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Volume 1

Introduction and Summary

B. E. White

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Technical Feasibility of Digital Three-Dimensional Cellular Communications for Air Traffic Control Applications

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Bedford, Massachusetts

Department Approval: ______________________

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MITRE Project Approval: ______________________

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ABSTRACT

MITRE's Center for Advanced Aviation System Development (CAASD) has proposed a set of concepts for improving VHF communications for air traffic control applications. One idea, called CTAG for Cellular Trunked Air Ground (CTAG) communications is to extend land-mobile cellular-trunked digital communications technology to air-ground communication between pilots and controllers. This study was aimed at addressing the technical feasibility of this approach. Detailed results show that significant benefits can indeed be obtained in not only automating routine communications functions but also in reducing the number of frequency channels required compared with existing analog voice-only procedures. Further work is required to quantify potential system costs, particularly those associated with the ground portions of the CTAG network.

PREFACE

This report is subdivided into three volumes. Volume 1 is the Introduction and Summary which contains an overview of the entire report including background, requirements, assumptions, and a summary of the principal results. Volume 2 contains Example System Design Details on all but the Ground Network Architecture work. The latter is contained in Volume 3.

VOLUMES 1 AND 2 ACKNOWLEDGMENTS

This work would not have been possible without the encouragement and technical support of MITRE's Center for Advanced Aviation System Development (CAASD). Particular thanks are extended to the CTAG Project Leader, Dr. L. del Cid, J. J. Dieudonne, D. J. Chadwick, and Dr. R. M. Harris.

Other MITRE/Bedford contributors to this study and/or report, in addition to the principal authors, include R. G. Bland, C-H. Chen, R. W. Davis, T. A. Reed, D. K. Snodgrass, and K. A. Wickwire. Their contributions are gratefully acknowledged.

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SECTION 1

INTRODUCTION AND SUMMARY

1.0 INTRODUCTION

This report is divided into three volumes. Volume 1 consists of Section 1 and includes an overview of the entire project. Volume 2 includes detailed results on all tasks except those associated with the ground network architecture. The latter is contained in Volume 3.

1.1 OVERVIEW

1.1.1 Background

MITRE's Center for Advanced Aviation System Development (CAASD) has conceived a vision for improving VHF communications for Air Traffic Control (ATC) applications based largely on the notion of extending land mobile cellular concepts and technology into three dimensions [1]. CAASD asked MITRE/Bedford's Tactical 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), at a level of about 2 SY, beginning on 21 March 1991. This report documents the results of this work.

1.1.2 Bedford Activities

Bedford's several basic CTAG tasks depicted in figure 1-1 included the following:

- Construction of 3-dimensional cell structures for extending land-mobile cellular concepts into the aeronautical dimension. Three layers of different sized cells have been selected to better organize communications handover from cell to cell taking into account interference among aircraft in different altitude bands.

- Consideration of ground network interfacing includes considerations on how to interface with existing ground systems utilized in the land-mobile arena such as the Public Switched Telephone Network (PSTN). One idea is to integrate CTAG functions into various communications stations and Area Control Facilities (ACFs).

- Creation of automated frequency change and controller handover procedures to improve the organizion of in-flight communications between aircraft crews and ground controllers to ease workloads both in the air and on the ground.

- Examination of multiple access techniques of various types, viz., TDMA, FDMA, and CDMA spread spectrum) for their applicability in terms of increasing the useful throughput of a 25-kHz channel while providing desirable functional capabilities such as reliable connectivity, situational awareness, multiple-addressing, etc. The sketch denotes a TDMA approach that has been worked out where aircraft do not require full-duplex radios while still providing full-duplex communications.

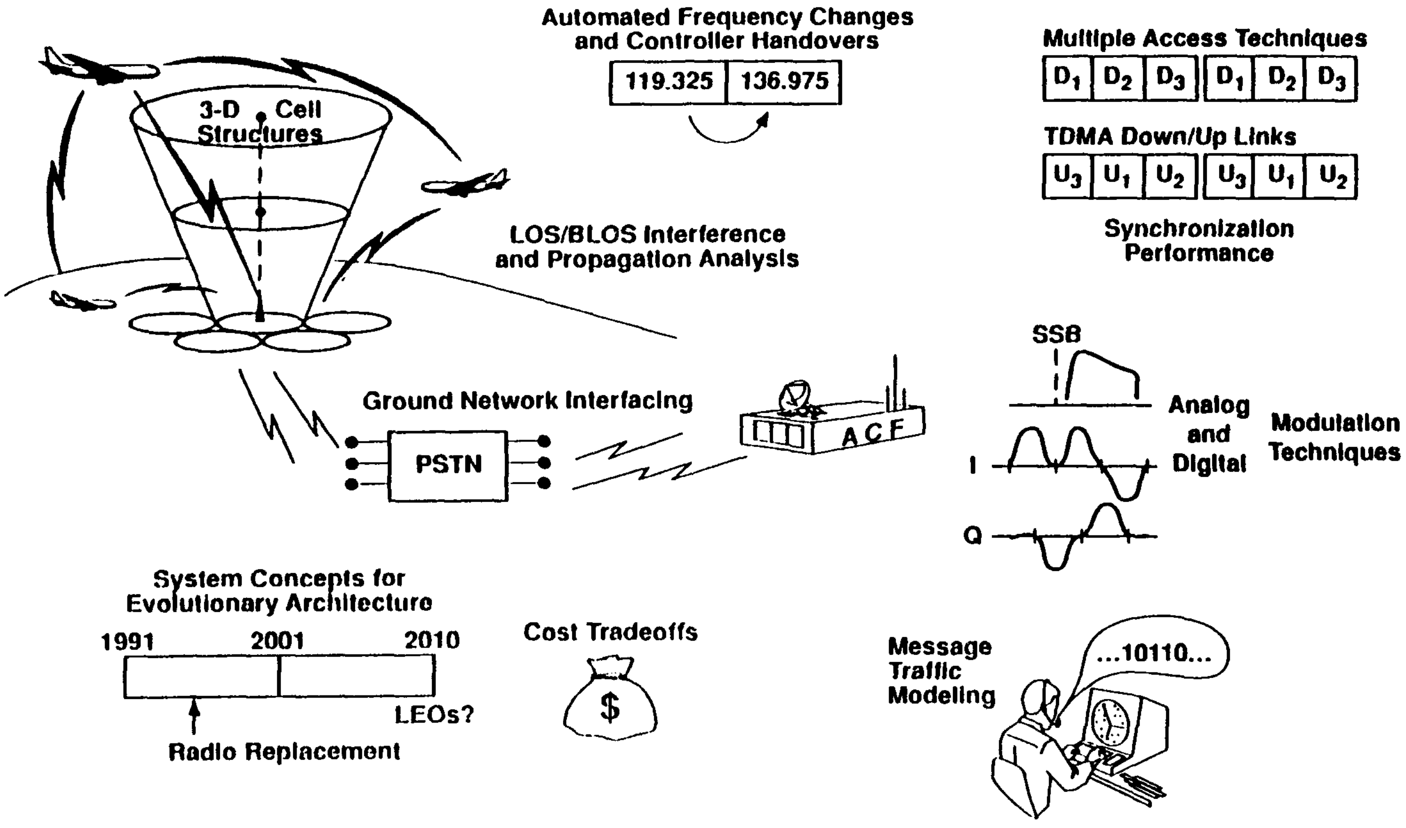


Figure 1-1. Bedford Activities on CTAG MSR

- Review of modulation techniques for applicability in both the short and long term. The future trend is to digital modulation (and coding), of course. Nevertheless traditional analog modulations are being considered for near-term radio replacement to the extent that this does not jeopardize a cost-effective evolution to the desired target system of the far term.
- Modeling of message traffic has produced an indication of expected communications traffic loads at a good-sized airport like Logan International in Boston. This will be useful in analyzing ways of employing data links to supplant voice communications of a routine nature.
- Conduct of detailed propagation analysis of both line-of-sight (LOS) and beyond LOS (BLOS) interference. A few standard propagation models available on our computers are being utilized and checked with respect to each other. The results will be used to determine whether the cell sizes selected in the 3-dimensional structure are really appropriate.
- Calculation showing that there are sufficient bits for reliably accomplishing synchronization in the TDMA scheme proposed.
- Contributions to CAASD efforts to show a reasoned, evolutionary and cost effective approach to improving ATC VHF/UHF communications.

1.2 OBJECTIVES/REQUIREMENTS

At a joint kick-off meeting of the CTAG CAASD/Bedford team, a working set of objectives and requirements for the study were defined [2]. Those that significantly impacted the work are summarized here.

The target users of the CTAG system constitute approximately 5000 commercial aircraft and about 200,000 general aviation (GA) aircraft. The Bedford team decided to emphasize the GA application in order to guide the design in the direction of a minimal cost airborne radio affordable to that large class of user. By attacking the potential mass production market at the low end of the cost spectrum, there may be cost benefit fall-out to the commercial market, as well. In the meantime the commercial user, particularly the airlines, will continue to field systems filling their own needs, almost regardless of what others do to influence this market. However, it is not clear that the GA user will buy systems developed solely from airline use.

Without changing fundamental ATC operational procedures involving pilots and controllers, one major objective of the CTAG system is to provide a means of automating frequency changes and controller handovers. Presently, these functions are accomplished at a human level entirely through voice communications over analog radios. Much of the ATC voice communications today are of a routine coordination nature solely for the purpose of setting up the appropriate frequency channels to conduct meaningful communications, even though there may be no need to actually communicate. Frequency assignments can change one or two dozen times even on a relatively short flight. In CTAG, controllers will still control these operations through positive action but the workload will decrease since they will be able to substitute voice instructions by "pushing a button" well in advance of the enactment of the these operations through positive action but the workload will decrease since they will be able to substitute voice instructions by "pushing a button" well in advance of the enactment of the actual frequency change or controller handover. Both the controller and the affected pilot would receive confirmation through some means, audible tone and/or radio console indication, that the change or handover has occurred. Normal voice communications would still be available for emergencies and the usual operational procedures, of course.

A goal of CTAG is to at least double the throughput currently available, i.e., one voice signal, in a 25 kHz channel allocation. Capacity could further expand to the extent that three or four voice signals can be packed into a single channel while still maintaining acceptable interference levels and providing existing or desirable operational features.

The ultimate (target) system should be digital to better realize greatly improved link reliability and be able to interoperate in a modern networking environment in concert with evolving interface standards. Backward compatibility with the existing system should be maintained during a periods of transition which undoubtedly will be very long. Presently, there are sufficient frequency allocations to accommodate the coexistence of CTAG with the older system. In the future, this excess capacity may be absorbed by growth in air traffic and its associated communications. As MITRE's Dr. Barry M. Horowitz has pointed out, there may not be that much time to accomplish this orderly transition if CTAG is delayed.

The new digital radio must be affordable to users. Unless CTAG radios for GA application are available for about $3K or less, there would probably be very few purchasers. Even with a cost of a couple of thousand dollars, the GA user will need to receive sufficient benefit from the CTAG system or he will keep what he already has. Airlines can afford more but will also expect more increase in capability. The $15-45K estimate for commercial and business aircraft radios should drop to the extent that CTAG is successful in providing affordable radios for GA. In other words, the airlines could benefit not only from the CTAG technical characteristics but also the corresponding technology made available for the GA user.

It is desirable to retain the push-to-talk (PTT) operational capability of the existing ATC VHF communications system. To avoid significant clipping of speech, 100 ms or so signal acquisition time is a good goal. This should not be considered a specification but more of a design guide. As will be seen later in the suggested time division multiple access (TDMA) example design, the 100 ms frame was chosen to be compatible with this delay objective. The technical communications system, CTAG, including its access and protocol schemes whatever they end up being, should not be the limiting factor in achieving effective end-to-end communications between the pilot and controller.

Naturally, CTAG should be designed to integrate well with the ATC infrastructure including all air-air (A-A), air-ground (A-G), and ground-ground (G-G) communications.

Various features such as situation awareness ("party line") should be retained at the option of the user, and new features such as group addressing, call waiting/emergency notification, etc., should be added as enhancements. The significant problem of the "stuck microphone" in today's system should also be eliminated. There are several straightforward ways to accomplish this in CTAG.

1.3 TECHNOLOGICAL/DESIGN ISSUES

Several of the more important issues to be addressed in this study are listed here. Basically, the focus is on technical feasibility of the CTAG concept which is to extend the land mobile cellular concept into three dimensions.

1.3.1 Single Channel vs. Spread Spectrum

One possibility to be considered is the use of code division multiple access (CDMA) utilizing spread spectrum (SS) techniques. This has the potential advantage of not requiring additional frequency allocations in that the power spectral density of the SS signal may be sufficiently small the it can overlay on the signals of other systems without causing undue interference. Two questions are: 1) whether there is sufficient bandwidth in the VHF ATC frequency allocations to provide enough processing gain to combat cochannel interference; and 2) whether the frequency management authorities would grant approval for SS use in these ATC (or other) bands.

1.3.2 Time vs. Frequency Division Multiple Access

There was a starting bias toward TDMA over FDMA for it is felt that less equipment is required and that there will be less interference with TDMA compared with FDMA. This was examined and confirmed.

1.3.3 Propagation Considerations

A key issue is the question of the rate of BLOS propagation attenuation to permit frequency reuse at suitable ranges over the horizon as seen from high altitude aircraft. Multipath effects and the possibility of ducting at VHF over long distances were to be examined. During the course of the work, several well known propagation models were applied and the effects of multipath, diffraction and tropospheric scattering were all taken into account. There was no specific effort addressed to ducting because the strategic system design decision of separating the aircraft uplinks from the downlinks to avoid A-A interference essentially obviates the ducting threat.

1.3.4 Doppler Shift

Obviously, CTAG must accommodate Doppler frequency shifts without difficulty. Computed as the ratio of relative speed to wavelength, Doppler shift is typically rather small, e.g., 137 Hz for a Mach 1 aircraft (traveling 300 m/s) and communicating on a frequency (137 MHz) at the high end of the ATC band. A simple phase tracking loop is adequate to handle such Doppler shifts in conventional digital receivers so Doppler will be of little concern in this respect.

1.3.5 Cochannel and Interchannel Interference

In the cellular concept several users may be operating on the same channel or frequency allocation. This is inevitable to some extent since frequencies are being reused to conserve spectrum. It is important to estimate how far down in received power the cochannel interference must be to permit acceptable overall system performance. Interchannel interference between adjacent 25 kHz frequency allocations is also important. Both of these potential error mechanisms lead to the need for good digital modulation and coding schemes that provide sufficient spectrum roll-off and error recovery. In addition, of course, better receiver design can mitigate various forms of interference.

1.3.6 Modulation and Coding

The future clearly lies with digital rather than analog modulation. Digital modulation and coding techniques have a much greater capability for providing reliable links, alternate routing/networking, and the incorporation of features impossible to contemplate in a strictly analog system. An in-phase and quadrature scheme is preferred since to first order this doubles the capacity over using just the in-phase channel, for example, as in binary phase shift keying (BPSK). Beyond that there are many well-known modulation and coding schemes from which to select a CTAG waveform. The principal factors in selecting the preferred scheme are robustness of performance in the ATC channel and simplicity of implementation to contain the cost.

1.3.7 Networking Scheme

Communications connections between pilots and controllers may give rise to both an airborne and a ground network. The topology is a function of the airborne systems, the cellular structure (cell sizes, altitude bands handled by the cell layers, and frequency reuse alternatives), the ground network architecture, and the other systems with which CTAG must interoperate or interface. End-to-end message delivery time must be acceptable in any environment but must be rather short, negligible compared to human decision time, in ATC for air traffic safety. Is there a CTAG design that can accommodate such a criterion, use the existing ground (cellular) network, and still be compatible with Open Systems Interconnection (OSI) model? If not, special effort should be initiated to consider alternatives, as in the case with AMSS for periodic ADS reports [3].

1.4 ASSUMPTIONS/CONSTRAINTS

Only the key assumptions and constraints established during the project's kickoff meeting are listed here. Each of these has had a definite influence on the work.

1.4.1 Frequency Bands of Operation

The CTAG radios should be tunable over the following portions of the VHF band: 118-137 MHz (transmit and receive) and 108-117.975 MHz (receive only) even though actual CTAG operation is anticipated only in the allocated ATC subbands shown in figure 1-2. If upon further study it appears that SS/CDMA is an attractive alternative for CTAG, there is

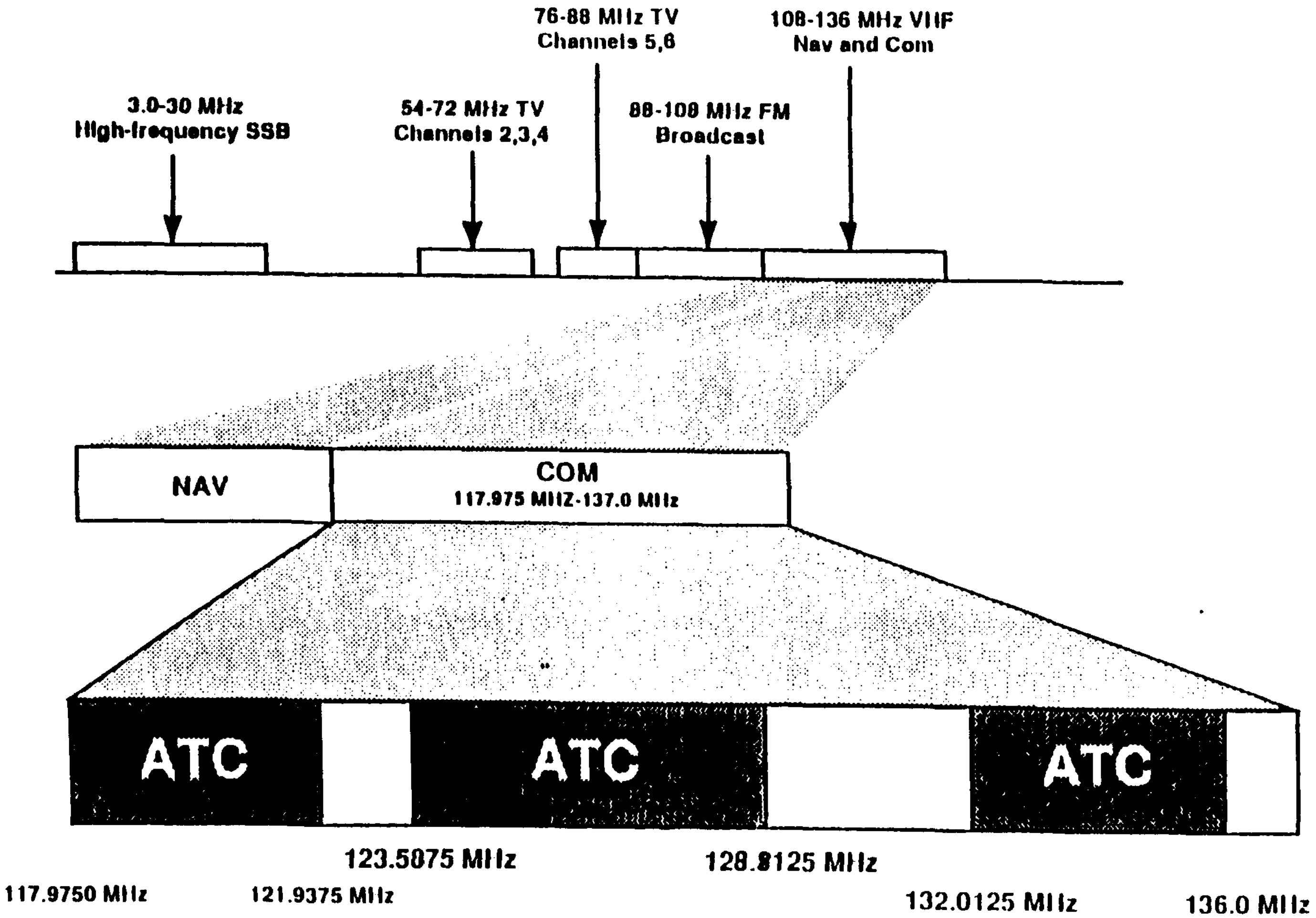


Figure 1-2. ATC Radio Spectrum

some possibility that there would be a recommendation to consider spreading outside the allocated ATC subbands. Perhaps this would even include the entire 108-137 MHz band, if it can be established that this would not cause undue interference to other systems.

1.4.2 Channel Allocations

A fundamental assumption in this study is the existence of 25 kHz frequency allocations. However, CTAG must coexist with the present system which includes many radios that still operate on 50 kHz centers. In addition, there was to be some evaluation of the European proposal to subdivide the present 25 kHz center structure to operate on 12.5 kHz allocations. Funding limitations and relative priorities precluded this; this is not a simple issue, since transceivers may need to be redesigned to accommodate a closer spacing.

Operation at 12.5 kHz channel spacings would obviously require more stringent frequency stability and bandwidth emission standards to maintain acceptable performance levels for interchannel interference. Although this might be possible utilizing improved AM (e.g., single side band (SSB)) radios, this is not recommended for a couple of reasons. Namely, 1) many users have not yet even transitioned to 25 kHz centers since there has not been sufficient motivation to do so; and 2) increases in capacity with digital schemes can be obtained very readily without resorting to another subdivision of the frequency band.

1.4.3 Digital Voice Rate

Even though the current generally accepted minimum data rate for vocoded speech that provides adequate speaker recognition (and intelligibility) is 9600 b/s, it is assumed that 4.8 kb/s vocoders will be available soon, if they are not already, that can perform nearly as well. One example under consideration is the Code Excited Linear Prediction (CELP) device [4].

Naturally, it is important to preserve the emotional content dimension of a speaker's voice. This is particularly true in emergency situations. There is still some question as to the ability of 4.8 kb/s devices to accomplish this. Future work may resolve this issue. In any event, the voice throughput/capacity results in this effort are based on this lower rate (4.8 kb/s) assumption.

1.4.4 Aeronautical Telecommunications Network

CTAG is intended to be compatible with the Aeronautical Telecommunications Network (ATN) standards currently under development within the ATC community. CTAG fits under the VHF communications portion of ATN, the other two aspects being Mode S and satellite communications.

CTAG should be compatible with the International Standards Organization (ISO) OSI seven layer reference model. In addition to providing a good foundation for interoperability within ATN, there is a much better possibility that CTAG would become accepted internationally if this model is used.

The implications of this desire have not yet been fully appreciated in this study. There are potentially some overhead penalties in throughput depending on to what extent CTAG reaches into the upper layers of the OSI model. The CTAG concepts analyzed thus far are mainly at the two lowest layers, viz., the Physical and Data Link layers.

1.4.5 Radio Technology

In the interests of having no restraints on the international applicability of CTAG nor on the availability of proven off-the-shelf (OTS) and commercial/consumer technology, the equipment utilized in CTAG should be "exportable," and "importable" for that matter.

1.4.6 ATC Procedures

To the extent possible CTAG operations must be in accordance with (IAW) existing ATC procedures. However, with the availability of data links, including CTAG which has significant data link capabilities, one should be mindful of suggestions for operating differently but in a more efficient and effective manner. There may be great savings in pilot and controller workloads, system efficiency, performance improvements, etc., without any sacrifice in air traffic safety, by operating with more innovative ATC procedures that take advantage of data link capabilities. For example, in a digitized communications system such as CTAG, one does not necessarily want to simply replicate on the new digital channel the current voice procedures for accomplishing routine frequency changes and controller handoffs.

1.5 SUMMARY OF RESULTS

The remainder of this section provides a synopsis of the technical results obtained during the study. First modulation and coding considerations and the implications on airborne and ground radio implementations and their estimated costs are described. A discussion of SS/CDMA follows. Then the results of a traffic model analysis for the Boston Center (New England and Logan International airport) are presented. The three-dimensional (3-D) cellular model and its associated propagation analysis is described next. Operational procedures that provide the basis of the TDMA design example and the ground network architecture are mentioned. A specific TDMA approach to CTAG and an alternative but analogous FDMA scheme are described. Finally, the rudiments of a CTAG ground network with sufficient capacity to handle heavy and critical communications traffic is outlined.

1.5.1 Modulation and Coding

Part of the CTAG modulation and coding study effort was devoted to considering analog modulations that are improved compared to the standard double side band transmitted carrier (DSBTC) method used widely today. Although it seems clear that digital schemes will be used eventually, there is an opportunity to modernize ATC radios within the next few years. There is some possibility that an improved analog radio with more capable RF hardware equivalent to that of a target digital radio would be of interest as an evolutionary option. Such a radio, which would have greater frequency stability, better filter characteristics, more linearity, etc., could be built to be able to accommodate field modification to add digital modules at a later date. Nevertheless, emphasis was placed on digital techniques.

The criteria used for comparing various modulation and coding methods include: 1) capacity; 2) bandwidth and power efficiency; 3) resistance to co-channel and interchannel interference; 4) performance in channels with Doppler shift, fading, etc.; 5) amenability for feature enhancement; 6) design complexity; and 7) relative cost.

Various schemes are compared quantitatively, or at least semi-quantitatively, assuming: 1) coherent or non-coherent receivers; 2) uncoded or coded; 3) practical implementation losses or theoretical ideal performance; 4) additive white Gaussian noise (AWGN) or fading channel; etc.

1.5.1.1 Analog Modulation Techniques

A number of well known analog modulation techniques were reviewed and compared, at least semiquantitatively, for the CTAG application. The results are shown in table 1-1; the reader is referred to subsection 2.1 for details.

1.5.1.2 Digital Modulation Techniques

More extensive review and analysis of uncoded digital modulation tehcniques were performed. Results are shown in tables 1-2 and 1-3 for coherent and non-coherent detection techniques using the system noise bandwidth definition as a criterion (see subsection 2.2).

1.5.1.3 Digital Coding Techniques

Recent analysis condensed into tables 1-4 and 1-5 has provided a comparison of these digital modulations with specific coding schemes to give indications of how the power efficiency can be improved and at what expense in bandwidth efficiency. See subsection 2.3 for more detail

1.5.2 Radio Implementations and Cost Estimates

The technical approach to obtaining rough cost estimates of CTAG radios was as follows. A block diagram of the standard AM (DSBTC) radio was developed and costed using sample cost information on existing subsystem components available from typical manufacturers and the FASTE cost model [5] available within the cost center (D093) at Bedford. Perturbations to the baseline block diagram were then proposed for each of several improved modulation schemes which highlighted which components would be different. The relative complexity and size of these components were then estimated and the cost model applied. The modulations chosen, listed in order of their estimated cost in 1991 dollars, were:

- Standard AM - $1200
- Narrowband AM (more stable oscillator, improved selectivity filters, etc.) - $1600
- Gaussian MSK (minimum shift keying) - $2500
- Aviation QPSK (quadrature shift keying) - $2800
- SSB (single side band in addition to the above improved narrowband AM) - $3300
- 16-QAM (quadrature amplitude modulation) - $3800

Table 1-1. Semi-Quantitative Comparison of Several Well-Known Analog Modulations

Analog Modulation Technique	# Voice Channels /25 kHz	Doppler Tracking Reqmnts	Power Efficiency Relative to DSBSC	Minimum S/I or C/I Required	Design Complexity	Conferencing Ability	Multipath Performance
DSBTC	2 to 2.5	none	poor -5 to -10 dB	high 20 dB	simple	audible carrier heterodyning	fair
DSBSC	2 to 2.5	Costas loop accurate phase	good 0 dB	moderate ~ 15 dB	Costas loop phase tracker linear Tx/RX	Doppler distortion	fair
QAM	4 to 5	Costas loop accurate phase	good 0 dB	moderate ~ 15 dB	Costas Loop phase tracker linear Tx/Rx	quadrature distortion	fair
SSB	4 to 5	pilot tone carrier error <20 Hz (voice)	good -1 dB	moderate ~ 16 dB	stable osc. tracking loop linear Tx/Rx	quasi-linear w/o different Dopplers	fair
VSB	3 to 4	pilot tone low audio frequencies	good -1 dB	moderate ~ 16 dB	stable osc. tracking loop linear Tx/Rx	quasi-linear w/o different Dopplers	fair
FM	1	none	excellent 8 dB	low 10 dB	simple const. env. Tx	distortion or surpression of weaker signal	very good
NBFM	2	none	good -1 dB	moderate ~ 15 dB	simple const. env. Tx	distortion and less surpression of weaker signal	good

DSBTC — Double Side Band Transmitted Carrier
DSBSC — Double Side Band Surpressed Carrier
QAM — Quadrature Amplitude Modulation
SSB — Single Side Band
VSB — Vestigial Side Band
FM — Frequency Modulation (28 kHz)
NBFM — Narrow Band FM (10 kHz)

S/I — Signal to Interference ratio
C/I — Carrier to Interference ratio
Tx — Transmitter
Rx — Receiver

Table 1-2 Quantitative Comparison of Several Advanced Digital Modulations

(Additive White Gaussian Noise)

Digital Modulation Technique	Spectral Compactness * Normalized to Rb**	Bandwidth Efficiency (b/s/Hz)	Power Efficiency Eb/No(dB) for BER 10-2	10-4	10-6	Detection Scheme
MSK	0.62	1.6	4.3	8.4	10.5	coherent
GMSK (BT=0.25)***	0.5 - 0.62	2.0 - 1.6	6.4	10.0	12.0	coherent
A-QPSK****	≤ 0.5	≥ 2.0	5.1	9.2	11.3	coherent
π/4-QPSK	0.5	2.0	4.3	8.4	10.5	coherent
8-FSK	1.33	0.75	4.0	7.3	9.2	coherent
16-PSK	0.25	4.0	11.4	16.0	18.8	coherent
8-PSK	0.33	3.0	7.3	11.7	13.9	coherent
BPSK	1.0	1.0	4.3	8.4	10.5	coherent
4-OQAM	0.5	2.0	4.3	8.4	10.5	coherent
16-OQAM	0.25	4.0	7.8	12.2	14.4	coherent
16-QAM	0.25	4.0	7.8	12.2	14.4	coherent

---

* All based on the noise bandwidth defined by $B_o = [1/G(0)] \int_0^{\infty} G(f)df$, where G(f) is the power spectral density of the modulation waveform, except for the 8-FSK which is based on the frequency separation for orthogonality.

** Rb = bit rate, 8 kb/s.

*** B is the 3 dB bandwidth of the Gaussian filter and T is the bit duration

**** Aviation QPSK

Table 1-3. Quantitative Comparison of Several Advanced Digital Modulations

(Additive White Gaussian Noise)

Digital Modulation Technique	Spectral Compactness * Normalized to Rb**	Bandwidth Efficiency (b/s/Hz)	Power Efficiency Eb/No(dB) for BER			Detection Scheme
			10-2	10-4	10-6	
MSK	0.62	1.6	8.1	11.5	13.6	Limiter/ Discriminator
GMSK (BT=0.25)***	0.5 - 0.62	2.0 - 1.6	8.7	13.6	15.9	Limiter/ Discriminator
A-QPSK****	≤ 0.5	≥ 2.0	7.6	11.6	13.7	Phase comparison
π/4-QPSK	0.5	2.0	6.8	10.8	12.9	Phase comparison
8-FSK	2.67	0.38	5.2	8.2	9.9	Noncoherent
16-PSK	0.25	4.0	14.2	19.2	21.1	Phase comparison
8-PSK	0.33	3.0	10.2	14.6	17.6	Phase comparison
BPSK	1.0	1.0	5.9	9.3	11.2	Phase comparison

* All based on the noise bandwidth defined by $B_o = [1/G(0)]\int_0^\infty G(f)df$, where G(f) is the power spectral density of the modulation waveform, except for the 8-FSK which is based on the frequency separation for orthogonality.

** Rb = bit rate, 8 kb/s.

*** B is the 3 dB bandwidth of the Gaussian filter and T is the bit duration

**** Aviation QPSK

Table 1-4 Quantitative Comparison of Several Advanced Digital Modulations

(Additive White Gaussian Noise)

Digital Modulation Technique	Uncoded Spectral Compactness * Normalized to Rb**	Rate 1/2 Coded Bandwidth Efficiency (b/s/Hz)	Power Efficiency Eb/No(dB) for BER = 10-6		Detection Scheme
			No coding	Coding+	
MSK	0.62	0.8	10.5	7.1	coherent
GMSK (BT=0.25)***	0.5 - 0.62	1.0 - 0.8	12.0	9.1	coherent
A-QPSK****	≤ 0.5	≥ 1.0	11.3	7.9	coherent
π/4-QPSK	0.5	1.0	10.5	7.1	coherent
8-FSK	1.33	0.38	9.2	6.8	coherent
16-PSK	0.25	2.0	18.8	14.1	coherent
8-PSK	0.33	1.5	13.9	10.2	coherent
BPSK	1.0	0.5	10.5	7.1	coherent
4-OQAM	0.5	1.0	10.5	7.1	coherent
16-OQAM	0.25	2.0	14.4	12.5	coherent
16-QAM	0.25	2.0	14.4	12.5	coherent

---

* All based on the noise bandwidth defined by $B_o = [1/G(0)]\int_0^{\infty} G(f)df$, where G(f) is the power spectral density of the modulation waveform, except for the 8-FSK which is based on the frequency separation for orthogonality.

** Rb = information bit rate, 8 kb/s.

*** B is the 3 dB bandwidth of the Gaussian filter and T is the information bit duration

**** Aviation QPSK

\+ Viterbi convolutional coding, rate 1/2, constraint length 7, hard decisions

Table 1-5 Quantitative Comparison of Several Advanced Digital Modulations
(Additive White Gaussian Noise)

Digital Modulation Technique	Uncoded Spectral Compactness* Normalized to Rb**	Rate 1/2 Coded Bandwidth Efficiency (b/s/Hz)	Power Efficiency Eb/No(dB) for BER = 10-6		Detection Scheme
			No coding	Coding+	
MSK	0.62	0.8	10.5	7.1	Limiter/ Discriminator
*** *GMSK (BT=0.25)*	*0.5 - 0.62*	*1.0 - 0.8*	12.0	9.1	Limiter/ Discriminator
A-QPSK****	≤ 0.5	≥ 1.0	11.3	7.9	Phase comparison
π/4-QPSK	0.5	1.0	10.5	7.1	Phase comparison
8-FSK	1.33	0.19	9.2	6.8	Noncoherent
16-PSK	0.25	2.0	18.8	14.1	Phase comparison
8-PSK	*0.33*	*1.5*	*13.9*	*10.2*	*Phase comparison*
BPSK	1.0	0.5	10.5	7.1	Phase comparison

---

* All based on the noise bandwidth defined by $B_o = [1/G(0)]\int_0^{\infty} G(f)df$, where G(f) is the power spectral density of the modulation waveform, except for the 8-FSK which is based on the frequency separation for orthogonality.

** Rb = information bit rate, 8 kb/s.

*** B is the 3 dB bandwidth of the Gaussian filter and T is the information bit duration

**** Aviation QPSK

+ Viterbi convolutional coding, rate 1/2, constraint length 7, hard decisions

Without placing too much stock in the absolute values, note that the range of the relative cost estimates is approximately 2.4:1 from the simplest analog upgrade to the most complex digital radio currently contemplated. Each user in the GA community would need to perform some sort of cost benefit analyze to decide whether he should invest in a CTAG radio upgrade. Even if the lowest cost improved AM radio was an available option, it is not yet obvious that this hypothetical user would be willing to spend in the neighborhood of $1500 for a new radio provided his current radio was still operating satisfactorily!

Ground radios were also costed using similar methods for the same modulations. Without the linear power amplifier for generating 50 W which probably is not required for this application, the range of relative costs was again about 2.4. However, absolute values were higher by a factor of about 15. This appears to be too high and bears further investigation.

1.5.3 Spread Spectrum Multiple Access

Initially it was felt that there was insufficient bandwidth in just the few MHz of an allocated ATC subband to provide enough processing gain to overcome the "near-far" problem of the SS/CDMA alternative. This problem arises because of the rather large range ratio (range of one a/c compared to another aircraft relative to the same ground station) that could be encountered in any A-G communications system. Since every SS signal occupies the same subband, the interfering signals from closeby aircraft could overwhelm the desired signal in the ground receiver, for example.

However, upon more careful analysis, it appears that if a combination of adaptive power control and receiver antenna nulling is incorporated, then there would be sufficient processing gain to support up *to eight simultaneous user signals* in a single CTAG cell. The processing gain assumed is 24 dB = 2 MHz (SS bandwidth)/8 kb/s (channel data rate). This 2 MHz spreading limit allows some guard band for minimizing potential interference in other VHF subbands outside a 4 MHz ATC allocation. Much more work would be required to ascertain the viability of SS/CDMA for this application, so this is a potential issue for future funding.

1.5.4 Voice Message Traffic Model

The Boston Center was selected as a logical candidate to study in gaining some additional first hand knowledge of present practice involving voice message traffic within a medium sized ATC region. The Nashua, New Hampshire en route control center and the Manchester, New Hampshire TRACON were both visited by the Bedford study teams. In addition, Logan International Airport communications traffic was monitored on an *ad hoc* basis, and conversations were held with several experienced pilots and controllers. Of course, much existing relevant documentation containing information on which a message traffic model can be built was also reviewed. Particularly useful were CAASD's WP-90W00559 (February 1991) [6] and the FAA Airport/Facility Directory - Northeast U.S., FAA, April 1991 [7].

The voice message traffic model developed provides estimates of the average number of message exchanges and their average durations during peak periods of aircraft traffic both en route and in the largest terminal area (arrivals and departures at Logan). Flight Service Stations and overflights at Logan, which constitute a small fraction of total message or aircraft traffic, are ignored in this model. More data is required to model the non-Poisson distributed message generation times within a peak period.

A terminal controller typically uses one fixed frequency. An en route controller uses 1 to 3 low altitude and 1 to 3 high altitude frequencies but in either case 1 frequency is most likely. Exchanges are bimodal with call and response lengths about equal (totalling approximately 6 s and 20-30 s, respectively).

Terminal and En Route Voice Message Traffic is characterized in figures 1-3 and 1-4 respectively. The voice message traffic loading is shown in table 1-6. The estimated quantities are mostly self explanatory; Logan is the "largest airport", and the number of remotes refers to the communications facilities typically remoted from the TRACONs or terminals. Using the results depicted in figures 1-3 and 1-4, the calculated quantities show that the voice message traffic loading can be quite heavy during peak periods. Based on average statistics note that the duty factor of a communications channel is as high as about 50% since exchanges are typically 6 s long.

Table 1-6 Voice Message Traffic Loading

Quantity (Estimated)	**Terminal**	**En Route**
Duration of peak period of aircraft traffic	2 to 4 hours	2 to 4 hours
Number of flights during peak	250	2200
Number of flights handled by largest airport	175 (70%)	--
Number of control frequencies	9	61
Quantity (Calculated)		
Average number of exchanges per flight	27 (11 departing + 16 arriving)	16 (N = 5)
Average number of exchanges per frequency	525 (175 x 27/9)	577 (2200 x 16/61)
Average time between calls	13.7 to 27.4 s (7200 to 14,400/525)	12.5 to 25.0 s (7200 to 14,400/577

From data readily available [8] it is estimated that there are about 100 controllers on duty during the busy hour in the Boston Center. This is divided between about 50 en route controllers and 50 terminal area controllers distributed among the 13 TRACONs and RAPCONs in New England.

1.5.5 Three-Dimensional Cellular Solution

The extension of the land mobile cellular concept into the third dimension where airplanes fly is the cornerstone of the CTAG approach. Naturally it is crucial that this generalization be technically feasible, for it is not obvious that land mobile type communications will work without undue interference since A-A and A-G signals propagate great distances with a LOS

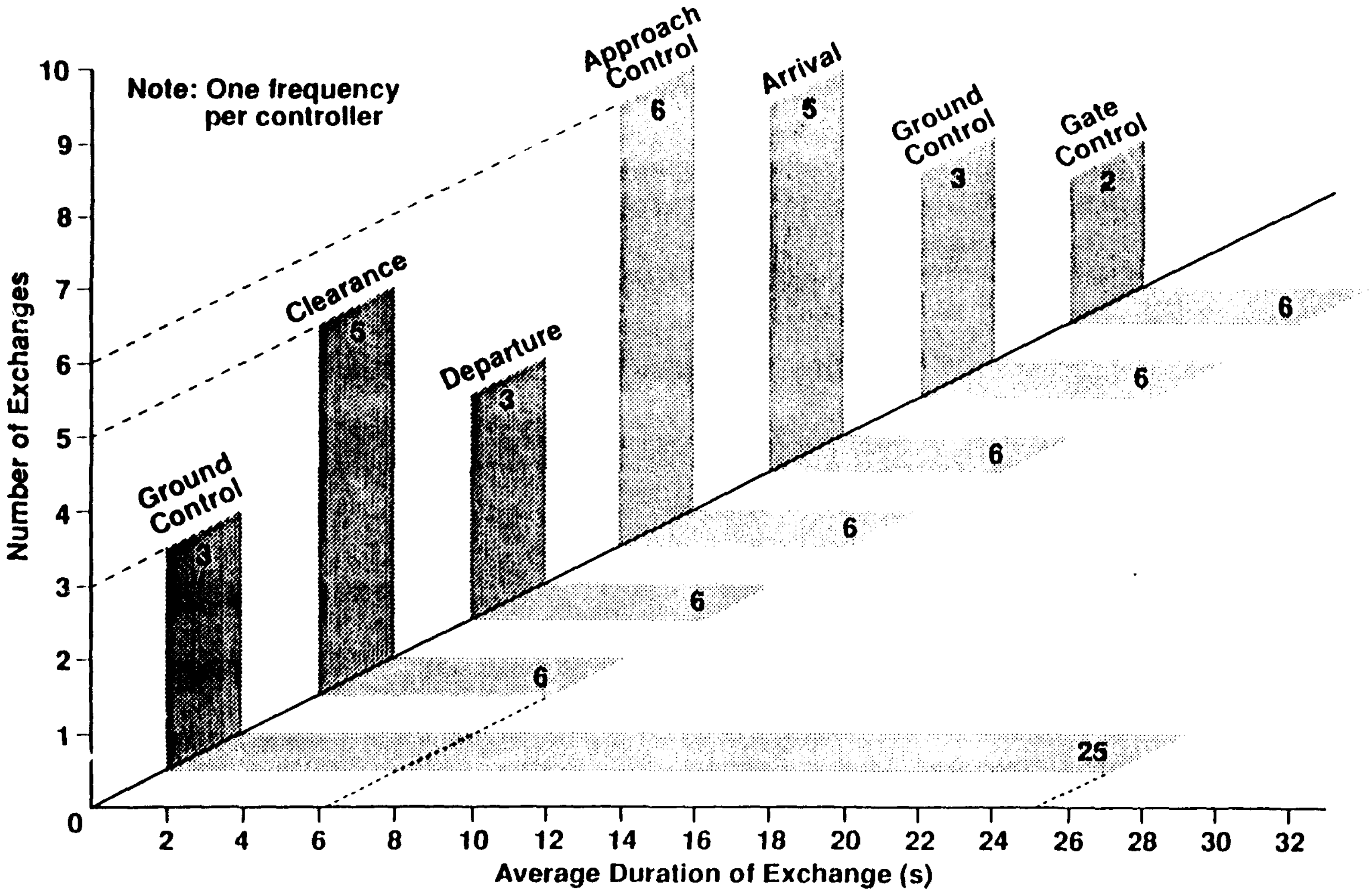
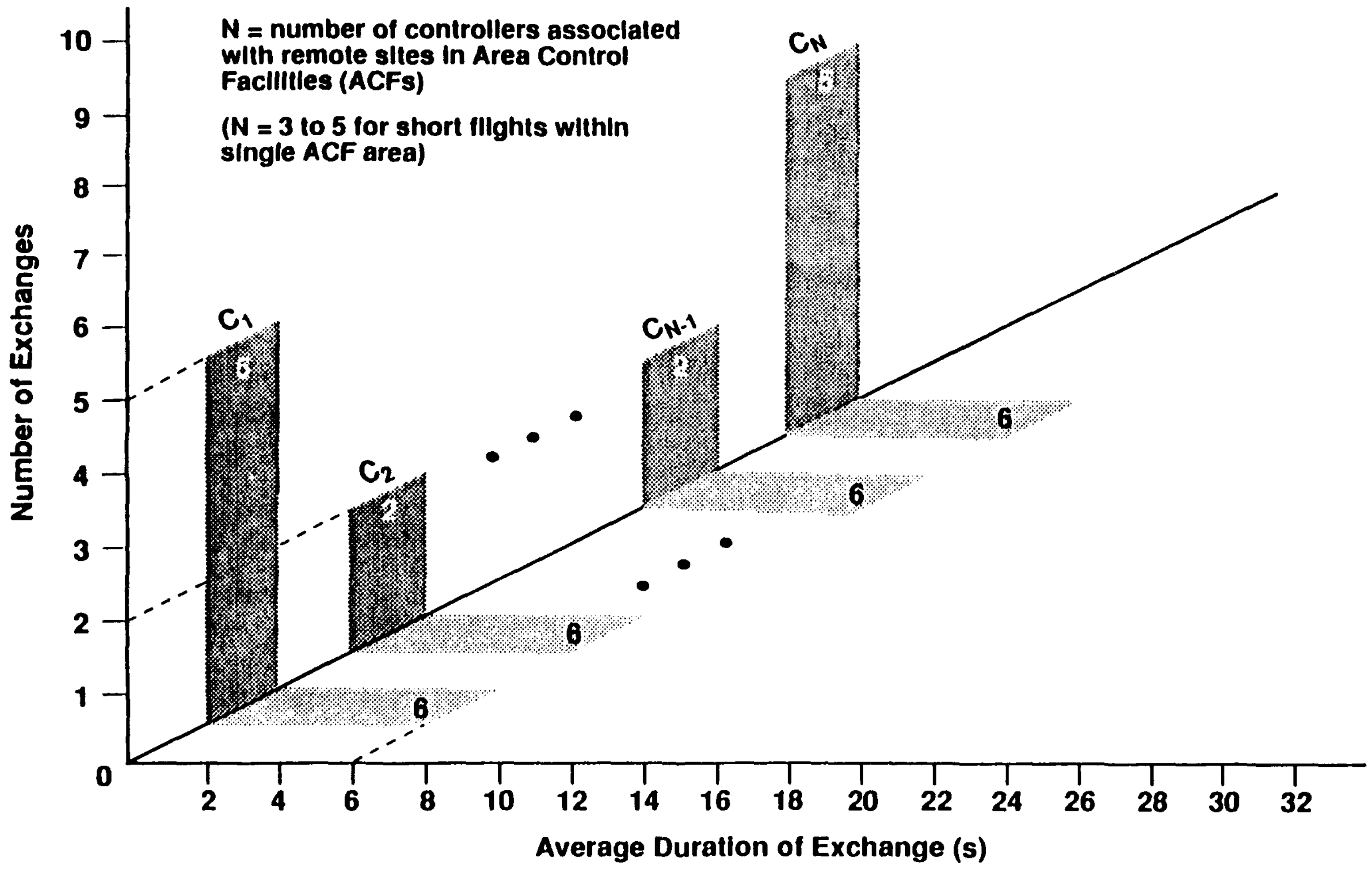


Figure 1-3. En Route Voice Message Traffic



Notes: One to three low altitude and one to three high altitude frequencies per controller

N = number of controllers associated with remote sites in Area Control Facilities (ACFs)

(N = 3 to 5 for short flights within single ACF area)

Figure 1-4. Terminal Voice Message Traffic attenuation that is proportional to only the inverse square of the range. In the land mobile environment, of course, signals are beyond BLOS at much shorter ranges; there they are attenuated much more rapidly, typically proportional to the inverse fourth power of range.

The issues addressed included cochannel interference, propagation phenomena, frequency reuse, and path redundancy. The relevant parameters are the size(s) of the cells, the definition of altitude bands associated with different cell layers, the number of cells in the same layer which separate cells using the same frequencies, and the number of frequencies that need to be scanned to determine the cell location. In devising a practical solution several characteristics evolved.

First the uplink and downlink frequencies were chosen to be distinct to simplify the A-A interference problem. It can be shown that without this assumption, which requires twice the number of allocated frequency channels compared to a land mobile system where a two-way conversation takes place on the same frequency, at least four times the number of frequencies would be required. This follows because the maximum LOS distance doubles with A-A communications compared with A-G communication, and since the number of distinct frequencies required is proportional to the square of this distance.

Secondly, A-A connectivity among aircraft under control of the same controller is maintained by ground relay through that controller. Thus situation awareness by the pilots is preserved should they want to listen to conversations between the controller and other aircraft in the vicinity.

Thirdly, a capability for independent dual coverage redundancy is afforded by the fact that any aircraft is always within LOS of at least two different towers located in different cells. This enhancement to channel availability leads to a triangular shaped structure of cells in contrast to the usual hexagonal shaped patterns.

The multiple coverage is illustrated in figure 1-5. Here the shaded regions indicate areas of triple coverage, i.e., an aircraft in this region can see three different towers instead of only two. The traditional hexagons are unnecessary and are only included for reference.

Finally, in order to cover all altitudes spanning 2000 ft to 70,000 ft, three layers of cells are required. Below 4500 ft altitude aircraft operate with cells which have a "radius" of approximately 40 nmi (distance between the center of the triangle and one of its vertices). About 1300 such cells would cover the U.S. including Alaska; about 1100 would cover CONUS. Between 4500 ft and 18,000 ft the cell radius doubles to about 80 nmi. There are about 325 of these cells, one-fourth the number of the smallest cells. Above 18,000 ft the size of the cells again approximately doubles to about 160 nmi radius and the number of cells is reduced by a factor of four to about 81.

The nesting of the three different sized triangles is shown in figure 1-6, where the hexagons are also included for reference.

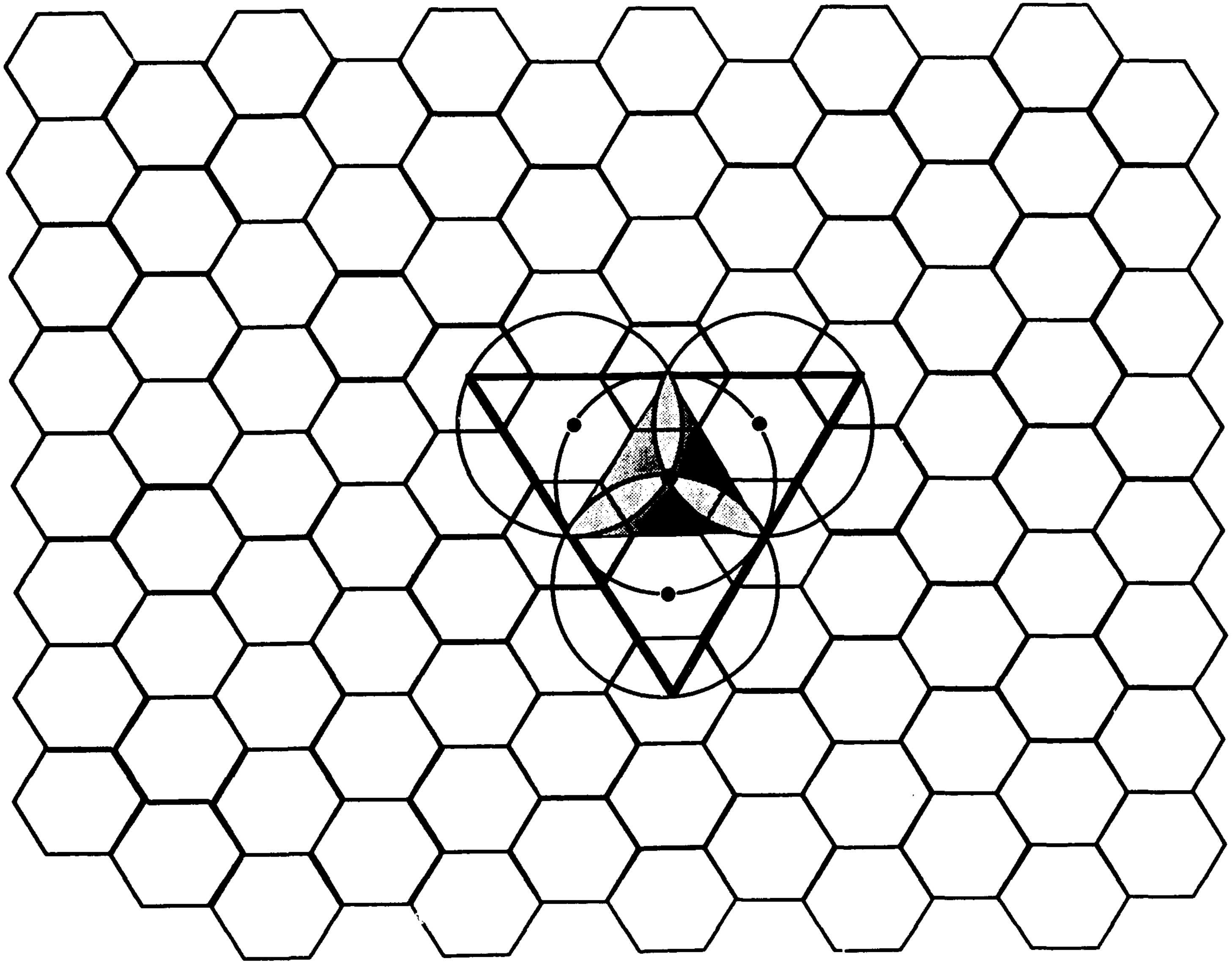


Figure 1-5. Two-Thirds Population of Hexagonal Cells Assuming at Least Double Coverage

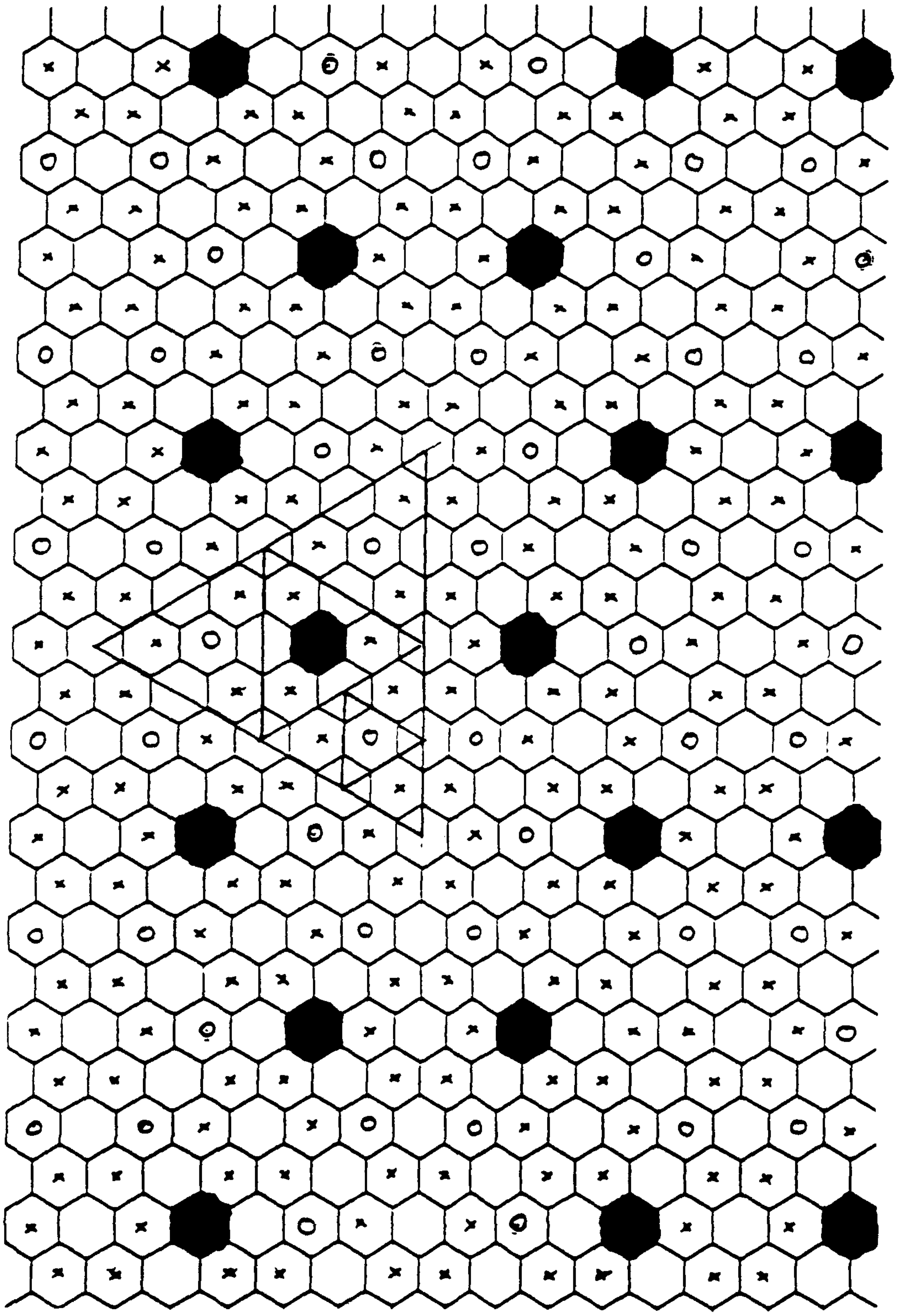


Figure 1-6. Nesting of Three-Sized Triangles.

Eight scanning frequencies per layer appear to be quite viable. Since there three layers of cells, at most 24 frequencies must be scanned. Of course, depending on the degree to which the airborne equipment already knows its location, the number of frequencies scanned might be reduced. This requires further analysis based on operational scenarios.

Figure 1-6 also depicts the three different types of communications towers. First note that only 2/3 of the hexagonal cells are populated with towers. An unshaded cell has no tower at its center; those cells marked by an "x" constitute triangles of the smallest size; those marked by an "o" are at the center of the medium sized triangles; and those marked by solid black are at the center of the largest sized triangle. The nesting is indicated by the different sized triangles shown. The towers associated with the centers of the largest triangles utilize three distinct service frequencies, one for each of the three altitude layers and corresponding triangles on which that tower is centered. The towers associated with the centers of the o's operate on two distinct service frequencies associated with the lower two layers, while the towers marked by the x's operate with just one service frequency relegated to the lowest layer.

1.5.6 Propagation Modeling

The principal question is the characterization of the attenuation of BLOS A-A and A-G communications signals. This is to assure that there is enough separation between cells utilizing the same frequencies so that cochannel self interference is tolerable. As indicated above, 8 frequencies per layer appear to be necessary. However, with this assumption the initial propagation modeling link power budget margins calculated suggest that the maximum number of scanning frequencies might be reduced to only 6 instead of 8 per layer or a total of 18 instead of 24. This was recently explored but for detailed reasons explained in section 7, 8 frequencies per layer should be maintained for planning purposes.

1.5.7 Operational Procedures

Considerable effort was expended to develop rudimentary procedures for how CTAG concepts might work in an operational environment. A sequence of step by step logical events were prepared taking the points of view of the pilot/crew, the airborne terminal, the ground system, and the air traffic controller. The important procedures for entering the system, handing over an aircraft from cell to cell, and handing off control from one controller to another were emphasized. Details can be found in section 8.

1.5.8 TDMA Example Design

At the start of the study there were two opinions expressed, one favoring TDMA and one advocating FDMA, although that was in the minority. Spread spectrum was viewed as a less likely alternative because of the limited bandwidth over which to spread (see subsection 1.5.3 and section 4). Because TDMA seemed to be more popular, it was examined first. Later a similar FDMA approach was considered but TDMA appears to have the technical edge. Before describing how TDMA might work (see figure 1-7), the design decisions and system assumptions, operational features, and technical performance of the example design are described.

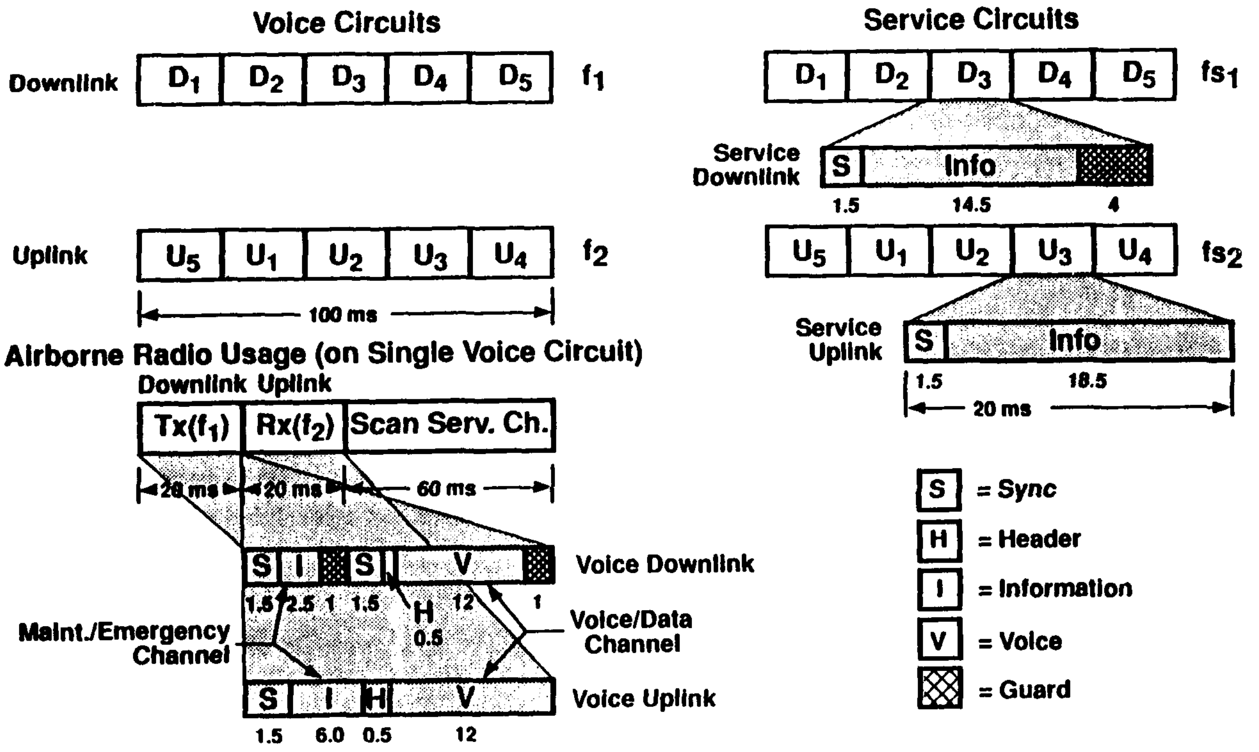


Figure 1-7. TDMA Example Design Architectural Organization

First the design decisions and assumptions are listed. As pointed out earlier the uplinks and downlinks are separated in frequency to avoid A-A interference. Separate uplink and downlink time slots are employed to simplify the airborne terminal. A-A connectivity is provided via relay through ground control. Up to 16 aircraft in a cell share a voice/data channel with a controller; the design could easily be modified to handle up to 32 aircraft. Voice is digitized at 4.8 kb/s with no coding; 10^{-2} bit error rate (BER) is assumed to be acceptable. Up to 24 service channels may need monitoring. The modulation is some form of quaternary signaling at a 20 kbaud burst rate, i.e., a 40 kb/s instantaneous burst rate.

Data for network maintenance, emergency access, cell handover, etc., is protected by a rate 1/2 code, e.g., a Golay (20,9) code. A synchronization preamble of 60 b lasting 1.5 ms is used in every transmission. The aircraft radio is slaved to cell time that is provided by a service channel uplink; an oscillator stability of only 10^{-6} is necessary. Radios must be capable of changing between transmit and receive in only 1 ms; although not trivial technically, this requirement should not be very difficult to meet with modern frequency synthesizers.

Secondly, the operational features are listed. Automatic net entry is accomplished via the service channel of the aircraft's cell. There are provisions for user identity, not only tail/flight number but aircraft index number in the group of 16 aircraft in a time slot. The system has a ranging capability that maintains aircraft range to accuracy within about 2 mi (10 μs). Aircraft equipment automatically monitors the uplink service channels to measure channel quality, and assessments of channel quality are transmitted to the ground system via the downlink service channels. There is automatic cell handover to the best next cell when the situation warrants. The system can build in checks and balances to ensure that spurious cell handovers are rare events. There are automatic frequency assignments, automatic voice time slot assignments, and automatic channel change information is supplied from the ground under the direction and cognizance of the controller. Although the concepts are straightforward, detailed algorithms for accomplishing these automatic procedures still need to be developed.

The "party line" (situational awareness) capability for aircraft can be retained as a system option selectable by the pilots. The controller controls whether aircraft can talk or not; if the controller pushes to talk, aircraft transmissions are automatically shut down by the system. Pilots can activate "call waiting" and emergency "break-in" features in the system to alert the controller that they wish to talk. In cases of simultaneous emergencies, there is an effective procedure for deconflicting most conflicts.

Finally, the technical performance of the example design is noted. Propagation delays between aircraft and the communications tower at the center of its cell are corrected by the ground system to an accuracy of about 10 μs so that each aircraft's signal arrives at the same time within this tolerance. The time required to complete the uplink service channel monitoring update is about 2.4 s = 100 ms frame/channel x 24 channels. Cell handover preparation takes a few seconds; the indication of channel degradation to new channel indication would be 1 to 2 s, and preparation of ground connections for no interruptions of service would require slightly more than a second. Emergency access time is only 100 ms if no one is "talking"; this frame duration upper bounds how long an aircraft must wait for its time slot to arrive. If someone is talking, it could take 300 ms for emergency access, and in the case of simultaneous emergencies, it could take as long as 2.4 s in most cases.

A preamble synchronization pulse of 60 b (1.5 ms duration) is about 9.5 dB stronger than the "data" portion of the signal. With only 40 b (1.0 ms duration) the sync is 7.7 dB stronger; 40 b is probably adequate but there is plenty of overhead capacity for growth features in the waveform, anyway. Assuming phase-comparison detection of QPSK, the required Eb/No for a 10^{-2} BER is 8.0 dB. The synchronization detection probability is 0.9999 = $1 - 10^{-4}$ and the false alarm probability is 10^{-2}. Data protection for network maintenance, emergency access, cell handover, etc., is accomplished to a codeword error probability of 4×10^{-5} at a channel BER of 1%.

The principal performance factor of interest, of course, is throughput. In this TDMA example design, one can sustain up to five 4.8 kb/s two-way "conversations" (exchanges) per pair of 25 kHz uplink and downlink channel assignments. The b/s/Hz goodness parameter for "useful data" is 5 x 4800 b/s/25 kHz = 0.96. The overhead for architectural organization, all operational features, etc., equals 40% of every time slot (8 ms out of 20 ms) plus the twenty-four 25 kHz service channel assignments, of course.

The number of frequencies required for CTAG in the Boston Center can now be estimated. First of all, 48 frequencies (25 kHz allocations) are required for the uplink and downlink service channels. As was seen the 24 uplink service channels are paired with 24 downlink channels used for the purposes of providing channel quality information and ranging. Secondly, 2.5 times as many two-way conversations per 25 kHz channel allocation can take place with the TDMA approach as explained above as compared to present day capabilities where only one conversation is possible in each 25 kHz channel. The 2.5 increase in voice (or data) capacity includes the conservative assumption of 40% overhead for maintenance and emergency features to be explained later, and the more optimistic assumption that digital voice can be transmitted reliably and with enough speaker recognition quality at 4.8 kb/s.

Since Boston Center has about 100 active controllers during the busy hour, each typically now requiring a separate 25 kHz channel (see subsection 1.5.4), as evidenced by the TDMA example design, CTAG can reduce the number of channels by a factor of 2.5 to only 40. Along with the 48 service channels that may be required, this means that 88 channels can easily handle all the ATC voice communications in New England. Assuming that New England is typical of the average across the U.S., because of the frequency reuse afforded by the cellular structure, this implies that these 88 or so channels would be sufficient for the entire country, albeit some regions would require more and some less depending on air traffic densities.

1.5.9 FDMA Comparison

In the FDMA design example, which is quite similar to the TDMA example design just summarized, only the differences are mentioned here. Instead of time slots, FDMA employs separate uplink and downlink FDM frequencies in a (5 per) 25 kHz allocation. Voice/data or service circuits are each a 5 kHz bandwidth assignment with 8 kb/s instantaneous data rate. The 60 b synchronization preamble now consumes 7.5 ms. The radios are full-duplex on an instantaneous basis so they do not need to switch between transmit and receive. On the other hand, two receivers are required and either two or three synthesizers (see below). The TDMA radios were only half-duplex, although operationally they appear to be full-duplex since the TDMA frame of 100 ms is so short.

No timing adjustments are necessary in FDMA. There are FDM voice/data channel pair assignments instead of time slots pairs. Timing/range accuracy performance is about 5 times less accurate, i.e., about 50 µs or 10 mi. The time required for channel monitoring, cell handover, and emergency access is the same as for the TDMA example. Synchronization takes 5 times longer but has the same relative "strength" and performance probabilities as in the TDMA design. Data protection is also the same. The throughput is identical, although the access schemes would be different.

FDMA has an advantage over TDMA in that the peak power requirement is 5 times less, i.e., 7 dB less EIRP is needed. This may not be a compelling advantage since in the TDMA approach only about a 10 W transmitter is required. FDMA is more susceptible to Doppler shifts and frequency error, e.g., from less stable oscillators. Full-duplex aircraft radios are needed in FDMA with two receivers and either two or three synthesizers depending on whether a receiver that scans service channels can share a synthesizer with the transmitter. Intermodulation problems with multiple radios at ground sites would be likely and difficult with FDMA. On balance, TDMA seems to be the preferred approach.

1.5.10 Ground Network Design

To some extent the ground network for CTAG had to await the definition of the airborne subsystem. Early work concentrated on the land mobile telephone network as background. Initially it was thought that much of the in place hardware, switches and trunks as well as mobile radio equipment could be used for CTAG with only new switch software required. Nevertheless, the latter was felt to represent a significant cost, either in modified or new software. However, it now appears that CTAG would require its own network of switches to avoid blocking which cannot be afforded with the 0.99999 end-to-end circuit availability required for ATC communications.

Although the architecture of the CTAG ground network has now been established, and the switches sized, there was insufficient funding to embark on cost estimates. This would be the highest priority first task of the next phase once appropriate funding is obtained.

A mesh type architecture of primary high-level switches is suggested with each such CTAG Ground Master Switch (CGMS) connected to at least two others for redundancy. In the order of 10 or 20 T1 trunks connect adjacent pairs of CGMSs. Each T1 operates at 1.544 Mb/s and is composed of twenty four 64 kb/s channels representing 35 voice conversations and their associated service uplinks and downlinks. Details of the multiplexing can be found in Volume 3.

There are 55 cell site switches connected to each CGMS. Each cell site transmits one T1 carrier as primary; the second T1 is used only if the primary fails. Again, see Volume 3 for details. Common Channel Signaling System #7 is recommended for call control and handoffs between cells/controllers.

Although various requirements for the ground network have been collected and utilized to establish the architecture, little analysis has been performed as yet to guarantee that this network indeed meets all the requirements. Further traffic analysis and computer simulations are necessary before one can determine whether the network can be reduced in size and complexity while still meeting the requirements.

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VOLUMES 1 AND 2 GLOSSARY

A-A - Air - Air
ADS - Automatic Dependent Surveillance
ACF - Area Control Facility
AFB - Air Force Base
A-G - Air - Ground
ALC - Automatic Level Control
AMSS - American Mobile Satellite Service
AM - Analog Modulation
A-QPSK - Aviation QPSK
ARTCC - Air Route Traffic Control Center
ASK - Amplitude Shift Keying
ATC - Air Traffic Control
ATN - Aeronautical Telecommunications Network
AWGN - Additive White Gaussian Noise

BCH - Bose-Chaudhuri-Hocquenhem
BER - bit error rate
BLOS - Beyond Line of Sight
BPSK - Binary Phase Shift Keying

CAASD - Center for Advanced Aviation System Development
CDMA - Code Division Multiple Access
CELP - Code Excited Linear Predictor
CGMS - CTAG Ground Master Switch
C/I - Carrier to Interference
C/N - Carrier to Noise
CONUS - Contiguous United States
CTAG - Cellular Trunked Air Ground

DS - Direct Sequence
DSBTC - Double Side Band Transmitted Carrier
DSBSC - Double Side Band Suppressed Carrier
DSPN - Direct Sequence Pseudo Noise

EIRP - Effective Isotropic Radiated Power

FAA - Federal Aviation Administration
FASTE - Freiman Analysis of Systems Techniques Equipment
FDM - Frequency Division Multiplexed
FDMA - Frequency Division Multiple Access
FH - Frequency Hopping
FM - Frequency Modulation
FSK - Frequency Shift Keying

VOLUMES 1 AND 2 GLOSSARY
(Continued)

GA - General Aviation
G-G - Ground - Ground
GMSK - Gaussian Minimum Shift Keying

IAW - In Accordance With
ID - Identity
ISO - International Standards Organization

LOS - Line of Sight

M/E - Message/Emergency
MSK - Minimum Shift Keying
MSR - MITRE Sponsored Research

NAS - National Airspace System
NBFM - Narrow Band Frequency Modulation

OQAM - Offset Quadrature Amplitude Shift Keying
OSI - Open Systems Interconnection
OTS - Off the Shelf

PN - Pseudo Noise
PSK - Phase Shift Keying
PSTN - Public Switched Telephone Network
PTT - Push to Talk

QAM - Quadrature Amplitude Modulation
QPSK - Quadrature Phase Shift Keying

RAPCON - Radar Approach Control
RCAG - Remote Control Air-Ground
RCO - Remote Communications Outlet
RF - Radio Frequency
RTT - Round Trip Timing
Rx - Receiver

S/I - Signal to Interference
S/N - Signal to Noise
SNR - Signal-to-Noise Ratio
SSB - Single Side Band

VOLUMES 1 AND 2 GLOSSARY
(Concluded)

TBD - To Be Determined
TCM - Trellis Coded Modulation
TDM - Time Division Multiplexed
TDMA - Time Division Multiple Access
TRACON - Terminal Radar Approach Control
Tx - Transmitter

V/D - Voice/Data
VSB - Vestigial Side Band

WBS - Work Breakdown Structure

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