VHF Air/Ground Communications for Air Traffic Control: A Decision Tree Approach to System Innovations

M 93B0000096V1
July 1993

Cheng-Hong Chen
James W. Howland
Robert I. Millar
Brian E. White
Warren J. Wilson

MITRE
Bedford, Massachusetts

REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE July 1993	3. REPORT TYPE AND DATES COVERED

4. TITLE AND SUBTITLE VHF Air/Ground Communications for Air Traffic Control: A Decision Tree Approach to System Innovations 6. AUTHOR(S) Cheng-Hong Chen, James W. Howland, Robert I. Millar, Brian E. White, Warren J. Wilson	5. FUNDING NUMBERS DTFA01-93-C-00001
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) The MITRE Corporation 202 Burlington Road Bedford, MA 01730-1420	8. PERFORMING ORGANIZATION REPORT NUMBER M 93B0000096V1
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) FAA	10. SPONSORING/MONITORING AGENCY REPORT NUMBER
11. SUPPLEMENTARY NOTES	
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited.	12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Improvements to VHF air/ground communications for civil aviation in the 118-137 MHz aeronautical mobile frequency band are systematically explored by means of a decision tree approach. Seven individual papers analyze in detail the operational and technical factors involved in making these improvements. Basic tradeoffs between analog and digital modulation are discussed to frame the problem. Near-term improvements utilizing various analog modulations with closer channel spacing are first reviewed. Then far-term improvemnts employing a wide range of digital modulation and coding techniques are considered. Multiplexing methods - frequency, time, and code division - are discussed in detail. Methods for random access to a shared communications channel are compared, with emphasis upon real-time operations for air traffic control. Volume I provides an executive summary of this work, while Volume II presents the technical details.

14. SUBJECT TERMS VHF air/ground communications, analog modulation, digital modulation, multiplexing methods, air traffic control	15. NUMBER OF PAGES 38 16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited

VHF Air/Ground Communications for Air Traffic Control: A Decision Tree Approach to System Innovations

M 93B0000096V1
July 1993

Cheng-Hong Chen
James W. Howland
Robert I. Millar
Brian E. White
Warren J. Wilson

Contract Sponsor FAA
Contract No. DTFA01-93-C-00001
Project No. 177GA
Dept. D050

Approved for public release; distribution unlimited.

MITRE
Bedford, Massachusetts

ABSTRACT

Improvements to VHF air/ground communications for civil aviation in the 118-137 MHz aeronautical mobile frequency band are systematically explored by means of a decision tree approach. Seven individual papers analyze in detail the operational and technical factors involved in making these improvements. Basic tradeoffs between analog and digital modulation are discussed to frame the problem. Near-term improvements utilizing various analog modulations with closer channel spacing are first reviewed. Then far-term improvements employing a wide range of digital modulation and coding techniques are considered. Multiplexing methods — frequency, time, and code division — are discussed in detail. Methods for random access to a shared communications channel are compared, with emphasis upon real-time operation for air traffic control. Volume I provides an executive summary of this work, while Volume II presents the technical details.

ACKNOWLEDGMENTS

The authors acknowledge the continued interactions with CAASD, particularly department F085, ATC Communications Systems. Special thanks are due Lisandro del Cid, Chris Moody, Dave Chadwick, and Amr ElSawy for their encouragement, project guidance, and technical suggestions. The involvement of our FAA sponsor, ASE-200, in this work has been very helpful, viz., Bruce Eckstein's program management oversight; Cindy Peak provided the original impetus for the decision tree approach. The interest of RTCA Special Committee 172 participants has also been stimulating.

Other members of the Bedford team deserve recognition for their contributions in preparing this document as well: Cho-Chau Li, Anne Doherty, Ginny Fitzgerald, Lynn Lacroix, and Nancy MacLeod.

Significant contributions to Section 6 of Volume II were made by Ivan La-Garde and Dave Snodgrass of Department D053.

TABLE OF CONTENTS

LIST OF FIGURES

FIGURE | **PAGE**

LIST OF TABLES

SECTION 1

INTRODUCTION AND OVERVIEW

1.1 ORGANIZATION OF THE REPORT

This report is divided into two volumes. Volume I presents the motivation for the work, describes a decision tree approach to system innovations, and explains which branches of the decision tree were selected for detailed investigation. Then an executive summary of each of seven individual decision tree papers is given. Finally, some conclusions are drawn about the utility of the decision tree approach and recommendations for further work are made.

Volume II is a compilation of seven individual decision tree papers. Each paper provides some background about where it fits in the larger picture, delineates the relevant technical and operational issues, discusses engineering tradeoffs in some detail, summarizes the impact and importance of these tradeoffs, reviews the criteria for decision, and provides the connectivity and relationship with other branches of the decision tree. The seven decision tree papers and their authors are:

- Analog versus Digital Modulation (Millar)
- Analog Modulations (Millar)
- Spectrum Utilization — Closer Channel Spacing (Howland)
- Digital Modulations (Chen)
- Coding Techniques (Chen)
- Multiplexing (Wilson)
- Random Access (White)

1.2 INTRODUCTION

MITRE's Center for Advanced Aviation System Development (CAASD) conceived a vision for improving VHF communications for air traffic control applications based largely on the notion of extending land mobile cellular telephone concepts and technology into three dimensions [1]. CAASD asked MITRE/Bedford's Communications Division D050 to take this collection of ideas and consider their technical feasibility. The Bedford effort was funded as a FY91 MITRE Sponsored Research (MSR) project, Project 91550, Cellular Trunked Air Ground (CTAG) Communications for Air Traffic Control (ATC) beginning on 21 March 1991. The results of this work were documented in a comprehensive three-volume report [2].

During FY92 and FY93, staff members in the Communications Division supported FAA sponsored work on VHF air/ground communications under the direction of CAASD. Along with members of CAASD, the authors participated in RTCA Special Committee 172, which is considering a wide range of possible improvements to VHF air/ground communications in the 118-137 MHz aeronautical mobile frequency band. Working Group 1 is considering new system architectures including different modulation techniques and Working Group 2 is preparing Minimum Aviation System Performance Standards to define the signal-in-space characteristics for advanced VHF digital data communications including compatibility with digital voice techniques. By active participation in both working groups, the authors became aware of past and current efforts to improve VHF air/ground communications by other organizations and became aware of technical and operational issues needing further investigation and clarification. In particular, a systematic exploration of technical alternatives and a comparison of those alternatives with evolving operational requirements seemed to be needed. Furthermore, the notion of a decision tree, originally suggested by the FAA sponsor, appeared to be a good approach to making such a comparison. Two significant operational requirements were a need for more air/ground communication channels in the 118-137 MHz band and a need to provide data communications as well as voice communications. The major technical questions were how to meet the need for more channels with various analog and digital modulations, and what were the best coding, multiplexing, and random access methods to allow many ground and airborne users to efficiently share these channels for both voice and data communications.

1.3 THE DECISION TREES

The first two decision trees (figures 1 and 2) delineate as branches the options for improved spectrum utilization and increased communications throughput in the aeronautical mobile frequency band. One branch, Closer Channel Spacing, is explored in detail in the paper entitled Spectrum Utilization — Closer Channel Spacing while another branch, Advanced Modulation/Coding, is explored in detail in the four papers entitled Analog versus Digital Modulation, Analog Modulations, Digital Modulations, and Coding Techniques. Other branches of the spectrum utilization tree — Higher Frequency Reuse, Existing Allocation Usage, and Assignment Optimization — are addressed to some extent at various places in the seven decision tree papers. Another branch of the communications throughput tree, channel access by Random Access is explored in detail in the paper entitled Random Access. Fixed Assigned and Demand Assigned channel access methods are discussed to a limited extent in the paper entitled Analog versus Digital Modulation. The Frequency/Time/Space Usage branch of the communications throughput tree is explored in detail in the paper entitled Multiplexing.

The branches of the system changes tree (figure 3) are discussed at various places in the seven decision tree papers. Means for improving Availability and for Workload Mitigation are discussed in the papers entitled Analog versus Digital Modulation, Multiplexing, and Random Access. Means for improving Communications Performance by increasing Message Integrity are addressed in all seven papers, while the Reduced Delay branch is treated in detail in the Random Access paper.

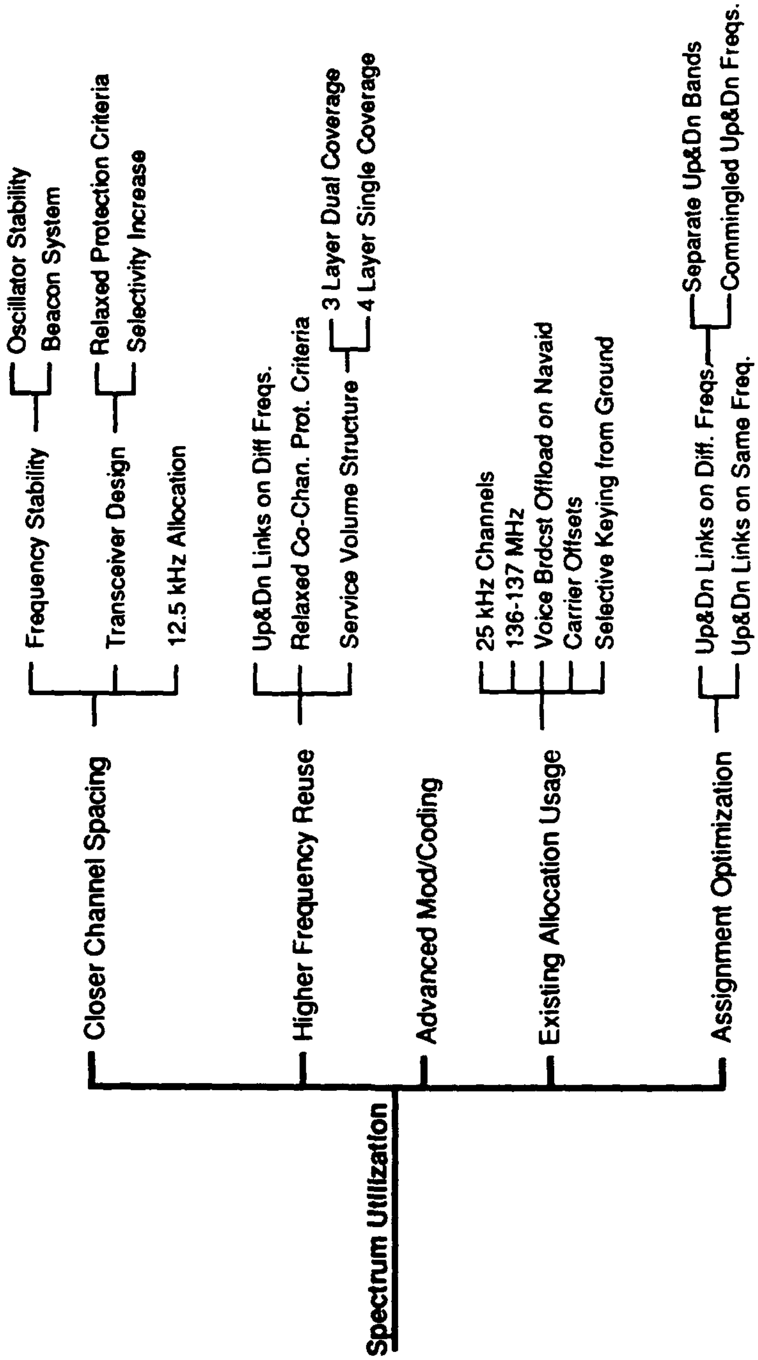

Figure 1. Spectrum Utilization Decision Tree

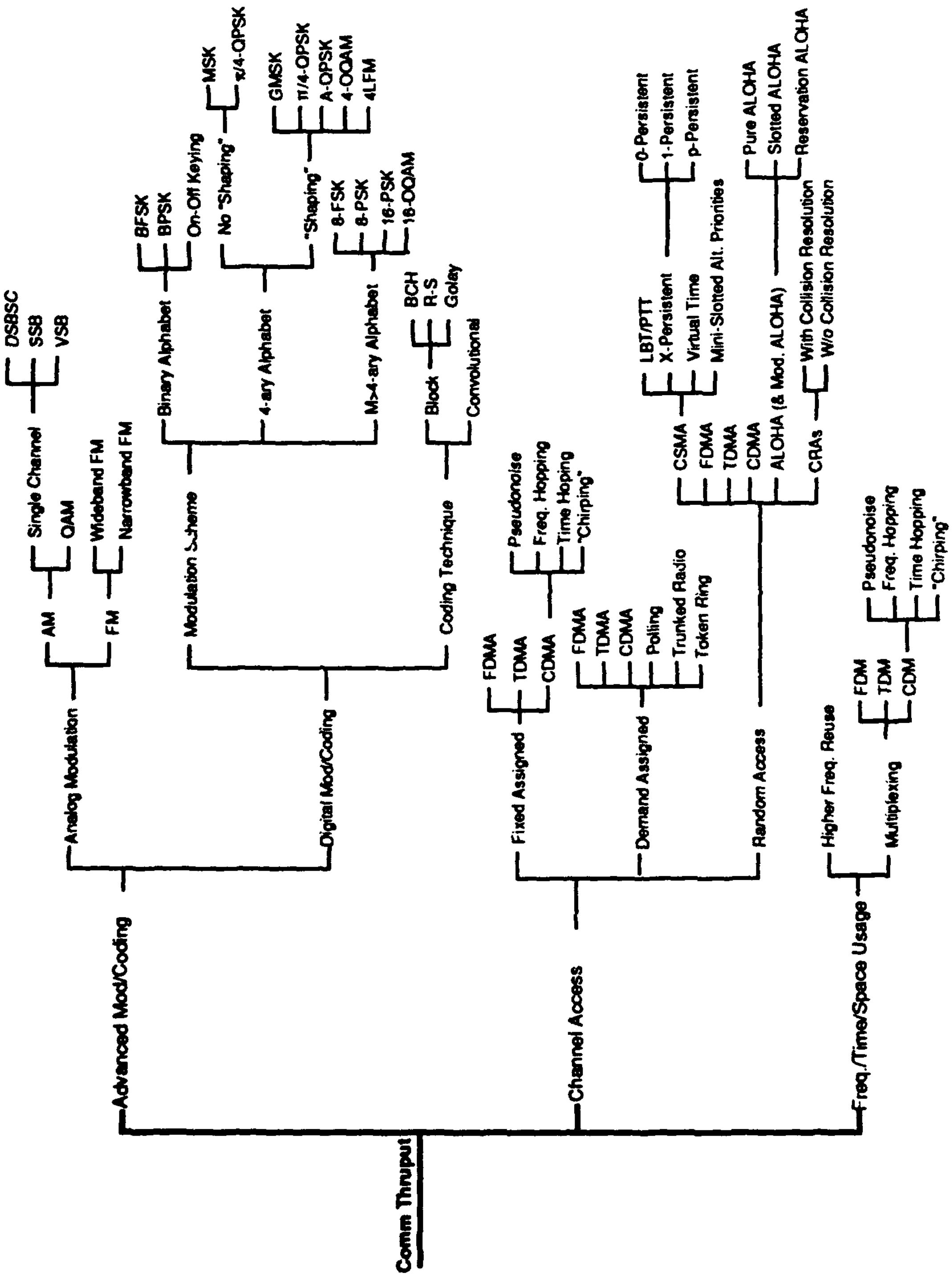

Figure 2. Communications Throughput Decision Tree

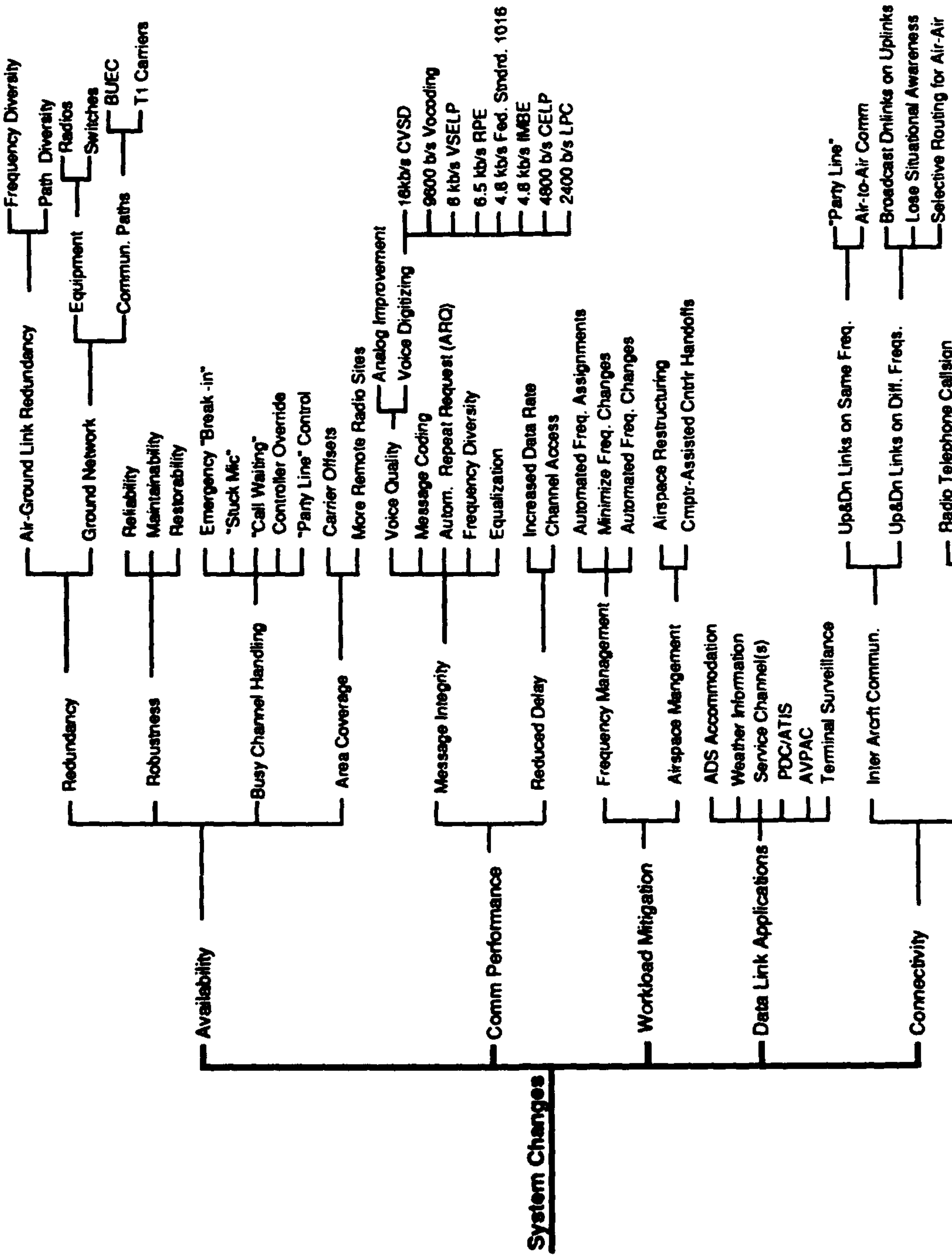

Figure 3. System Changes Decision Tree

SECTION 2

EXECUTIVE SUMMARIES OF EACH DECISION TREE PAPER

2.1 ANALOG VERSUS DIGITAL MODULATION: Technical and Operational Issues in Choosing Between Analog and Digital Communications

Improvements to VHF air/ground communications in the 118-137 MHz aeronautical mobile frequency band fall into two general categories: (1) improving the current air/ground communications system while maintaining the same concept of operations and (2) adding new capabilities that change the concept of operations of the air/ground communications system. Choosing between analog and digital modulation can be viewed in the context of these two categories of improvements. Many of the improvements in the first category can be obtained with either analog or digital modulation, but many of the improvements in the second category are more readily provided with digital modulation.

Some fifteen specific technical and operational criteria are defined against which to consider the choice of analog or digital modulation. Five of these criteria — number of voice channels, power efficiency, susceptibility to interference, performance degradation due to fading, and speech intelligibility — fall into the first category. Six criteria — data transmission, compatibility with multiplexing, compatibility with new channel access methods, evolutionary growth capability, compatibility with channel availability and message integrity improvements, and compatibility with advanced user features — fall into the second category. Four criteria — need for coherent demodulation, radio design complexity, technical maturity and design risk, and backward compatibility with current AM radios — relate to the practicality of new modulations.

To compare analog and digital modulation against these fifteen criteria, two representative modulations of each type are chosen. Analog modulation is represented by amplitude modulation (AM) and single sideband (SSB). Digital modulation is represented by 4-ary offset quadrature amplitude modulation (4-OQAM) and 16-ary offset quadrature amplitude modulation (16-OQAM). In each case, we have chosen both a simple limited performance waveform and a more complex higher performance waveform to illustrate the range of capabilities available.

Evaluation of these four representative analog and digital modulations against the fifteen technical and operational criteria is done in sufficient detail in this paper to produce some insights into alternative courses of action for the decision maker. The first such alternative is to continue to use AM for VHF air/ground communications in the 118-137 MHz aeronautical mobile band, but reduce channel spacing to 12.5 kHz or less. This accommodates the need for more voice channels (currently an urgent need in Europe), but offers no other significant benefits to aircraft owners in return for investing in a new (or retrofitted) radio with better frequency selectivity.

A second alternative is to replace current AM radios with an improved analog radio using single sideband modulation at a channel spacing of 6.25 kHz or less. A single sideband technique called Amplitude Modulation Equivalent (AME) has been presented to RTCA Special Committee 172 by the UK CAA. It employs 5 kHz channel spacing and provides some degree of interoperability with AM radios. Use of single sideband provides for many more voice channels, but offers only a few performance improvements to the aircraft owner in return for investing in a new radio.

A third alternative is to employ new analog radios, either AM or single sideband, both to provide more voice channels and to incorporate new features into the radio that are of value to aircraft owners and to the air traffic control system. The number of new features which can be provided with analog radios is limited, however, and implementing them with in-band signaling requires some interruption of voice, which may reduce user acceptance.

A fourth alternative is to employ new digital radios, both to provide more voice channels and to incorporate new features. With digital radios, a wider range of new features can be provided than with analog radios, increasing the value of the new radio to aircraft owners and to the air traffic control system. Furthermore, by using separate time division multiplexed signaling and control channels to implement the new features, no interference with the voice channels will occur.

2.2 ANALOG MODULATIONS: An Evaluation of Seven Specific Types

Use of analog modulation in improved VHF air/ground radios is a near-term improvement of limited scope, intended primarily to address the immediate need for more voice communications channels in the aeronautical mobile frequency band. It could represent an intermediate step toward an eventual digital communications system or a lower-technology alternative for certain classes of users for whom low cost is critical. Seven well-known analog modulations are considered to meet the need for more voice communications channels:

- Amplitude modulation (AM) which lets the amplitude of a speech waveform control the amplitude of a radio-frequency carrier. AM is sometimes called double sideband transmitted carrier (DSBTC). The speech waveform is transmitted as both upper and lower sidebands of a radio frequency carrier.

- Double sideband suppressed carrier (DSBSC), which transmits the speech waveform as both upper and lower sidebands, but does not transmit the radio-frequency carrier.

- Quadrature amplitude modulation (QAM) which *transmits two non-interfering* signals in the same bandwidth by modulating them onto two radio frequency carriers with the same frequency but 90° apart in phase. QAM can be implemented with two DSBSC signals, if the two carriers are used as phase references for modulation, but not transmitted.

- Single sideband (SSB) which transmits a speech waveform as the upper sideband of a radio frequency carrier, suppressing the lower sideband and not transmitting the carrier. SSB has found wide application in high frequency (HF) radio communications and in analog frequency-division multiplexed (FDM) telephony. VHF air-ground communications has a special requirement (need to tolerate Dopper shift) which HF communications and FDM telephony do not. Modifications to SSB to accommodate this special requirement are needed, including a transmitted pilot tone.

- Vestigial sideband (VSB) which allows part of the lower sideband to be transmitted along with all of the upper sideband. In North American television, VSB is used with a transmitted carrier for the picture signal.

- Frequency modulation (FM) which lets the amplitude of a speech waveform control the frequency of a radio-frequency carrier, with the carrier frequency deviation being larger than the audio frequencies in the speech waveform. The transmitted frequency spectrum of FM does not resemble the frequency spectrum of the original speech.

- Narrowband frequency modulation (NBFM) which is similar to FM except that the carrier frequency deviation is reduced in order to limit the required channel bandwidth.

The criteria against which the seven analog modulations are considered are the number of voice channels provided by each analog modulation, relative power efficiency, susceptibility to interference, performance in signal fading, intelligibility under a two-speaker overload condition, need for Doppler tracking, and radio design complexity. Significant differences are found to exist between analog modulation types when compared against these criteria as summarized in Table 1.

Analog modulation allows in principle either an approximate doubling or a quadrupling of the number of channels in the 118-137 MHz frequency band. The number of channels can be doubled with AM, DSBSC, or NBFM. There are no compelling reasons to choose DSBSC over AM, except for power efficiency which is not one of the more important decision criteria; together with the much greater complexity of a DSBSC radio over an AM radio, this tends to rule out DSBSC modulation as a choice. Both AM and narrowband FM are simple to implement and well understood by industry; the choice between them could be deferred until a finer-grain comparison is made. One aspect of such a comparison would be to calculate the increase in the useful number of channels in situations where cosite interference is a limiting factor.

Table 1. Comparison of Several Analog Modulations

ANALOG MODULATION TECHNIQUE	# VOICE CHANNELS PER 25 KHZ	POWER EFFICIENCY RELATIVE TO DSBSC	SUSCEPTIBILITY TO INTERFERENCE	FADING PERFORMANCE	TWO-SPEAKER CONFERENCING ABILITY	DOPPLER TRACKING REQUIREMENT	RADIO DESIGN COMPLEXITY
AM (DSBTC)	2 to 2.5	Poor -5 to -10 dB	High	Fair	Audible carrier heterodyning	None	Simple linear Tx/Rx
DSBSC	2 to 2.5	Good 0 dB	Moderate	Fair	Doppler distortion	Costas loop accurate phase	Costas loop phase tracker linear Tx/Rx
QAM	4 to 5	Good 0 dB	Moderate to High	Fair	Severe quadrature distortion	Costas loop very accurate phase	Costas loop phase tracker linear Tx/Rx
SSB	4 to 5	Good -1 dB	Moderate	Fair	Quasi-linear with different Dopplers	Pilot tone carrier error <20 Hz (voice)	Tracking loop linear Tx/Rx
VSB	3 to 4	Good -1 dB	Moderate	Fair	Quasi-linear with different Dopplers	Pilot tone accurate phase	Tracking loop linear Tx/Rx
FM	1	Good +4 dB	Low	Very good	Supression of weaker signal	None	Simple constant envelope Tx/Rx
NBFM	2	Fair -3 dB	Moderate	Good	Less supression of weaker signal	None	Simple constant envelope Tx/Rx

AM - Amplitude Modulation
DSBTC - Double Side Band Transmitted Carrier
DSBSC - Double Side Band Suppressed Carrier
QAM - Quadrature Amplitude Modulation
SSB - Single Side Band
VSB - Vestigial Side Band
FM - Frequency Modulation (25 kHz)
NBFM - Narrow Band FM (12.5 kHz)
Tx - Transmitter
Rx - Receiver

If an approximate quadrupling of the number of channels is required, this can be done in principle with either QAM or SSB. There are no compelling advantages of QAM over SSB, while QAM is more complex to implement than SSB, its performance suffers much more from phase tracking errors, and its channels must be paired on the same platform. Thus, SSB appears to be the analog modulation of choice for a large increase in number of channels. This large apparent increase in the number of channels must be tempered with practical limitations of cosite interference in some geographical areas. There is no good reason to chose VSB over SSB. The strong point of VSB is a baseband frequency response extending to very low frequencies. While this factor is important to reception of television pictures (for which VSB is presently used) it is not important to voice transmission.

Finally, although FM with a large modulation index has a number of good points — simple implementation, very good power efficiency, resistance to fast fading, and interference rejection — it cannot provide more channels and can probably be dropped from consideration.

2.3 SPECTRUM UTILIZATION — CLOSER CHANNEL SPACING: An Evaluation of Technical Feasibility

The ability to offer the Air Traffic Control (ATC) communications community an improved system with additional capabilities is closely coupled to matching near and far term requirements with cost effective implementations utilizing modern day technology and design practices. The finite nature of frequency allocations for communications in the radio frequency (RF) spectrum steers the system designer to consider many factors to realize an increased capability. One such factor is efficient utilization of the allocated frequency bandwidth currently in use. Closer channel spacing has been one method employed to increase the number of available channels as technology has evolved over the past several decades.

The present day systems are assigned to 25 kHz frequency centers which has recently evolved from the previous allocation of 50 kHz. An upgrade to 12.5 kHz (or less) impacts several system components within a conventional AM transceiver: the synthesizer, IF down conversion circuitry, demodulation circuitry, exciter stages, and the power supply. Any plan to replace these components, in order to permit closer channel spacings, must take into account adjacent channel interference (ACI) requirements and unit production costs in particular. In the design of the resulting communications system, in addition to these factors, the type of modulation (if different), the system architecture, and backward compatibility must be considered.

The synthesizer must not only tune to the additional channels offered by frequency splitting but also must support the finer frequency steps needed for frequency shift keyed formats for data communications and/or multi-carriers within a common intermediate frequency (IF) bandwidth. In addition, the synthesizer must have a level of spectral purity to prevent ACI due to local oscillator (LO) phase noise.

In a 12.5 kHz channelized system the reference oscillator for the synthesizer needs to be an order of magnitude more stable than the current frequency reference oscillators in transceivers of today. The cost associated with a built-in upgrade would be acceptable in commercial multi-function avionics but unwarranted in the simpler (and less costly) transceivers used by general aviation (GA). An alternative solution would be to provide a distributed reference frequency system. Spatially distributed ground transmitters could relay coded signals based on a highly stable frequency source which would be processed by airborne users within a coverage volume. This could be replaced in the far term by integral reference oscillators of sufficient stability as technology continues to evolve and its integration becomes cost effective.

The IF filter must be able to provide the requisite adjacent channel rejection and the system selectivity if all of the 12.5 kHz channels are to be used. Unfortunately, the characteristics of narrow bandwidth filters can be detrimental to specific types of modulation. The amount of waveform distortion which is deemed correctable through post demodulation processing must be traded-off against the system processor complexity.

The integration and use of the next generation ATC communication system must consider careful and judicious planning of the allocated channels used by co-located ground transceivers and their specific on-site locations. Current ATC radio site antennas are separated by no less than 80 feet. The radios of today are typically configured as separate transmitters and receivers, with all transmitters at one antenna site and all receivers at another. The next generation system most probably will be configured as a transceiver, where the isolation gained by the antenna separation could be lost unless transmissions are carefully orchestrated. Several potentially significant cosite problems exist in the ground ATC communication system. The presence of strong signals, close in frequency to a desired received signal, can desensitize the ground receiver. This effect is closely coupled with other strong signal interference mechanisms such as cross modulation and intermodulation product (IMP) interference. The bandwidths of the preselector or front-end filter and the IF filter coupled with the performance of the receiver's down-conversion circuitry (mixers, amplifiers, etc) determine the interference susceptibility of a receiver to these problems. Another source of interference in a co-location environment is transmitter back-intermodulation products. Signals from a nearby transmitter can be coupled into another transmitter through its antenna and be passed into its amplifier circuitry. The two signals in the amplifier intermodulate creating strong undesired products at $2f_1 - f_2$ and $2f_2 - f_1$. This source of interference is similar to the effects of two signals present in the passband of a receiver front-end, where IMPs can be created by nonlinearities in the amplifiers and mixers.

A factor of two improvement in the utilization of the existing VHF spectrum is possible at the expense of several significant upgrades to the current performance of the systems of today. The cumulative costs associated with an improved IF filter, a synthesizer with finer frequency resolution and better stability, and a revamping of the frequency assignments can at least triple the unit costs (average of both the ground and airborne transceivers) for even a system still based on the current modulation, double-sideband transmitted carrier amplitude modulation (DSBTC-AM). For example the costs of the modifications necessary to realize a finer channelization in a airborne transceiver of today significantly exceed the initial cost of the units to the level of making such modifications not practical. A new design would be more cost effective since many functions are integrated on common printed circuit boards.

In summary, a next generation system or an up-graded existing ATC communication system based on closer channel spacing is technologically feasible and perhaps warranted by the growing demands of the users. Practical realization of the additional channels gained with a finer channel allocation entails many design trade-offs and issues. The main point to keep in mind is that significant upgrades to all existing radios and the wholesale introduction of new radios are necessary to achieve a factor of two improvement in the utilization of the spectrum by channel splitting.

2.4 DIGITAL MODULATIONS: A Comparison of Power and Bandwidth Efficiency

The current air traffic control (ATC) VHF radio uses double sideband transmitted carrier (DSBTC) analog modulation for voice transmission. Data information (although not used for ATC purposes) is transmitted through the voice radio on a voice channel using an analog minimum shift keying (MSK) modem at a rate of 2400 bits per second (b/s). Digital modulation may be preferred for the future improvement of the ATC VHF air/ground communications system due to its ability to provide improved voice performance, significantly more data transmission capability, and to combine data and voice transmissions in a single radio.

The need to increase the capacity of ATC systems has led to the investigation of spectrally efficient modulation techniques to maximize bandwidth efficiency and thus help ameliorate the spectral congestion problem. Various bandwidth efficient digital modulations intended for potential application in the future improved ATC VHF air/ground communications system are assessed through a detailed review of the digital modulation techniques and specific tradeoff issues.

Comparisons are based on a modulation's power efficiency (error performance), bandwidth efficiency (information transmission rate), and implementation complexity as well as its ability to be tolerant of system nonlinearities and interferences such as adjacent channel interference (ACI). Error performance comparisons in the anticipated multipath fading ATC channel are also included.

Each digital modulation technique has advantages and disadvantages with respect to the issues discussed. The final choice of the digital modulation technique should be one which 1) maximizes the information transmission rate within a given channel bandwidth while achieving acceptable bit-error-rate performance in the anticipated ATC environment; 2) meets adjacent channel, co-channel and out-of-channel interference specifications; and 3) provides ease of implementation.

Figure 4 shows overall power-bandwidth tradeoffs for the various digital modulation techniques. Note that, except for A-QPSK, figure 4 shows modulation performance without channel shaping filters. With filter shaping, 4-OQAM and $\pi/4$-QPSK would be close to

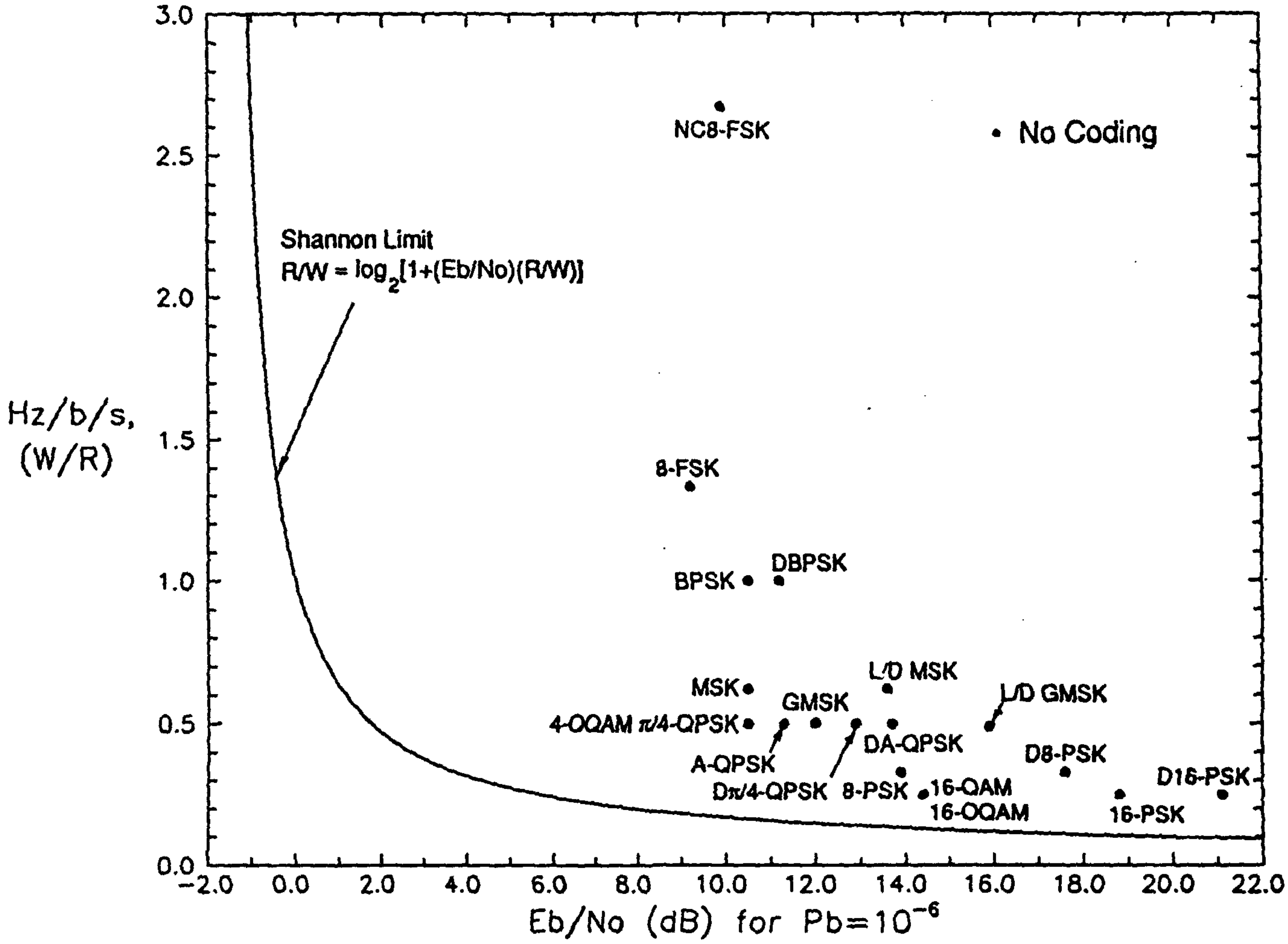

Figure 4. Channel Bandwidth-Power Tradeoff for
Various Digital Modulation Schemes Without Coding

A-QPSK. The use of either coherent or noncoherent detection depends in part on the occurrence of multipath fading in the ATC A/G channel. If coherent detection is to be used, 4-OQAM and A-QPSK have advantages over other modulation techniques due to their considerably better BER performance, high bandwidth efficiency and good resistance to nonlinearity effects and adjacent channel interference. However, severe multipath fading causes an irreducible BER and carrier recovery is difficult to obtain. In that case, noncoherent detection would be preferred, and phase comparison π/4-QPSK and GMSK, detected noncoherently with a limiter and discriminator, appear to be good candidates.

2.5 CODING TECHNIQUES: For Error Control on Air/Ground Radio Links

Many branches of the decision tree require the use of digital modulation. With the possible exception of digital voice applications, where a very low bit-error-rate (BER) may not be required, digital modulation alone will not provide reliable data communications in the VHF air/ground radio environment, where signal receptions between the ground station and the aircraft can occur via multiple random propagation paths in addition to the primary direct path. For example, multipath fading may appear on the received signal and cause bursts of errors. Error control coding techniques combined with digital modulation can provide reliable data communications, and also allow alternate routing/networking and other improved features that are difficult to implement with analog modulation.

Various error control coding techniques could be combined with digital modulation for application in a future ATC VHF air/ground communications system. Two categories of the error control techniques, forward error correction (FEC) coding and automatic repeat request (ARQ) for retransmission, are reviewed. In the FEC coding category, linear block codes and convolutional codes are considered. In the block code family, the best Golay, Bose-Chaudhuri-Hocquenghem (BCH) and Reed-Solomon (RS) codes are emphasized. In the convolutional code family, attention is concentrated on the most commonly used convolutional codes (constraint lengths 7 and 9) with Viterbi decoding. In the ARQ error control schemes, three basic ARQ strategies (Stop-and-Wait, Go-back-N and Select-Repeat ARQ) and a hybrid of FEC and ARQ are discussed.

The error control techniques mentioned specifically above are assessed based on their effects on the error performance, bandwidth efficiency and data throughput, robustness and implementation complexity. As a result of this assessment, it is concluded that FEC with data interleaving is desirable in addition to ARQ error detection and retransmission since, in the ATC VHF air/ground channels, the expected number of digital modulation errors without correction might otherwise require excessive retransmissions.

In addition to the above conclusion, for situations where messages are treated in packets, block codes may be preferred for both error detection and error correction due to their blocked data format. Furthermore, if very little redundancy is available, high rate RS codes, such as the RS (255,249) 256-ary code, may be preferred for the error correction coding over the BCH codes because the RS encoder and decoder logic works with 8-bit byte-based rather than binary-based arithmetic. This reduces the complexity of the logic as compared to a BCH binary code of the same length.

2.6 MULTIPLEXING: Sharing The 118-137 MHz Frequency Band Among Multiple Users

There are a variety of ways to apply multiplexing to the problem of improving air/ground voice communications for air traffic management. The goals of the proposed improvements are to increase communications capacity, to provide for useful new features such as controller-assisted handoff, and to allow for the possible integration of limited amounts of data traffic into the system. The techniques which are investigated are frequency division, time division, and code division multiplexing. These are defined and discussed in detail in Volume II.

The applicability of each of the multiplexing techniques depends in a profound way on other aspects of the system design. The most important choice is the one between analog and digital voice modulation. As explained in the paper, analog modulation precludes all techniques but frequency division. With digital modulation all choices remain open. (Note that digital voice modulation may also be more amenable to the inclusion of data communications in the system.) The second important decision hinges on the types of additional features (if any) that the system will incorporate. Most of these features, which include controller-assisted handoff, emergency access, automatic emergency backup, etc., require full duplex operation, i.e., simultaneous transmission and reception. For reasons explained in the paper, full duplex operation is facilitated by the use of time division.

Another important feature of any new system is its ability to coexist with the current air traffic control (ATC) voice communications system since it is assumed that there will be a transition period of unknown duration. Code division may have some advantages in this regard, but there are a number of technical issues which have to be studied before this conjecture is verified. The final issue is one of cost. The new system must be affordable. Both the airborne radio sets and the ground infrastructure must provide enhanced performance at a reasonable cost. Cost is not addressed directly, but it is assumed to be closely related to complexity, which is addressed on a comparative basis.

Results are summarized in table 2. The table does not tell the whole story since combinations of the multiplexing techniques can also be used. The optimum combination of techniques will depend on the specific requirements which are levied on the system. Ultimately, the choice of requirements will depend on an iterative process which combines the results of the complete set of decision tree papers.

Table 2. Comparison of Multiplexing Techniques

	FDM 1)	TDM 1)	CDM 1)
Voice Modulation	Analog and Digital	Digital	Digital
Full Duplex Support	Moderately Difficult	Simple	Moderately Difficult
Capacity 2) High Duty Factor Low Duty Factor	 High High	 High High	 Moderate Highest
Self-Interference	Low	Low	Moderate
Intersystem Interference Separate Frequencies 3) Overlapping Frequencies 2)	 Low High	 Low High	 N/A Moderate
Fading Resistance	N/A	N/A	N/A
Complexity	Low/Moderate	Low/Moderate	High

1) All systems assume separate uplink and downlink frequencies.
2) Assume systems use full 14 MHz allocation.
3) Assume systems use frequencies not used by current ATC system.

2.7 RANDOM ACCESS: Suitability to Support Real-Time Communications

A survey and analysis of better known random access (RA) techniques and their expected throughput versus delay performance has been made. The principal question of interest is the extent to which the more attractive techniques can support real-time communications. Real-time for this purpose is defined as transmit-to-receive delay of no more than 200 ms for information packets received correctly. We find that only near-real time or non-real time is feasible using these techniques for aeronautical mobile VHF air/ground (A/G) communications. However, two RA schemes, called p-persistent CSMA and Virtual Time CSMA, can sustain high throughput levels above 50% of channel capacity under certain realistic conditions where the accompanying transmit-to-receive delays are in the order of 1s, i.e., near-real time. The Airlines Electronic Engineering Committee (AEEC) has adopted a non-adaptive form of the p-persistent Carrier Sense Multiple Access algorithm for use in a new VHF Data Radio development for commercial aviation [3]. A simpler RA technique, namely, modified Slotted ALOHA which attains only medium throughput levels around 25% of channel capacity, may be more suitable for general aviation use. However, for either class of users, the main emphasis should be on meeting Air Traffic Services (ATS) and Aeronautical Operational Control (AOC) requirements; less complex (simpler) systems that do not meet these requirements are unacceptable. The other RA schemes examined are shown in figure 5.

Considerable effort has been invested in ascertaining the ability of these RA schemes to operate in real-time, taking propagation delays of various aircraft altitude regimes and typical data rates and message lengths into account. Definitions of all the relevant parameters are covered in Volume II. Each RA scheme is defined separately, their advantages and disadvantages are discussed, and their throughput and delay performance is quantified, often using parametric curves. Some of the work on mini-slotted alternating priorities represents new research. All the results are based on detailed analyses which build on previous results from the literature of the field.

Precautions have been taken to use consistent terminology and to compare the RA schemes on a fair basis. A summary of the comparisons is found in Table 3, derived in Volume II.

The best RA scheme performers are p-persistent CSMA and Virtual time CSMA. Virtual Time CSMA outperforms p-persistent CSMA with respect to real-time operations (see figure 12, in Volume II) but Virtual Time CSMA is a more complex algorithm. The <u>in</u>ability of any of the RA schemes to support real-time communications with high confidence in acceptable delay is corroborated by an independent analysis of p-persistent CSMA accomplished by consultants to Transport Canada (see references [19] and [23] in section 11 of Volume II). Their analysis included formulas for expressing delays that do not exceed a specific delay requirement with some given probability, e.g., 95%. The analysis in volume II was restricted to mean (50% expected) delays. An assessment of this Canadian work and reasons for cautioning the reader on real-time results based only on the <u>expected</u> delay measure are included in section 11 of Volume II.

CHANNEL UTILIZATION	low	medium	high
high		CA[2] p-Persistent CSMA[1]	Virtual Time CSMA[1] Reservation ALOHA(can only support <u>non</u>-real-time operation)
medium	GA[3] Slotted ALOHA	Collision Resolution Algorithms	Mini-Slotted Alternating Priorities
low	Pure ALOHA		

COMPLEXITY

<u>Notes:</u>

1. Carrier Sense Multiple Access
2. Commercial Aviation selection
3. General Aviation possibility

Figure 5. Qualitative Assessment of Random Access Algorithms with Respect to Their Feasibility of Supporting Real-Time Operations

RA Scheme	Maximum Packet Length For Real-Time Operation			Sustainable Throughput	Impact of Parameter a *	Stability	Required Timing Accuracy	Complexity
	20 kb/s		40 kb/s					
Pure ALOHA	512 b		1024 b	0.125	negligible	unstable	none	lowest
Slotted ALOHA	512 b		1024 b	0.25	negligible	unstable	~1ms	low
Reservation ALOHA	----------- Cannot support real-time or near-real-time operations, only non-real-time -----------							
Collision Resolution Algorithms	256 b		512 b	0.25	negligible	stable	~1ms	medium
Mini-Slotted Alternating Priorities	512 b - - -	(n=16) (n=32)	1024 b 512 b	0.53 (utilization)	significant (a=0.1)	stable	0.13 ms	medium high
p-Persistent CSMA	2048 b		4096 b	0.3 to 0.35	significant (a=0.04)	unstable	0.2 ms	medium
Virtual Time CSMA	512 b		1024 b	0.6 to 0.7	insensitive (a=0.08)	unstable	0.2 ms	highest

* a = τ/T, ratio of maximum one-way propagation delay to packet duration

n = number of users

Table 3. Characteristics of the RA Algorithms Discussed With Emphasis on Their Ability to Support Real-Time Operations

The real-time issue, throughput and complexity tradeoffs, and suitability of certain RA schemes to commercial aviation and general aviation users are also discussed in Volume II. Finally, decisions about RA techniques may interact with other types of decisions regarding multiple access, type of modulation, separation of uplink and downlink frequencies, timeliness of message delivery, etc.

SECTION 3

CONCLUSIONS AND RECOMMENDATIONS

3.1 RECAPITULATION OF DECISION TREE PAPERS

The seven decision tree papers summarized in Volume I and presented in detail in Volume II provide a systematic review of many, but not all, of the possible alternatives for improving VHF air/ground communications in the 118-137 MHz aeronautical mobile frequency band.

(1) The paper on Analog versus Digital Modulation lays out basic choices between analog and digital techniques for the evolution of VHF air/ground radio communications, addressing a wide range of technical and operational issues bearing upon this choice. It shows that the need for more voice channels in the 118-137 MHz band can be met with new radios using either analog or digital modulation, but that digital modulation offers a wider range of new features and performance improvements than does analog modulation, increasing the value of these new radios to both aircraft owners and to the *air traffic control system.* Examination of all relevant criteria favors digital modulation as the solution for improving the VHF air/ground system and satisfying the requirements in such high traffic density areas as the continental U.S.

(2) The paper on Analog Modulations explores technical details of seven specific analog modulations. It concludes that two workable analog alternatives for obtaining more air/ground voice channels are amplitude modulation (AM) with channel spacing reduced from 25 kHz to 12.5 kHz and single sideband (SSB) with a channel spacing of 5 kHz or 6.25 kHz. Use of AM with 12.5 kHz channel spacing can nominally double the number of voice channels, but the number of usable channels can be much less, depending upon collocation interference at ground radio installations. In addition, AM with 12.5 kHz channel spacing produces no other improvements over the present air/ground system. Use of SSB with 5 kHz or 6.25 kHz channel spacing can nominally provide many more voice channels, with the number of usable channels also depending upon collocation interference limitations. Single sideband also offers improved power efficiency and link performance. But neither AM nor

SSB can provide the wide range of new features and performance improvements available with digital modulation.

(3) The paper on Spectrum Utilization — Closer Channel Spacing looks at radio design considerations for closer channel spacing. It shows that changes are needed in reference oscillators, frequency synthesizers, and bandpass filters. It also examines how radio collocation interference phenomena — intermodulation and crossmodulation product interference and receiver desensitization — are made worse by closer channel spacing. It concludes that the use of closer channel spacing is a technically feasible way to provide more channels to air/ground users, but that significant upgrades to all existing radios and widespread introduction of new radios is the price to be paid.

(4) The paper on Digital Modulations compares a large number of digital modulations on the basis of both bandwidth efficiency and power efficiency. It finds that quadrature phase shift keying (QPSK) and its derivatives offer the best tradeoff between bandwidth and power efficiency. The paper shows that it is possible to double the data rate in a given channel bandwidth by using 16-ary modulations such as 16-ary offset quadrature amplitude modulation (16-OQAM) instead of QPSK, but at the price of greater transmitter power and reduced tolerance for radio nonlinearities and channel fading. Proven digital modulations like QPSK are shown to offer a data rate adequate to support up to four multiplexed voice channels in a 25 kHz frequency channel. The possibility exists of providing an even larger number of multiplexed voice channels in 25 kHz with 16-ary modulations, but further research and development is needed to establish their suitability for VHF air/ground communications.

(5) The paper on Coding Techniques shows that reliable data communications is possible in the presence of both random errors and bursts of errors (due to multipath fading) on the VHF radio channel. Both forward error correction and automatic repeat request (ARQ) techniques can be useful for this purpose and a combination of the two techniques may be needed to meet all operational requirements for data communications, when they are defined. Use of coding and digital modulation on VHF air/ground channels can allow the same radio equipment to be used for both voice and data communications (not necessarily simultaneously).

(6) The paper on Multiplexing explores alternative ways to share the 118-137 MHz frequency band among many air/ground radio links. At present, each AM voice air/ground radio link uses one 25 kHz frequency channel. Time division multiplexing (TDM) combined with digital modulation is shown to be another way to share the band among multiple air/ground links. An increase in the number of radio links with AM or any other analog modulation requires further splitting of the band into narrower frequency channels, while TDM can provide more radio links by multiplexing several digital radio links into one 25 kHz frequency channel. For a given data rate per radio link, the number of links possible in a given radio frequency bandwidth with either alternative is about the same. However, TDM offers much more flexibility to accommodate additional features like duplex operation, signaling and control channels, variable data rates, evolutionary growth, discrete addressing, etc. Code division multiplexing (CDM) using spread spectrum waveforms is also considered in the paper on multplexing. Some difficulties in using CDM for VHF air/ground communications are delineated.

(7) The paper on Random Access reviews techniques allowing multiple radio users access to the same radio channel whenever they have a need, characterizing the different techniques primarily by their channel throughput and delay performance. The principal question of interest is the extent to which the more attractive techniques can support real-time voice and data link for Air Traffic Services (ATS) and Aeronautical Operational Control (AOC) communications. The paper concludes that none of these random access techniques can support real-time voice communications with high channel utilization, but that many of these random access techniques can support non real-time data communications. Tradeoffs between complexity and channel utilization for a wide range of random access techniques are presented in the paper, which also serves as a comprehensive review of the field.

In total, these seven papers provide a substantial body of work that the authors hope will be useful in clarifying the fundamental issues involved in improving VHF air/ground communications, and provide some guidance to decision makers in choosing among the alternatives presented to them.

Due to the finite time and resources available, a number of other technical and operational issues are either not covered here or are not covered in sufficient detail. The authors recommend that future work on VHF air/ground communications improvements investigate the following areas:

- Characteristics of low data rate voice coders, particularly their performance in cockpit acoustic noise and their tolerance for channel bit errors. The viability of digital voice communications with good spectral efficiency depends upon voice coders able to operate at low data rates — on the order of 4800 b/s or less.

- Tradeoffs among channel data rate, radio design complexity, and allowable adjacent-channel interference. Bandwidth efficiency of digital communications may be unduly reduced if adjacent-channel interference specifications are unnecessarily stringent. Differences in allowable adjacent channel interference between single-frequency and dual-frequency plans for ground-to-air and air-to-ground links need to be considered in this investigation.

- Detailed analysis of channel fading effects upon digital modulation and coding, particularly 16-ary modulations and high-rate error correcting codes. Reliable communications are particularly important on links between an air traffic controller and pilots.

- Cost versus performance tradeoffs in implementing various digital modulation, coding, multiplexing, and multiple access techniques. Cost is particularly critical to general aviation, so that two levels of VHF radio performance may be necessary — one for airlines and one for general aviation.

- Methods to transition the present analog VHF air/ground communications to digital communications. The most critical problem is how to find enough channels in the 118-137 MHz band during the long transition period when both old and new systems must coexist.

- Use of spread spectrum modulation for VHF air/ground communications. Direct sequence CDMA cellular technology has recently been successfully field tested by QUALCOMM, Inc. [4] and European digital cellular is incorporating frequency hopping [5]. Efforts to improve VHF air/ground communications have focused upon the relative merits of narrowband analog modulations (5 to 25 kHz channel spacing) versus narrowband digital modulations (25 kHz channel spacing). Perhaps a wider range of possibilities should be considered.

3.2 SUGGESTED SYSTEM ALTERNATIVE

The value of the decision tree approach to system architecture studies lies in its systematic nature, providing decision makers with an objective basis for their decisions. The decision tree lays out the design alternatives in a clear way and facilitates choices among these alternatives. Technical and operational tradeoffs and connections among different branches of the decision tree are illustrated graphically and the process sometimes suggests overlooked alternatives.

All this work begs the question: What *is* the recommended system alternative? As emphasized by the open issues listed in the last subsection, one cannot confidently predict the ultimate VHF air/ground (A/G) communications system solution for international use, especially for the next thirty years! World politics, institutional constraints, user preferences, and technology either change much too fast, or are too resistant to change, to make any credible statement along these lines. Furthermore, considerable additional work, namely, more detailed investigations of specific system architectures represented by distinct collections of paths through the decision subtrees, is really required. Nevertheless, it is important to assess the overall situation and make the best possible system recommendation of the moment, at least based on one's current understanding of most of the relevant technological factors. This recommendation, viewed as a future "target" system architecture to evolve towards, is summarized in Table 4. Individual entries in this table are explained briefly below.

Table 4. Envisioned Future (Target) A/G Radio System Architecture

Characteristic	Recommendation
Frequency Band	118-137 MHz
Channelization	25 kHz centers
Channel Structure	Two-frequency assignments (single-frequency assignments for analog modes)
Frequency Stability	≤ 10 ppm
Amplitude/Spectral Shaping	Constant envelope / ≤ 38 dB adjacent channel isolation (achievable by frequency-shaped 4LFM, for example)
Aggregate Channel Rate	32 kb/s with quaternary signaling
Modulation/Detection	Digital, with non-coherent detection (limiter/discriminators can be used with 4LFM))
Channel Access	Time Division Multiple Access (TDMA) (with "Listen Before Push-To-Talk" (LBPTT))
Operating Mode	Backward compatible, dual mode (analog and digital)
Voice	Digital low-bit-rate (4.8 kb/s or less) vocoded speech
Data	Integrated with digital voice so that either voice or data or both can be effected on the same RF channel
Cost	General Aviation (GA) market is a critical cost driver

The next-generation air/ground (A/G) radio system is envisioned to be operated within the currently allocated aeronautical-mobile VHF frequency bands in the 118-137 MHz region of the frequency spectrum. The current channelization of 25 kHz centers is assumed. These recommendations in themselves would require essentially no change in the existing spectrum allocations. In the U.S. the trend is to continue moving toward a complete implementation of 25 kHz radios. Some European nations favor subdividing the channels still further, as has been done in the past. The U.S. is generally against this historical approach as a temporary solution to spectrum congestion problems, because it will not offer sufficient motivation for users to re-equip.

Two-frequency assignments instead of the current single-frequency assignments are recommended because of the potential gain in overall spectrum efficiency anticipated from frequency reuse. Theoretically, a factor of two increase in spectrum efficiency can be obtained using the radio horizon as the criterion for limiting air-to-air interference. This gain is lessened when frequency protected service volumes and the 14 dB co-channel interference protection criteria favored by the U.S. are taken into account. It has been estimated that a minimum gain of 27% is feasible under these conditions; if the 20 dB co-channel used in Europe is adoptea, the minimum gain is estimated to be 69% [6, p. 47].

This "dual-frequency" recommendation, if accepted, should be accompanied by a reorganization of the VHF aeronautical-mobile band plan, however. Not only should uplinks and downlinks be separated but all the uplinks should be placed in different portion(s) of the allocated 118-137 MHz subbands from all the downlinks. This eases adjacent channel interference problems that might be caused by receiver desensitization, cross-modulation, intermodulation products arising from collocated radios at ground locations, etc.

In addition, analog and digital frequency assignments should be separated operationally to mitigate potential intersystem interference between the old and new systems. Extreme near/far geometries can be avoided through careful band planning and automated frequency management using computer-aided frequency assignment tools.

The transmitted digital signal should be relatively stable in frequency, constant envelope, and spectrally shaped to help provide for tolerable intrasystem interference in the adjacent channels. A significant improvement, e.g., of 5 to 10 parts per million (ppm), over today's 30 ppm tolerance in the existing analog radios is warranted. Added cost for even better stability may not be cost effective considering that Doppler effects can result in one or two ppm of frequency offset, and that radio costs must be minimized in the interest of General Aviation (GA) users. A constant envelope signal ensures that spectral sidelobes will not increase when the signal passes through nonlinearities such as typical of lower-cost Class C amplifiers. Furthermore, it is quite feasible to achieve a 38-dB adjacent channel interference (ACI) level with a digital, constant-envelope. frequency-shaped four-level frequency modulated (4LFM) waveform. This should be more than adequate for a dual-frequency system with judiciously as well as dynamically chosen frequency assignments.

A quaternary (symbol alphabet size of 4) digital modulation is recommended because it has roughly twice the bandwidth efficiency and the same power efficiency as binary modulations. Also, higher-order (e.g., 8-ary or 16-ary) modulations, although providing (50% or 100%) higher channel data rate, may not be required for improved ACI performance and/or may not be acceptable in terms of power efficiency, or, as in the case of non-constant envelope candidates such as 16-OQAM, desired performance in a fading environment. A total channel rate of 32 kb/s is deemed adequate for accomplishing an increased throughput of a factor of four as well as an attractive set of operational system improvements, such as emergency access and integrated voice and data, compared to the present analog voice system.

It is mostly because of these advanced system features that a digital modulation is recommended, although greater message integrity can also be obtained with digital coding techniques compared with analog voice. Non-coherent detection provides the lowest-cost option for the widest set of users. In particular, GA users will be able to better afford an investment in a new digital radio that offers data link features that ease pilot workload. In addition, non-coherent detection eases the job of synchronizing the receiver to an incoming burst of digital data; fewer synchronization symbols are required for the same level of performance. This can save precious slot-time in a Time Division Multiple Access (TDMA) system, for example (see below).

In order to satisfy real-time requirements the channel access scheme should be TDMA or something close to TDMA. Pilots and controllers contend for the analog channel today by "pushing to talk" when there is a need to communicate. Self discipline is relied upon to avoid "walking on" other talkers. Such a discipline is still implied within a "talk group" under the recommended TDMA scheme and its variants, except that the controller can be given priority over the pilots under his/her control by means of a data subchannel. In addition, by means of the subchannel, there are ways to give priority to emergency communications from the pilots, and introduce other system features.

A new channel access scheme called Distributed Reservation Multiple Access (DRMA) is currently under investigation at ARINC [7-9]. DRMA combines TDMA with Carrier Sense Multiple Access (CSMA) in an adaptive algorithm that uses CSMA for transmitting aperiodic data (under relatively light channel loading conditions), and for making reservations of future TDMA time slots as needed for periodic data (associated with heavier channel loading conditions). This hybrid scheme would effectively reduce to TDMA in times of heavy usage and/or when real-time requirements dominate.

Also, as suggested in the preceding subsection, some form of Code Division Multiple Access (CDMA), even "fast" frequency hopping, might prove to be worthwhile. This possibility would require further study, and until then, not all forms of CDMA can be rejected.

Clearly, based on past experience and other factors, any transition to a new system will be very long, and the new system must coexist with the old analog system. Therefore, it is recommended that the new digital radios be built with an embedded backward-compatible analog voice mode. In areas where there is either inadequate or no ground infrastructure, direct air-air communications may be accomplished using the old analog mode.

In order to maximize throughput and achieve a four-fold increase in voice capacity based on a new digital modulation scheme alone, it is necessary to use vocoders of no more than 4.8 kb/s data rate. As indicated in the preceding subsection, this rate appears quite promising and is generally accepted as sufficient for aeronautical use today, even though 9.6 kb/s was officially recommended for airline use in the recent past. It is fairly certain that the performance 4.8 kb/s vocoders in the presence of background acoustic noise and channel fading will improve with time. So for a long-term recommendation, 4.8 kb/s seems quite reasonable. In fact, it could very well be that 2.4 kb/s will become viable; this would mean an even higher increase in throughput which would be achievable at little or no cost to the system since the digital architecture to accommodate a lower vocoder rate would already be in place.

The last two entries in Table 4 have already been covered above.

Again, this future (target) system architecture recommendation is offered for consideration by the readers of this report, particularly those in the position of "decision maker." Readers in this category should not hesitate to contact the authors for more information on any of the above topics. If and when these recommendations change significantly, the authors plan to reissue some form of update to this report.

LIST OF REFERENCES

1. Richards, R. L., T. R. Lehnert, and L. del Cid, *Cellular-Trunked Air/Ground Radio: A Concept for Improving Aeronautical Communications*, MP-90W00017, Coordination Draft, The MITRE Corporation, McLean, Virginia, January 1991.

2. Leiter, M., R. I. Millar, J. L. Ramsey, R. D. Sakamoto, B. E. White, and W. J. Wilson, *Technical Feasibility of Digital Three-Dimensional Cellular Communications for Air Traffic Control Applications*, M91-112, Volumes 1-3, The MITRE Corporation, Bedford, Massachusetts, December 1991.

3. "Draft 3 of Project Paper 750 VHF Data Radio," Aeronautical Radio, Inc., Annapolis, MD, 14 September 1992.

4. Viterbi, A. J., and R. Padovani, *Implications of Mobile Cellular CDMA*, IEEE Communications Magazine, December 1992, pp 38-41.

5. Potter, A. R., *Implementation of PCNs Using DCS 1800*, IEEE Communications Magazine, December 1992, pp 32-36.

6. Elnoubi, S. M., and Moody, J. C., "Evaluation of a Single Frequency versus Dual Frequency Channel Structure for VHF A/G Communications," MTR-92W0000254, The MITRE corporation, McLean, VA, December 1992.

7. "Report of the VHF Data Radio (VDR) Subcommittee Meeting Held December 15-17, 1992 in San Francisco, California," AEEC Letter 93-013/VHFC-58, Airlines Electronic Engineering Committee, ARINC, Annapolis, MD, 27 January 1993, p. 2.

8. Friedman, S., Preliminary Simulation Results of a New MAC Algorithm to Mix Periodic and Aperiodic Data," Aeronautical Radio, Inc., Annapolis, MD, submitted to RTCA Special Committee (SC) -172, Working Group (WG) 2 as Working Paper (WP) 49, 28 January 1993.

9. Friedman, S., and Folz, C., "A New VHF MAC Algorithm to Mix Periodic and Aperiodic Data," Aeronautical Radio, Inc., Annapolis, MD, submitted to RTCA Special Committee (SC) -172, Working Group (WG) 2 as Working Paper (WP) 50, 28 January 1993.

GLOSSARY

ACI	Adjacent Channel Interference
AEEC	Airlines Electronic Engineering Committee
A/G	Air/Ground
ALOHA	A simple random access technique originated by the University of Hawaii
AM	Amplitude Modulation
AME	Amplitude Modulation Equivalent
AOC	Aeronautical Operational Control
A-QPSK	Aviation-Quadrature Phase Shift Keying
ARQ	Automatic Repeat Request
ATC	Air Traffic Control
ATS	Air Traffic Services
BCH	Bose-Chaudhuri-Hocquenghem
BER	Bit Error Rate
CAASD	Center for Advanced Aviation System Development
CDM	Code Division Multiplexing
CDMA	Code Division Multiple Access
CSMA	Carrier Sense Multiple Access
CTAG	Cellular Trunked Air/Ground
DRMA	Distributed Reservation Multiple Access
DSBSC	Double Sideband Suppressed Carrier
DSBTC	Double Sideband Transmitted Carrier
FAA	Federal Aviation Administration
4LFM	Four-Level FM
FDM	Frequency Division Multiplexing
FEC	Forward Error Correction
FM	Frequency Modulation
GA	General Aviation
GMSK	Gaussian Minimum Shift Keying
ICAO	International Civil Aviation Organization
IF	Intermediate Frequency
IMP	Intermodulation Product
LBPTT	Listen Before Push-To-Talk
LO	Local Oscillator
MSK	Minimum Shift Keying
MSR	MITRE Sponsored Research
N/A	Not Applicable
NBFM	Narrowband Frequency Modulation

OQAM	Offset Quadrature Amplitude Modulation
QAM	Quadrature Amplitude Modulation
QSPK	Quadrature Phase Shift Keying
RA	Random Access
RF	Radio Frequency
RS	Reed-Solomon
RTCA	Radio Technical Commission for Aeronautics (only initials, not former name, used now)
SSB	Single Sideband
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
UK CAA	United Kingdom Civil Aviation Authority
VHF	Very High Frequency
VSB	Vestigial Sideband