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NASA Unmanned Aircraft (UA) Control and Non-Payload Communication (CNPC) System Waveform Trade Studies

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June 2014

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17 December 2013	Allan Hammell	Additional Trade Study Examinations, Explanation of commonly suggested systems and approaches
28 March 2014	Allan Hammell	Minor Corrections, Cross References, etc

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NASA Unmanned Aircraft (UA) Control and Non-Payload Communication (CNPC) System Waveform Trade Studies

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1. Introduction

1.1 Project Overview / Trade Study Context

Unmanned Aircraft Systems (UAS) represent a new capability that will provide a variety of services in the government (public) and commercial (civil) aviation sectors. The growth of this potential industry has not yet been realized due to the lack of a common understanding of what is required to safely operate UAS in the National Airspace System (NAS). To address this deficiency, NASA has established a project called UAS Integration in the NAS (UAS in the NAS), under the Integrated Systems Research Program (ISRP) of the Aeronautics Research Mission Directorate (ARMD). This project provides an opportunity to transition concepts, technology, algorithms, and knowledge to the Federal Aviation Administration (FAA) and other stakeholders to help them define the requirements, regulations, and issues for routine UAS access to the NAS.

The safe, routine, and efficient integration of UAS into the NAS requires new radio frequency (RF) spectrum allocations and a new data communications system which is both secure and scalable with increasing UAS traffic without adversely impacting the Air Traffic Control (ATC) communication system. These data communications, referred to as Control and Non-Payload Communications (CNPC), whose purpose is to exchange information between the unmanned aircraft and the ground control station to ensure safe, reliable, and effective unmanned aircraft flight operation. A Communications Subproject within the UAS in the NAS Project has been established to address issues related to CNPC development, certification and fielding. The focus of the Communications Subproject is on validating and allocating new RF spectrum and data link communications to enable civil UAS integration into the NAS. The goal is to validate secure, robust data links within the allocated frequency spectrum for UAS.

A vision, architectural concepts, and seed requirements for the future commercial UAS CNPC system have been developed by RTCA Special Committee 203 (SC-203) in the process of determining formal recommendations to the FAA in its role provided for under the Federal Advisory Committee Act. NASA intends to conduct its research and development in keeping with this vision and associated architectural concepts. The prototype communication systems developed and tested by NASA will be used to validate and update the initial SC-203 requirements in order to provide a foundation for SC-203's Minimum Aviation System Performance Standards (MASPS).

Within the Communication Subproject, NASA has entered into a jointly funded Cooperative Agreement with Rockwell Collins to achieve the following tasks:

- Identify signal waveforms and access techniques to meet CNPC requirements within the UAS CNPC frequency bands in a manner which efficiently utilizes the spectrum compatibly with other co- and adjacent channel bands services
- Develop radios capable of enabling CNPC system testing and validation
- Perform relevant testing and validation activities

1.2 Trade Study Objectives, Motivation and Boundaries

This document describes the waveform trade studies to identify the fundamental signal waveform characteristics and access techniques best suited to fulfill anticipated CNPC requirements. This is not a complete waveform specification. Rather it identifies the basic waveform architecture for the physical layer, addressing issues such as duplexing and multiple access techniques. In the months ahead detailed analyses and waveform designs will expand this basic framework into a complete waveform characterization which will be implemented in the current effort. There will be three releases of the waveform specification, each building on the foundation of the earlier works. These future documents will expand the coverage to deal with topics such as channel bandwidth, symbol rates, estimated link margins, etc. as the design matures.

Within the Cooperative Agreement framework, NASA has the responsibility to define the message protocols, network architectures, security and other functions that implement the higher layers of the communication protocol stack. Rockwell Collins' focus is on the design of the physical signal-in-space (SIS) and media access layers. These trade studies are confined to those topics, and do not represent a comprehensive set of trades for the complete CNPC architecture and implementation.

The trades herein focus on factors directly impacting design of SIS and media access such as:

- Maximum number of simultaneous users that must be accommodated by each ground station
- Data rate of services that must be provided to various classes of users
- Accommodating the high frame rates required to support real time control operations

Factors in higher level system architecture / design (e.g. specific security or encryption techniques) are represented indirectly in these trades through overhead allocations. Allocations were selected such that there is a reasonable expectation the ensuing trade study results will support the range of higher level protocols and design solutions that are currently under consideration.

The CNPC waveform solution must support the higher level objectives for all users of the airspace, not just the performance of an individual aircraft. Key attributes of concern are:

- **Availability, Integrity, and Continuity of Function:** The CNPC is a system which will enable UAS to share congested airspace with manned aviation, and above populated areas. System availability, integrity and continuity of function capabilities need to be sufficient for this intended application.

- **System Capacity**. Many UAS currently operate with a dedicated point-to-point communication architecture, which is not scalable to the capacities anticipated for fully fielded UAS. The spectrum allocations are limited, and the actual demand for UAS may exceed anticipated loading levels. Given the complexity and cost to implement the broader CNPC architecture in general, selecting strategies that more easily support potential expanded demand in the future are required so that the network is not obsolete by the time it is fielded.

- **Complexity**. Increased complexity of either airborne or ground components will lead to both higher acquisition cost (more components, more lines of code, more combinations and variations, etc.) and higher life cycle costs (such as potentially higher component count, and higher retesting / recertification costs for software changes).

As the waveform is only one element of the total system architecture, the specific parameters in the trades may not bear these names directly. For example "link margin" is used as a direct evaluation criterion, whereas the underlying broader system goal being addressed is system "availability".

The CNPC solution will include airborne radio equipment that must ultimately be installed and certified on UAS as a required element on all but the smallest UAS that will operate in the NAS. There are several key factors that inform the selection of evaluation criteria:

- **Size, Weight, and Power (SWAP):** There will be numerous UAS that weigh as little as 55 pounds that will require CNPC. SWAP is a critical consideration for application to this class of aircraft. For example, airborne radio transmitter power and required linearity are considerations of primary importance.

- **Cost:** CNPC airborne systems will have significant cost pressures for the smaller sized vehicles, reflective of their generally lower costs. This implies reductions in both hardware complexity and size of software implementation. Qualification of the software will be performed using DO-178 processes, which can become quite expensive. Reducing the total number of lines of code and isolating higher criticality functions can help reduce the cost.
- **Certification Risk:** The CNPC will be a system that will require high levels of availability, integrity and continuity of function. In general, it is desirable to implement solutions that are relatively straightforward to build and test, even if they are not the most absolutely efficient. Determinism, repeatability and predictability are important characteristics that help mitigate certification risk and the associated costs.

Encompassing all the criteria above was the overarching desire from our contractual documents that the solution is “on a path to certification”. Our focus has been on the format of the signal in space, and not the specific radio hardware and software instantiations for the prototype demonstrations.

Rockwell Collins has decades of experience certifying avionics equipment, with over 11,000 Technical Service Orders approvals on our wide range of equipment. The FAA certification process requires solutions which exhibit repeatable, consistent and deterministic (or at least bounded deterministic) behaviors. Systems which have higher absolute performance but do not exhibit repeatable, consistent and deterministic behaviors are typically not certifiable. Our fundamental goal has been to identify the simplest and most cost effective waveform solution that could provide acceptable performance. As noted above, this also directly impacts the cost of system development.

This study has been a “ground up” assessment from a “clean sheet of paper” point of view. It is complemented by a trade study completed by NASA which evaluates the performance and appropriateness of dozens of currently existing waveforms for their potential suitability for CNPC.

To reiterate, this document describes the waveform trade studies to identify the fundamental signal waveform characteristics and access techniques best suited to fulfill anticipated CNPC requirements. This is not a complete waveform specification and is not a design of a CNPC system. Rather it identifies the basic waveform architecture for the physical layer, addressing issues such as duplexing and multiple access techniques.

1.3 Methodology

The trades below are conducted using the Analytical Hierarchy Process (AHP) / pairwise comparison method. This method is a standard system engineering technique for trades involving various factors that do not have inherent numerical scoring using a consistent measure. It was developed by Dr. Thomas Saaty (University of Pittsburg) in the 1970s and matured to a widely applied methodology today in both government and private sectors. This is the technique recommended by the International Council of Systems Engineering for this class of problem. A complete example with intermediate steps for the first trade is included for reference in Appendix A.

The following steps comprise the method:

1. **Select the Evaluation Criteria** – These criteria should be characteristics within the trade space of feasible solutions, and not the firm requirements that set boundary conditions that would fundamentally eliminate a particular candidate.
2. **Select the Weighting on Evaluation Criteria** – Based on system requirements, concept of operations, discussions with user community, etc. weights are placed on each of the evaluation criteria. In this way one defines the "best" solution from within the feasible set of solutions which could all meet the requirements.
3. **Select Candidate Solutions** – The intent is to consider the breadth of potential solutions without bias as to anticipated results. Any candidate put forward must first meet all boundary constraints in the systems requirements so that it is possible to generate at least one feasible solution using this candidate.
4. **Rate Each Candidate Against Evaluation Criteria** – Each of the candidates are compared in a pairwise basis and assigned a weight comparing the alternatives. Within the AHP method there is some standard terminology that has been proposed to assist in consistency of ratings. Furthermore, the method computes an internal consistency ratio in order to flag situations in which internally inconsistent evaluations may have been made.
5. **Determine the Preferred Solution** – Results of the pairwise comparisons are synthesized into an eigenvector and weighted according to the evaluation criteria values. The result is a normalized priority vector which gives a relative value of "goodness" of each of the alternatives. If two alternatives are very close at the top of the evaluation, then more careful scrutiny of the alternatives may be appropriate.

We determined the evaluation criteria and corresponding weights, and selected the candidate solutions based on joint peer review and a consensus process. Weights were assigned to the evaluation criteria using the following definitions:

- Minor significance – Weight of 1
- Moderate significance – Weight of 3
- Major significance – Weight of 5
- Maximum significance – Weight of 7

We then performed evaluations of candidates in a two-step process:

1. **Stoplight Evaluation** – Candidates were given one of three levels of rating against each of the evaluation criteria:
    - Green – This candidate clearly fulfills the needs of this criterion.
    - Yellow – This candidate partially fulfills the needs of this criterion.
    - Red – This candidate marginally fulfills the needs of this criterion, if at all.
2. **Numerical Scoring** – A weight was assigned to each pairwise comparison based on the relative color ratings. Red ratings were penalized more strongly against the others. The following definitions were used:
    - Same color – Weight of 1
    - Green to yellow – Weight of 3
    - Yellow to red – Weight of 5
    - Green to red – Weight of 7

The resulting pairwise comparisons were combined with the evaluation criteria weighting to generate a weighted priority vector indicating the relative merits of the candidates.

1.4 *Concept of Operation / System Level Requirements*

The Control and Communication Subgroup of RTCA SC-203 has been active since 2007 working on a variety of tasks associated with communications system architectures, spectrum, security, availability, integrity, and continuity. They were instrumental in helping the FAA prepare the U.S. position for the recently completed World Radio Conference 2012 at which the initial spectrum allocations were agreed for terrestrial based communication for CNPC functions. Their work forms the basis of this tasking in the Cooperative Agreement in general, and the trade studies in particular.

1.4.1. Reference Documents

As this trade study is focused on physical layer SIS and network access, only a subset of SC-203 documents are primary to this effort. Most of the papers are still internal to the work of SC-203, subject to change as the work progresses and not yet available publicly. However, by contract, these are the foundation of this work. Relevant information from the SC-203 papers is captured in this document to provide an independent snapshot of the initial requirement set we will use. Results from simulation and actual flight test by the NASA Communication Subproject will provide data to inform SC-203 as they finalize their work and provide formal recommendations to the FAA.

Four key documents inform the system level technical requirements / concept of operation used herein for these waveform trades:

- **NASA Cooperative Agreement NNC11AA01A Unmanned Aircraft Control And Non-Payload Communication System**, effective date 11/1/2011: This is our contract, which contains a limited number of explicit requirements. The broader body of work from SC-203 is referenced and embodied en masse in the contract in the following language: "This prototype system must be designed to address the initial 'seed' requirements from SC-203 and must be on a path to certification."
- **Report ITU-R M.2171 (12/2009) Characteristics of Unmanned Aircraft Systems and Spectrum Requirements to Support Their Safe Operation in Non-Segregated Airspace:** This is the specific language and supporting analysis behind the agenda item adopted at World Radio Conference 2012 establishing terrestrial based CNPC spectrum allocation. In practice, the majority of underlying content was generated within SC-203, working in conjunction with the FAA Spectrum Office.
- **Paper SC203-CC019_Terrestrial Architectures for UAS Control Links_vC_20DEC10, Terrestrial L-Band and C-Band Architectures for UAS Control and Non-Payload Communications (CNPC):** This is an SC-203 internal paper, which is subgroup approved but not yet a portion of any document that has been approved for release to the FAA as a formal recommendation. This represents preliminary work at present, but is the best available characterization of considerations for a scalable CNPC system architecture.
- **Paper SC203-CC016_UAS_CC_RCP_vA_12Jul11, UAS Control and Communications Link Required Communications Performance Availability, Continuity and Integrity:** This is an SC-203 internal paper, which is subgroup approved but not yet a portion of any document that has been approved for release to the FAA as a formal recommendation. This represents preliminary work at present, but is the best characterization available of characterizing required communication performance parameters for a CNPC system.

1.4.2. Concept of Operations Overview

The basic high level concept of operation is as depicted in Figure 1 below. Key elements of the architecture include:

- Primary connection from Local Control Station to Unmanned Aircraft (UA) is via a Service Provider who manages the Terrestrial Network (including the Ground-to-Air subsystem). The network is envisaged as a cellular structure with a gridded, repeating frequency reuse schema. Handoff between ground towers would be transparent to the pilot of the UA. The towers with the light blue and green range rings in the diagram form this primary network. ***It is the characterization of this Signal in Space and network access technique that is the subject of this trade study.***

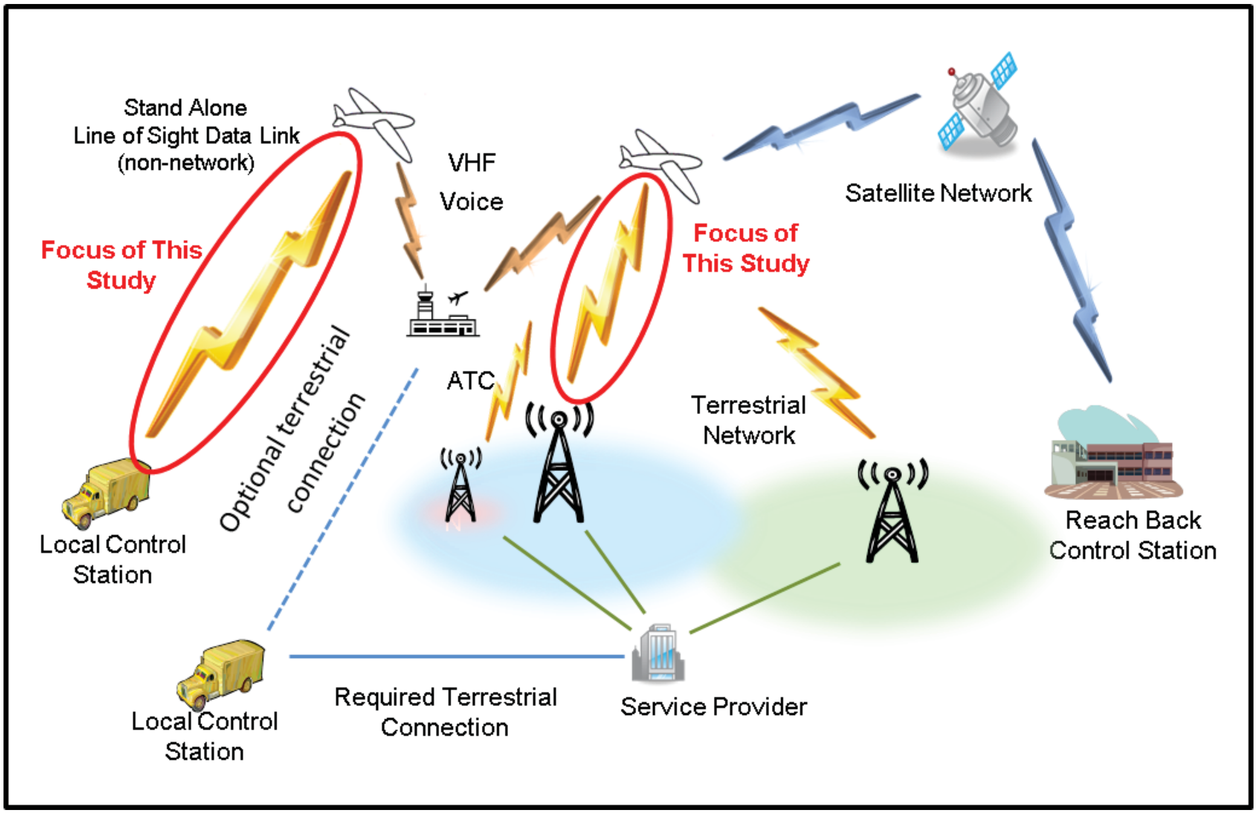

Figure 1: High Level Operational Concept Drawing

- Secondary link via Satellite Network may also be implemented to connect to a Reach Back Control Station which is not connected to the Terrestrial Network. Characterization of this network is beyond the scope of the current effort. Allocation of satellite frequencies for CNPC usage will not be considered until World Radio Conference 2015.
- The primary required voice communication path from UAS pilot to Air Traffic Control (ATC) is via digitized voice passed to the aircraft through the CNPC network, which is then converted to analog voice for transmission like other aircraft in the area. There is consideration for an optional direct connection from Local Control Station to ATC via terrestrial land lines if such operations are approved in the future.
- The architecture will require localized cells at airports or other locations where UAS need to operate at lower altitudes or have LOS difficulties due to intervening terrain. The smaller tower with the magenta range ring in the figure depicts such an element.

- The architecture must have provisions to allocate portions of the spectrum within a region for other UAS traffic which is not participating in the network. Control of such operations would have to be accomplished using frequency allocation management and notification through the service provider and ATC. This document refers to these point-to-point links as Stand-Alone links.

In the ITU-R M2171 paper, three classes of UAS services are characterized, with varying airspace densities and data performance needs. The size classes of UAs are listed as small, medium and large. There are also three classes of downlink service that are characterized:

- **Basic Service** – Also referred to as C2 This class includes tele-command and telemetry data, traffic targets and digitized voice to support communication with ATC.
- **Weather Radar Downlink** – This class would be limited to C band operation for full resolution, but may use compressed formats across L band.
- **Video** – This class of service would be used for surface maneuver (e.g. reading runway signage) and terminal operations (e.g. verifying that a runway is clear for landing). This class would be limited to C band operation due to its high bandwidth requirements.

1.4.3. System Level Requirements

Key system level requirements which impact the SIS and network access trades are summarized in Table 1 below, with the source of each requirement identified.

Table 1: Key System Level Requirements

Requirement	Source	Notes
Radios must operate in frequency bands 960 – 977 MHz (L band) and 5030 – 5091 (C band)	NASA Contract	2012 WRC granted access to 960-1164 MHz and 5030 – 5091 MHz bands. 960-977 may be the only viable option in L-band.
L band and C band operations must be independent	NASA Contract	SC 228 C2 White Paper, Section 6.2.2. has similar recommendation
RF link availability for any single link >= 99.8% Availability for simultaneous operation of L band and C band >= 99.999%	CC016	
Non-proprietary waveform	NASA Contract	
Must operate both air-to-ground and ground-to-air modes	NASA Contract	
Aircraft density assumptions Small UAs = 0.000802212 UA/ km^2 Medium UAs = 0.000194327 UA/ km^2 Large UAs = 0.00004375 UA/ km^2	ITU-R M.2171 P.54	

Requirement	Source	Notes
Cell Service Volume Radius = 75 miles (L-Band)	CC016	SC 228 C2 White Paper, Section 5.6.14 uses a 76 NM Radius
Maximum number of UAs supported per cell = 20 (basic services) Maximum number of UAs supported per cell = 4 (weather radar) Maximum number of UAs supported per cell = 4 (video)	CC019	
Tower height = 100 feet	RC Assumption	
Uplink Information Rates (Ground-to-Air) Small UAs = 2424 bps Medium and Large UAs = 6,925 bps	ITU-R M.2171 Table 13	Same as SC 228 C2 White Paper, Section 5.4.1
Downlink Information Rates (Air-to-Ground) Small UAs (basic services only) = 4,008 bps Medium and Large UAs (basic services only) = 13,573 bps Medium and Large UAs (basic and weather radar) = 34,133 bps Medium and Large UAs (basic, weather radar and video) = 234,134 bps	ITU-R M.2171 Table 13	Same as SC 228 C2 White Paper, Section 5.4.1
Frame rate must support 20 Hz to enable real time control	ITU-R M.2171 Table 23/24	Same as SC 228 C2 White Paper, Section 5.4.1
Aviation Safety Link Margin = 6 dB	CC019	
Airborne radio transmit power = 10 W	CC019	

1.5 Summary of Results

Table 2 and Figure 2 below summarize the NASA CNPC waveform trade study results. Subsequent sections elaborate on each trade study, including the rationale for each selection. Uplink channel refers to the Ground-to-Air link, and the Downlink channel refers to the Air-to-Ground link.

Table 2: Summary of Trades

Trade Study	Candidates	Selection
Uplink/downlink duplexing	Frequency division duplexing (FDD) Time division duplexing (TDD)	TDD
Uplink multiple access	Code division multiple access (CDMA) Frequency division multiple access (FDMA) Time division multiple access (TDMA)	TDMA
Downlink multiple access	Code division multiple access (CDMA) Frequency division multiple access (FDMA) Time division multiple access (TDMA)	FDMA
Uplink modulation type	Constant envelope	Constant

Trade Study	Candidates	Selection
	Single-carrier non-constant envelope Multi-carrier (e.g. OFDM)	Envelope
Downlink modulation type	Constant envelope Single-carrier non-constant envelope Multi-carrier (e.g. OFDM)	Constant Envelope
Uplink modulation order	Binary 4-ary 8-ary	Binary
Downlink modulation order	Binary 4-ary 8-ary	Binary

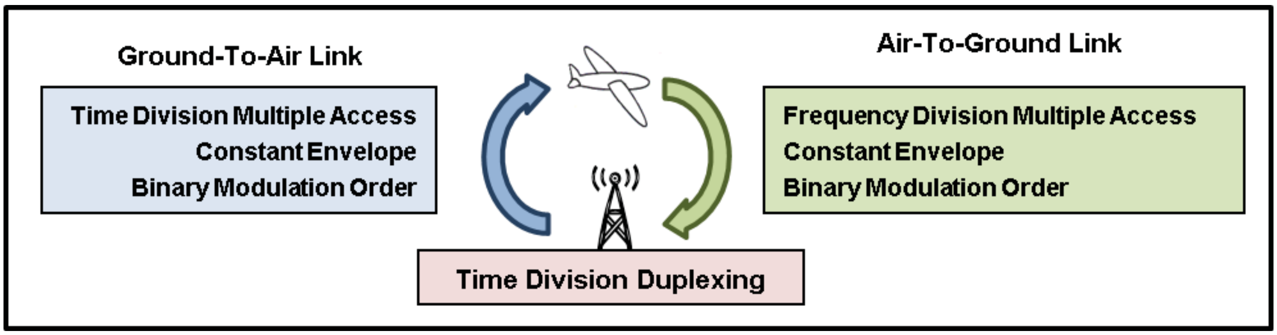

Figure 2: Summary of Proposed Communication Link Design

Figure 3 shows the basic multiple access architecture. It shows the transmissions from a ground station to multiple UAs (uplink) and from multiple UAs to the single ground station (downlinks) in Frequency and Time. The transmissions to and from each specific UA have a specific color. It is intended for display purposes and is not to exact scale, but does depict some size relationship.

Key elements of the basic waveform architecture include:

- The uplink and downlink are Time Division Duplex, alternating in time with a small guard time in between each transmission. The frame time would be 50 msec to support the 20 Hz message requirement for real time control applications.
- The uplink is Time Division Multiple Access, comprised of multiple sequential messages in each uplink sub frame, one directed to each UA.
- The downlink is Frequency Division Multiple Access. Each UA transmits a message on a specific frequency (assigned by the ground station). All downlink transmissions occur at the same time.
- All transmissions are Gaussian Minimum Shift Keying (GMSK) modulation.
- The orange color depicts a Stand Alone C2 uplink and downlink.

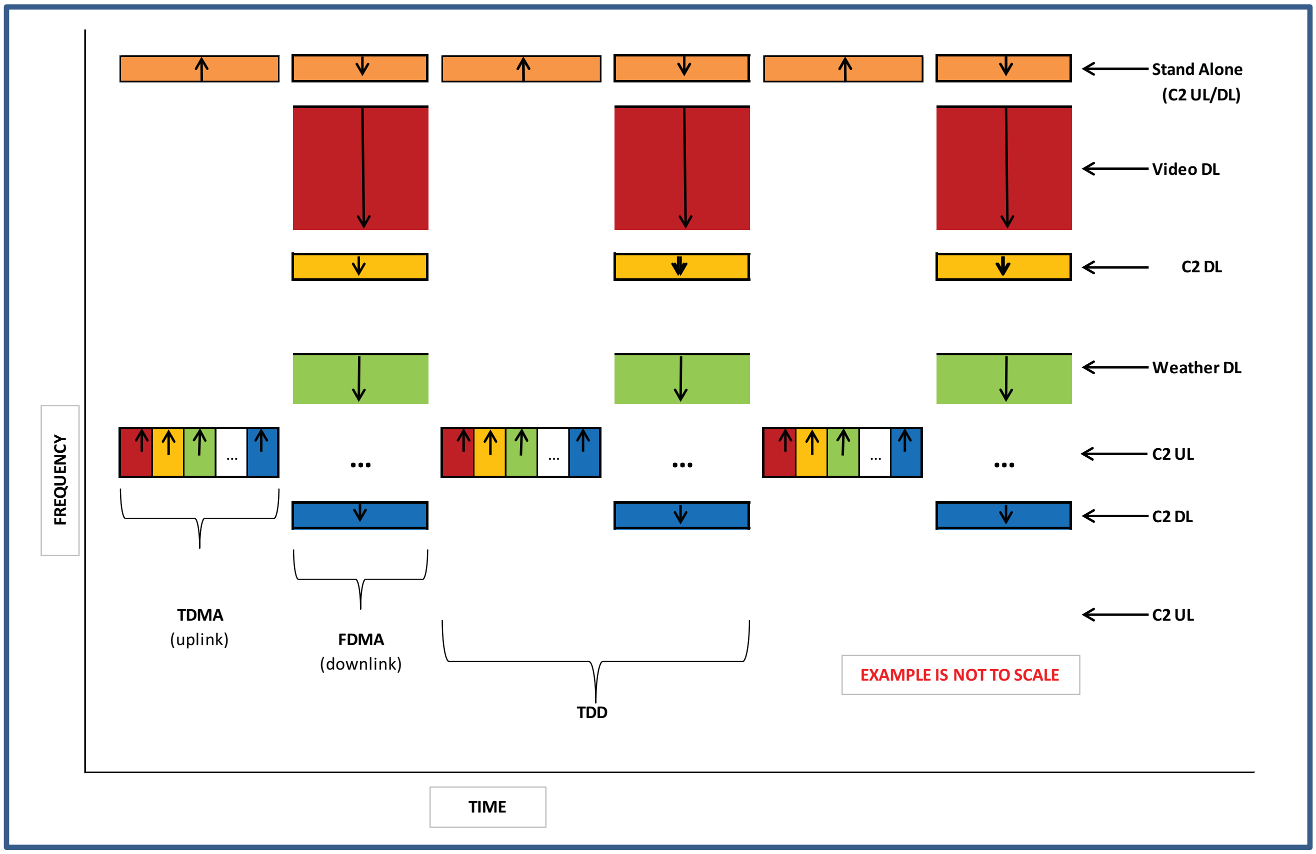

Figure 3: Overview of Proposed Multiple Access Architecture

1.6 System Level Assumptions

One of the key System Level requirements listed in Table 1: Key System Level Requirements is System Availability. The waveform definition can impact the Availability, but is more influenced by the system architecture, which is not part of this trade study. A major system design requirement is the need to mitigate effects due to multipath. Based on the limited available system bandwidth, channels are likely to be narrow, which would result in flat fading. The following system approaches may be necessary to address this situation:

- UAs may be required to have multiple antennas.
- Each cell may be required to have multiple networked ground stations.
- UAs may need to be able to receive redundant messages from separate ground stations (separate frequency/time reception).
- UAs operating with a Stand-Alone link may need more restrictive limits than other UAs. These restrictions could include altitude limits and visual line-of-sight.
- UAs in this system may need protocols to handle link outages.
- Power control may be required to optimize system performance.

2. Detailed Trades

As indicated in section 1.3, many of the specific evaluation criteria used herein as individual components will contribute to a broader system level analysis of required performance. To assist in making that connection, each of the specific evaluation criteria is listed along with the higher level system objectives to which it contributes most directly.

2.1 *Uplink/Downlink Duplexing*

2.1.1. Duplexing Evaluation Criteria and Design Candidates

Table 3 lists the uplink / downlink duplex evaluation criteria and associated weights:

Table 3: Uplink / Downlink Duplex Evaluation Criteria

Evaluation Criteria	Weight	System Level Factors Addressed
Uplink/Downlink Isolation	7	Availability, System Capacity, SWAP
Link Margin	3	Availability
RF Spectrum Utilization	3	System Capacity
System Synchronization	1	Cost, Complexity

Two candidates for uplink/downlink duplexing were considered:

- Frequency Division Duplexing (FDD)
- Time Division Duplexing (TDD).

2.1.2. Duplexing Analysis

Table 4 provides a summary and stoplight ratings for Uplink / Downlink Duplexing trade, as detailed in the analysis in the paragraphs below.

Table 4: Uplink / Downlink Duplex Analysis

Evaluation Criteria	Uplink/Downlink Duplexing Candidates	
	FDD	TDD
Uplink/Downlink Isolation	Infeasible	Not required
Link Margin	+3 dB	+0 dB
RF Spectrum Utilization	71%	92%
System Synchronization	Not required	Using GPS, < 5% added complexity

UPLINK / DOWNLINK ISOLATION

With FDD, sufficient isolation must be provided between the uplink and downlink frequencies in order to mitigate co-site interference. This isolation is achieved by having separate uplink and downlink frequency bands. An unused guard band must exist between the uplink and downlink bands in order to achieve the required isolation with fixed RF filtering. The guard band may be reduced if a complicated tunable RF filtering is employed. With TDD there is no requirement for isolation between uplink and downlink frequencies.

The frequency allocations in L band and C band are both less than a 2% bandwidth (width of the band divided by the band center frequency). It is probably infeasible to provide sufficient isolation between FDD uplink and downlink bands within either the L band or C band allocations. (Note that independent operation is required of L band and C band. Thus, FDD uplink and downlink frequencies *cannot* be divided between L band and C band.)

The requirements for a practical duplexer filter for the L-Band FDD application are quite strict. Assuming an equal split between transmit and receive bands, one band would have to exist between 960 and 968.5 MHz, while the other would be from 968.5 to 977 MHz. The major design challenges are to ensure that the insertion loss in each band is very low, that there is sufficient isolation between bands, and the usable bandwidth is maximized. In addition, the duplexer must handle significant power levels from the transmitter.

Section 3.3 contains the discussion on RF Filter performance. In order to handle the RF Power, it is necessary to use a cavity filter. One was identified which provides 40 dB of selectivity and low loss (1 dB). However, even this level of filter is still unable to mitigate performance issues due to spurious and intermodulation as described below.

Typical PA spurious performance is -70 dBc, which if not filtered could be an in-band interferer. The noise floor for the basic Command and Control channel (87.5 KHz symbol rate, thermal noise at -174 dBm/Hz, 4 dB NF) is -123.6 dBm/Hz. In order to minimize the impact of the interferer, the spurious should be down an additional 10dB (-133.6 dBm/Hz). With a 10 Watt PA (+40 dBm), this requires a total of 173.6 dB rejection from RF filtering and Power Amplifier (PA) spurious performance. If the PA has 70 dB of spurious rejection, over 100 dB of RF filtering would be required. This level of filtering is not realizable.

Intermodulation (IM) is also a major concern. Third order intermodulation products will be extremely strong. If either FDMA or CDMA was selected for the air-to-ground access, there would be multiple carriers. Typically a two tone IM would be down 50 dB from one of the carriers. With each carrier being 10 Watts (+40 dBm), the third order IM product would be -10 dBm. This would require a total of 123.6 dB of RF filtering which is not feasible.

The only way to mitigate this would be to introduce an approach to assign a new air-to-ground channel if the current channel is unusable. If the interferer was on the air-to-ground access channel, a secondary access channel would be required, or the conditions causing the spurious or IM would need to be changed.

TDD has better Availability and System Capacity because it eliminates potential spurious, IM, and the need for additional channels. TDD also eliminates the size, weight, and cost associated with RF Filters. ***The TDD approach is significantly superior to FDD.***

LINK MARGIN

FDD allows for simultaneous uplink and downlink communication. In TDD, time is divided between uplink and downlink communication. Since time does not have to be divided between uplink and downlink for FDD, this enables lower over-the-air data rates which would result in a 3 dB improvement in link margin over TDD assuming there is no loss in the duplexing filters. The high performance cavity filter listed in Section 3.3 has 1 dB of loss. The TDD configuration would have a T/R switch which would have approximately 1 dB of insertion loss which offsets the filter loss for FDD. ***The net result is the FDD configuration has approximately 3 dB more link margin than TDD.***

RF SPECTRUM UTILIZATION

In TDD, time is divided between uplink and downlink communication. This allows the system to use the full 17 MHz of RF Spectrum to be utilized. A 2 msec RX and TX guard time would be required to accommodate the propagation delay and other time uncertainty. The combination of this guard time with a 20 Hz repetition rate would reduce the overall RF Spectrum Utilization to 92%.

FDD allows for simultaneous uplink and downlink communication. Since time does not have to be divided between uplink and downlink, no guard time is required. The optimistic bandwidth utilization would be 12 MHz out of the 17 MHz available, resulting in an overall RF Spectrum

Utilization of 71%. See Section 3.3, for information on RF Filtering. ***TDD would result in improved system capacity.***

System Synchronization

With TDD, all ground stations and air vehicles must be synchronized, and unused guard time must exist in order to avoid interference between uplink and downlink communication. TDD synchronization would be based on GPS UTC. With an FDD system synchronization is not required. It is likely that the radio will have access to GPS time even if the FDD configuration was selected. ***There is essentially no complexity difference between FDD and TDD with respect to System Synchronization. .***

2.1.3. Duplexing Trade Study Results

Using the methodology described in Section 1.3, the weighted evaluation criteria are applied to the evaluation results of the design alternatives, as shown in Table 5 below.

Table 5: Uplink / Downlink Duplex Trade Results

Determine Uplink / Downlink Duplex Method						
	Evaluation Criteria	**Weight**		**Alternatives**	**Raw**	**%**
1	Uplink / Downlink Isolation	0.500	1	FDD	0.313	45
2	Link Margin	0.214	2	TDD	0.688	100
3	RF Spectrum Allocation	0.214				
4	System Synchronization	0.071				

Time Division Duplexing is the preferred Uplink / Downlink Duplex technique, with significant margin over assessment of Frequency Division Multiplexing. This is primarily because it is infeasible to achieve the uplink/downlink isolation required by FDD.

2.2 Uplink Multiple Access

The ground station must transmit uplink signals to multiple air vehicles. Each airborne receiver is responsible only for receiving the uplink signal meant for it. The selection of an uplink multiple access technique is made in the context of this hub-and-spoke network.

2.2.1. Uplink Multiple Access Evaluation Criteria and Design Candidates

Table 6 lists the uplink multiple access evaluation criteria and associated weights.

Table 6: Uplink Multiple Access Evaluation Criteria

Evaluation Criteria	Weight	System Level Factors Addressed
Link Margin at Full Capacity	7	Availability
Ground Transmitter Average Power	7	SWAP, Cost, Complexity
Ground Transmitter Linearity Required	5	SWAP, Cost, Complexity
Ground Sectored Antenna PAs	3	SWAP, Cost, Complexity
Multipath Mitigation	3	Availability, Cost, Complexity
Airborne Signal Processing Complexity	3	Cost, Complexity
Guard Time Overhead	1	System Capacity

Three candidates for uplink multiple access were considered:

- Code Division Multiple Access (CDMA)
- Frequency Division Multiple Access (FDMA)
- Time Division Multiple Access (TDMA)

2.2.2. Uplink Multiple Access Analysis

Table 7 provides a summary and stoplight ratings for this trade, as detailed in the analysis in the paragraphs below. FDMA is used as the basis for comparison for criteria needing a reference point.

Table 7: Uplink Multiple Access Analysis

Evaluation Criteria	Uplink Multiple Access Candidates		
	CDMA	**FDMA**	**TDMA**
Link Margin at Full Capacity	Unacceptable	Reference	Same as FDMA
Ground Transmitter Average Power	200 Watts	200 Watts	200 Watts
Ground Transmitter Linearity Required	High	High	Low
Ground Sectored Antenna PA's	1 PA per Sector Minimum of 4 PAs Required (3 Sectors + 1 Overhead)	1 PA per Sector Minimum of 4 PAs Required (3 Sectors + 1 Overhead)	1 PA Total PA switched to applicable Sector (1x4 Switch)
Multipath Mitigation	Link margin, spreading, RAKE processing	Link margin	Link margin, adaptive equalization
Airborne Receiver Signal Processing Complexity	10-20% added complexity	Reference	<5% added complexity
Guard Time Overhead	None	None	None if all uplink slots are adjacent

LINK MARGIN AT FULL CAPACITY

When supporting 20 UAs, TDMA and FDMA will have equivalent link margins. FDMA splits power between the 20 UAs among 20 frequencies, whereas TDMA splits the power across 20 time slots. However, the CDMA approach will have each UA receiving the desired signal as well as interference from up to 19 signals intended for other UAs. Even with sectored antennas, there exists the potential that all the UAs could be in the same sector. If this were the case, then regardless of the PA power available, the Signal-to-Interference ratio could never be high enough to meet the 99.8% availability requirement, see 3.4 for analysis of this case. ***FDMA and TDMA have equivalent acceptable link margins and CDMA would have unacceptably low availability.***

GROUND TRANSMITTER LINEARITY REQUIRED

The ground transmitter for either CDMA or FDMA must transmit 20 uplink signals simultaneously. For CDMA, this is the sum of 20 spread spectrum signals using orthogonal spreading codes and occupying the same bandwidth simultaneously (synchronous CDMA). For FDMA, this is 20 narrowband signals at 20 different center frequencies. In either case, the ground transmitter is required to have a high degree of linearity in order to transmit 20 signals without producing intermodulation, and thus interference, between signals. A minimum Peak-to-Average ratio of 6-7 dB is typical for CDMA systems. FDMA systems would likely require a Peak-to-Average ratio of 10-12 dB. For either of these two approaches the peak power would need to exceed 800 Watts. Section 3.1 provided details on the technology required for the Uplink PA. At C band, providing 200 Watts of output power requires combining multiple stages. Quadrupling the output power increases the complex and cost by an order of magnitude. Even with good linearity, intermodulation products of -50 dBc are likely. These IM products could be a co-channel interferer with the uplink channel from other ground transmitters. The interference level would be a function of the path loss to each ground transmitter, multipath, and the actual IM product signal level. By contrast, a TDMA ground transmitter must transmit only a single signal at any time, and can function properly with a relatively low degree of linearity, thus eliminating the IM issues associated with multiple carriers. ***The TDMA approach has improved availability (due to IM interference) and improved PA SWAP and cost.***

GROUND SECTORED ANTENNA PAS

The ground antennas are expected to be sectored antennas in order to provide the additional gain necessary to close the link. For both CDMA and FDMA configurations, there could be UAs operating in either a single sector or multiple sectors. Although the average power is only 200 Watts for either of these configurations, the power would need to be allocated on a per sector basis according to the number of UAs in that sector. To address this, it is likely that one PA would be allocated per sector. For L band operation, a likely configuration would be three 120 degree lateral sectors and one sector to cover overhead UAs. For C- band operation, additional gain will be required, with a minimum of six 60 degree lateral sectors and one sector for overhead UAs.

In the TDMA configuration, there is only one specific UA that needs to receive the ground to air transmission at a time. This allows the PA output to be switched to the applicable antenna sector via a high-power RF switching circuit. ***TDMA provides improved Cost/Complexity over FDMA and CDMA by significantly reducing the number of PAs required.***

AIRBORNE RECEIVER SIGNAL PROCESSING COMPLEXITY

FDMA enables the lowest airborne receiver signal processing complexity, since only a single narrowband signal must be received and processed. Receiver signal processing complexity is somewhat greater for TDMA, because the signal bandwidth is approximately 20 times greater than for FDMA. CDMA requires the highest receiver complexity, necessitating the reception, de-spreading, and processing of a wideband signal. CDMA receiver complexity goes with the spreading factor which would be at least 20. The hardware complexity is similar for all three access approaches. The higher speed processing may require either a higher speed DSP or use of a Field Programmable Gate Array (FPGA) to process the signal. ***The FDMA and TDMA access approaches have similar Receiver Signal Processing Complexity (<5% added hardware/software cost to optimize the design for higher speed). The CDMA approach is more complex with (10- 20% added hardware/software cost to optimize the design for higher speed).***

GUARD TIME OVERHEAD

Typically, TDMA requires some amount of unused guard time to prevent interference between users. However, all uplink signals are transmitted by the same ground transmitter. Thus, if all uplink time slots are adjacent, no guard time is required between them. CDMA and FDMA fundamentally require no guard time. ***No guard time overhead is associated with any of the uplink multiple access candidates.***

MULTIPATH MITIGATION

Multipath propagation is a fundamental phenomenon that may reduce link availability. Link margin as well as frequency and time diversity are the primary mitigation techniques used against multipath effects. However, a particular media access candidate and likely channel models may enable other mitigation techniques. For a given multipath channel model, coherence bandwidth, B_{coh}, can be derived from the rms delay spread of propagation paths. The coherence bandwidth is a measure of bandwidth over which the channel frequency response is approximately flat. The relationship between coherence bandwidth and desired signal bandwidth, B_{sig} is a key factor in determining the mitigation techniques used for multipath. For example, when $B_{sig} \ll B_{coh}$, as may be the case in FDMA, the channel is a flat fading channel. Thus, link margin is the only multipath mitigation likely to apply to FDMA. TDMA employs somewhat wider signal bandwidths. Depending on the multipath channel encountered, adaptive equalization may be used to mitigate frequency selective multipath for TDMA (at the expense of processing complexity). When $B_{sig} \gg B_{coh}$, the channel enables spread spectrum techniques such as RAKE processing to coherently combine propagation paths and mitigate the effects of multipath (at the expense of processing complexity). ***The CDMA approach is the most robust approach to address multipath. Due to the lower bandwidths and subsequent flat fading effect, FDMA and TDMA may have degraded performance for a given link margin. The TDMA approach could be more robust and complex than FDMA due to the adaptive equalization possible at the higher symbol rate.***

2.2.3. Uplink Multiple Access Trade Study Results

Using the methodology described in section 1.3 above, the weighted evaluation criteria are applied to the evaluation results of the design alternatives, as shown in Table 8 below.

Table 8: Uplink Multiple Access Trade Results

Determine Multiple Access Technique for Uplink							
	Evaluation Criteria	**Weight**		**Alternatives**	**Raw**	**%**
1	Link Margin at Full Capacity	0.241	1	CDMA	0.216	45
2	Ground Transmitter Average Power	0.241	2	FDMA	0.300	62
3	Ground Transmitter Linearity Required	0.172	3	TDMA	0.484	100
4	Ground Antenna Sectored Antenna PAs	0.103				
5	Multipath Mitigation	0.103				
6	Airborne Signal Processing Complexity	0.103				
7	Guard Time Overhead	0.034				

Time Division Multiple Access is the preferred uplink multiple access technique, with significant margin over all other candidates. This is primarily because it avoids the drawbacks of CDMA and FDMA in terms of ground transmitter linearity and the configuration of power amplifiers for sectored antennas. Also, CDMA cannot achieve acceptable link margin. Additional study information on Multiple Access and its consequences for transmitter linearity can be found in section 3.4.

2.3 Downlink Multiple Access

The ground station must receive downlink signals from multiple air vehicles. Each airborne transmitter is responsible only for transmitting a single downlink signal. The selection of a downlink multiple access technique is made in the context of this hub-and-spoke network.

2.3.1. Downlink Multiple Access Evaluation Criteria and Design Candidates

Table 9 lists the Downlink Multiple Access evaluation criteria and associated weights:

Table 9: Downlink Multiple Access Evaluation Criteria

Evaluation Criteria	Weight	System Level Factors Addressed
Link Margin at Full Capacity	7	Availability
Airborne Transmitter Peak Power	5	SWAP, Cost, Complexity
Multipath Mitigation	3	Availability, Cost, Complexity
Synchronization Required	3	Cost, Complexity
Power Control Required	3	Cost, Complexity
Ground Signal Processing Complexity	3	SWAP, Cost, Complexity

Three candidates for downlink multiple access were considered:

- Code Division Multiple Access (CDMA)
- Frequency Division Multiple Access (FDMA)
- Time Division Multiple Access (TDMA)

2.3.2. Downlink Multiple Access Analysis

Table 10 provides a summary and stoplight ratings for Downlink Multiple Access trade, as detailed in the analysis in the paragraphs below. FDMA is used as a basis for comparison for criteria needing a reference.

Table 10: Downlink Multiple Access Analysis

Evaluation Criteria	Downlink Multiple Access Candidates		
	CDMA	FDMA	TDMA
Link Margin at Full Capacity	Unacceptable	Reference	-13 dB for Identical PA
Airborne Transmitter Power	10 Watts peak	10 Watts peak	200 Watt peak
Multipath Mitigation	Link margin, spreading, RAKE processing	Link margin	Link margin, adaptive equalization
Synchronization Required	None beyond that required for TDD (for pseudorandom spreading codes)	None beyond that required for TDD	Tight synchronization for low guard time overhead
Power Control Required	Tight control mitigates near-far problem 10-20% added complexity	Gross control mitigates near-far problem	Gross control beneficial , but not required
Ground Signal Processing Complexity	10-20% added complexity	10-20% added complexity	Reference

Link Margin at Full Capacity

When supporting 20 UAs, downlink TDMA signal has a 20x wider bandwidth compared to FDMA. This results in a 13 dB advantage to FDMA over TDMA. Since FDMA has specific frequencies for each user, the capacity is known and each user has little effect on other users' performance. TDMA is similar in this regard, except users are separated by time. CDMA has every UA downlink signal transmitted at the same frequency at the same time but with a unique code. Each desired UA signal is interfered by 19 other UA signals. Based on SC-203 CDMA paper (Section 3.4), at peak capacity, the CDMA approach cannot support the required Signal-to-Interference ratio to meet the 99.8% availability requirement**. *FDMA has a 13 dB link margin advantage over TDMA and CDMA would have unacceptable availability.***

AIRBORNE TRANSMITTER POWER

Based on link analysis (by RTCA SC-203 assuming FDMA), the peak and average airborne transmitter power for CDMA or FDMA is on the order of 10 Watts. In the case of TDMA, the average power is also 10 Watts. Since time must be divided amongst downlinks from 20 air vehicles, the over-the-air rate is approximately 20 times faster than for CDMA or FDMA. Thus, the airborne peak transmitter power for TDMA is 200 Watts. The FDMA and CDMA approaches are similar because they have identical peak and average transmit power. ***The TDMA is ranked lower due to the additional Cost/Complexity required to support the 200 Watts peak airborne transmit power.***

GROUND RECEIVER SIGNAL PROCESSING COMPLEXITY

FDMA enables the lowest receiver signal processing complexity, since only a single narrowband signal must be received and processed. Receiver signal processing complexity is somewhat greater for TDMA, because the signal bandwidth is approximately 20 times greater than for FDMA. CDMA requires the highest receiver complexity, necessitating the reception, de-spreading, and processing of a wideband signal. CDMA receiver complexity goes with the spreading factor which would be at least 20. In the FDMA approach, the ground receiver must receive and process 20 downlink signals at different frequencies simultaneously. This requires parallel receivers, which increases the complexity. In all cases, adding additional receivers will be necessary to improve system availability, ***The TDMA approach provides the lowest Cost/Complexity with the FDMA and CDMA approaches having 10-20% added hardware/software cost to support the added receivers or higher speed.***

POWER CONTROL REQUIRED

For CDMA and FDMA, the ground station must receive multiple downlink signals simultaneously. As a result, the ground receiver is subject to the near-far problem, where its finite dynamic range cannot simultaneously handle a strong downlink signal from a near air vehicle and a weak downlink signal from a far air vehicle. To mitigate the near-far problem, a CDMA system must employ tight power control of the airborne transmitters such that all downlink signals arrive at the ground receiver with approximately the same power. This is especially important for CDMA since all downlink signals are on the same frequency, where only the spreading gain can be used to separate signals. (Note that *asynchronous* CDMA using pseudorandom spreading sequences is considered for downlink multiple access. This is in contrast to *synchronous* CDMA using orthogonal spreading sequences. This is because synchronous CDMA requires that all downlink signals arrive at the ground receiver under extremely tight synchronization.) For FDMA, gross power control is sufficient to mitigate the near-far problem, since each downlink signal is on a different frequency and filtering can be used to separate signals. While gross power control may be beneficial for TDMA, it is not necessary. ***The FDMA and TDMA access approaches have similar Power Control Complexity. The CDMA approach is more complex with 10-20% added hardware/software cost to optimize the design for tighter power control.***

SYNCHRONIZATION REQUIRED

While TDMA does not require power control, it does require tight synchronization of downlink signals at the ground receiver. This means that each airborne transmitter must adjust its timing to account for the propagation delay from the air vehicle to the ground station. If tight synchronization is not maintained, then large amounts of unused guard time must be inserted in order to handle downlink signals with differing amounts of propagation delay. The result is prohibitive amounts overhead lost to guard time. In contrast, CDMA and FDMA require no more synchronization than that required for time division duplex (TDD), as discussed above. ***The TDMA is ranked lower due to the additional Complexity (5-10%) required to maintain tight synchronization.***

MULTIPATH MITIGATION

Multipath propagation is a fundamental phenomenon that may reduce link availability. Link margin as well as frequency and time diversity are the primary mitigation techniques used against multipath effects. However, a particular media access candidate and likely channel models may enable other mitigation techniques. For a given multipath channel model, coherence bandwidth, B_{coh}, can be derived from the rms delay spread of propagation paths. The coherence bandwidth is a measure of bandwidth over which the channel frequency response is approximately flat. The relationship between coherence bandwidth and desired signal bandwidth, B_{sig} is a key factor in determining the mitigation techniques used for multipath. For example, when $B_{sig} \ll B_{coh}$, as may be the case in FDMA, the channel is a flat fading channel. Thus, link margin is the only multipath mitigation likely to apply to FDMA. TDMA employs somewhat wider signal bandwidths. Depending on the multipath channel encountered, adaptive equalization may be used to mitigate frequency selective multipath for TDMA (at the expense of processing complexity). When $B_{sig} \gg B_{coh}$, the channel is a spread spectrum channel like CDMA, that uses RAKE processing to coherently combine propagation paths and mitigate the effects of multipath (at the expense of processing complexity). Due to the lower bandwidths and subsequent flat fading effect, FDMA and TDMA may have degraded performance for a given link margin. The TDMA approach could be more robust and complex than FDMA due to the adaptive equalization possible at the higher symbol rate. ***The CDMA approach is the most robust approach to address multipath.***

2.3.3. Downlink Multiple Access Trade Study Results

Using the methodology described in Section 1.3 above, the weighted evaluation criteria are applied to the evaluation results of the design alternatives, as shown in Table 11 below.

Table 11: Downlink Multiple Access Trade Results

Determine Multiple Access Technique for Downlink						
	Evaluation Criteria	**Weight**		**Alternatives**	**Raw**	**%**
1	Link Margin at Full Capacity	0.292	1	CDMA	0.299	62
2	Airborne Transmitter Power	0.208	2	FDMA	0.479	100
3	Multipath Mitigation	0.125	3	TDMA	0.223	47
4	Synchronization Required	0.125	4			
5	Power Control Required	0.125	5			
6	Ground Signal Processing Complexity	0.125	6			

FDMA is selected as the best candidate for downlink multiple access, with significant margin over all other candidates. This is primarily because it avoids the poor spatial frequency reuse and tight power control associated with CDMA and the high airborne transmitter power and tight synchronization required by TDMA. Additional study information on Multiple Access and its consequences for transmitter linearity can be found in section 3.6.

2.4 Uplink Modulation Type

2.4.1. Uplink Modulation Type Evaluation Criteria and Design Candidates

Table 12 lists the uplink modulation type evaluation criteria and associated weights:

Table 12: Uplink Modulation Type Evaluation Criteria

Evaluation Criteria	Weight	System Level Factors Addressed
Ground Transmitter Total Power	5	Cost, Complexity
Ground Transmitter Linearity Required	5	Cost, Complexity
Multipath Mitigation	3	Availability
Airborne Signal Processing Complexity	3	SWAP
Timing Recovery Required	1	Cost, Complexity
Tolerance to Frequency Offset	1	Cost, Complexity

Three candidates for uplink modulation type were considered:

- **Constant envelope:** Constant envelope modulations include (single-carrier) signaling schemes with no variation in signal amplitude such as Gaussian minimum shift keying (GMSK) and continuous phase modulation (CPM)
- **Single-carrier non-constant envelope:** Single-carrier non-constant envelope modulations include phase shift keying (PSK) and quadrature amplitude modulation (QAM)
- **Multi-carrier:** Multi-carrier modulation primarily refers to orthogonal frequency modulation (OFDM)

2.4.2. Uplink Modulation Type Analysis

Table 13 provides a summary and stoplight ratings for this trade, as detailed in the analysis in the paragraphs below.

Table 13: Uplink Modulation Analysis

Evaluation Criteria	Uplink Modulation Type Candidates		
	Constant Envelope	Single-carrier Non-constant Envelope	Multi-carrier (e.g. OFDM)
Ground Transmitter Total Power	200 Watt	200 Watt	200 Watt
Ground Transmitter Linearity Required	None	Medium	High
Multipath Mitigation	Time domain equalization 10-20% added complexity	Time domain equalization 10-20% added complexity	Frequency domain equalization
Airborne Receiver Signal Processing Complexity	Reference	Similar to Constant Envelope	10-20% added complexity
Timing Recovery Required	<5% added complexity	<5% added complexity	Reference
Tolerance to Frequency Offset	Good	Good	<5% added complexity

GROUND TRANSMITTER TOTAL POWER

As discussed above, the ground transmitter total (average) power will be approximately 200 Watts for all three modulation types. ***The three modulation types are evaluated as having identical Ground Transmitter Total Power.***

GROUND TRANSMITTER LINEARITY REQUIRED

The level of linearity required depends on the modulation type selected. Constant envelope modulations require no linearity, and thus can be used with highly efficient saturating amplifiers. Single-carrier non-constant envelope signals require moderate linearity, since these signals have moderate peak-to-average ratios. Multi-carrier signals have very high peak-to-average ratios, requiring high levels of transmitter linearity. Assuming a minimum Peak-to-Average ratio of 3 dB for the single carrier non-constant amplitude signal, and 6-7 dB for the multicarrier signal, the peak power would need to exceed 400/800 Watts respectively. Section 3.1 provided details on the technology required for the Uplink PA. At C band, providing 200 Watts of output power requires combining multiple stages. Doubling or quadrupling the output power increases the complexity and cost by an order of magnitude. Even with good linearity, intermodulation products of -50 dBc are likely for multi-carrier approaches. These IM products could be a co-channel interferer with the uplink channel from a different ground transmitter. The interference level would be a function of the path loss to each ground transmitter, multipath, and the actual IM product signal level. By contrast, a single carrier ground transmitter must transmit only a single signal at any time, and can function properly with a relatively low degree of linearity, and eliminate the IM issues associated with multiple carriers. ***The Constant Envelope approach has improved PA SWAP, Cost/Complexity over Single-carrier Non-constant Envelope approach and improved PA SWAP, Cost/Complexity and Availability (due to IM interference) over the Multi-carrier approach.*** Additional study information on Multiple Access and its consequences for transmitter linearity can be found in section 3.6.

MULTIPATH MITIGATION

If frequency selective multipath is encountered, it may be mitigated using equalization. Multicarrier modulations like OFDM uses long symbol duration and a guard time (cyclic prefix) to eliminate Inter-Symbol Interference (ISI). Residual equalization may be performed using simpler frequency domain equalization. ***The multi-carrier approach is the least complex approach to address multipath, and the two single carrier approaches being 10-20% more complex.***

AIRBORNE RECEIVER SIGNAL PROCESSING COMPLEXITY

Airborne receiver complexity is relatively low for constant envelope and single-carrier non-constant envelope modulations, and somewhat higher for multi-carrier modulations. This is because the multiple carriers must be separated prior to subsequent processing. This is typically implemented using an efficient fast Fourier transform (FFT) for Orthogonal Frequency Division Multiplexing (OFDM). ***The two single carrier approaches have similar Signal Processing Complexity. The multi-carrier approach is more complex with 10-20% added hardware/software.***

TIMING RECOVERY REQUIRED

Multi-carrier modulation does not require as tight of timing recovery as the single-carrier techniques, since the symbol rate on each sub-carrier is much less than the single-carrier symbol rate. Neither should particularly difficult to achieve. ***The three access approaches have similar timing Recovery Complexity (<5% added software cost to optimize the design tighter timing recovery).***

TOLERANCE TO FREQUENCY OFFSET

Tolerance to frequency offset for multi-carrier signaling is much worse than for single-carrier techniques. This is because each sub-carrier is much narrower in bandwidth than a single-carrier signal. This has the potential to affect the availability of the system. Frequency offsets will be caused by Doppler Effect and by clock oscillator inaccuracies. Assuming a 1 part per million (ppm) oscillator offset at the transmitter and at the receiver, and 600 knots of relative velocity, frequency offsets greater than 3 kHz at L band and greater than 15.7 kHz at C band can occur. These offsets may be a fraction of a single-carrier signal bandwidth, but they are likely larger than the sub-carrier spacing of a multi-carrier signal. While either a single-carrier or a multi-carrier receiver must estimate and remove the frequency offset, the multi-carrier receiver must remove it much more accurately. This is because a residual frequency offset may result in a loss of orthogonality between sub-carriers in a multi-carrier system such as OFDM. ***The three access approaches have similar timing Tolerance to Frequency Offset Complexity (<5% added software cost to optimize the design for OFDM).***

2.4.3. Uplink Modulation Type Trade Study Results

Using the methodology described in section 1.3 above, the weighted evaluation criteria are applied to the evaluation results of the design alternatives, as shown in Table 14 below.

Table 14: Uplink Modulation Type Trade Results

Determine Uplink Modulation						
	Evaluation Criteria	**Weight**		**Alternatives**	**Raw**	**%**
1	Ground Transmitter Total Power	0.278	1	Constant Envelope	0.415	100
2	Ground Transmitter Linearity	0.278	2	Single Carrier Non-constant Envelope	0.312	75
3	Multipath Mitigation	0.167	3	Multicarrier	0.273	66
4	Airborne Signal Processing Complexity	0.167				
5	Timing Recovery Required	0.056				
6	Tolerance to Frequency Offset	0.056				

Constant envelope modulation is a good candidate for uplink modulation type, with moderate margin over single carrier non-constant envelope and significant margin over multicarrier techniques. This is primarily because it eliminates the need for a linear ground transmitter, enabling the use of highly efficient saturating amplifiers. Given 200 Watt ground transmitter total (average) power, high linearity requires peak powers in the kilowatt realm. This kind of high power and high linearity is not desirable for ground transmitter implementation. Even modest linearity requires peak powers at least twice the average power, which has a significant impact on transmitter efficiency.

2.5 Downlink Modulation Type

2.5.1. Downlink Modulation Type Evaluation Criteria and Design Candidates

Table 15 lists the downlink modulation type evaluation criteria and associated weights:

Table 15: Downlink Modulation Type Evaluation Criteria

Evaluation Criteria	Weight	System Level Factors Addressed
Airborne Transmitter Total Power	7	SWAP
Airborne Transmitter Linearity Required	7	SWAP
Multipath Mitigation	3	Availability
Ground Signal Processing Complexity	3	SWAP
Timing Recovery Required	1	Cost, Complexity
Tolerance to Frequency Offset	1	Cost, Complexity

Three candidates for uplink modulation type were considered:

- **Constant envelope** – Constant envelope modulations include (single-carrier) signaling schemes with no variation in signal amplitude such as Gaussian minimum shift keying (GMSK) and continuous phase modulation (CPM).
- **Single-carrier non-constant envelope** – Single-carrier non-constant envelope modulations include phase shift keying (PSK) and quadrature amplitude modulation (QAM).
- **Multi-carrier** – Multi-carrier modulation primarily refers to orthogonal frequency modulation (OFDM).

2.5.2. Downlink Modulation Type Analysis

Table 16 provides a summary and stoplight ratings for the Downlink Modulation Type trade, as detailed in the analysis in the paragraphs below. For some criteria, a baseline was needed to compare one Candidate against the others. These are listed as ‘Reference’.

Table 16: Downlink Modulation Analysis

Evaluation Criteria	Downlink Modulation Type Candidates		
	Constant Envelope	Single-carrier Non-constant Envelope	Multi-carrier (e.g. OFDM)
Airborne Transmitter Total Power	10 Watt	10 Watt	10 Watt
Airborne Transmitter Linearity Required	None	10-20% added complexity	20-40% added complexity
Multipath Mitigation	Time domain equalization 10-20% added complexity	Time domain equalization 10-20% added complexity	Frequency domain equalization
Ground Signal Processing Complexity	Reference	Similar to Constant Envelope	10-20% added complexity
Timing Recovery Required	<5% added complexity	<5% added complexity	Reference
Tolerance to Frequency Offset	Good	Good	<5% added complexity

AIRBORNE TRANSMITTER TOTAL POWER

The airborne transmitter total (average) power is 10 Watts for all three modulation types. ***The three modulation types are evaluated as having identical Airborne Transmitter Total Power.***

AIRBORNE TRANSMITTER LINEARITY REQUIRED

Level of linearity required depends on the modulation type. Constant envelope modulations require no linearity, and thus can be used with highly efficient saturating amplifiers. Single-carrier non-constant envelope signals require moderate linearity, since these signals have moderate peak-to-average ratios. Multi-carrier signals have very high peak-to-average ratios, requiring high levels of transmitter linearity. The Single Carrier Non-Constant Envelope approach would need to support a peak power of greater than 20 Watts, and would add 10-20% complexity to the PA design. The Multi-Carrier approach would need to support a peak power of greater than 40 Watts, and would add 20-40% complexity to the PA design. ***The Single Carrier Constant Envelope approach is the least complex design.*** Additional study information on Multiple Access and its consequences for transmitter linearity can be found in section 3.7.4.

MULTIPATH MITIGATION

If frequency selective multipath is encountered, it may be mitigated using equalization. Multicarrier modulations like OFDM uses long symbol duration and a guard time (cyclic prefix) to eliminate InterSymbol Interference (ISI). Residual equalization may be performed using simpler frequency domain equalization. ***The multi-carrier approach is the least complex approach to address multipath, and the two single carrier approaches being 10-20% more complex.***

GROUND SIGNAL PROCESSING COMPLEXITY

Ground receiver complexity is relatively low for constant envelope and single-carrier non-constant envelope modulations, and somewhat higher for multi-carrier modulations. This is because the multiple carriers must be separated prior to subsequent processing. This is typically implemented using an efficient Fast Fourier Transform (FFT) for OFDM. ***The three access approaches have similar Signal Processing Complexity (<5% added software cost to implement multi-carrier modulation).***

TIMING RECOVERY REQUIRED

Multi-carrier modulation does not require as tight of timing recovery as the single-carrier techniques, since the symbol rate on each sub-carrier is much less than the single-carrier symbol rate. ***The three access approaches have similar timing Recovery Complexity (<5% added software cost to optimize the design tighter timing recovery).***

TOLERANCE TO FREQUENCY OFFSET

On the other hand, tolerance to frequency offset for multi-carrier signaling is much worse than for single-carrier techniques. This is because each sub-carrier is much narrower in bandwidth than a single-carrier signal. This has the potential to affect the availability of the system. Frequency offsets will be caused by Doppler Effect and by clock oscillator inaccuracies. Assuming a 1 part per million (ppm) oscillator offset at the transmitter and at the receiver, and 600 knots of relative velocity, frequency offsets greater than 3 kHz at L band and greater than 15.7 kHz at C band can occur. These offsets may be a fraction of a single-carrier signal bandwidth, but they are likely larger than the sub-carrier spacing of a multi-carrier signal. While either a single-carrier or a multi-carrier receiver must estimate and remove the frequency offset, the multi-carrier receiver must remove it much more accurately. This is because a residual frequency offset may result in a loss of orthogonality between sub-carriers in a multi-carrier system such as OFDM. ***The three access approaches have similar timing Tolerance to***

Frequency Offset Complexity (<5% added software cost to optimize the design for OFDM).

2.5.3. Downlink Modulation Type Trade Study Results

Using the methodology described in section 1.3 above, the weighted evaluation criteria are applied to the evaluation results of the design alternatives, as shown in Table 17 below.

Table 17: Downlink Modulation Type Trade Results

Determine Downlink Modulation						
	Evaluation Criteria	**Weight**		**Alternatives**	**Raw**	**%**
1	Airborne Transmitter Total Power	0.318	1	Constant Envelope	0.429	100
2	Airborne Transmitter Linearity	0.318	2	Single Carrier	0.311	73
3	Multipath Mitigation	0.136	3	Multicarrier	0.261	61
4	Ground Signal Processing Complexity	0.136				
5	Timing Recovery Required	0.045				
6	Tolerance to Frequency Offset	0.045				

Constant envelope modulation is a good candidate for downlink modulation type, with moderate margin over non-constant envelope single carrier and significant margin over multicarrier techniques. This is primarily because it eliminates the need for a linear airborne transmitter, enabling the use of highly efficient saturating amplifiers. Given 10 Watt class airborne transmitter total (average) power, high linearity requires peak powers in the 50 Watt realm. This kind of high power and high linearity is not compatible with low SWAP airborne transmitter implementation. Even modest linearity requires peak powers at least twice the average power, which has a significant impact on transmitter efficiency.

2.6 Uplink Modulation Order

Modulation order refers to the number of possible values for a transmitted symbol.

2.6.1. Uplink Modulation Order Evaluation Criteria and Design Candidates

Table 18 lists the uplink modulation order evaluation criteria and associated weights:

Table 18: Uplink Modulation Order Evaluation Criteria

Evaluation Criteria	Weight	System Level Factors Addressed
Required Signal-to-Noise	7	Availability
RF Bandwidth Utilization	5	System Capacity
Airborne Signal Processing Complexity	3	SWAP

Given that constant envelope modulation is the selection for uplink modulation type, three candidates for uplink modulation type were considered:

- **Binary:** Gaussian minimum shift keying (GMSK) is an example of binary constant envelope modulation
- **4-ary:** Continuous phase modulation (CPM) can provide 4-ary constant envelope signaling
- **8-ary**: Continuous phase modulation (CPM) can provide 8-ary constant envelope signaling

2.6.2. Uplink Modulation Order Analysis

Table 19 provides a summary and stoplight ratings for this trade, as detailed in the analysis in the paragraphs below. Binary Modulation is used as a basis for comparison for all the critieria, and is labeled as 'Reference'.

Table 19: Uplink Modulation Order Analysis

Evaluation Criteria	Uplink Modulation Order Candidates		
	Binary	4-ary	8-ary
Required Signal-to-Noise Ratio	Reference	3 dB Higher SNR	6 dB Higher SNR
RF Bandwidth Utilization	Reference	Similar to Binary	Similar to Binary
Airborne Signal Processing Complexity	Reference	1.6 as complex as Binary (Demodulator)	2.2 as complex as Binary (Demodulator)

REQUIRED SIGNAL-TO-NOISE

While higher order modulations are more spectrally efficient, they also require a greater level of signal-to-noise ratio (SNR) at the receiver. This increase in required SNR corresponds to a reduction in link margin and a decrease in tolerance to interference and frequency selective multipath. ***GMSK is 3 dB better than 4-ary and 6 dB better than 8-ary which provides improved System Availability.***

RF BANDWIDTH UTILIZATION

Modulation order corresponds to the number of bits that can be transmitted per symbol, one for binary, two for 4-ary, and three for 8-ary. The number of bits per symbol is a measure of the spectral efficiency of the modulation. Because of the higher SNR needed for 4-ary and 8-ary, increased channel spacing is needed to reduce interference. This additional channel spacing reduces the potential utilization. ***Overall the spectral efficiency of the higher order modulations are negated by the additional channel spacing, thus making the modulations equivalent for RF bandwidth utilization.***

AIRBORNE SIGNAL PROCESSING COMPLEXITY

The major difference in the signal processing complexity, due to modulation order, is in the demodulator. Compared to the Binary demodulator, the 4-ary demodulator is 1.6 times more complex and the 8-ary is 2.2 times more complex. ***Binary provides the lowest complexity.***

2.6.3. Uplink Modulation Order Trade Study Results

Using the methodology described in section 1.3 above, the weighted evaluation criteria are applied to the evaluation results of the design alternatives, as shown in Table 20 below.

Table 20: Uplink Modulation Order Trade Results

Determine Uplink Modulation Order							
	Evaluation Criteria	**Weight**		**Alternatives**	**Raw**	**%**
1	Required Signal-to-Noise	0.467	1	Binary	0.544	100
2	RF Bandwidth Utilization	0.333	2	4-ary	0.297	55
3	Airborne Signal Processing Complexity	0.200	3	8-ary	0.159	29

Binary modulation (i.e. GMSK) is a good candidate for uplink modulation order, with significant margin over other alternatives. This is primarily because of the low level of required SNR, corresponding to better link margin and better performance against interference and frequency selective multipath. Additional study information on modulation schemes can be found in section 3.7.

2.7 Downlink Modulation Order

Modulation order refers to the number of possible values for a transmitted symbol.

2.7.1. Downlink Modulation Order Evaluation Criteria and Design Candidates

Table 21 lists the Downlink modulation order evaluation criteria and associated weights:

Table 21: Downlink Modulation Order Evaluation Criteria

Evaluation Criteria	Weight	System Level Factors Addressed
Required Signal-to-Noise	7	Availability
RF Bandwidth Utilization	5	System Capacity
Ground Signal Processing Complexity	1	SWAP

Given that constant envelope modulation is the selection for uplink modulation type, three candidates for uplink modulation type were considered:

- **Binary**: Gaussian minimum shift keying (GMSK) is an example of binary constant envelope modulation.
- **4-ary**: Continuous phase modulation (CPM) can provide 4-ary constant envelope signaling
- **8-ary**: Continuous phase modulation (CPM) can provide 8-ary constant envelope signaling

2.7.2. Downlink Modulation Order Analysis

Table 22 provides a summary and stoplight ratings for this trade, as detailed in the analysis in the paragraphs below. Binary Modulation is used as a basis for comparison for all the critieria, and is labeled as 'Reference'.

Table 22: Downlink Modulation Order Analysis

Evaluation Criteria	Downlink Modulation Order Candidates		
	Binary	4-ary	8-ary
Required Signal-to-Noise Ratio	Reference	3 dB Higher SNR	6 dB Higher SNR
RF Bandwidth Utilization	Reference	Similar to Binary	Similar to Binary
Ground Receiver Signal Processing Complexity	Reference	1.6 as complex as Binary (Demodulator)	2.2 as complex as Binary (Demodulator)

REQUIRED SIGNAL-TO-NOISE

While higher order modulations are more spectrally efficient, they also require a greater level of signal-to-noise ratio (SNR) at the receiver. This increase in required SNR corresponds to a reduction in link margin and a decrease in tolerance to interference and frequency selective multipath. ***GMSK is 3 dB better than 4-ary and 6 dB better than 8-ary which provides improved system availability.***

RF BANDWIDTH UTILIZATION

Modulation order corresponds to the number of bits that can be transmitted per symbol, one for binary, two for 4-ary, and three for 8-ary. The number of bits per symbol is a measure of the spectral efficiency of the modulation. Because of the higher SNR needed for 4-ary and 8-ary, increased channel spacing is needed to reduce interference. This additional channel spacing reduces the potential utilization. ***Overall the spectral efficiency of the higher order modulations are negated by the additional channel spacing, thus making the modulations equivalent for RF bandwidth utilization.***

GROUND SIGNAL PROCESSING COMPLEXITY

The major difference in the signal processing complexity, due to modulation order, is in the demodulator. Compared to the Binary demodulator, the 4-ary demodulator is 1.6 times more complex and the 8-ary is 2.2 times more complex. ***Binary provides the lowest complexity.***

2.7.3. Downlink Modulation Order Trade Study Results

Using the methodology described in section 1.3 above, the weighted evaluation criteria are applied to the evaluation results of the design alternatives, as shown in Table 23 below.

Table 23: Downlink Modulation Order Trade Results

Determine Downlink Modulation Order						
	Evaluation Criteria	Weight		Alternatives	Raw	%
1	Required Signal-to-Noise	0.538	1	Binary	0.528	100
2	RF Bandwidth Utilization	0.385	2	4-ary	0.300	57
3	Ground Signal Processing Complexity	0.077	3	8-ary	0.172	33

Binary modulation (i.e. GMSK) is a good candidate for uplink modulation order, with significant margin over other alternatives. This is primarily because of the low level of required SNR, corresponding to better link margin and better performance against interference and frequency selective multipath. Additional study information on modulation schemes can be found in section 3.7.

3. Additional Design Considerations / Supporting Information

3.1 Uplink Power Amplifier Approach

The 960 to 977 MHz frequency band being discussed is adjacent to commercial cellular bands. This allows the use of commercial devices for power amplification. The ideal technology of choice for this frequency band and output power will be LDMOS (laterally diffused MOSFET). This technology has been used in commercial applications for over 20 years. These power amplifier devices are very mature and robust. They provide high output power exceeding 200 Watts in a single low cost, small form-factor package. Typical gains of these devices exceed 15 dB per stage with drain efficiencies approaching 60% when using constant envelope modulation. The entire power amplifier module will have an approximate DC power requirement of less than 500 Watts.

The frequency band 5030 to 5091 MHz is not as easily addressed as the L band above with existing technology. At C band the most applicable solid state devices are Power GaAs (gallium arsenide) FET and GaN (gallium nitride) FET transistors. Typical output power for the last stage amplification devices are nominally 30-45 Watts. Obtaining an output power exceeding 200 Watts will require multiple stages connected together either in a balanced or push-pull architecture. Expected efficiency of the power amplifier will be approximately 10-15% using a constant envelope modulation. The entire power amplifier module will have an approximate DC power requirement of 1-2 kilowatts.

3.2 Downlink Power Amplifier Approach

The proposed approach for downlink is a constant envelope FDMA waveform with 10 Watts output power. The assumptions made in Section 2.3 are valid for the downlink architecture. The optimum technology for the 960-977 MHz frequency band is LDMOS. Similar gain for transistor devices and drain efficiencies can be assumed. Since the output power is significantly less for the airborne node, the DC power required will be roughly 25 Watts.

For the frequency band 5030 to 5091 MHz the lower output power will significantly improve the overall efficiency of the power amplifier. Combining as many as eight devices will not be required for the airborne node and thus, reduce the losses between the final stage transistor(s) and the antenna. The overall amplifier efficiency should improve from 10-15% to between 20-25%. The DC power requirement will be roughly 50 Watts.

3.3 Radio Frequency Filtering

A parameter commonly used to determine if a technology is suitable for a filtering application is the Quality Factor, or Q, of the component structures used in the filter. For the example displayed in Figure 4, the circuit Q is approximated by the center frequency divided by the bandwidth. For a filter centered at 963 MHz with a 5 MHz bandwidth, circuit Q is 190. A rule of thumb is that the component Q must be 5-10 times the required circuit Q, or 1000-2000 for this example. Figure 4 shows the effects of component Q. In the simulation, component Q is swept from 100 (m1 in Figure 4) to 1000 (m2 in Figure 4). For a Q of 1000, the insertion loss of the filter is 1 dB. Loss increases to 8 dB as Q is reduced to 100. For a filter with bandwidth reduced to increase isolation between bands, the loss is as high as 20 dB with lower Q components.

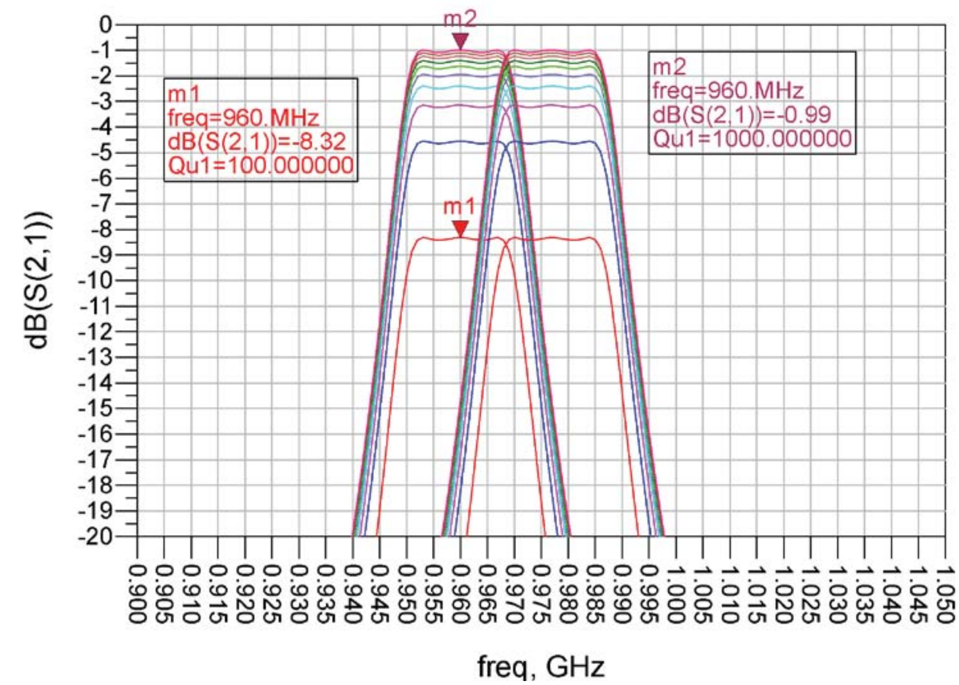

Figure 4: Insertion Loss for Q's Ranging from 100 to 1000

Figure 5 shows Quality Factors versus technology type and usable frequency ranges.

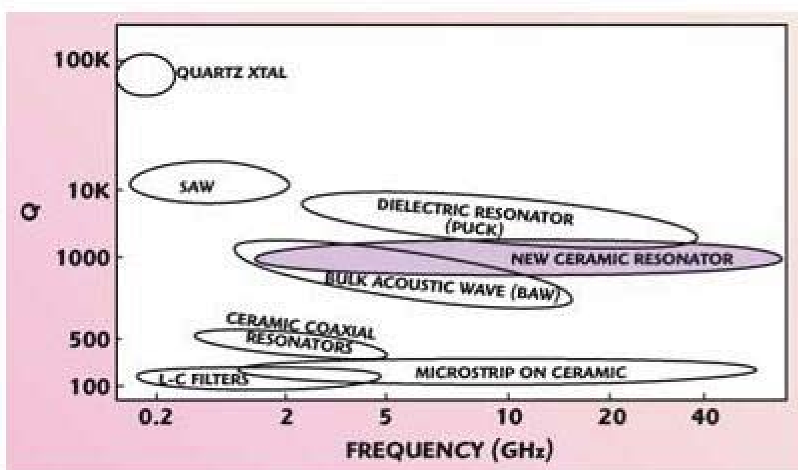

Figure 5: Quality Factor of Typical Filter Technologies (*source: Dielectric Labs*)

For the example in Figure 4, L-C filters with Qs between 100 and 200 are not adequate. Candidate technologies include Bulk Acoustic Wave (BAW) and Surface Acoustic Wave (SAW). These technologies are commonly used in commercial radio products such as cell phones. A limitation not shown in the figure is power handling. BAW and SAW filters cannot handle more than 1 W of transmitter power, significantly less than what's required for the proposed system.

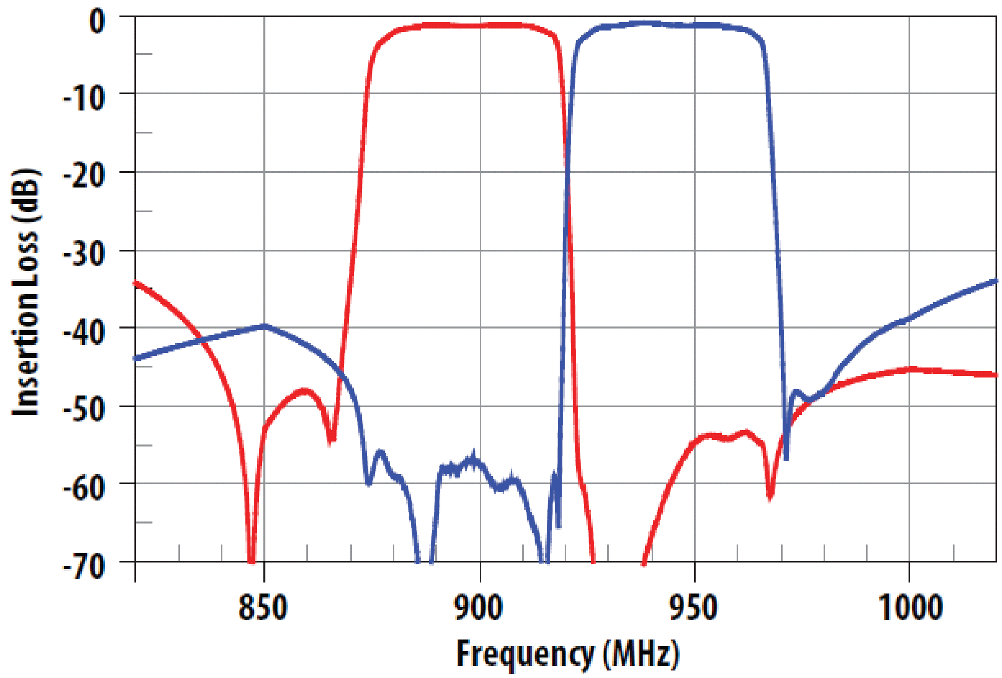

Figure 6: Commercial BAW Duplexer for GSM Band (Avago ACMD-7610)

Figure 6 shows the sharp skirts available from BAW technology but the filter is limited to 1 W maximum power.

Although not shown in Figure 6, cavity filters can provide good isolation, low insertion loss, and support the power handling capability. These filters are very large and expensive. They are commonly used in base stations and other applications where co-located interference must be rejected.

Figure 7 below shows the frequency response for a cavity filter designed for one side of a duplexer suitable for use in the FDD system. The available bandwidth is approximately 6 MHz for each band, 6 MHz for the uplink and 6 MHz for the downlink. It would only be capable of utilizing 12 MHz of the 17 MHz allocated spectrum. The downside to this filter is the prohibitively large size. Figure 8 shows the mechanical form factor for *one half* of the duplexer cavity filter. It's approximately 12" x 5.5" x 1.8", a total volume of 120 in^3.

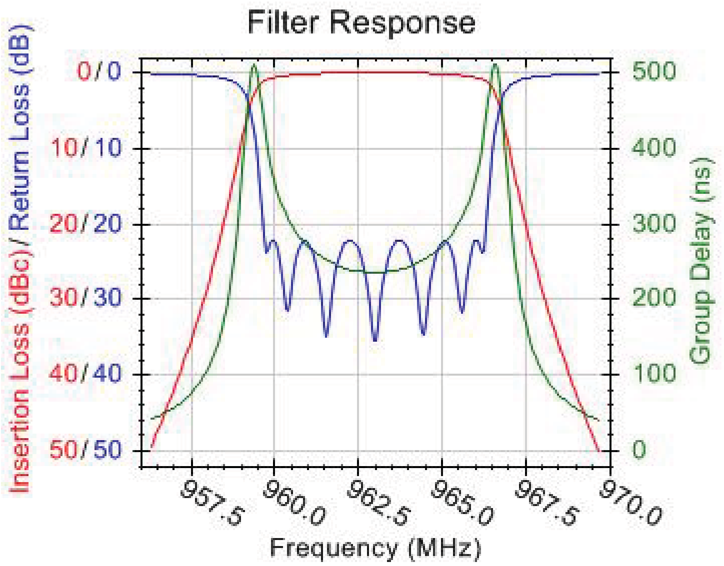

Figure 7: Cavity Filter Response Curves (K&L Microwave)

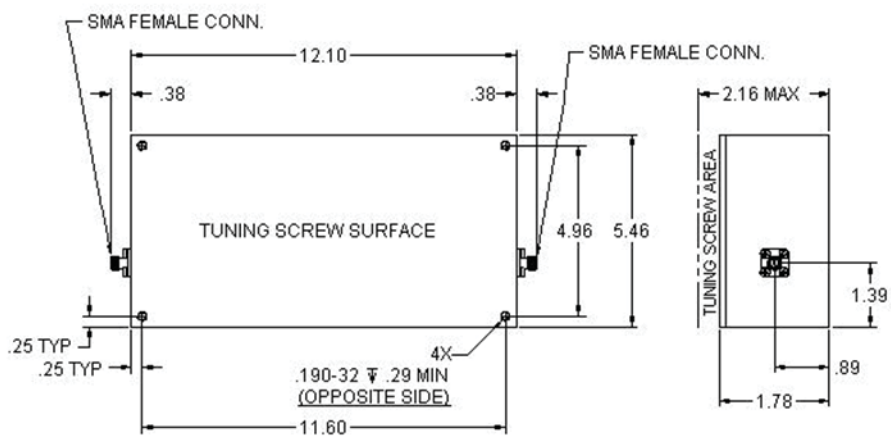

Figure 8: Cavity Filter Mechanical Form Factor (two required for duplexer)(Inches)

3.4 Code Division Multiple Access (CDMA) Signal-to-Interference Analysis

The following indented text is an executive summary of a SC-203 white paper that was generated by Warren Wilson (MITRE). It outlines why a CDMA approach would be a difficult or impossible to design under the current CNPC architecture constraints.

> The current straw man architecture uses a grid of hexagons to approximate spatial distribution of areas containing ground stations. These grids currently are assigned frequencies in a k=12 reuse pattern with cell radius equal to 69 nmi. With the assumed UA densities, this equates to a peak capacity of 20 UAs per cell.
>
> Using a comparable amount of bandwidth as an FDMA approach (9.6 MHz), 128 bits per chip could be BPSK modulated. This spreading yields a processing gain (PG) of 21 dB:
>
> PG = 10 log10(128) = 21 dB.

Since CDMA uses coding to separate signals, all signals would be at the same time and frequency as the others, thus each signal interferes with all other signals. Assuming perfect power control each desired signal is received at the same power as 19 interferers during peak capacity. The Signal-to-Interference (SIR) ratio becomes:

SIR = 21 – 10 log10(19) = 8.2 dB

In reality, power control will not be perfect. 3 dB is usually removed for “headroom” to account for power control inaccuracy, bringing the subtotal to 5.2 dB. BPSK has a theoretical Eb/N0 requirement of 4 dB to result in acceptable message-error rates. Subtracting this, there is only 1.2 dB left for implementation loss. There is clearly no allowance left to cover the 6 dB “aeronautical safety margin.” This would make the system based on CDMA uncertifiable. In addition, the RTCA SC-228 WG2 has indicated that the peak number of UAs in a sector could be significantly higher if smaller UAs use the CNPC spectrum and waveform. This would further degrade the system margin performance under a CDMA approach.

If more bandwidth were available, the system could use a higher spreading factor and overcome the interference from the other users. Gaining additional bandwidth is not viable considering the 978 – 1164 MHz band is already heavily utilized,

In order to improve the link margin in typical terrestrial cell systems using CDMA, the cell size is decreased. This decreases the number of users in the cell which decreases the interference. The shorter range also allows the power to be reduced, which further decreases interference. These systems are able to limit the cell radius by a combination of reducing the transmit power and reducing the ground station antenna coverage area via antenna patterns. On average, using sectored antennas on a CNPC system would decrease the interference, but the system would still need to meet its availability requirement even if many or all the UAs of a cell were to be in the same sector. CDMA would not be able to meet this requirement.

Cell size could be decreased to help the matter. Reducing the cell size reduces the number of UAs that would need to be supported in each cell, but it would come at a cost of more ground stations and still would not be very effective. As cell size gets smaller, interference from other cells becomes an increasing factor.

At the currently assumed UA density, allowed bandwidth, cell size, and needed margins, CDMA does not provide sufficient link margin to be certifiable.

3.5 Orthogonal Frequency Division Multiple Access

While Orthogonal Frequency Division Multiple Access (OFDMA) is not explicitly addressed in the preceding sections, many of its aspects are. In an OFDMA system, the uplink would employ an OFDM signal with orthogonal sub-carriers assigned to each airborne receiver. This is a form of FDMA for uplink multiple access as discussed above in section 2.2, with the same drawbacks in terms of transmitter linearity and the configuration of power amplifiers for sectored antennas. For the downlink in an OFDMA system, multiple adjacent sub-carriers are assigned to a particular airborne transmitter. The airborne transmitter modulates a single-carrier signal that occupies the total bandwidth of the sub-carriers assigned to it. This is a form of FDMA for downlink multiple access as discussed above with the same advantages in terms of link margin and airborne transmitter power. Also, OFDMA suggest the use of a single-carrier modulation for the downlink as discussed above with same advantages in terms of transmitter linearity.

3.6 Multiple Access, Modulation, and Consequences for Transmitter Linearity

3.6.1. Introduction

This study considers the following multiple access techniques, associated modulation schemes, and the consequences they have in terms of transmitter linearity.

- Code division multiple access (CDMA)
- Frequency division multiple access (FDMA)
- Time division multiple access (TDMA)

This study also has bearing on orthogonal frequency division multiple access (OFDMA) as a multiple access technique and orthogonal frequency division multiplexing (OFDM) as a modulation scheme.

3.6.2. Uplink Multiple Access

The following assumptions are made when considering multiple access techniques for uplink from the ground transmitter to an airborne receiver.

- CDMA employs QPSK (quadrature phase shift keying) spreading codes. A raised-cosine-roll-off factor of r = 0.2 offers a small excess bandwidth while still being realizable. Adjacent channels are spaced by the chip rate plus the excess bandwidth. The transmitted signal consists of the sum of 20 signals, each using a unique spreading code and occupying the same bandwidth simultaneously.
- FDMA employs GMSK (Gaussian minimum shift keying) modulation for each carrier. A bandwidth-time product of BT = 0.2 allows close spacing of adjacent channels (0.875 of the GMSK symbol rate) without losing significant performance to inter-symbol interference. The transmitted signal consists of the sum of 20 modulated carriers spaced by a number of channels equal to the cellular reuse factor.
- TDMA employs GMSK modulation. A bandwidth-time product of BT = 0.2 allows close spacing of adjacent channels (0.875 of the GMSK symbol rate) without losing significant performance to inter-symbol interference. The transmitted signal consists of a single modulated carrier with time slots supporting 20 users.

Table 24 summarizes the ground transmitter linearity required for each multiple access technique in order to maintain acceptable levels of adjacent channel rejection (ACR) at the airborne receiver. The estimated peak-to-average-power ratio (PAPR) shown must be supported at the output of a ground transmitter. The estimated 2-tone 3^{rd}-order intermodulation (IMD3) characterizes the linearity required of a ground transmitter for a 2-tone input signal with the same total power as the actual signal for each multiple access technique. The estimated ACR refers to the amount of selectivity provided by a receiver to an adjacent-channel interferer. ACR approaching 30 dB (along with appropriate cellular reuse of channels) allows for link margin for availability and aviation safety. Inter-carrier-interference (ICI) is of concern for FDMA. It should be significantly below ACR in order to maintain link margin. It is arguable that ICI should be even less than the -34 dB shown. However, this would place even more difficult linearity requirements on a ground transmitter.

Table 24: Uplink Multiple Access and Ground Transmitter Linearity

	CDMA	FDMA	TDMA
PAPR	6 dB	10 dB	0 dB
2-Tone IMD3	-26.4 dB	-38.3 dB	-
ACR	29.8 dB	29.7 dB	29.7 dB
ICI	-	-34 dB	-

Note that TDMA does not place any linearity requirement on a ground transmitter. This is because only a single signal must be transmitted at time and the associated modulation, GMSK, is constant-envelope (peak power is equal to average power). CDMA and FDMA, by contrast, both require the transmission of the sum of multiple signals simultaneously by a ground transmitter, which requires a high degree of linearity.

Note that OFDMA (orthogonal frequency division multiple access) is a special case of FDMA. For an OFDMA uplink, the ground transmitter employs an OFDM (orthogonal frequency division multiplexing) signal with orthogonal sub-carriers assigned to each airborne receiver. Nevertheless, OFDMA requires the simultaneous transmission of multiple carriers, and requires linearity similar to that shown for FDMA in Table 24, depending on the number of sub-carriers. This is, of course, true of OFDM as a modulation scheme as well.

The estimates in Table 24 are determined as follows. Given the channel spacing, the required transmitter linearity is determined for each modulation scheme based on simulation using a hyperbolic tangent (tanh) function to model amplitude non-linearity. This model assumes no amplitude-to-phase non-linearity. The required linearity is determined by varying how far the signal is driven into the tanh non-linearity while observing the effect on ACR.

As an example, Figure 12 shows the results of an ACR simulation for a TDMA ground transmitter employing 1-MHz GMSK with a bandwidth-time (BT) = 0.2 and 875-kHz adjacent channel spacing. The airborne receiver filter consists of a cascade of 4 boxcar filters, each of length equal to the GMSK symbol time. The total power in the filtered interferer is 29.7 dB below the total power of the adjacent channel interferer prior to filtering. Note that GMSK, being constant-envelope, places no linearity requirements on the transmitter in order to maintain spectral containment. Thus, this ACR performance is achieved regardless of ground transmitter non-linearity.

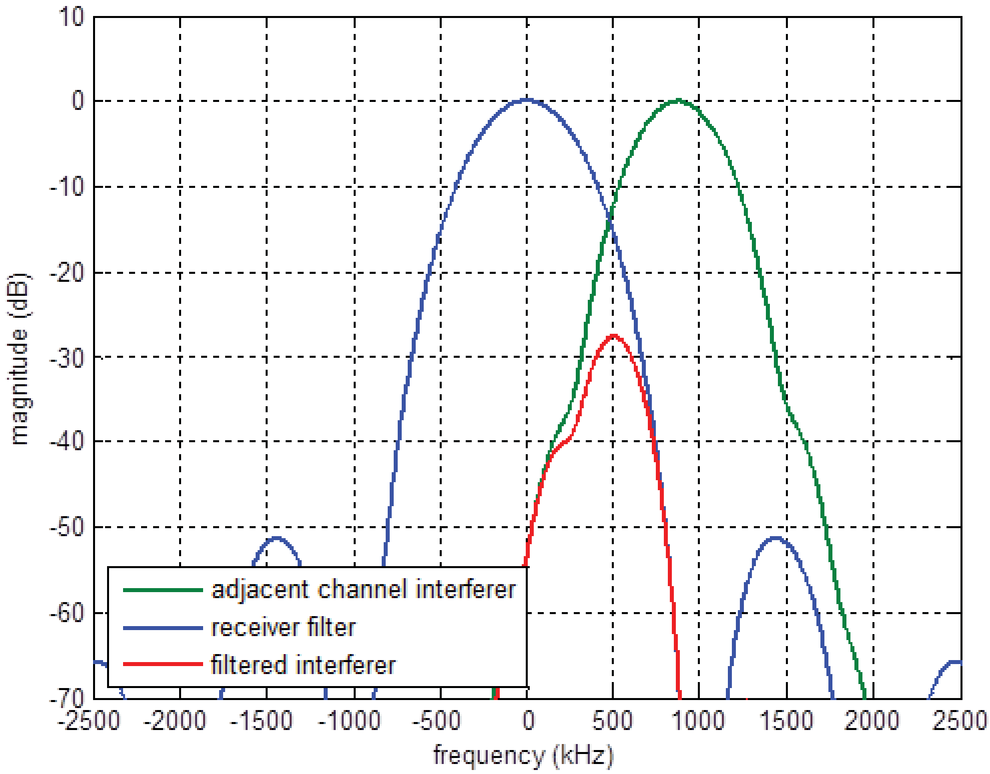

Figure 9: TDMA ACR Simulation (1-MHz GMSK)

As another example, Figure 10 shows the results of an ACR simulation for a CDMA ground transmitter employing 1-MHz QPSK spreading with *r* = 0.2 and 1.2-MHz adjacent channel spacing. The transmitted signal consists of the sum of 20 signals, each using a unique spreading code and occupying the same bandwidth simultaneously. The airborne receiver filter is a matched filter with length equal to 11 chips. The total power in the filtered interferer is 29.8 dB below the total power of the adjacent channel interferer prior to filtering. To achieve this ACR, the CDMA ground transmitter must support the estimated PAPR and 2-tone IMD3 shown in Table 24. Also note that, in this example, QPSK requires greater adjacent channel spacing (1.2 MHz) than does GMSK (875 kHz) in order to achieve similar ACR.

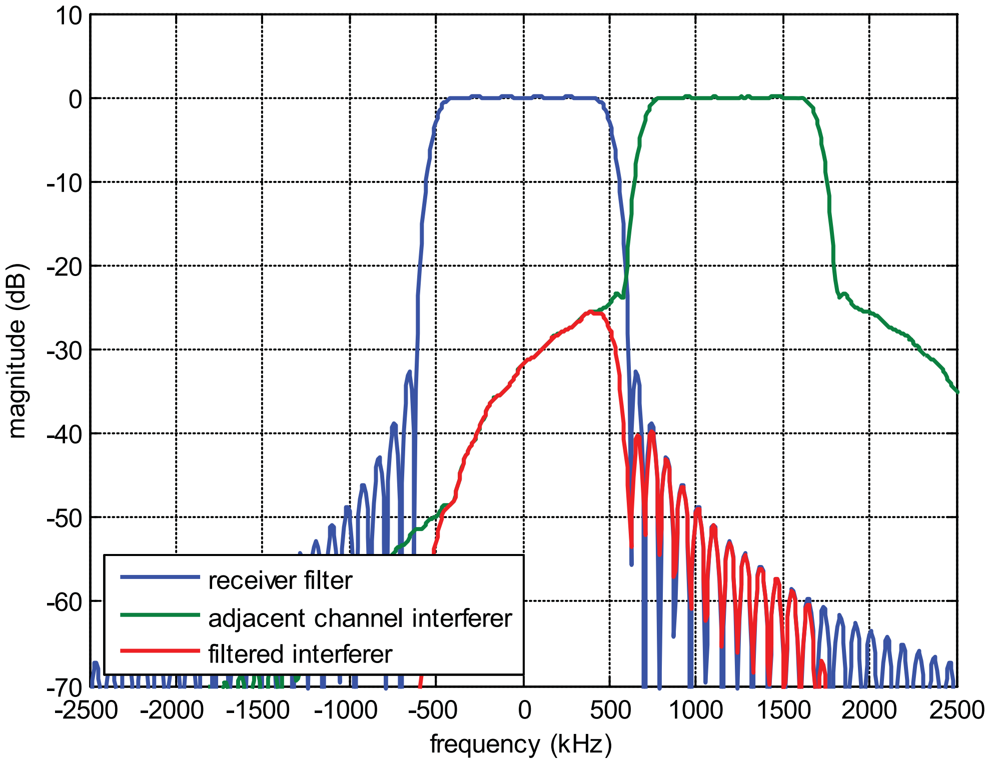

Figure 10: CDMA ACR Simulation (20 signals, 1-MHz QPSK)

As a final example, Figure 11 shows the results of an ICI simulation for a FDMA ground transmitter employing 50-kHz GMSK with *BT* = 0.2 and 43.75-kHz adjacent channel spacing. (Note that channel spacing as narrow as 43.75 kHz is not practical for large Doppler shifts, particularly at C band. Nevertheless, it is assumed that ACR of 29.7 dB is achieved.) The transmitted signal consists of the sum of 19 modulated carriers spaced by 525 kHz, which corresponds to a cellular reuse factor of 12. The zero-frequency carrier is omitted so that the ICI of -34 dB can be observed. To achieve this level of ICI, the FDMA ground transmitter must support the estimated PAPR and 2-tone IMD3 shown in Table 24.

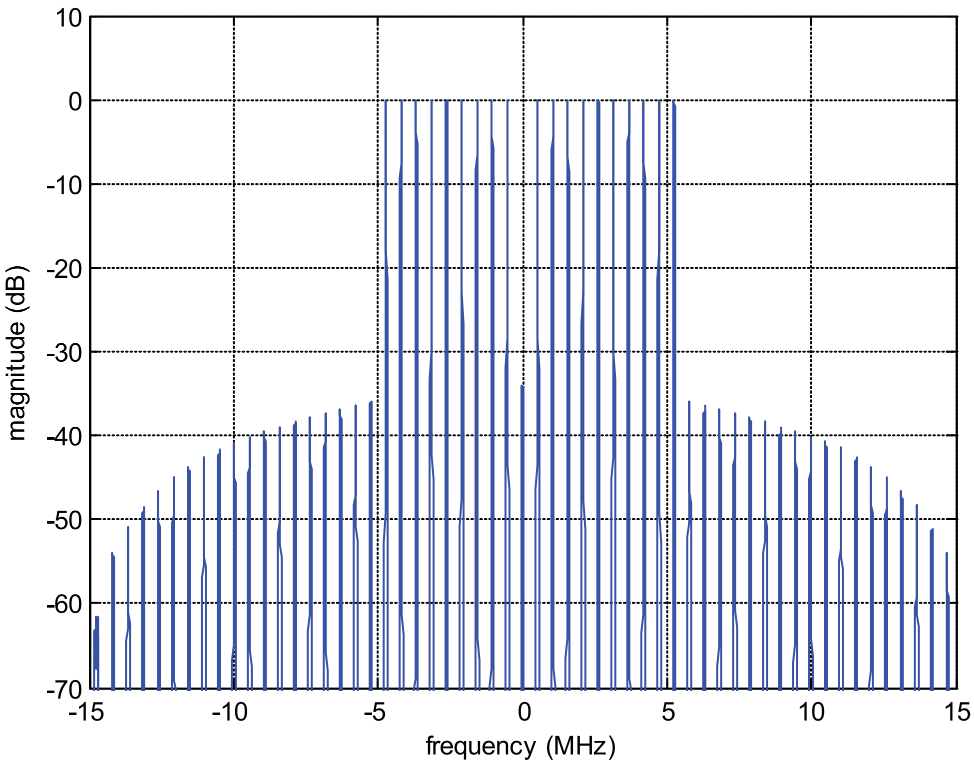

Figure 11: FDMA Simulation (20 signals, 50-kHz GMSK)

3.6.3. Downlink Modulation

Downlink multiple access technique has little effect on airborne transmitter linearity. This is because, unlike a ground transmitter, an airborne transmitter is not required to transmit multiple unique signals destined for different receivers. As a result, airborne transmitter linearity requirements are determined primarily by the downlink modulation scheme.

Table 25 summarizes the airborne transmitter linearity required for representative modulation schemes in order to maintain acceptable levels of adjacent channel rejection (ACR) at the ground receiver (approximately 30 dB). The estimated peak-to-average-power ratio (PAPR) shown must be supported at the output of an airborne transmitter. The estimated 2-tone 3rd-order intermodulation (IMD3) characterizes the linearity required of an airborne transmitter for a 2-tone input signal with the same total power as the actual signal for each modulation scheme. These estimates are determined in a similar fashion to those in Table 24.

Table 25: Downlink Modulation and Airborne Transmitter Linearity

	GMSK	π /4 QPSK	OFDM
PAPR	0 dB	3 dB	10 dB
2-Tone IMD3	-	-22.9 dB	-38.3 dB

Note that GMSK, being constant-envelope, places no linearity requirements on the transmitter. A single-carrier non-constant-envelope modulation such as π /4 QPSK requires modest transmitter linearity. π/4 QPSK is considered here over ordinary QPSK because it exhibits a somewhat lower peak-to-average-power ratio without any loss in performance. A raised-cosine-roll-off factor of r = 0.2 offers a small excess bandwidth while still being realizable. A multi-carrier modulation such as OFDM requires a high degree of linearity.

3.6.4. Transmitter Estimates

To put the transmitter linearity requirements in context, the characteristics of a practical transmitter power amplifier were estimated for L band and C band, and for both ground and airborne transmitters. The following tables summarize the estimated practical transmitter characteristics. These tables show the average and peak power required to support each uplink multiple access technique or downlink modulation scheme. Average power is assumed to be 200 Watts for uplink and 10 Watts for downlink. Peak power is based on the PAPR from Table 24 and Table 25. The tables below also include the estimated back-off, efficiency, DC power, and dissipated power necessary to achieve the required average and peak powers. The L band transmitter estimates are based on eighth generation Freescale LDMOS devices. The C band transmitter estimates are less refined due to the lack of available off-the-shelf devices. Solid state devices are assumed for the C band airborne transmitter while traveling-wave tube (TWT) amplifiers are assumed for the ground transmitters because of the high powers required. Somewhat better C band efficiencies may be possible by developing custom devices.

Table 26: L Band Ground Transmitter

	CDMA	FDMA	TDMA
Average Power	200 W	200 W	200 W
Peak Power	800 W	2000 W	200 W
Back-off	6 dB	10 dB	0 dB
Efficiency	35.0%	22.0%	60.0%
DC Power	571.4 W	909.1 W	333.3 W
Dissipated Power	371.4 W	709.1 W	133.3 W

Table 27: C Band Ground Transmitter

	CDMA	FDMA	TDMA
Average Power	200 W	200 W	200 W
Peak Power	800 W	2000 W	200 W
Back-off	6 dB	10 dB	0 dB
Efficiency	10.0%	6.0%	33.0%
DC Power	2000.0 W	3333.3 W	606.1 W
Dissipated Power	1800.0 W	3133.3 W	406.1 W

Table 28: L Band Airborne Transmitter

	GMSK	π /4 QPSK	OFDM
Average Power	10 W	10 W	10 W
Peak Power	10 W	20 W	100 W
Back-off	0 dB	3 dB	10 dB
Efficiency	63.0%	47.0%	25.0%
DC Power	15.9 W	21.3 W	40.0 W
Dissipated Power	5.9 W	11.3 W	30.0 W

Table 29: C Band Airborne Transmitter

	GMSK	π /4 QPSK	OFDM
Average Power	10 W	10 W	10 W
Peak Power	10 W	20 W	100 W
Back-off	0 dB	3 dB	10 dB
Efficiency	33.0%	17.0%	4.0%
DC Power	30.3 W	58.8 W	250.0 W
Dissipated Power	20.3 W	48.8 W	240.0 W

3.6.5. Conclusion

From Table 26 and Table 27 it is clear that TDMA is the uplink multiple access technique that places the least difficult requirements on the ground transmitter. The practical transmitter characteristics required for CDMA and FDMA are, by comparison, undesirable in terms of DC power and dissipated power. This is because, unlike TDMA, CDMA and FDMA both require the transmission of the sum of multiple signals simultaneously by a ground transmitter, which requires a high degree of linearity.

Similarly, from Table 28 and Table 29 it is clear that a constant envelope modulation scheme such as GMSK places the least difficult requirements on the airborne transmitter. The practical transmitter characteristics required for non-constant-envelope modulation schemes are, by comparison, undesirable in terms of DC power and dissipated power.

3.7 Modulation Study

3.7.1. Introduction

This study considers the following modulation schemes.

- GMSK (Gaussian minimum shift keying), bandwidth-time product BT = 0.2
- π/4 QPSK (π/4-shifted quadrature phase shift keying), raised-cosine-roll-off r = 0.2
- 8PSK (8-ary phase shift keying), raised-cosine-roll-off r = 0.2
- 16QAM (16-ary quadrature amplitude modulation), raised-cosine-roll-off r = 0.2

GMSK (BT = 0.2) has been selected for the NASA UA CNPC waveform under development by Rockwell Collins and NASA. π/4 QPSK, 8PSK, and 16QAM are considered here to show the effects of modulation schemes with higher constellation density, and therefore higher spectral efficiency (bits-per-second-per-Hertz), on the NASA UA CNPC system. GMSK, π/4 QPSK, 8PSK, and 16QAM are commonly employed by a number of existing wireless standards. A raised-cosine-roll-off factor of r = 0.2 offers a small excess bandwidth while still being realizable. π/4 QPSK is considered here over ordinary QPSK because it exhibits a somewhat lower peak-to-average-power ratio without any loss in performance.

Table 30 summarizes a few important properties of the modulation schemes considered here. Required E_b/N_0 is the bit-energy-to-noise-spectral-density ratio (signal-to-noise ratio (SNR) per bit) needed for successful demodulation. This assumes coherent demodulation and soft-decision decoding of a turbo code with a code rate of approximately one-half, as is employed in the current NASA UA CNPC waveform. Required E_s/N_0 is the symbol-energy-to-noise-spectral-density ratio (SNR per symbol) needed for successful demodulation.

Table 30: Signal-to-Noise Ratio Properties of Modulation Schemes

	GMSK	π /4 QPSK	8PSK	16QAM
Required Eb/N0	2.5 dB	2.5 dB	5.2 dB	5.9 dB
Required Es/N0	-0.5 dB	2.5 dB	7.0 dB	8.9 dB

A few observations can be made from the parameters in this table, assuming constant link parameters such as distance, bit rate, noise figure, and antennas.

- Based on required Eb/N0, 8PSK and 16QAM require 2.7 dB and 3.4 dB greater average transmitter power, respectively, than GMSK.
- Based on required Es/N0, π/4 QPSK, 8PSK, and 16QAM require 3.0 dB, 7.5 dB, and 9.4 dB greater SNR in the receiver bandwidth, respectively, than GMSK. This increased SNR corresponds to an increase in required adjacent channel rejection.

This paper addresses the following topics with respect to these modulation schemes.

- Adjacent Channel Rejection
- Channel Spacing
- Transmitter Power and Linearity

3.7.2. Adjacent Channel Rejection

The following assumptions apply to the discussion of adjacent channel rejection (ACR) required to maintain link margin.

- The frequency re-use scheme eliminates any significant co-channel interference by placing co-channel interferers over the horizon. This is necessary to maintain link margin, since no filtering can be brought to bear on a co-channel interferer.
- Interference is dominated by a single adjacent-channel interferer located in an adjacent cell area. All other adjacent-channel interferers are placed farther away by the frequency re-use scheme.
- The total required link margin is 15 dB. This consists of 9 dB of availability margin and 6 dB of aviation safety margin. The availability margin assumes that an aircraft has two independent antennas and makes use of redundant links to three ground stations. (See SC203-CC016_UAS_CC_RCP_vA_28Sep2011 UAS Control and Communications Link Required Communications Performance Availability, Continuity and Integrity.)
- Interference behaves like Gaussian noise of the same power.
- ACR refers to the amount of selectivity provided by a receiver to an adjacent-channel interferer.

The total required link margin of 15 dB can be allocated between noise and interference. Suppose this is done such that the link margin to noise is 16 dB and the link margin to interference is 22 dB. Thus, the link margin to noise-plus-interference is 15 dB and the link is limited primarily by transmitter power and receiver sensitivity.

At the edge of coverage, an adjacent-channel interferer may be at the same distance to the intended receiver as the desired transmitter. Thus, the interferer and the desired signal would experience similar free-space path loss. In the worst case, suppose that the interferer may experience a multipath boost of 6 dB. Then, assuming identical transmitter power, the interferer would arrive at the intended receiver with 6 dB greater power than the desired signal. The required ACR is then the sum of the required link margin to interference, the multipath boost of 6 dB, and the required SNR per symbol (E_s/N_0), all in dB. Table 31 summarizes the required ACR for each modulation scheme considered here. Note that choosing a modulation with a higher constellation density results in a greater required ACR.

Table 31: Required Adjacent Channel Rejection

	GMSK	π /4 QPSK	8PSK	16QAM
Required ACR	27.5 dB	30.5 dB	35.0 dB	36.9 dB

3.7.3. Channel Spacing

The following assumptions apply to the discussion of the channel spacing needed to achieve the required ACR.

- The GMSK symbol rate is 87.5 kHz. This corresponds to the narrowest (and most common) bandwidth selected for the current NASA UA CNPC waveform development.
- The symbol rates for π/4 QPSK, 8PSK, and 16QAM are 43.75 kHz, 29.167 kHz, and 21.875 kHz, respectively. Thus, each modulation scheme achieves the same over-the-air bit rate of 43.75 kHz, assuming a half-rate code.

- 650 knots airspeed
- 200 knots wind speed
- 1 ppm aircraft oscillator error
- 0.5 ppm ground oscillator error
- The receiver estimates the frequency shift of the desired signal and centers its final bandwidth on the desired signal.

In order to achieve the required ACR discussed above, a minimum amount of frequency separation must be maintained between the desired signal and the interferer. Based on simulation, GMSK (87.5 kHz symbol rate, BT = 0.2) requires at least 74.38 kHz of separation between the desired signal and the interferer. This assumes the receiver filter chosen for the current waveform development which is a cascade of 4 boxcar filters, each of length equal to the GMSK symbol time. Referring to Figure 12, the total power in the filtered interferer is at least 27.5 dB below the total power of the adjacent channel interferer prior to filtering. Note that GMSK, being constant-envelope, places no linearity requirements on the transmitter in order to maintain spectral containment. Thus, this ACR performance is achieved for GMSK regardless of transmitter non-linearity.

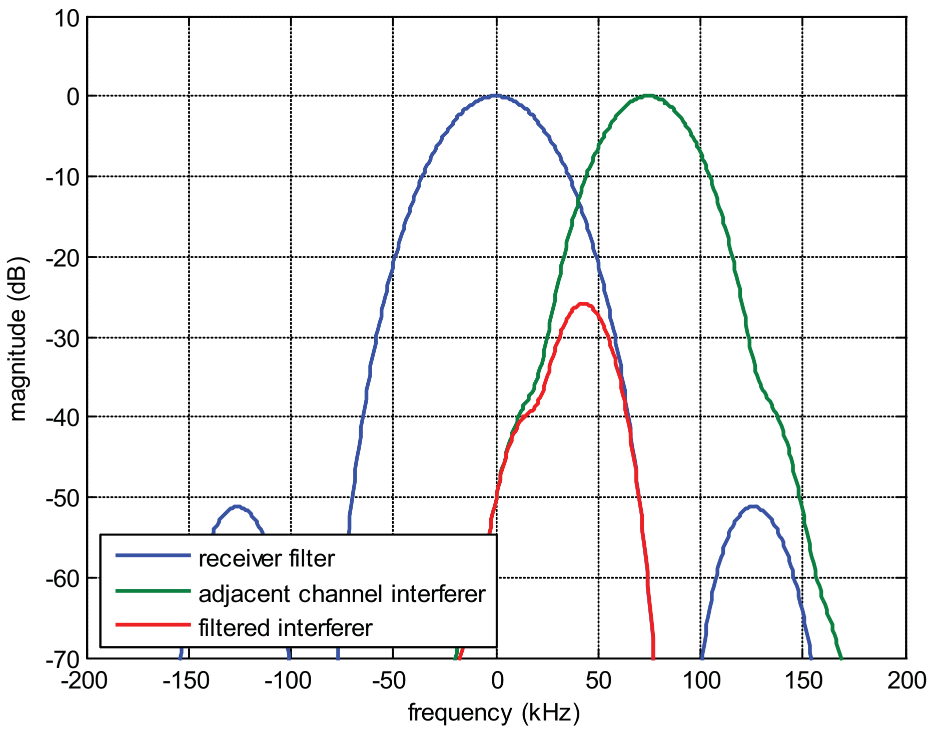

Figure 12: GMSK Adjacent Channel Rejection Simulation

For π/4 QPSK, 8PSK, and 16QAM, frequency separation equal to the symbol rate plus the excess bandwidth guarantees that the main lobe of the interferer spectrum does not overlap the main lobe of the receiver filter frequency response. In this case, ACR is limited only by the side lobes of the interferer spectrum and the side lobes of receiver filter. For raised-cosine-roll-off r = 0.2, the frequency separation is equal to 1.2 times the symbol rate.

Figure 13 depicts the case for 16QAM (21.875 kHz symbol rate). In this example, the interferer has ideal transmitter linearity. The interferer pulse-shaping filter and the receiver matched filter are 11 symbol times long. No other practical effects, such as phase noise or receiver non-linearity, are included. In this idealized case, the ACR is better than 45 dB. Unfortunately, practical transmitter non-linearity limits the achievable ACR. The transmitter linearity required to achieve the required ACR is discussed in the next section.

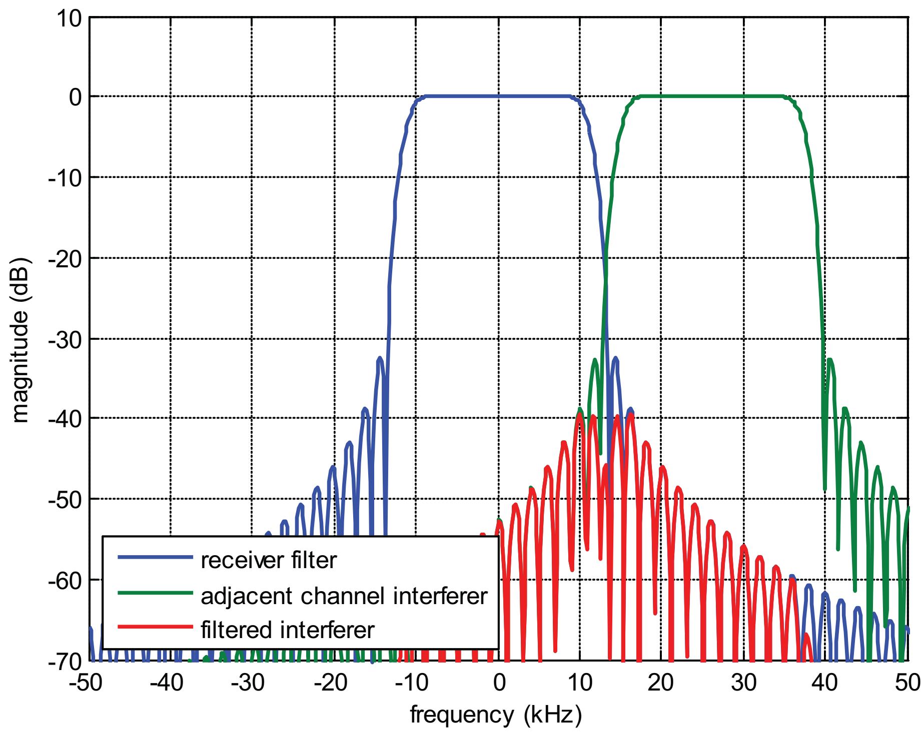

Figure 13: 16QAM Adjacent Channel Rejection Simulation (ideal transmitter linearity)

Table 32 below summarizes the minimum interferer frequency separation necessary to achieve the required ACR for each modulation scheme considered here. The minimum channel spacing required is determined by adding the worst-case relative frequency shift between adjacent channels (due to Doppler shift and oscillator error) to the minimum interferer frequency separation shown in the table. This guarantees that the desired signal is sufficiently separated in frequency from the adjacent channel interferer even in the presence of Doppler shifts and oscillator errors.

Table 32: Minimum Interferer Frequency Separation (43.75 kHz over-the-air bit rate)

	GMSK	π /4 QPSK	8PSK	16QAM
Ground-to-Air	74.38 kHz	52.50 kHz	35.00 kHz	26.25 kHz

The worst-case relative frequency shift between adjacent channels is determined as follows. Consider ground-to-air communication as shown in Figure 14. Suppose the airborne receiver is flying directly toward the ground transmitter and directly away from the ground interferer. The desired signal from the transmitter shifts up in frequency as a result of the fast transmitter oscillator and the 850-knot closing velocity of the airborne receiver. An interfering signal shifts down in frequency as a result of the slow interferer oscillator and the 850-knot receding velocity of the airborne receiver. Any airborne receiver oscillator error shifts both desired signal and interferer by (very nearly) the same amount. Suppose the interferer is on the upper adjacent channel. In this case, the desired signal and the interferer shift closer to each other by the sum of the ground oscillator errors and the Doppler shift corresponding to twice the total velocity of the airborne receiver. This relative frequency shift is 3.83 kHz for L band (977 MHz) and 19.94 kHz for C band (5091 MHz). A similar situation can also occur with a lower adjacent channel interferer.

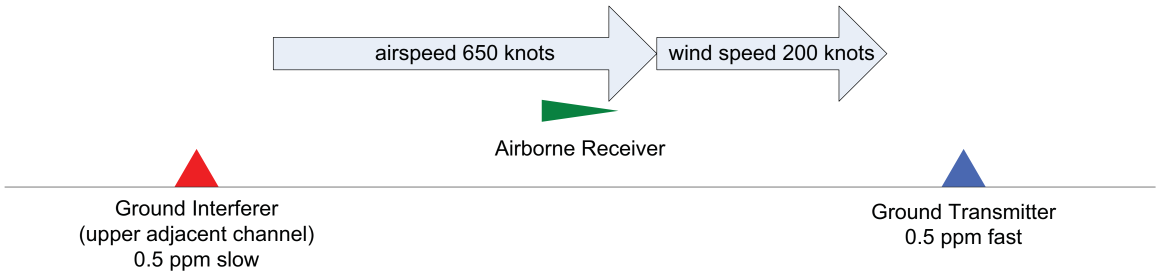

Figure 14: Ground-to-Air Communication

Consider air-to-ground communication as shown in Figure 15. Suppose the airborne transmitter is flying directly toward the ground receiver and the airborne interferer is flying directly away from the ground receiver. In this case, the desired signal and the interferer shift closer to each other by the sum of the airborne oscillator errors and the Doppler shift corresponding to twice the total velocity of the airborne transmitters. This relative frequency shift is 4.80 kHz for L band (977 MHz) and 25.03 kHz for C band (5091 MHz). Again, a similar situation can also occur with a lower adjacent channel interferer.

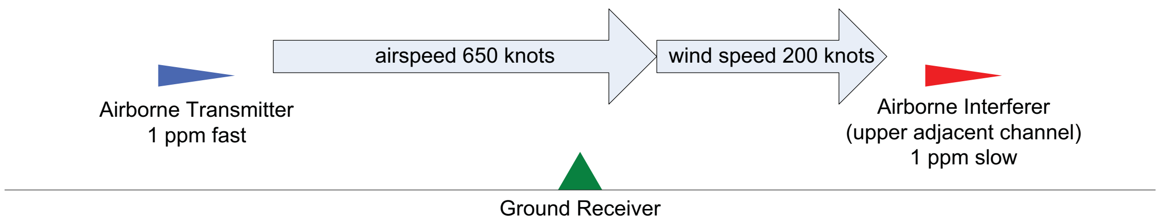

Figure 15: Air-to-Ground Communication

Table 33 and Table 34 summarize the minimum channel spacing necessary to achieve the required ACR for each modulation scheme considered here for an over-the-air bit rate of 43.75 kHz. The channel spacing minimums are the sum of the minimum interference frequency separations and the worst-case relative frequency shifts between adjacent channels as discussed above. Results are shown for ground-to-air and air-to-ground links for L band and C band.

Table 33: Minimum L Band Channel Spacing (43.75 kHz over-the-air bit rate)

	GMSK	π /4 QPSK	8PSK	16QAM
Ground-to-Air	78.20 kHz	56.33 kHz	38.83 kHz	30.08 kHz
Air-to-Ground	79.18 kHz	57.30 kHz	39.80 kHz	31.05 kHz

Table 34: Minimum C Band Channel Spacing (43.75 kHz over-the-air bit rate)

	GMSK	π /4 QPSK	8PSK	16QAM
Ground-to-Air	94.32 kHz	72.44 kHz	54.94 kHz	46.19 kHz
Air-to-Ground	99.41 kHz	77.53 kHz	60.03 kHz	51.28 kHz

Note that the worst-case relative frequency shift (due to Doppler and oscillator error) significantly limits how narrow the channel spacing can be, particularly at C band. For instance 16QAM only requires 26.25 kHz of interference frequency separation to achieve ACR, but needs 51.28 kHz of channel spacing at C band in order to guarantee that separation for air-to-ground communication. Note that choosing a modulation with a higher constellation density does reduce channel spacing. However, channel spacing can only approach the worst-case relative frequency shift, even for extremely dense constellations.

3.7.4. Transmitter Power and Linearity

The previous discussion establishes the minimum channel spacing in order to achieve the required ACR for each modulation scheme considered here. Given the channel spacing, the required transmitter linearity is determined for each modulation scheme based on simulation using a hyperbolic tangent (tanh) function to model amplitude non-linearity. This model assumes no amplitude-to-phase non-linearity. The required linearity is determined by varying how far the signal is driven into the tanh non-linearity while observing the effect on ACR. Figure 16 depicts an example where a 16QAM adjacent-channel interferer is passed through the tanh model. In this figure, the ACR just exceeds the required 36.9 dB from Table 31.

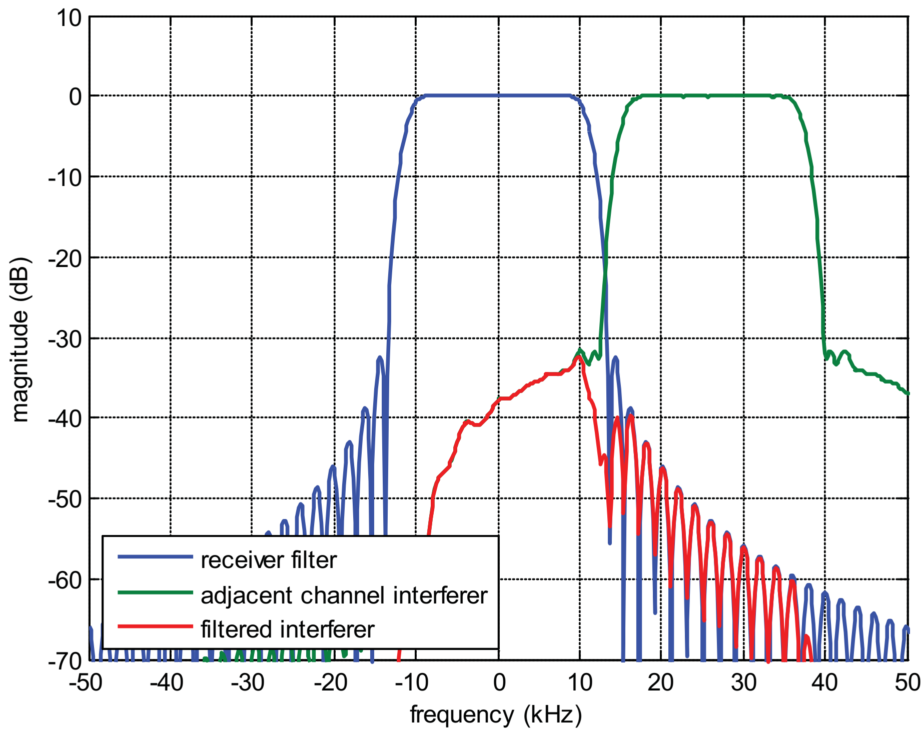

Figure 16: 16QAM Adjacent Channel Rejection Simulation (practical transmitter linearity)

Table 35 summarizes the linearity required for each modulation scheme in order to maintain the required ACR. Input peak-to-average-power ratio (PAPR) characterizes each modulation scheme prior to any non-linearity. Output PAPR is the minimum PAPR allowed after the tanh non-linearity while still achieving the required ACR. 2-tone 3rd-order intermodulation (IMD3) characterizes the non-linearity for a 2-tone input signal with the same total power as the actual signal for each modulation scheme. As noted previously, GMSK, being constant-envelope, places no linearity requirements on the transmitter. Note that choosing a modulation with a higher constellation density increases the PAPR, which leads to requirements for better transmitter linearity.

Table 35: Linearity for Adjacent Channel Rejection

	GMSK	π /4 QPSK	8PSK	16QAM
Input PAPR	0 dB	4.9 dB	5.5 dB	8.0 dB
Output PAPR	0 dB	3.0 dB	4.0 dB	6.0 dB
2-Tone IMD3	Not applicable	22.9 dB	27.4 dB	31.8 dB

To put the transmitter linearity requirements in context, the characteristics of a practical transmitter power amplifier were estimated for each modulation scheme. This was done for both L band and C band, and for both airborne and ground transmitters. Note that the airborne transmitter may also serve as the ground transmitter for a stand-alone solution. For a networked solution, it is assumed that the ground transmitter must produce a single-carrier time-division multiplexed (TDM) signal supporting 20 slots, resulting in 20 times the over-the-air data rate. Thus, the ground transmitter is required to produce 20 times the total power of the airborne transmitter to operate at the same range. Note that an equivalent 20-carrier frequency-division multiplexed (FDM) ground transmitter solution would require even better linearity than that presented here.

The following tables summarize the estimated practical transmitter characteristics. These tables show the average and peak power required for a π/4 QPSK, 8PSK, or 16QAM waveform to achieve the same link margin as the current GMSK waveform with the current transmitter power assumptions. Relative average power is based on the E_b/N_0 values in Table 30, assuming constant link parameters such as distance, bit rate, noise figure, and antennas. Peak power is based on the output PAPR in Table 35. The tables also include the estimated back-off, efficiency, DC power, and dissipated power necessary to achieve the required average and peak powers. The L band transmitter estimates are based on eighth generation Freescale LDMOS devices. The C band transmitter estimates are less refined due to the lack of available off-the-shelf devices. Solid state devices are assumed for the C band airborne transmitter while traveling-wave tube (TWT) amplifiers are assumed for the ground transmitters because of the high powers required.

Table 36: L Band Airborne Transmitter (or Stand-alone Ground Transmitter)

	GMSK	π /4 QPSK	8PSK	16QAM
Average Power	10.0 W	10.0 W	18.6 W	21.9 W
Peak Power	10.0 W	20.0 W	46.7 W	87.6 W
Back-off	0 dB	3.0 dB	4.0 dB	6.0 dB
Efficiency	63.0%	47.0%	43.0%	36.5%
DC Power	15.9 W	21.3 W	43.3 W	60.0 W
Dissipated Power	5.9 W	11.3 W	24.7 W	38.1 W

Table 37: L Band Ground Transmitter (Networked)

	GMSK	π /4 QPSK	8PSK	16QAM
Average Power	200 W	200 W	372 W	438 W
Peak Power	200 W	400 W	934 W	1750 W
Back-off	0 dB	3.0 dB	4.0 dB	6.0 dB
Efficiency	60.0%	45.0%	42.0%	35.0%
DC Power	333.3 W	444.4 W	885.7 W	1251.4 W
Dissipated Power	133.3 W	244.4 W	513.7 W	813.4 W

Table 38: C Band Airborne Transmitter (or Stand-alone Ground Transmitter)

	GMSK	π /4 QPSK	8PSK	16QAM
Average Power	10.0 W	10.0 W	18.6 W	21.9 W
Peak Power	10.0 W	20.0 W	46.7 W	87.6 W
Back-off	0 dB	3.0 dB	4.0 dB	6.0 dB
Efficiency	33.0%	17.0%	10.7%	7.9%
DC Power	30.3 W	58.8 W	173.8 W	277.2 W
Dissipated Power	20.3 W	48.8 W	155.2 W	255.3 W

Table 39: C Band Ground Transmitter (Networked)

	GMSK	π /4 QPSK	8PSK	16QAM
Average Power	200 W	200 W	372 W	438 W
Peak Power	200 W	400 W	934 W	1750 W
Back-off	0 dB	3.0 dB	4.0 dB	6.0 dB
Efficiency	33.0%	17.0%	12.0%	10.0%
DC Power	606.1 W	1176.5 W	3100.0 W	4380.0 W
Dissipated Power	406.1 W	976.5 W	2728.0 W	3942.0 W

3.7.5. Conclusion

GMSK has been selected for the current NASA UA CNPC waveform under development by Rockwell Collins and NASA. A modulation scheme with a higher constellation density, and therefore higher spectral efficiency (bits-per-second-per-Hertz), could be chosen in the pursuit of more efficient use of the spectrum. Doing so does reduce channel spacing. However, channel spacing can only approach the worst-case relative frequency shift, even for extremely dense constellations. For instance, as shown in Table 33, increasing the bits-per-symbol by a factor of 3 (GMSK to 8PSK) only decreases the channel spacing for L band by about a factor of 2. As shown in Table 34, decreasing C band channel spacing by about a factor of 2 requires increasing the bits-per-symbol by a factor of 4 (GMSK to 16QAM). Therefore, attempts to reduce the channel spacing are limited by Doppler shift and oscillator error.

Furthermore, choosing a modulation scheme with a higher constellation density incurs the following consequences. First, signals with higher constellation densities require greater adjacent channel rejection for the same link margin (see Table 31). Second, and more prominently, choosing a modulation with a higher constellation density requires a transmitter with higher power to maintain the same link margin and better linearity in order to achieve the required adjacent channel rejection (see Table 35). GMSK places no linearity requirement on the transmitter. The practical transmitter characteristics required for modulation schemes with higher constellation densities are, by comparison, undesirable in terms of DC power and dissipated power (see

Table 36 through Table 39).

The following additional considerations are not addressed in this paper, and should be addressed in the future.

- Receiver linearity
- Transmitter and receiver phase noise

3.8 Brief Explanations of Commonly Suggested Technical Approaches and Systems

Below are a series of sections that offer brief executive summary explanations of why certain technical approaches and common systems are not viable. These explanations are not meant to be comprehensive but offer a few main points showing why the consideration is unacceptable. These are explained in more detail in the main body of this document. The most common technical approach questions are on potential use of CDMA or OFDMA. The most common system questions are on the potential use of LTE or WiMAX. These questions are addressed below.

3.8.1. CDMA

Code Division Multiple Access (CDMA) uses coding to transmit multiple signals at the same time and frequency on a single wideband channel. CDMA has been used in mobile systems using the 3G standard. The issue with CDMA is that as the number of transmitters/users increases, each signal becomes added noise to all other signals. This situation can reach a point where increasing PA power by all transmitters does not overcome the signal-to-noise ratio problem because as each signal is amplified, the noise (the other users' signals) is amplified as well. Section 3.4 analyses the situation where 20 UAs are operating in a cell. The analysis indicates the added undesired signal power from the other UAs degrades the link margin to the point where it does not support the required "Aviation Safety Margin". This lack of margin makes the CNPC system using CDMA uncertifiable.

Section 3.4 also discusses approaches that typical CDMA systems use to mitigate added noise from additional transmitters. These approaches work well for systems which have ground mobile users, and for ground stations which can limit their cell area by their antenna pattern or antenna sectors. These mitigation approaches are not viable for the CNPC system due to the inability of the base station to limit the cell area by the antenna pattern.

Even with sectored antennas on the ground station, there exists the potential that many or all of the UAs of a given cell are in the same sector. In this case the sectored antennas would not provide any improvement in the system link margin.

In addition, when UAs operate at nominal altitudes (e.g. 8000 feet) they will have line-of-sight to many ground stations. Their transmitted signals will arrive at ground stations in adjacent cells causing interference because their signals are not separated in time or frequency. This situation would further degrade the system link margin in a system that used CDMA.

CDMA also is undesirable in terms of DC power and dissipated power. This is because, unlike TDMA, CDMA requires the transmission of the sum of multiple signals simultaneously by a ground transmitter, which requires a high degree of linearity. This is discussed further in section 3.6.

Based on the analysis above, use of CDMA is not viable for the CNPC system.

3.8.2. OFDMA

In an Orthogonal Frequency Division Multiple Access (OFDMA) system, the uplink would employ an OFDM signal with orthogonal sub-carriers assigned to each airborne receiver. This is a form of FDMA for uplink multiple access as discussed in section 2.2 with the same drawbacks in terms of transmitter linearity and the configuration of power amplifiers for sectored antennas. OFDMA is undesirable for the uplink in terms of DC power and dissipated power. **For comparison, as per the example in section 3.6.4, comparing two ground stations with an average power of 200W, the OFDMA ground station would need a peak of 2000W compared to the TDMA ground station's peak of 200W**. This is because, unlike TDMA, OFDMA requires the transmission of the sum of multiple signals simultaneously by a ground transmitter, which requires a high degree of linearity. Obtaining L-Band and C-Band linear power amplifiers which support the OFDMA peak power output requirements are not cost effective. This is discussed further in section 3.6.

For the downlink in an OFDMA system, multiple adjacent sub-carriers are assigned to a particular airborne transmitter. The airborne transmitter modulates a single-carrier signal that occupies the total bandwidth of the sub-carriers assigned to it. This is a form of FDMA for downlink multiple access. FDMA was the selected as the preferred approach for the CNPC waveform for the downlink multiple access.

Based on the analysis above, OFDMA has significant disadvantages for the uplink because of the difficulties deploying a high power linear transmitter.

3.8.3. Common Mobile Systems

Ideally, an existing RF communication system would be capable of supporting all of the requirements of the CNPC system without modification. NASA completed a trade study which evaluated 24 different communication systems. The top two technologies ranked were WiMAX and LTE. The NASA study evaluated the overall characteristics of the various systems, but allowed the physical layer characteristics to deviate from the standards. The following section describes why it was necessary to implement a different physical layer than is normally used in these two systems

3.8.3.1. LTE

LTE (Long Term Evolution) is a standard for wireless communication of high-speed data for mobile phones and data terminals. It supports both TDD and FDD. Based on the available spectrum, TDD would be required. LTE utilizes OFDMA for the ground station to user link and SC-FDMA for the user to ground station link. The core disadvantage of LTE is that it utilizes OFDMA for the ground station to user link. OFDMA requires the transmission of the sum of multiple signals simultaneously by a ground transmitter, which requires a high degree of linearity. The difficulty associated with a high power, linear transmitter is discussed in brief in section 3.8.2 and in further detail in section 3.6.

In addition, the minimum channel of LTE is 1.4 MHz. Supporting aircraft at higher altitudes require a higher frequency reuse factor (k factor) to reduce co-channel interference. Given the proposed cell radius, supporting an aircraft at 60,000 feet will require a k-factor of 12. This would consume 16.8 MHz (12 x 1.4 MHz) of the available 17 MHz of allocated spectrum. It is unlikely that the full 17 MHz will be usable in order to coexist with systems operating in adjacent bands. Supporting the smallest 1.4 MHz channel severely limits the flexibility of the system.

Based on the analysis above, use of the LTE physical layer is not viable for the CNPC system due to the difficulty in deploying a high power, linear PA; and the severe limitation on the system flexibility due to supporting a 1.4 MHz channel.

3.8.3.2. WiMAX (Worldwide Interoperability for Microwave Access)

WiMAX is a wireless communication standard designed to provide 30-40 megabit/s data rates. It supports both TDD and FDD, but the mobile WiMAX is restricted to TDD. It uses Scalable OFDMA for both the uplink and downlink. Like LTE, the core disadvantage that it utilizes OFDMA for the ground station to user link. OFDMA requires the transmission of the sum of multiple signals simultaneously by a ground transmitter, which requires a high degree of linearity. The difficulties associated with a high power, linear transmitter are discussed in brief in section 3.8.2 and in further detail in section 3.6.

Under current WiMAX mobile profiles, the smallest channel size is 5 MHz. At the proposed cell radius, supporting an aircraft at 60,000 feet will require a reuse (k-factor) of 12. This would consume 60 MHz of spectrum (12 x 5 MHz). This significantly exceeds the 17 MHz of allocated spectrum.

Based on the analysis above, use of the WiMAX physical layer is not viable for the CNPC system due to the difficulty in deploying a high power, linear PA; and the severe limitation on the system flexibility due to supporting a 5 MHz channel.

3.9 Analytical Hierarchy Process Example

The numerical evaluations of these trades were conducted using the Analytic Hierarchy Process (AHP). The first trade, on Uplink/Downlink Duplex, is explained below as an example of how the process was applied to all the other trades as well.

The AHP / pairwise comparison method is a standard system engineering technique for trades involving various factors that do not have inherent numerical scoring using a consistent measure. It was developed by Dr. Thomas Saaty (University of Pittsburg) in the 1970s and matured to a widely applied methodology today in both government and private sectors. This is the technique recommended by the International Council of Systems Engineering for this class of problem.

This appendix is not intended as a tutorial on the AHP method. There are many books and technical articles that deal with this technique, including:

- *"Fundamentals of Decision Making and Priority Theory with the Analytic Hierarchy Process",* Thomas L. Saaty, 2000.
- *"Systems Engineering Handbook"*, Version 2.0, July 2000, International Council on Systems Engineering (INCOSE), p. 270 and following.

We now apply the 5 steps of AHP to the Uplink/Downlink Duplex trade.

Step 1 – Selection the Evaluation Criteria.

Through peer review process of the waveform technical team, the following evaluation criteria were identified:

Evaluation Criteria
Uplink/Downlink Isolation
Link Margin
RF Spectrum Utilization
System Synchronization

Step 2 – Select the Weighting on the Evaluation Criteria

The evaluation criteria were weighted using the following qualitative descriptors:

- Minor significance – Weight of 1
- Moderate significance – Weight of 3
- Major significance – Weight of 5
- Maximum significance – Weight of 7

The resulting table shows the weights.

Evaluation Criteria	Raw Weight	Normalized Weight
Uplink/Downlink Isolation	7	.500
Link Margin	3	.214
RF Spectrum Utilization	3	.214
System Synchronization	1	.071

Step 3 – Select Candidate Solutions

Two candidates for uplink/downlink duplexing were considered:

- Frequency Division Duplexing (FDD)
- Time Division Duplexing (TDD).

Step 4 – Rate Each Candidate Against the Evaluation Criteria

Ratings were established using a two-step process:

1. **Stoplight Evaluation** – Candidates were given one of three levels of rating against each of the evaluation criteria:
   - Green – This candidate clearly fulfills the needs of this criterion.
   - Yellow – This candidate partially fulfills the needs of this criterion.
   - Red – This candidate marginally fulfills the needs of this criterion, if at all.

2. **Numerical Scoring** – A weight was assigned to each pairwise comparison based on the relative color ratings. Red ratings were penalized more strongly against the others. The following definitions were used:
   - Same color – Weight of 1
   - Green to yellow – Weight of 3
   - Yellow to red – Weight of 5
   - Green to red – Weight of 7

The stoplight scoring results (as detailed in section Duplexing Analysis2.1.2) are shown below.

Evaluation Criteria	Uplink/Downlink Duplexing Candidates	
	FDD	TDD
Uplink/Downlink Isolation	Infeasible	Not required
Link Margin	+3 dB	+0 dB
RF Spectrum Utilization	71%	92%
System Synchronization	Not required	Using GPS, < 5% added complexity

Pairwise comparison of the candidates for each evaluation criteria is placed in a matrix using the numerical scoring listed above. The eigenvector of the resulting matrix is computed and normalized to generate the priority vector for this criterion.

Specifically, these matrices for this trace are below.

Determine Uplink / Downlink Duplex Method -- Uplink / Downlink Isolation

	FDD	TDD	Eigenvector Estimate	Priority Vector
FDD	1	1/7	0.378	**0.125**
TDD	7	1	2.646	**0.875**

Determine Uplink / Downlink Duplex Method -- Link Margin

	FDD	TDD	Eigenvector Estimate	Priority Vector
FDD	1	3	1.732	**0.750**
TDD	1/3	1	0.577	**0.250**

Determine Uplink / Downlink Duplex Method -- RF Spectrum Allocation

	FDD	TDD	Eigenvector Estimate	Priority Vector
FDD	1	1/3	0.577	**0.250**
TDD	3	1	1.732	**0.750**

Determine Uplink / Downlink Duplex Method -- System Synchronization

	FDD	TDD	Eigenvector Estimate	Priority Vector
FDD	1	1	1.000	**0.500**
TDD	1	1	1.000	**0.500**

Step Five – Determine the Preferred Solution

The resulting pairwise comparisons were combined with the evaluation criteria weighting to generate a weighted priority vector indicating the relative merits of the candidates.

Determine Uplink / Downlink Duplex Method -- Trade Study Results

	Uplink / Downlink Isolation	Link Margin	RF Spectrum Allocation	System Synchronization	Raw Totals	Normalized Results
FDD	0.500	0.214	0.214	0.071		
	0.125	0.750	0.250	0.500		
	0.063	0.161	0.054	0.036	0.313	**0.313**
TDD	0.500	0.214	0.214	0.071		
	0.875	0.250	0.750	0.500		
	0.438	0.054	0.161	0.036	0.688	**0.688**

A summary table was generated combing the evaluation criteria and the candidate solution scoring. One final normalization was performed so that the highest rated alternative is set to 100% and relative scores of other alternatives can be computed. Stoplight color ratings were assigned to the final normalized results as below:

85% - 100%	Green
70% - 85%	Yellow
<70%	Red

The final table for Uplink / Downlink Duplex Method is below.

Determine Uplink / Downlink Duplex Method

	Evaluation Criteria	Weight		Alternatives	Raw	%
1	Uplink / Downlink Isolation	0.500	1	FDD	0.313	45
2	Link Margin	0.214	2	TDD	0.688	100
3	RF Spectrum Allocation	0.214				
4	System Synchronization	0.071				