to obtain exact values for the ILS receiver bandwidth, but given this bandwidth, it is simple to obtain the value for I_{DS}: for an ILS receiver bandwidth of B_{ILS}, we have $I_{DS} \cong P(B_{ILS}/R_c)$. Hence for any given value of bandwidth and received DS-SS power, we can easily compute the value of the ILS SNR. As a simple example we show in Figure A.8 the achievable ILS SNIR versus the DS-SS bandwidth, for three different values of ILS receiver bandwidth, 300 Hz, 1kHz, and 5 kHz. The SNR (without any DS-SS signal present) is 10 dB. Clearly, the lower the value of ILS receiver bandwidth and the larger the DS-SS bandwidth, the higher the resulting ILS SNIR.

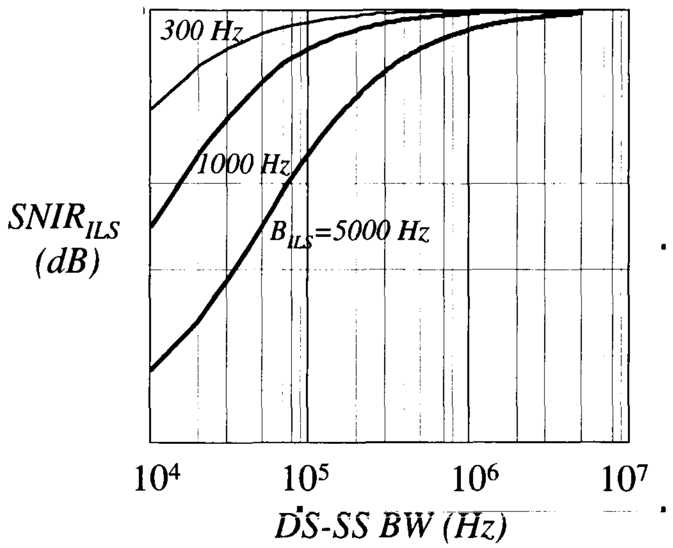

Figure A.8. ILS SNIR vs. DS-SS bandwidth; 3 ILS receiver bandwidths B_{ILS}. ILS SNR=10 dB.

A.4 Summary Remarks

In this appendix, we have explored the feasibility of the use of spectral overlay of DS-SS in the ILS glideslope band via use of classical analytical techniques and a first-order model for the channel. We developed expressions for the error probability performance of DS-SS in the presence of ILS interference, and for the signal-to-noise ratio performance of ILS in the presence of DS-SS. We corroborated these analytical results with computer simulations.

We identified the pertinent DS-SS signal parameters necessary for a proper evaluation: the DS-SS processing gain and data rate, and the transmit power. The ILS signal/system parameters of most importance are the ILS signal power and receiver bandwidth. Given a careful system design, and allowing either some small degradation to the ILS received SNR, or a slightly reduced ILS range, the use of a DS-SS spectral overlay is feasible.

Our results are the first of those required for a proper application of spectral overlay, and serve to illustrate the method. Additional work is required to firmly establish the feasibility of this technique. This work would begin with obtaining realistic values of the ILS receiver bandwidth, and minimally acceptable values of the ILS SNR. The use of realistic link ranges would also be needed to estimate potential performance and data rates of the DS-SS system. Other areas of research include the use of interference cancelling (filtering) of the ILS signal in the DS-SS receiver to improve DS-SS performance, and filtering the DS-SS transmissions (spcctral "notching") to improve ILS performance [27]. Finally, the use of multiple-carrier DS-SS signals should be explored [28]. The use of this signal type could remove the filtering that might be required in a single-carrier DS system.

APPENDIX B. Example Analysis for MLS Band: DS-SS Spectral Overlay

The analysis for the MLS band parallels that done in Appendix A for the overlay of DS-SS the ILS band. Hence in this appendix we only discuss the differences and cite some a result for illustration. The block diagram of Figure A.1 is identically applicable, with ILS replaced by MLS. The DS-SS signal description is identical to that given in Appendix A.

The MLS signal is a narrowband differential binary phase-shift keying signal (DBPSK), with a bit rate of R_{bM}=15.625 kbps. Hence, it can be described by an equation similar to that of (A.4)-(A.6) for the DS-SS signal, with the following changes: (1) set the spreading signal $c_s(t)=1$; (2) the signal d(t) in (A.5) employs a differentially-encoded sequence $\{d_k\}$, and the bit period is $T_{bM}=1/R_{bM}$.

Via an exactly analogous analytical technique, we can find the effect of the MLS signal on the performance of the DS-SS system. Using the exact same assumptions regarding the DS-SS signal (random spreading codes, phase coherence and ideal symbol timing), and typical assumptions regarding the MLS signal, including random data and rectangular pulse shaping, we can obtain an expression for the bit error probability of the DS-SS system:

$$P_b = Q\left(\sqrt{\frac{2E_b/N_0}{1+I_{MLS}}}\right) \tag{B.1}$$

where again, E_b is the received bit energy, equal to $P_{DS}T$, with P_{DS} the DS-SS signal power and T the DS-SS bit duration, N_0 is the one-sided thermal noise power spectral density, and the MLS interference term is given by

$$I_{MLS} = 2\frac{E_b}{N_0}\frac{P_{MLS}}{P_{DS}}\left(\frac{N-\frac{1}{3}}{N^2}\right) \tag{B.2}$$

with P_{MLS} equal to the received MLS signal power, and N is the DS-SS processing gain. These equations also assume averaging over the relative delay between the two digital signals, and that the carrier frequencies and phases are identical. This latter assumption is again worst-case from the perspective of the DS-SS system.

In Figure B.1 we show a plot analogous to Figures A.4 and A.5, for the DS-SS performance. The JSR is P_{MLS}/P_{DS}, and the JSR=-∞ dB case is the reference DS-SS performance without any MLS signal present. The curves labeled a-d describe the following conditions:

a. R_c=20MHz, R_b=10kbps, JSR=25 dB
b. R_c=200MHz, R_b=2Mbps, JSR=10 dB
c. R_c=20MHz, R_b=20kbps, JSR=20 dB
d. R_c=200MHz, R_b=20kbps, JSR=30 dB

As is evident, the wider the DS-SS bandwidth, the better the performance. With these expressions, additional results are easily generated for different parameters.

The effect of the DS-SS signal on the MLS performance can be approximated, as in the ILS case, by adding an additional Gaussian term to the thermal noise. This term is $P(B_{MLS}/R_c)$, with B_{MLS} equal to the MLS signal bandwidth. This approximation is very good for DS-SS bandwidths as small as a few times B_{MLS}.

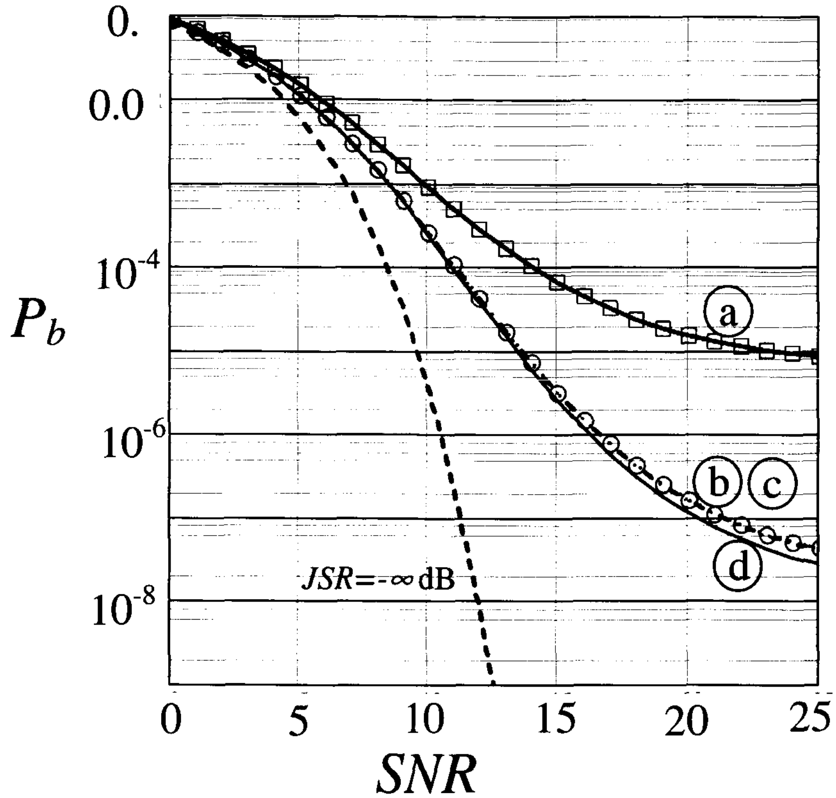

Figure B.1 DS-SS P_b vs. E_b/N_0, in presence of MLS signal. Various data rates and JSR values.

APPENDIX C. Illustrative Performance Parameter List for Candidate System Evaluation

Table C.1 below, taken from [29], illustrates a more complete set of parameters useful for evaluation of potential data links. This table is provided only as an example means of viewing and sorting the large amount of information required to properly conduct a comparative evaluation among competing candidate technologies.

In deriving this performance parameter set, we relied first on traditional measures of system performance such as bit error ratio (BER) versus signal-to-noise ratio (SNR). These are quantifiable measures, but they do still require precise definition. For example, the BER may be that of a particular message block, before or after error correction/detection; and, the point in the receiver chain at which the SNR is defined must be precisely specified. Nonetheless, these types of measures and characteristics are well understood and provide a foundation for experimental tests and equipment evaluations.

We emphasize that this table was composed with existing systems in mind, specifically the Mode-S "squitter," UAT, and VDL mode 4, which were candidate systems for ADS-B. The table and notes below hence apply only to these systems.

Note 1: For clarity, the table rows that describe parameters or characteristics that are NOT measurable are shaded; the rows that describe parameters or characteristics that ARE measurable are left unshaded. We have also added a column with heading "Analyzable?" This designation refers to whether or not the quantity or characteristic in question can be derived from theoretical results, simulations/emulations, or other measured quantities.

Note 2: The column heading "Measurable?" refers to whether or not the parameter or characteristic can be measured, not if measurement is simple, or even possible for a specific set of equipment. We note that a comparison according to this table would provide a "first-round" evaluation of the candidate systems, and it would likely raise additional questions and areas for investigation.

Table C.1 Illustrative Performance Parameter List for Candidate System Evaluation [29].

Parameter or Characteristic	Qualitative (L) or Quantitative (#)	Layer	Measurable? (Y/N)	Analyzable? (Y/N)	Comments
1. P_b vs. SNR	#	PHY	N	Y	This can be computed approximately from message error probabilities. For a given modulation scheme, it can also be computed for uncoded symbols. Translation to coded symbol error rates can be done using specific FEC code parameters. This translated P_b can then be compared with that computed from message error probabilities.
2. P_b vs. Interference				Y	As with #1, P_b vs. SNR, this can be estimated from message probabilities. CCI will be same-system, processed (scaled, delayed, etc.) as appropriate; ACI will also be same-system, but in addition may be signals from systems in adjacent bands (e.g., FM broadcast).
CCI	#	PHY	N		
ACI	#	PHY	N		
3. P_m vs. Interference				?	$P_m = P_{message}$. An analysis of message error probability would require knowledge of channel effects (correlations) over blocks of messages. This may or may not be obtainable. Regarding the interferences, the same comments as in #2 apply. For UAT and MSSq, some measured results available from JHU-APL. Note that to be fair among different systems, messages must be of identical length.
CCI	#	PHY	Y		
ACI	#	PHY	Y		
4. $P_{message}$ vs. SNR	#	PHY/ DLC	Y	?	Comments similar to that in #3.
5. P_{sync} vs. SNR	#	PHY	N	N	P_{sync} = probability of achieving correct synchronization. Ideally, several levels of synchronization (carrier, bit, frame, etc.) tested. Synchronization loop performance is a direct function of SNR, but accurate analysis is not feasible, due to the nonlinear nature of the loops. Good approximations are possible, but detailed loop parameter data is required for these, and this data is unlikely to be available. Information on P_{sync} can be useful for understanding the mechanism behind message errors, but is likely not of interest at higher levels.

Parameter or Characteristic	Qualitative (L) or Quantitative (#)	Layer	Measurable? (Y/N)	Analyzable? (Y/N)	Comments
6. Bandwidth	#	PHY	Y	Y/N	Bandwidth for the linear modulation schemes (8PSK) can be analytically obtained, at least approximately. Precision in these analyses requires detailed data on transmitter filters. Bandwidths for the CPM schemes can be found by numerical techniques and/or simulations. For UAT, some measured results available from JHU-APL.
7. Out-of-band emissions, transients	#	PHY	Y	N	Transients, characterized in both time and frequency domains, will depend upon implementations. The analytical characterizations of transients are typically intractable. For UAT, some measured results available from JHU-APL.
8. RF Link: Noise Figure	#	PHY	Y	N	Noise figures can be measured, but the value in measurement is questionable, since external (to receiver) noise is often dominant. For UAT and MSSq, some measured estimates available from JHU-APL.
9. RF Link: $P_{transmit}$	#	PHY	Y	NA	For UAT, some measured results available from JHU-APL.
10. P_b vs. Multipath	#	PHY	N (possibly Y in future)	Y?	As previously noted, NO typical or worst-case channel multipath profiles exist. The effect of multipath echoes on transmissions near airports (during takeoff/landing) is largely unknown. The effect is cited several times in JHU report as an area worthy of investigation. Once channel characteristics are obtained, performance for transmission schemes may be analyzed. (Note: The question mark after the "Y" under "Analyzable?" means that analysis is possible to some degree, i.e., analytical results may only be approximate.)
11. R_b (bps, messages/s)	#	PHY /DLC /MAC	PHY: Y DLC/MAC: ?	Y?	PHY R_b is measurable, and for the most part, is available from system design documents. DLC/MAC R_b must account for protocols, which may require several assumptions and may best be obtained via emulations and simulations. (Note: The question mark after the "Y" under "Analyzable?" means that analysis is possible to some degree, i.e., analytical results may only be approximate.)

Parameter or Characteristic	Qualitative (L) or Quantitative (#)	Layer	Measurable? (Y/N)	Analyzable? (Y/N)	Comments
12. Rx Complexity Detection (C/NC) Synchronization RF HW, BB proc Tech Maturity	 L L, # L, #? L	 PHY PHY PHY PHY /DLC…	 N N N N	 Y Y? Y Y?	Most of the analysis under receiver complexity will amount to quantifying processing requirements.
13. Tx Complexity Synchronization RF Tx Cost BB Proc	 L L, (relative #) L, #?	 PHY PHY PHY	 N N N	 Y? Y Y	Similar comments to #12. In addition, cost can be related to RF.
14. Capacity	L, #	PHY /DLC /MAC	PHY:Y, DLC/MAC: ?		For PHY, capacity is mostly quantifiable, but does require assumptions, in particular regarding re-use distances and S/I requirements. As with R_b, overall system capacity requires that higher layer characteristics be incorporated, and hence its assessment will likely require emulation and simulation.
15. Adaptability	L	PHY /DLC	N	Y	Requirements for adaptability of system parameters such as R_b, P_{Tx}, have not been made. System "flexibility" can be addressed somewhat qualitatively.
16. Security AJ/A-spoof Diversity ARQ	 L L, # L, #	 PHY PHY DLC/ MAC	 N N N	 Y Y Y	Requirements on system security at the physical layer have not been made.
17. Spectrum Availability	L	PHY	N	Y	Concern primarily for UAT, but there are also transition issues for VDLM4 depending upon the communications/navigation distinction (functional separability) by regulatory bodies. Ultimately quantifiable (~measurable) as binary (yes/no) value.
18. Integration	L	PHY	N	Y	Can be crucial to cost, in particular if new antennas required.