

AD-A244 574



UN30

①

December 1991

M91-112

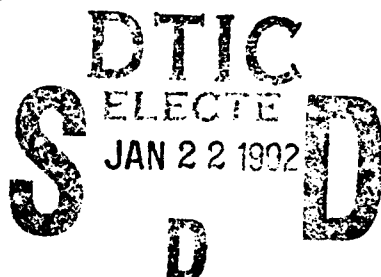
Volume 2

Example System Design Details

M. Leiter, R. I. Millar, J. L. Ramsey, B. E. White, W. J. Wilson, ed.

M. Leiter
R. I. Millar
J. L. Ramsey
R. D. Sakamoto
B. E. White
W. J. Wilson

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



92-01496



Approved for public release;
distribution unlimited.

MITRE

Bedford, Massachusetts

92 1 16 078

December 1991

M₉₁₋₁₁₂

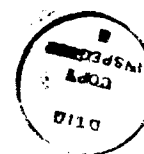
Volume 2

Example System Design Details

M. Leiter, R. I. Millar, J. L. Ramsey, B. E. White, W. J. Wilson, ed.

**M. Leiter
R. I. Millar
J. L. Ramsey
R. D. Sakamoto
B. E. White
W. J. Wilson**

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



Accession For	
NTIS	DTIC
DTIC	Unannounced
Justification	
By	
Dist. Bureau	
Availability	
Dist	Availability
A-1	

CONTRACT SPONSOR MITRE Sponsored Research
CONTRACT NO. N/A
PROJECT NO. 91550
DEPT. D053

Approved for public release;
distribution unlimited.

MITRE

The MITRE Corporation
Bedford, Massachusetts

Department Approval: M. Leiter
M. Leiter

MITRE Project Approval: B. E. White
B. E. White

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.

VOLUME 2 TABLE OF CONTENTS

SECTION	PAGE
2 Modulation and Coding	2-1
2.0 Introduction	2-1
2.1 Analog Modulation Techniques	2-1
2.2 Digital Modulation Techniques	2-7
2.3 Digital Coding Techniques	2-13
3 Radio Implementation and Cost Estimates	3-1
3.0 Introduction	3-1
3.1 Cost Analysis	3-1
3.1.1 Scope	3-1
3.1.2 Ground Rules and Assumptions	3-1
3.1.3 Approach	3-1
3.1.4 Estimating Methodology	3-2
3.2 Estimates for Ground Radio Equipment	3-3
4 Spread Spectrum Multiple Access	4-1
4.0 Introduction	4-1
4.1 Background	4-1
4.2 Advantages	4-1
4.3 Limitations	4-2
4.4 Conclusions	4-4
5 Voice Message Traffic Model	5-1
5.0 Introduction	5-1
5.1 Terminal Sequence	5-2
5.2 Enroute Sequence	5-3
5.3 Estimates of Mean Call Occurrence Times and Exchange Durations	5-4
5.4 The Distribution of Exchange Lengths	5-5
5.5 Estimating the Maximum and Minimum Number of Cells Needed in an Area	5-6
6 Three-Dimensional Cellular Solutions	6-1
6.1 Fundamental Considerations	6-1
6.2 Outline of Specific Solution	6-4
7 CTAG Frequency Reuse	7-1
7.0 Introduction	7-1
7.1 Background	7-1
7.2 Cell Structure	7-1
7.3 Required Signal-to-Noise Ratio	7-2
7.4 Frequency Reuse Patterns	7-2
7.5 Propagation Effects	7-5
7.6 Frequency Management	7-11
7.7 Summary	7-12

VOLUME 2 TABLE OF CONTENTS (Concluded)

SECTION	PAGE
8 Operational Procedures	8-1
8.0 Introduction	8-1
8.1 Cellular HandOff	8-1
8.1.1 Current Cellular Telephone HandOff Procedures and problems	8-1
8.1.2 CTAG Cell-Cell HandOff Concepts	8-2
8.2 How Does CTAG Work	8-3
8.3 Message Traffic Requirements for Routine Cellular HandOff in CTAG	8-3
9 TDMA Example Design	9-1
9.0 Introduction	9-1
9.1 Assumptions	9-1
9.2 Frame Structure	9-2
9.3 Key Procedures	9-2
9.3.1 Net Entry	9-2
9.3.2 Circuit Maintenance	9-4
9.3.3 Voice Communications	9-6
9.3.4 Cell Monitoring/Cell Handover	9-7
9.3.5 Emergency Communications	9-8
9.4 Link Synchronization	9-9
10 FDMA Comparison	10-1
10.0 Introduction	10-1
List of Volume 1 References	RE-1
Appendix 1	A1-1
Appendix 2	A2-1
Appendix 3	A3-1
Appendix 4	A4-1
Volumes 1 and 2 Glossary	GL-1
Distribution List	DL-1

VOLUME 2 LIST OF FIGURES

FIGURE	PAGE
2-1 Channel Bandwidth-Power Tradeoff for Various Modulation Schemes with Coding	2-13
2-2 Channel Bandwidth-Power Tradeoff for Various Modulation Schemes without Coding (BER = 10^{-6})	2-14
2-3 Channel Bandwidth-Power Tradeoff for Various Modulation Schemes without Coding (BER = 10^{-2})	2-15
4-1 ATC Radio Spectrum	4-3
6-1 Two-Thirds Population of Hexagonal Cells Assuming at Least Double Coverage	6-5
6-2 Nesting of Three-Sized Triangles	6-7
6-3 Frequency Reuse Relationships for Cells with Double Coverage	6-8
7-1 6-Frequency Pattern	7-4
7-2 7-Frequency Pattern	7-4
7-3 8-Frequency Pattern	7-4
7-4 Excess Path Loss at 1,125 ft.	7-6
7-5 Excess Path Loss at 4,500 ft.	7-7
7-6 Excess Path Loss at 18,000 ft.	7-8
7-7 Excess Path Loss at 72,000 ft.	7-9
8-1 Entering the System	8-4
8-2 Cell Hand-off	8-5
8-3 Controller Hand-off	8-6
8-4 Procedure for Routine Cellular Handoff	8-8
8-5 Circuit Preparation in New Cell	8-10
8-6 Procedure for Cellular Transition at the Aircraft (A/C)	8-11
8-7 Bookkeeping Functions at Old Switch (A/C = aircraft)	8-13

VOLUME 2 LIST OF FIGURES (Concluded)

SECTION	PAGE
9-1 TDMA Example Design Architectural Organization	9-3
9-2 Maintenance/Emergency Organization	9-5
10-1 Alternative FDMA Organization	10-2

VOLUME 2 LIST OF TABLES

TABLE	PAGE
2-1 Semi-Quantitative Comparison of Several Well-Known Analog Modulations	2-2
2-2 Quantitative Comparison of Several Advanced Digital Modulations	2-8
2-3 Quantitative Comparison of Several Advanced Digital Modulations	2-9
2-4 Quantitative Comparison of Several Advanced Digital Modulations	2-10
2-5 Quantitative Comparison of Several Advanced Digital Modulations	2-11
2-6 Quantitative Comparison of Several Advanced Digital Modulations	2-16
2-7 Quantitative Comparison of Several Advanced Digital Modulations	2-17
6-1 Cochannel Interference for Half-Duplex Operation	6-1
6-2 Cochannel Interference for Full-Duplex Operation	6-3
7-1 Service Volume Sizes	7-2
7-2 Frequency Reuse Pattern Data	7-3
7-3 Frequency Reuse Pattern Characteristics	7-3
7-4 Uplink S/I Ratios	7-10
7-5 Downlink S/I Ratios	7-10

SECTION 2

MODULATION AND CODING

2.0 INTRODUCTION

A review of modulation and coding techniques is documented in this section. Well known analog techniques are summarized for possible dual-mode radio use in a potential transition phase to the future mostly-digital system. Some of the better known digital techniques are also listed along with some newer, lesser known types. Standard coding gains to be expected are also documented.

2.1 ANALOG MODULATION TECHNIQUES

Table 2-1 characterizes several analog modulations.

1. An improved Double Sideband Transmitted Carrier (DSBTC) scheme can be described as follows. Channel spacing is expressed as the number of channels that might be packed into a 25 kHz bandwidth allocation. There are 2 or 2.5 channels per 25 kHz. The audio bandwidth is 3.5 kHz. One needs a 7 kHz RF bandwidth centered on the carrier frequency. Almost 1 kHz (a few ppm) for oscillator drift plus Doppler shift needs to be allowed. Also, there must be allowance for filter rolloff. One can use a 10 kHz or 12.5 kHz channel spacing. New transceiver designs will be required with closer tolerances on local oscillator frequency drift, narrower IF filter bandwidths, and a much better receiver selectivity. Characteristics of this narrowband AM (other than capacity) can be itemized as follows:

2. Need for Doppler tracking (for coherent demodulation), not required.
3. Power efficiency, usually expressed as carrier-to-noise ratio (C/N) needed for satisfactory intelligibility of speech, poor. Most of the transmitted power is in the carrier.

$(S/N)_{\text{audio}} \cong m^2 (C/N)$, $C/N \gg 1$, where m is the modulation index.

For 10 dB audio SNR with $m = 30\%$, a 20.5 dB C/N is required.

4. Susceptibility to adjacent-cell and adjacent-channel interference, usually expressed as signal-to-interference ratio (S/I) or carrier-to-interference ratio (C/I) required, C/I required is same order of magnitude as C/N.
5. Complexity of radio design required to transmit and receive the modulation, simplest of any modulation.

Table 2-1. Semi-Quantitative Comparison of Several Well-Known Analog Modulations

Analogue 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 suppression of weaker signal	very good
NBFM	2	none	good -1 dB	moderate ~ 15 dB	simple const. env. Tx	distortion and less suppression of weaker signal	good

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 (28 kHz)
 NBFM - Narrow Band FM (10 kHz)

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

6. Speech intelligibility with two talkers inadvertently using the same channel (the conferencing effect), with older radios having less accurate local oscillators, carrier heterodyning usually produces a super-audible tone and quasi-linear conferencing occurs; with newer radios having more accurate local oscillators, however, carrier heterodyning can produce an audible tone and considerable distortion results.
7. Performance degradation in multipath propagation conditions, multipath fading is an amplitude fluctuation. If the fading occurs at a rate commensurate with audio frequencies, it can cause speech distortion. Similarly, for the other analog modulations schemes, referring to table 2-1.

Double Sideband Suppressed Carrier (DSBSC)

1. There are 2 or 2.5 channels per 25 kHz. Audio bandwidth is 3.5 kHz. Need a 7 kHz bandwidth centered on (suppressed) carrier. Allow for oscillator drift, Doppler, and filter rolloff. Can use 10 kHz or 12.5 kHz channel spacing.
2. Need accurate tracking of both carrier frequency and carrier phase. Can be recovered from DSBSC signal with a Costas loop.
3. Good. All power in modulation sidebands. There is no noise reduction (as there is with FM), however. There is no detector threshold.

$$(S/N)_{\text{audio}} = 2 (C/N)_{\text{in}}$$

4. Better than AM because interfering signals have no carrier.
5. Need a Costas loop to reconstruct the (suppressed) carrier for synchronous demodulation. Otherwise comparable to a SSB transceiver.
6. Considerable distortion results because two DSBSC signals are offset in frequency by Doppler shift. The carrier tracking loop must be mismatched to at least one signal.
7. DSBSC is still an amplitude modulation technique. Fading at audio frequency rates will cause speech distortion.

Quadrature Amplitude Modulation (QAM) (Using two DSBSC signals)

1. There are four or five channels per 25 kHz. Can use 10 kHz or 12.5 kHz channel spacing, but can send two (quadrature) virtual channels in each frequency channel. Need for Doppler tracking (for coherent demodulation).

2. Need accurate tracking of both carrier frequency and carrier phase. Can be recovered from DSBSC signal with a Costas loop. Must track phase accurately to separate the two quadrature signals.
3. Good. All power in modulation sidebands. There is no noise reduction (as there is with FM), however. There is no detector threshold.
4. Better than AM because interfering signals have no carrier.
5. Need a Costas loop to reconstruct the (suppressed) carrier for synchronous demodulation. Need to maintain linearity in transmitter and receiver to keep quadrature signals from mixing and producing intermodulation distortion.
6. Considerable distortion will result. May not be possible to separate quadrature channels.
7. QAM is still an amplitude modulation technique. Fading at audio frequency rates will cause speech distortion.

Single Sideband (SSB)

1. There are four or five channels per 25 kHz. Channel spacing of 5 or 6.25 kHz could be used, providing for a 3.5 kHz audio band, with allowances for oscillator drift, Doppler shift, and filter rolloff.
2. Need to transmit a pilot tone (attenuated carrier) for Doppler tracking. Carrier error must be less than 20 Hz, typically, for voice. This is much less than the Doppler shift at Mach 1. Therefore, a Doppler tracking loop is required.
3. Good. Most of the power is in the modulation sideband. There is no noise reduction (as there is with FM), however. Since SSB reception is (conceptually) a direct translation to baseband, input and output SNR of detector are equal. At first glance, it appears that SSB is 3 dB poorer than DSBSC in this regard, but remember that the SSB radio frequency bandwidth is half that of DSBSC, so that SSB has half the noise to start with. This SSB and DSBSC have the same power efficiency (on an average power basis).
4. Better than AM because interfering signals have no carrier.
5. Need a stable local oscillator plus a carrier tracking loop (for local oscillator offset between radios plus Doppler shift). Need a linear transmitter and receiver to accommodate peaks of audio signal; there is no carrier to drive an automatic level control (ALC) in the power amplifier.
6. Quasi-linear conferencing may occur if Doppler shifts of two talkers aren't too different.

7. SSB is still an amplitude modulation technique. Fading at audio frequency rates will cause speech distortion.

NOTE: Because SSB is a frequency translation of the baseband signal, Fourier series components that were harmonically related at baseband are no longer harmonically related after the frequency translation. Thus, the time envelope of the SSB signal is grossly different from the time envelope of the baseband signal. (See [9], Section 5.5.) This effect is not too bad for speech, but may be a problem for data communication.

Vestigial Sideband (VSB)

1. Intermediate between SSB and DSBSC cases. Could probably employ channel spacing of 6.25 kHz or 8.33 kHz. providing 3 or 4 channels per 25 kHz. Channel spacing depends upon how much of the vestigial sideband is transmitted, which depends upon filter rolloff.
2. Probably need a pilot tone (attenuated carrier) for Doppler tracking. VSB frequency response extends to low audio frequencies.
3. Good. Most of the power is in the modulation sideband. There is no noise reduction (as there is with FM), however. Generally similar to SSB.
4. Better than AM because interfering signals have no carrier.
5. Comparable to a single sideband radio. Need a stable local oscillator, plus a linear transmitter and receiver to accommodate peaks of audio signal; there is no carrier to drive an automatic level control (ALC) in the power amplifier.
6. Quasi-linear conferencing may occur if Doppler shifts of the two talkers aren't too different.
7. VSB is still an amplitude modulation technique. Fading at audio frequency rates will cause speech distortion.

NOTE: The signal envelope distortion experienced by SSB also occurs with VSB, because the two modulations are so similar.

Frequency Modulation (FM)

1. One channel per 25 kHz, with a modulation index between 2 and 3.
2. Not required.
3. Good at large modulation index. FM threshold occurs around 10 dB CNR (lower for threshold-extension demodulators). Audio SNR is 10-15 dB higher than CNR, once CNR is above threshold.

4. If C/I is above the FM threshold of 10 dB, the interference is suppressed by the FM improvement factor. Thus, FM is much better than AM in this regard.
5. FM receiver is relatively simple, only slightly more complex than an AM receiver. Transmitter for constant envelope FM waveform is simpler than a linear transmitter.
6. Considerable distortion occurs when amplitudes are about equal. When one signal is much stronger, it "captures" the FM demodulator and suppresses the weaker signal.
7. FM is very resistant to multipath fading. This is the main reason it is used for cellular telephones.

From Swartz, Bennett, & Stein, p. 120: [10]

$$\frac{S_o}{N_o} = 3\beta^2 \frac{S_c}{N}, \beta = \frac{\Delta f}{f_m} = \frac{\text{frequency deviation (one-sided)}}{\text{highest modulating frequency}}$$

Example:

$$f_m = 3.5 \text{ kHz}$$

$$\Delta f = 10 \text{ kHz}$$

$$\beta = 2.86$$

$$3\beta^2 = 24.5 \quad (13.9 \text{ dB})$$

With S_c/N at 10 dB, which is the

FM threshold,

$$S_o/N_o = 23.9 \text{ dB}$$

From Carson's rule, the two - sided RF bandwidth is

$$2B \cong 2(f_m + \Delta f) = 2(3.5 + 10) = 27 \text{ kHz}$$

Wideband FM is defined as:

$$\beta > \pi/2, 3\beta^2 > 7.4 \text{ (8.7 dB)}$$

Narrowband Frequency Modulation (NBFM)

1. Two channels per 25 kHz, or a spacing of 12.5 kHz, might be possible with a modulation index < 1 . But there is little FM noise improvement with such a small modulation index.
2. Not required.
3. Somewhat better than AM. $S_o/N_o = C/N$ with NBFM, whereas $S_o/N_o \approx m^2 C/N$ with AM.

4. Not as good as FM with a large modulation index, but may be better than AM.
5. Relatively simple. FM receiver is only slightly more complex than an AM receiver. FM transmitter for constant envelope waveform is simpler than a linear transmitter.
6. Considerable distortion occurs. Larger signal capture effect is weak at a small modulation index.
7. Poorer performance than FM with a large modulation index, but may still be better than AM.

For a 12.5 kHz channel spacing, assume an RF bandwidth of 10 kHz can be used, with 2.5 kHz guard space for filter rolloff.

Let $f_m = 3.2$ kHz

From Carson's rule, $2B = 2 f_m (1 + \beta)$

If $2B = 10$ kHz,

$$1 + \beta = \frac{10}{6.4} = 1.56 \quad \beta = 0.56,$$

or the frequency deviation Δf is

$$\Delta f = \beta f_m = 1.8 \text{ kHz.}$$

$$\frac{S_o}{N_o} \equiv 3\beta^2 \frac{S_c}{N}$$

The FM noise improvement factor, $3\beta^2$, is

$$\frac{S_c}{N} > 10$$

$$3\beta^2 = 0.95, \text{ so that } \frac{S_o}{N_o} \approx \frac{S}{N_c} \text{ above threshold}$$

2.2. DIGITAL MODULATION TECHNIQUES

Tables 2-2 through 2-5 summarize the bandwidth and power efficiencies of several digital modulation techniques for both coherent and non-coherent detection. The first two tables use a noise bandwidth definition of the power spectrum, while the second two tables compare the modulations with respect to where the power spectral densities have rolled off to only the 3 dB down points.

Table 2-2 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			Detection Scheme
			10-2	10-4	10-6	
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 $B_0 = [1/G(0)] \int_0^\infty G(f)df$, 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 2-3. 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 $B_0 = [1/G(0)] \int_0^\infty G(f)df$, 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 2-4 Quantitative Comparison of Several Advanced Digital Modulations
(Additive White Gaussian Noise)**

Digital Modulation Technique	3 dB Bandwidth Normalized to R_b *	Bandwidth Efficiency (b/s/Hz)	Power Efficiency E_b/N_0 (dB) for BER			Detection Scheme
			10-2	10-4	10-6	
MSK	0.59	1.69	4.3	8.4	10.5	coherent
GMSK (BT=0.25)**	0.50	2.0	6.4	10.0	12.0	coherent
A-QPSK ***	≤ 0.44	≥ 2.27	5.1	9.2	11.3	coherent
$\pi/4$ -QPSK	0.44	2.27	4.3	8.4	10.5	coherent
8-FSK	1.33	0.75	4.0	7.3	9.2	coherent
16-PSK	0.22	4.55	11.4	16.0	18.8	coherent
8-PSK	0.30	3.41	7.3	11.7	13.9	coherent
BPSK	0.88	1.14	4.3	8.4	10.5	coherent
4-OQAM	0.44	2.27	4.3	8.4	10.5	coherent
16-OQAM	0.22	4.55	7.8	12.2	14.4	coherent
16-QAM	0.22	4.55	7.8	12.2	14.4	coherent

* R_b = bit rate, b/s

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

*** Aviation QPSK

Table 2-5 Quantitative Comparison of Several Advanced Digital Modulations
(Additive White Gaussian Noise)

Digital Modulation Technique	3 db Bandwidth Normalized to R_b *	Bandwidth Efficiency (b/s/Hz)	Power Efficiency E_b/N_0 (dB) for BER			Detection Scheme
			10-2	10-4	10-6	
MSK	0.59	1.69	8.1	11.5	13.6	Limiter/Discriminator
GMSK (BT=0.25)	0.5	2.0	8.7	13.6	15.9	Limiter/Discriminator
A-QPSK***	≤ 0.44	≥ 2.27	7.6	11.6	13.7	Phase comparison
$\pi/4$ -QPSK	0.44	2.27	6.8	10.8	12.9	Phase comparison
8-FSK	2.67	0.38	5.2	8.2	9.9	Noncoherent
16-PSK	0.22	4.55	14.2	19.2	21.1	Phase comparison
8-PSK	0.30	3.41	10.2	14.6	17.6	Phase comparison
BPSK	0.88	1.14	5.9	9.3	11.2	Phase comparison

* R_b = bit rate, 8 kb/s.

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

*** Aviation QPSK

Figures 2-1 through 2-3 show the spectral and power efficiencies with respect to the Shannon limit using the noise bandwidth definition, since that data could be obtained from literature sources relatively early.

2.3 DIGITAL CODING TECHNIQUES

Improvements in power efficiency (E_b/N_0) at some expense in bandwidth efficiency Hz/(b/s) are shown in tables 2-6 and 2-7 using standard rate 1/2 convolution coding techniques. Trellis coding admits the possibility of coding gain without bandwidth expansion, at least in terms of the number of information bits per symbol bandwidth definition, where the symbol transmission rate is held constant (see Appendix 1); this corresponds to the zero crossing bandwidth being held fixed.

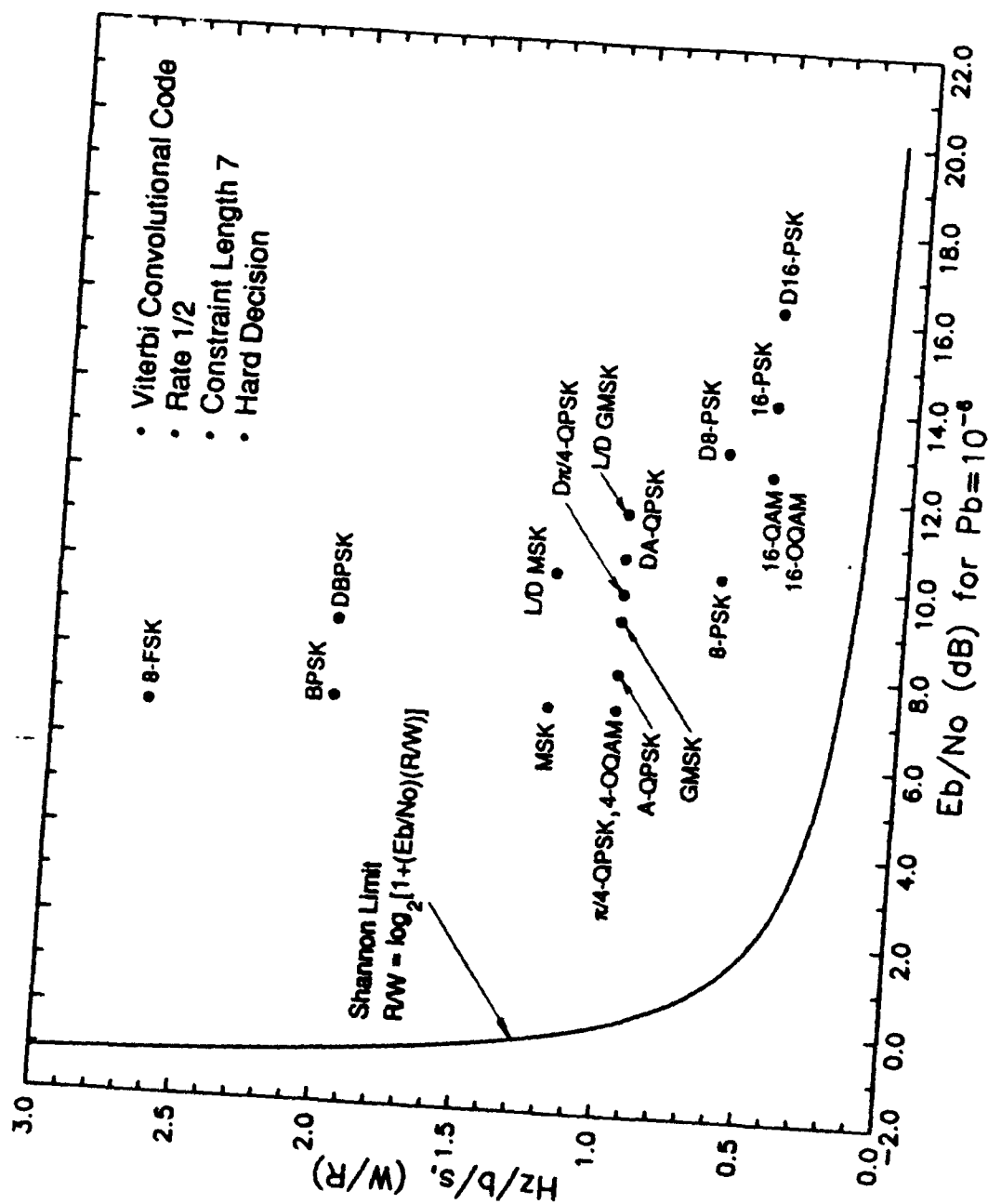


Figure 2-1. Channel Bandwidth-Power Tradeoff for Various Modulation Schemes with Coding

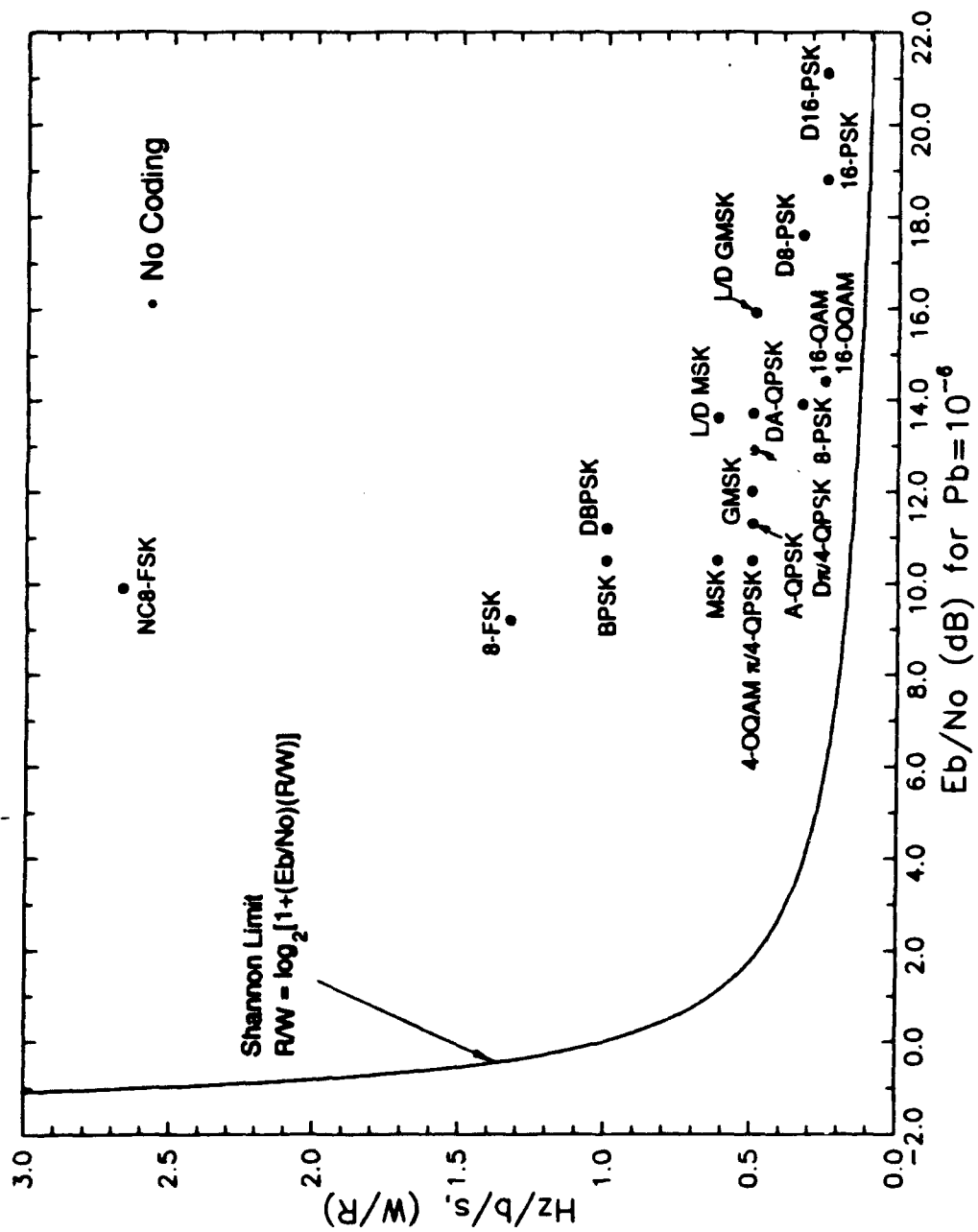


Figure 2-2. Channel Bandwidth-Power Tradeoff for Various Modulation Schemes without Coding (BER 10^{-6})

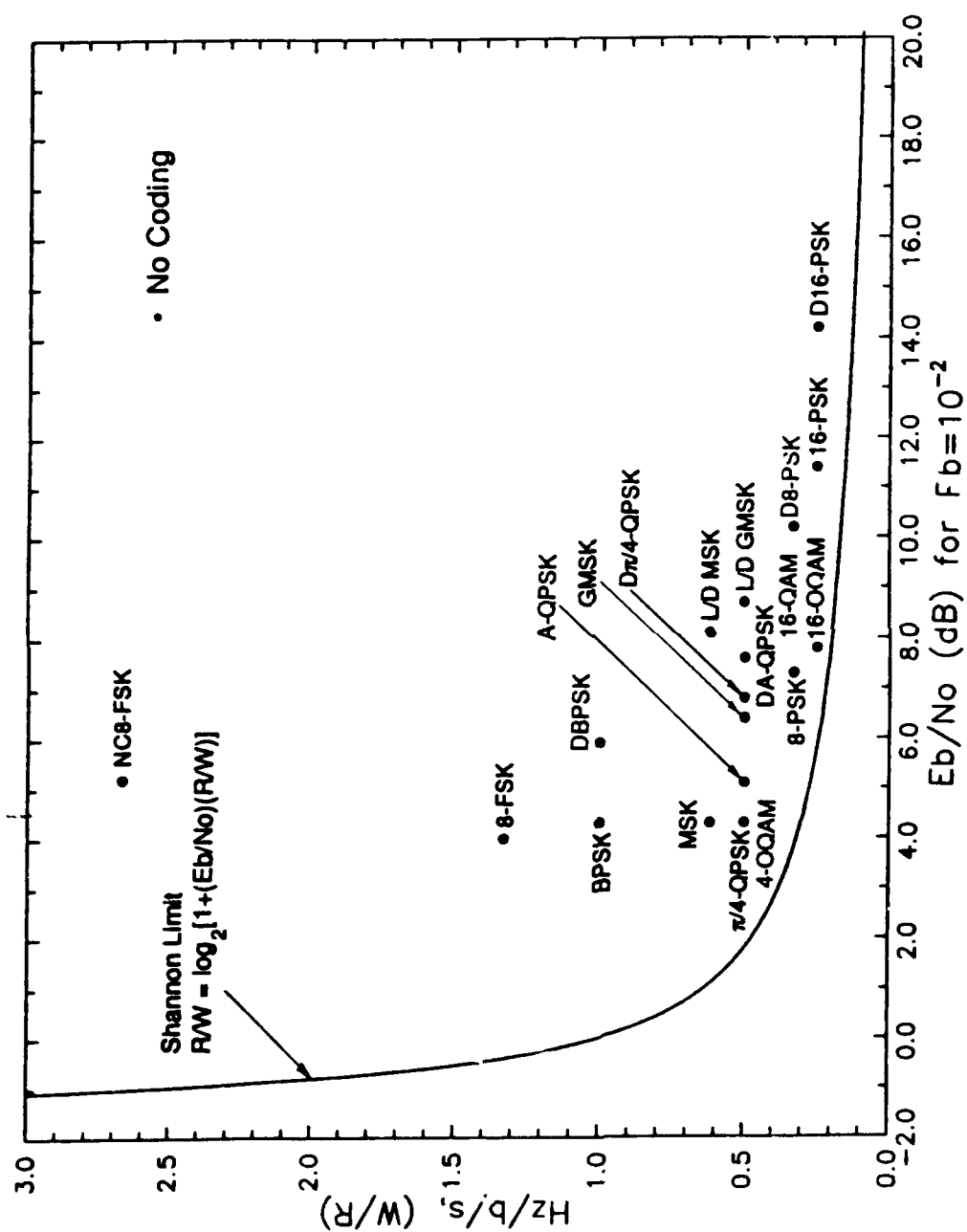


Figure 2-3. Channel Bandwidth-Power Tradeoff for Various Modulation Schemes without Coding ($BER = 10^{-2}$)

Table 2-6 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 ⁺	
M ^{***}	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 $B_0 = [1/G(f)] \int_0^\infty G(f) df$, 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 2-7 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		Detection Scheme
			Eb/No(dB) for BER = 10 ⁻⁶ 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 $B_0 = [1/G(0)] \int_0^\infty G(f)df$, 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

SECTION 3

RADIO IMPLEMENTATION AND COST ESTIMATES

3.0 INTRODUCTION

This section documents the efforts of the Cost Analysis Technical Center (D093) in taking a first look at the estimated prices of CTAG airborne and ground radios [11].

3.1 COST ANALYSIS

3.1.1 Scope

The analyses documented here cover only the conceptual designs of the front end of airborne and ground radios that could be used in the CTAG system. Work breakdown structures (WBSs) for both development and production have been outlined and are included in Appendix 2. The estimates discussed herein relate only to WBS elements 1.1.1 (ground radio receiver), 1.1.3 (ground radio exciter), and 1.2 (airborne commercial radios), and do not include any estimates of software that might be required or installation costs.

3.1.2 Ground Rules and Assumptions

This analysis is based on vendor prices for equipment manufactured in roughly 10,000 unit production lots. It is assumed that similar lot sizes will be used to produce the new radio equipment.

It is assumed that all prices obtained from manufacturers include allowances for all non-recurring development costs, all recurring production costs, costs of certification, and profit. Therefore, it is assumed that the estimated prices derived from the model will contain a profit margin. However, the exact value of the margin is unknown.

The cost of any circuitry to accomplish multiple access schemes was not considered, because a multiple access design solution has not been selected to date.

Complex packaging concepts that might be required to reduce weight and volume of the radios were not considered.

All prices are in 1991 dollars.

3.1.3 Approach

A number of candidate modulation waveforms have been considered, including both analog and digital schemes. The modulations selected for cost analysis include two analog waveforms (Narrowband AM, and SSB), and three digital waveforms (GMSK, A-QPSK, and 16-QAM). Radio front end block diagrams were designed for each waveform by D. K. Snodgrass (D053). These block diagrams considered all circuitry to receive and demodulate,

or modulate and transmit, each waveform. The designs are based on a TDMA approach but did not include any circuitry to effect a TDMA set up. The block diagrams are reproduced in Appendix 3.

The FASTE parametric cost estimating model was used [5]. Parametric cost estimating is the process of transforming performance characteristics of items into costs through specific (though unknown to the user) relationships between those characteristics and costs. The use of parametric cost estimating is most appropriate when design data and definitive information about a project are not available. This is especially true for a project like CTAG that is in the early stages of concept evolution.

FASTE uses the following relationship to estimate the cost of an item.

$$\text{COST} = f(\text{ENTYPE}, \text{PLATFORM}, \text{PMX}, \text{WEIGHT}) \quad (1)$$

ENTYPE is a variable that expresses the character of technology of the item. ENTYPE has a range from 40 to 140, where 40 represents the highest level of technology and 140 represents the lowest level of technology. FASTE suggests a range of 40 to 45 for electronics so a value of 43 was chosen.

PLATFORM is the variable that reflects the requirements for an item in terms of quality, reliability, maintainability, ease of use, safety, performance, and environmental conditions. PLATFORM can range in value from 0.9 to 3.5 with 1.0 generally used for ground or commercial equipment and 2.3 to 2.5 used for manned space systems. FASTE suggests a range of 1.6 to 1.7 for commercial aircraft so a value of 1.65 was chosen for the airborne radio. For a ground environment, FASTE suggests a range of 1.2 to 1.4 for military equipment so a value of 1.3 was chosen for the ground radio. The baseline standard AM ground radio is considered a military item since it carries a nomenclature (i.e., the receiver is listed as AN/GRR-23(V)10). This is the same ITT radio that the FAA uses in Remote Control Air-Ground (RCAG) ground sites. The Navy has also used this radio.

PMX is the variable that indicates a manufacturer's resources, skills, experience, and productivity; the item's design and scope; and the production methods. This factor was determined through calibration of the model based on price quotations obtained from the manufacturers.

COST and WEIGHT were values obtained from manufacturers' literature.

3.1.4 Estimating Methodology

First, FASTE was calibrated. Specifically, the data for a standard AM radio were input into the model, which used the cost relationship in equation (1) to determine the value of PMX. Next, block diagrams of the candidate modulation schemes were generated. Engineering judgement was used to assess the complexities of those schemes as a percentage of the standard AM radio complexity. The complexity percentage values were then used to multiply both PMX and WEIGHT of the standard AM radio. This procedure assumes that a design of greater complexity will also weigh more unless steps are taken to reduce the weight

and/or volume through the extensive use of chip packaging concepts (e.g., ASICs, hybrids, or other specialized integrated circuits).

3.2 ESTIMATES FOR AIRBORNE RADIOS

The standard AM radio selected can be purchased from Bendix/King General Aviation Avionics Division for \$1,210 as model number KY 96A. The unit weighs 2.9 pounds and can receive and transmit in 760 - 25 kHz channels from 118 to 137 MHz. Using this radio as a baseline design, block diagrams were generated for the candidate modulations being considered and their complexities were assessed as listed below:

<u>Candidate Modulation</u>	<u>Complexity Percentage</u>
Standard AM	100%
Narrowband AM	115%
GMSK	150%
A-QPSK	160%
SSB	175%
16-QAM	190%

To estimate the prices of the candidate waveforms the parameters PMX and WEIGHT were increased by the complexity percentage factors. The resultant prices estimated by FASTE are tabulated below:

<u>Candidate Modulation</u>	<u>Price</u>
Standard AM	\$1,210
Narrowband AM	\$1,581
GMSK	\$2,515
A-QPSK	\$2,816
SSB	\$3,310
16-QAM	\$3,804

Observe that the prices of the candidate modulations are comparable to the \$3K/radio goal mentioned for GA users (see subsection 1.2, Volume 1).

3.3 ESTIMATES FOR GROUND RADIO EQUIPMENT

The ground radio equipment, the GRR-23(V)10, selected is available from ITT Aerospace/Communications Division. The ground radio is an ITT Model # 3101 VHF Receiver designed to receive 1,360 - 25 kHz channels from 116 to 150 MHz. The unit weighs 22 pounds and can be purchased from ITT for \$8,460. The transmitter consists of two chassis, a 10 watt exciter, and a 50 watt linear amplifier. The unit is capable of

transmitting in 1,360 - 25 kHz channels from 116 to 150 MHz. The exciter weighs 45 pounds and can be purchased for \$12,135. The linear amplifier weighs 75 pounds and can be purchased for \$11,375.

The cost relationship of equation (1) used for the airborne radio also applies to the ground equipment. COST and WEIGHT were obtained from the ITT literature. The value for PLATFORM was chosen as 1.3 for ground military equipment. A value of 43 was selected for ENTYPE (same as the airborne radio). Data were input into the model and the model was calibrated to obtain a value for PMX.

Block diagrams for the standard AM radio receiver and exciter to be used as a baseline were again developed by D. K. Snodgrass (see Appendix 4). As with the airborne radios, block diagrams were then generated for both receivers and exciters for each of the five candidate waveforms and the complexities of their designs (as a percentage relative to that of the standard AM radio) were assessed. The amplifier was judged to be acceptable for all modulation types since it is a linear amplifier and capable of handling the proposed modulation waveforms. A summary of the percentage complexities for the receiver, exciter, and amplifier for each waveform modulation is as follows:

<u>Candidate Modulation</u>	<u>Percentage Complexity of the Receiver</u>	<u>Percentage Complexity of the Exciter</u>	<u>Percentage Complexity of the Amplifier</u>
Standard AM	100%	100%	100%
Narrowband AM	110%	105%	100%
GMSK	120%	150%	100%
A-QPSK	150%	160%	100%
SSB	160%	150%	100%
16-QAM	180%	180%	100%

As with the airborne radios, to estimate the prices of the receiver and exciter the parameters PMX and WEIGHT were adjusted by the percentage complexity factors. The resultant prices estimated by FASTE are tabulated below:

<u>Candidate Modulation</u>	<u>Price of the Receiver</u>	<u>Price of the Exciter</u>	<u>Price of the Amplifier</u>
Standard AM	\$8,460	\$12,135	\$11,375
Narrowband AM	\$10,180	\$12,921	\$11,375
GMSK	\$11,848	\$24,931	\$11,375
A-QPSK	\$17,381	\$27,866	\$11,375
SSB	\$19,427	\$24,931	\$11,375
16-QAM	\$23,803	\$32,469	\$11,375

Link budgets performed in conjunction with Sections 6 and 7 show that the 50W amplifier is unnecessary for CTAG. This reduces the price of the ground radios significantly, about a third to a sixth, depending on the complexity of the modulation scheme. Nevertheless, this ground radio cost estimate for CTAG still appears to be exaggerated. Further cost modeling work in the radio area is warranted.

SECTION 4

SPREAD SPECTRUM MULTIPLE ACCESS

4.0 INTRODUCTION

A communication system whose transmission bandwidth greatly exceeds its information rate, and which can effectively operate at a low channel signal-to-noise ratio, is generally referred to as a spread spectrum system. Common examples of spread spectrum are direct sequence pseudo noise (DSSS) and frequency hopping (FH) systems. The basic question here is whether CTAG can usefully employ spread spectrum to avoid the need for additional frequency allocations. Sufficient bandwidth must be available, and there must be tolerable self interference and acceptable interference to other systems.

4.1 BACKGROUND

Code Division Multiple Access (CDMA) communications employing spread spectrum has been advocated for mobile cellular telephony, personal communication networks, and wireless local area networks by QUALCOMM [12] and others [13, 14]. Most of the proposals employ DSSS rather than FH. Claimed advantages of CDMA are: 1) a much larger number of users who can share a given spectrum allocation; and 2) the ability to overlay new CDMA users on existing narrowband users.

The basic issue is the possible relevance of spread spectrum CDMA to CTAG. Do the claimed advantages apply to VHF A-G communications [15]? What are the limitations of spread spectrum CDMA? Before attempting to answer these questions, one should note the fundamental differences between cellular telephony and CTAG. In cellular telephony capacity is all important. The economic feasibility of cellular telephone systems depends upon maximizing capacity, i.e., the number of simultaneous users who can operate in a given geographic area. Quality of service obtained versus cost tradeoffs are acceptable, e.g., occasional loss of service for tens of seconds or even minutes is tolerable in order to provide an affordable system.

On the other hand, reliability, or more precisely, link availability, is all important for CTAG. The required capacity is driven by the growth of aviation traffic. A high quality of service must be provided; loss of service is unacceptable. This usually implies that redundant communications links must be provided and that relatively rare events must be considered in the system design.

4.2 ADVANTAGES

The most important attraction of CDMA is the promise of increased capacity, i.e., more users sharing a given spectrum allocation. This occurs because: 1) the entire frequency allocation can be used in every spatial CTAG "cell", and 2) the voice duty factor, i.e., periods of silences inherent in speech, can be more easily exploited in interference-limited CDMA than by bandwidth-limited TDMA and FDMA. Another strong advantage is the relatively

soft limit on capacity because of the gradual degradation under overload in CDMA, as opposed to the hard limit on capacity encountered with TDMA and FDMA.

Also, the overlaying of spread spectrum CDMA waveforms on the existing frequency allocations of narrowband users may be acceptable to those users. The typical interference of CDMA with any given narrowband channel is small and noiselike. Conversely, CDMA users can employ reduced transmitter powers and still communicate if they excise narrowband interference at their receivers.

In addition, accurate ranging is possible with a DSPN waveform. This would be useful in CTAG for cell-to-cell handover.

Finally, there is inherent privacy with spread spectrum CDMA as afforded by the DSPN code sequence. On the other hand, privacy is not difficult to achieve with narrowband digital communications through simple encryption techniques.

4.3 LIMITATIONS

A basic consideration in spread spectrum CDMA systems is the so-called "near-far" problem, viz., when the signal from a nearby transmitter dominates those arriving from relatively far away. As will be shown in more detail in subsection 6.1, in CTAG the separation of the uplink and downlink frequency bands reduces the magnitude of the near-far interference problem.

The same cell near-far interference on VHF A-G links is the limiting problem for spread spectrum CDMA. With fixed transmitter power, the dynamic range of signals received at the ground station can exceed the spread spectrum processing gain. Adaptive power control of airborne transmitters is required to reduce this dynamic range. Also, an adaptive array antenna at ground station can further reduce the dynamic range because near and far aircraft transmitters will usually be at different angles with respect to the ground station. The other self interference problem in cellular communication systems is adjacent cell interference. This is worse for VHF A-G communications than for cellular telephone systems because of the inverse-square propagation characteristic of LOS paths, as opposed to inverse-fourth-power propagation in land mobile cells.

The available processing gain of spread spectrum CDMA is about $250 = 2 \times 10^6 / 8 \times 10^3$, or 24 dB, assuming a spread spectrum bandwidth of 2 MHz and a baseband data rate of 8 kb/s. As shown in figure 4-1, there are three allocated segments of VHF bandwidth for ATC. Two of these are about 4 MHz wide. A spreading bandwidth of only 2 MHz allows some margin for decreasing potential interference in adjacent bands even further. The baseband data rate of 8 kb/s permits vocoded speech and the coding of digital data at 4.8 kb/s or less.

It is not unreasonable to assume that the cochannel interference limit (I/S) of AM radio is about -15 dB. Thus, without any power control within the CDMA system, the near-far margin for a single A-G CDMA link is only 9 dB. This corresponds to a relative range ratio of only $(10^{0.9})^{1/2} = 2.8$. There are still likely scenarios where signals from nearby aircraft would undesirably interfere with those from three times away.

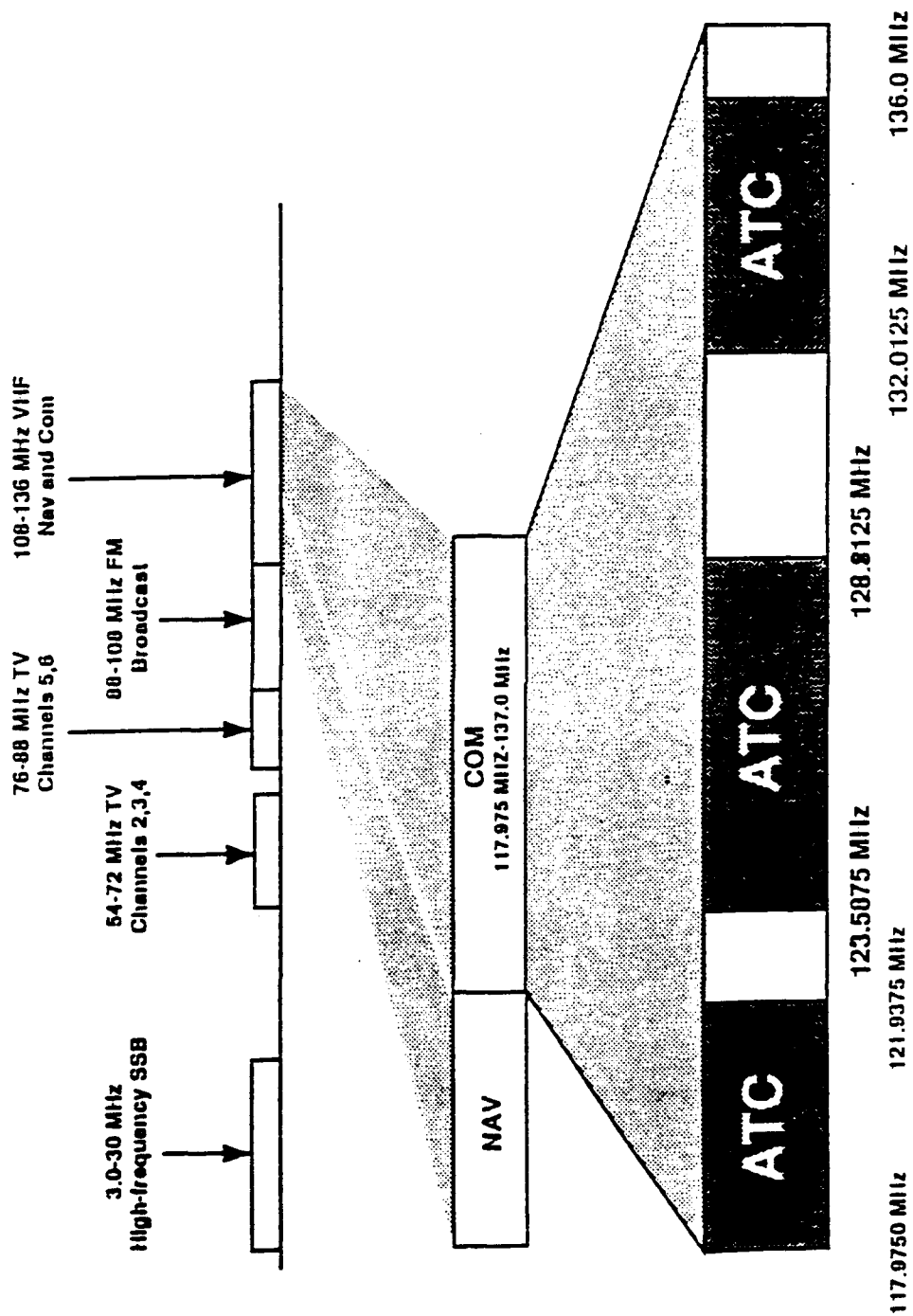


Figure 4-1. ATC Radio Spectrum

With perfect adaptive power control, i.e., if this 9 dB variation in received signal strength is controlled so that all CDMA signals are received with the same power regardless of the aircraft range, then $10^{0.9} = 8$ simultaneous CDMA A-G links can operate in each spatial cell [16].

To lessen potential interference to existing AM radios operating in the same band, operating the CDMA radios at a lower received signal level than the AM radios can provide additional margin against interference to these AM radios. However, AM radio interference to the CDMA system obviously gets worse when this is done. This latter situation can be mitigated by excising narrowband AM signals in the spread spectrum CDMA receivers. This is relatively straightforward using notch filters if the AM frequencies are known and fixed. If the AM frequencies are variable, some sort of adaptive excising technique would be necessary. In either case the complexity of the spread spectrum CDMA receiver would be increased compared to one without the excision feature.

In any event a transition from narrowband AM to spread spectrum CDMA within existing frequency allocations would be difficult. One would need to convince the frequency managers that the present AM equipment would not be adversely affected by the introduction of CDMA. This would undoubtedly require, at the minimum, interference testing in operational environments where the interference of the spread spectrum CDMA system was viewed as negligible.

Perhaps only one of the three ATC bands would be allowed for CDMA. Of course, if CDMA could be proven to be effective and non-interfering, one might hope to obtain permission to spread over larger bandwidths to attain increased processing gain.

4.4 CONCLUSIONS

From a cursory examination it is not possible to eliminate CDMA as a potential alternative for CTAG. It remains an interesting one and deserves further analysis.

However, adaptive power control and/or adaptive array ground antennas are needed to realize the theoretical advantages of increased system capacity and a CDMA overlay on AM users.

The implementation of CDMA is more "high tech" than the implementation of a new narrowband radio. Much more extensive analysis, and simulation for that matter, is required to properly evaluate CDMA for CTAG. But again, spread spectrum CDMA should not be rejected based upon the cursory analysis performed thus far.

SECTION 5

VOICE MESSAGE TRAFFIC MODEL

5.0 INTRODUCTION

This section develops a model for the generation of voice traffic between airplanes and ground controllers within the jurisdiction of a typical U.S. ARTCC, viz., Boston Center [17]. The model produces estimates of the average number of message exchanges associated with en route and terminal activities within the center's area during a peak period of aircraft traffic. In the case of terminal activities (aircraft arrivals and departures), the model reflects message traffic at Logan International Airport. Overflights at Logan have been neglected because they constitute a small fraction of the terminal traffic. The model also gives estimates of the length of exchanges.

It will be seen that the model lacks some desired details. For example, it doesn't treat the distribution of message generation times within a peak period, which may not be exponential (exchanges come in bunches). To account for this distribution more detailed traffic information is needed.

Although Boston center includes all of New England and a large portion of New York State, it is not the largest center. Logan International, is of category 4 (on a scale of 1 to 5, small to large) in size of the traffic it handles; Chicago (O'Hare) and Atlanta are in category 5. Boston also has a significant amount of international and over-the-ocean air traffic. Trans-oceanic traffic to and from the Boston area is handled by a special facility under the New York center. The Boston area is thus on the large side in terms of traffic and has a wide variety of traffic types. For these reasons it appears to be a suitable standard starting example for a larger airport CTAG analysis. Later, one may want to consider tougher cases in which there are more than one large airport in the center's area, for example, New York City.

The en route and terminal operations of a typical flight in terms of the number, lengths and frequencies of the associated message exchanges with ground controllers are described in this model. Monitoring of traffic and discussions with pilots and controllers suggest that the numbers of exchanges during departure and arrival are roughly the same. The current radios used by controllers appear to be set more or less permanently on one frequency in the VHF aircraft band (118-137 MHz).

After consideration of a typical flight's exchanges, estimates of the total numbers of terminal operations and en route flights in a center's area during the peak traffic period [6], the duration of the peak, and the fraction of the total peak terminal traffic that uses Logan are combined with the information on individual operations. This leads to estimates of

- the average number of exchanges per frequency during the peak, and
- the average fraction of the peak period occupied by exchanges on one frequency.

These two numbers will give us an idea of what message volume or duty factor per frequency the CTAG system will have to handle in a typical center's area.

The duration of the peak (gathered during a visit to the Manchester, New Hampshire TRACON) may be pretty rough, as is the estimate of the total terminal traffic Logan handles, which is based only on a controller's confirmation of a suggested number.

5.1 TERMINAL SEQUENCE

In this subsection, "controllers" associated with departures and landings and the average number and length of exchanges associated with each controller for each flight are listed. A controller is defined here as a fixed radio position that is usually on one frequency at a time. Near a large airport, or when an en route controller is handling more than one sector, a controller may have exchanges with one airplane on one frequency that are broadcast on other frequencies to other airplanes.

Note that different controllers may be located at the same place, and that communications antennas associated with terminal operations are not necessarily at airports. Exchanges may be initiated by a controller or an aircraft. As a general rule, aircraft appear to initiate the majority of the exchanges up to departure, and controllers the majority (in particular, frequency hand offs) after take off. In each case, a typical value is given in parentheses. The typical values are taken from FAA publications [7] channel monitoring and discussions with pilots and controllers. Note also that when the weather is bad there will be more traffic—including more repeats—than the amounts given here.

Let *NDGC*, *NCL* and *NDC* equal the average number of exchanges between an aircraft and a ground controller, clearance controller, and departure controller, and let *TDGC*, *TCL* and *TD* (with examples in seconds) be the corresponding mean exchange lengths. These variables are displayed (with example values for Boston-Logan) in the following table, which summarizes exchanges during a typical departure.

Departure:

Controller	No. of exchanges*	Avg. length of exchanges (examples in seconds)
Ground control	<i>NDGC</i> (3) (flight plan [#] , other advisories)	<i>TDGC</i> (25)
Clearance	<i>NCL</i> (5) (pre-taxi clearance, clearance delivery)	<i>TCL</i> (6)
Departure	<i>NDC</i> (3) (takeoff)	<i>TD</i> (6)

 * At the start of nearly every exchange there is a brief check in by the aircraft to confirm the new frequency and establish connection.

[#] Filed via radio by only a fraction of aircraft. Most file by telephone from a terminal.

Arrival:

In the next table, *NTA*, etc., stand for the corresponding average numbers of exchanges, and *TTA*, etc., to the corresponding mean exchange lengths, with examples in seconds.

Controller	No. of exchanges	Avg. length of exchanges
(Terminal) Approach control	<i>NTA</i> (6)	<i>TTA</i> (6)
Arrival	<i>NA</i> (5)	<i>TA</i> (6)
Ground control	<i>NAGC</i> (3)	<i>TAGC</i> (6)
Gate control	<i>NGT</i> (2)	<i>TGC</i> (6)

5.2 ENROUTE SEQUENCE

The table in this section lists the en route controllers associated with the Nashua, New Hampshire ARTCC. Each en route controller, whose antennas are located at ARTCC *remoted sites*, has at least one *low altitude* frequency. About half the ARTCC remotes in a typical center's area also have at least one *high altitude* frequency. A few remotes in each area have as many as three low altitude and three high altitude frequencies. Thus, the number of frequencies associated with an en route controller will vary between one and about six. The table's format is the same as for the terminal listing.

En route:

In the table below, *RART i* is a controller (sitting at the ARTCC) associated with the *ith* ARTCC remote site, *NART i* stands for the average number of exchanges with that *ith* ARTCC controller and *TART i* is the corresponding mean exchange length, with examples in seconds. A RART may have access to more than one frequency, so that the correspondence between controllers and frequencies used is not strictly one-to-one.

Controller	No. of exchanges	Avg. length of exchanges
<i>RART 1</i> #	<i>NART 1</i> (5)	<i>TART 1</i> (6)
<i>RART 2</i> #	<i>NART 2</i> (2)	<i>TART 2</i> (6)
.	.	.
.	.	.
.	.	.
<i>RART N</i> #	<i>NART N</i> (5)	<i>TART N</i> (6)

The ARTCC remotes used at the start and finish of a flight are typically near large airports and will thus need to communicate more often with approaching aircraft than remotes far away from large airports.

The variable *N*, the number of ARTCC controllers talked to en route, is about three or four for a flight across an area, and goes up proportionately for longer flights.

5.3 ESTIMATES OF MEAN CALL OCCURRENCE TIMES AND EXCHANGE DURATIONS

To produce these estimates the following definitions are introduced:

TP = duration of peak traffic period in seconds (7,200 for morning peak, 14,400 for evening),

NER = number of en route flights in Boston Center area during the peak (2,200),

$NERF$ = number of en route frequencies ($\approx$ three times the number of ARTCC remotes) (61),

NT = number of terminal flights in Boston Center during peak (250),

NTF = number of terminal frequencies used at Logan during peak (9), and

α = fraction of NT handled by Logan (0.7).

(This artifice will not be necessary when we get statistics on the traffic at specific airports.)

Also let

$CD(CA)/(CER)$ = average number of exchanges during departure (arrival) (en route flight);

hence:

$CD = NDGC + NCL + NDC$ (11) (see the notation under *Departures* in subsection 5.1),

$CA = NTA + NA + NAGC + NGT$ (16) (see *Arrivals* in subsection 5.1), and

$$CER = \sum_{i=1}^N NART_i \quad (= 5 + 2 + 2 + 2 + 5 = 16 \text{ for } N [\text{no. of RARTs contacted}] = 5), \text{ since } CER$$

equals the average total number of exchanges with the N RARTs called en route (see *En route* in section 5.2).

Finally, let

$NXER$ = average number of (en route) exchanges per ARTCC controller during peak and

NXT = average number of (terminal) exchanges per TRADOC/ARTCC controller during peak.

Then for *en route* traffic in the Boston ARTCC

$NXER = NER \cdot CER \cdot 1/NERF = 2200 \cdot 16 \cdot 1/61 = 577$ en route exchanges/cell, and for Logan terminal traffic:

$$NXT = \alpha \cdot NT \cdot (CD + CA) \cdot 1/NTF = 0.7 \cdot 250 \cdot 27 \cdot 1/9 = 525 \text{ terminal exchanges/cell.}$$

Since some of the ARTCC locations are in remote locations, they may handle significantly less message traffic than those in busy areas, so $NXER$ should be kept in mind as an *average*.

Now let

$TBEXER$ = average time between en route calls in seconds, and

$TBEXT$ = average time between terminal calls in seconds.

If the exchanges are distributed *uniformly* across the peak period (they may not be), then one obtains

$$TBEXER = TP/NXER \text{ and}$$

$$TBEXT = TP/NXT.$$

The TRACON controller in Manchester, NH, stated that the *evening* peak there, when about the same amount of traffic is handled as in the morning peak, is about four hours long (14,400 s), whereas the morning peak is only two hours long, so for *en route* traffic in the Boston Center,

$$TBEXER = 7,200/577 = 12.5 \text{ s for the AM peak and } 14,400/577 = 25 \text{ s for the PM peak.}$$

For *terminal* traffic at Logan (assuming that the peaks at Logan last about as long as at Manchester)

$$TBEXT = 7,200/525 = 13.7 \text{ s (AM peak) and } 14,400/525 = 27.4 \text{ s (PM peak).}$$

The peak values of aircraft traffic cited and used above are instantaneous values, and I'm assuming that the peak instantaneous values persist during the peak period. One needs to know more about how air traffic changes during the peak period before these estimates of the TBs can be refined.

Another approach:

During the 6 June video teleconference with CAASD, J. E. Dieudonne mentioned anecdotically that Washington National handles about one aircraft every 27 s at peak. If one assumes that the same happens at Logan (which uses two runway frequencies), then the number of exchanges per second per runway frequency at Logan can be estimated as $1/27 \cdot 1/2 \cdot NA = (5/54)/s$, and $TBEXT$ as the reciprocal of this, or about 10 s. (Recall that $NA = 5$ is the average number of exchanges during a typical runway approach.) Given that National probably handles somewhat more peak traffic than Logan, this result provides some corroboration of the previous $TBEXT$ estimate.

5.4 THE DISTRIBUTION OF EXCHANGE LENGTHS

Monitoring of Logan and Manchester, NH, message traffic, and discussions with Manchester and Nashua controllers and general aviation pilots have led to the following observations:

- a. There is usually not much difference between the lengths of exchanges between controllers and commercial or general aviation aircraft. Because of their generally smaller experience, general aviation pilots may take slightly longer to complete their exchanges than commercial pilots.
- b. The distribution of exchange length (the great majority of calls bring forth an immediate response of roughly the same length as the call) seems to be bi-modal, with one mode at about 6 s and the other between about 20 to 30 s, primarily associated with filing or coordination of flight plans.

5.5 ESTIMATING THE MAXIMUM AND MINIMUM NUMBER OF CELLS NEEDED IN AN AREA

One way to estimate the *largest* number of cells needed to handle the en route and large-airport traffic in an ACF is to assume that these numbers equal the the numbers of en route and large-airport controller frequencies that planes *currently* use for exchanges in the ACF. The number of controllers, which is probably close to the *smallest* number of cells one might want to assume, is smaller than the number of frequencies to which controllers have access.

The number of ARTCC remote frequencies in an area is listed in the back of the *Airport/Facility Directory* [7] that applies to the ARTCC. In the Boston Center area there are 26 ARTCC remotes. They use 61 (high and low altitude) frequencies.

In the Boston Center area there are three Flight Service Stations. Associated with them are about 20 Remote Communications Outlets (RCOs), each with at least one frequency for two-way communications mainly with general aviation aircraft. The RCOs could conceivably be used as cells.

Associated with TRACONs are a number of Remote Control Air-Ground (RCAG) radio sites. A map in Nashua shows about 25 RCAGs used in the Boston Center. Some of the RCAG sites become RCAGs only at night, and are typically at airports. The Manchester TRACON has Loring AFB and the former Pease AFB [now used commercially] as RCAGs at night. The RCAGs are probably also candidates for cell status.

5.6 CONCLUDING REMARKS

The analysis is summarized by figures 1-3 and 1-4 and table 1-6 in subsection 1.5.4, Volume 1. Additional progress on the traffic model might benefit from additional information:

- More accurate data on the call occurrence and exchange length distributions for particular controllers (especially near large airports). Rough estimates of these can be inferred now, however.
- More detail on the correspondence between en route controllers and their use of the frequencies assigned to the ARTCC remote sites. This will probably help determine more accurately the cell site candidates.
- Length of the peak periods at typical, large airports (of less importance than the first two categories of information).

Two themes re-occurred in discussions with pilots and the Manchester controllers. One is the eagerness of both pilots and controllers to have an automatic means for assigning and switching airplane radios to new communications frequencies.

The second theme is the seriousness of the "stuck-mike" problem. One can easily imagine that one of the accoutrements of a CTAG solution to the frequency handoff problem would be an automatic means of informing pilots of stuck microphones. This could be done on the receiving frequency in use (in the current CTAG concept), or on a frequency a stuck radio is switched to by the CTAG system.

SECTION 6 THREE-DIMENSIONAL CELLULAR SOLUTION

6.0 INTRODUCTION

A three-dimensional cellular tessellation is proposed in this section. Propagation characteristics expected for LOS and BLOS signal paths are taken into account.

6.1 FUNDAMENTAL CONSIDERATIONS

Basic considerations on cell structure and frequency reuse are presented in this subsection [18].

Frequency reuse in CTAG will be limited primarily by cochannel interference. The degree of cochannel interference will depend upon whether or not the same channel is used for the uplink and downlink in each cell of a cellular structure. Usage of the same channel for the uplink and downlink is referred to as half-duplex operation, because most half-duplex radios use the same frequency for transmission and reception. However, it is possible, but uncommon, to have half-duplex operation with different transmitting and receiving frequencies. As will be seen, end users will enjoy full-duplex operation ("simultaneous" transmission and reception) even though the radios may only transmit or receive on an instantaneous basis.

Case 1: Consider half-duplex operation with a single channel (frequency) time-shared between the uplink and downlink in each cell, but no time coordination between cells; R is the signal propagation range.

Table 6-1. Cochannel Interference for Half-Duplex Operation.

Receiver in Cell A	Transmitter in Cell B	
	Ground	Airborne
Ground	Non LOS Signal strength approximately proportional to $1/R^4$	LOS to radio horizon Signal strength approximately proportional to $1/R^2$
Airborne	LOS to radio horizon Signal strength approximately proportional to $1/R^2$	LOS to radio horizon Signal strength approximately proportional to $1/R^2$

Let Cells A and B be any two cells which share the same channel (frequency). As table 6-1 shows, cochannel interference to a downlink (the first row of table 6-1) will be primarily due to airborne transmitters since these encounter less path loss than ground transmitters. There appear to be two limiting subcases:

a. With very large cells, one could separate cells A and B by more than the distance D to the radio horizon from a high-altitude aircraft. This would eliminate cochannel interference under normal propagation conditions. If the cells are large enough, the number of cells within the horizon distance, which must each be assigned different channels, is reasonable as compared to the number of available channels in CTAG.

b. With very small cells, one must reuse frequencies within the horizon distance D , in order that the number of cells requiring different channels not become too large relative to the number of available channels in CTAG. In this case, cells A and B are separated by less than the distance to the radio horizon from a high-altitude aircraft. An analysis of signal-to-interference (S/I) ratio is necessary to determine the necessary separation of cells A and B as a multiple of the cell dimension. Because signal strength falls off approximately as $1/R^2$ for VHF air-ground links, for link ranges somewhat less than the distance to the radio horizon, this separation multiple will be larger than the corresponding multiple for UHF cellular telephones, where signal strength for ground-to-ground links falls off approximately as $1/R^4$. If the separation multiple becomes large enough, the number of cells needing different channels may become too large compared to the number of available channels.

Cochannel interference to a half-duplex uplink (the second row of table 6-1) can occur from either ground or airborne transmitters. The same two limiting subcases exist.

c. With very large cells, Cells A and B could be separated by more than the radio horizon distance between two high-altitude aircraft, eliminating cochannel interference under normal propagation conditions. The necessary separation distance becomes approximately $2D$, twice that in subcase (a) above, resulting in approximately four times the number of cells needing different channels.

d. With very small cells, frequency reuse must occur within the horizon distance, as in subcase (b). An analysis of S/I is necessary for this subcase also. Note that on the uplink (this subcase) cochannel interference can be caused by both ground and airborne transmitters, whereas on the downlink, subcase (b), cochannel interference will be dominated by airborne transmitters. Thus, subcases (b) and (d) will be quantitatively different.

Case 2: Consider full-duplex operation with separate channels (frequencies) for the uplink and downlink in each cell.

Table 6-2. Cochannel Interference for Full-Duplex Operation.

Receiver in Cell A	Transmitter in Cell B	
	Ground	Airborne
Ground	No cochannel interference	LOS to radio horizon Signal strength approximately proportional to $1/R^2$
Airborne	LOS to radio horizon Signal strength approximately proportional to $1/R^2$	No cochannel interference

With full-duplex operation, only a downlink in cell B can interfere with a downlink in cell A, and only an uplink in cell B can interfere with an uplink in cell A, as table 6-2 shows. Cochannel interference to a full-duplex downlink (the first row of table 6-2) comes only from airborne transmitters. Since these were the primary source of cochannel interference in half-duplex operation, the allowable cell spacing for frequency reuse should be about the same for either half-duplex or full-duplex operation. The same two limiting subcases of very large and very small cells will exist.

Cochannel interference to a full-duplex uplink (the second row of table 6-2) comes only from ground transmitters. There is a significant difference in allowable cell spacing for frequency reuse between full-duplex and half-duplex operation. Consider again the two limiting cases of cell size:

- e. With very large cells, cells A and B could be separated by more than the distance D to the radio horizon from a high-altitude aircraft, which would eliminate cochannel interference under normal propagation conditions. One notes that the required cell spacing to eliminate cochannel interference to an uplink is only half as large for full-duplex operation (this subcase) as for half-duplex operation (subcase c).
- f. With very small cells, frequency reuse must occur within the horizon distance D . An analysis of S/I is necessary for this case. Results will be quantitatively different for a full-duplex uplink (this subcase) than for a half-duplex uplink, subcase (d), because there are fewer sources of cochannel interference with full-duplex operation, as can be seen by comparing the second rows of tables 6-1 and 6-2.

It seems clear, even before performing detailed S/I analysis, that one should probably separate the uplinks and downlinks in frequency to minimize the separation between cells able to reuse the same frequencies.

6.2 OUTLINE OF SPECIFIC SOLUTION

An outline of a possible solution to the cellular problem for CTAG [19] is contained in this subsection. The requirements used for this solution include the following:

1. The volume to be covered includes the airspace over the U.S. from 2000 ft to 60,000 ft (at least).
2. Any place in the above volume should be "covered" by at least two antennas.
3. The total number of sites allowed is about 1200.
4. Frequencies should be reused so as to minimize the total number of service channel frequencies that need to be scanned.

A quick look at this problem is enough to realize that a multitiered approach is required. In order to provide coverage at low levels antennas must be closely spaced. However, at high levels many antennas will be in view so that frequency reuse is not effective if the same frequencies are used for both high and low aircraft. It is shown below that a three level approach works well.

It is also assumed that separate sets of frequencies are used for uplinks and downlinks. As pointed out by R. I. Millar [18], this reduces A-A interference problems. When using this approach all A-A connectivity is accomplished via ground relay and would be under the control of the air traffic controller.

In a typical cellular problem only single coverage is required. The coverage provided by a single omnidirectional antenna is presumed to be circular. A close-packed array of antennas thus produces a hexagonal pattern where the long dimension of each hexagon is equal to the diameter of the coverage circle. In this situation one wants dual coverage. Multiple coverage can be achieved by making the distance between antennas be equal to the radius of the coverage circle. However, if all cells in a hexagonal pattern are occupied it turns out that any point is within view of three antennas. Since one only needs double coverage only two thirds of the cell sites are populated. The resulting pattern is shown in figure 6-1. The smaller circle represents the LOS range of the antenna at its center. This range clearly depends on the height of the aircraft. In this case that height is taken to be the lowest altitude served by the cell. If more small circles were drawn it would be easy to see that the entire surface is covered by at least two circles. Note that the resulting pattern is really triangular. Some of the triangles have been drawn in the figure. However, since most readers will be familiar with the hexagonal approach the hexagons are retained. One should bear in mind, however, that each antenna covers its own triangular cell and one third of each of its three neighbors — for a total of two cells.

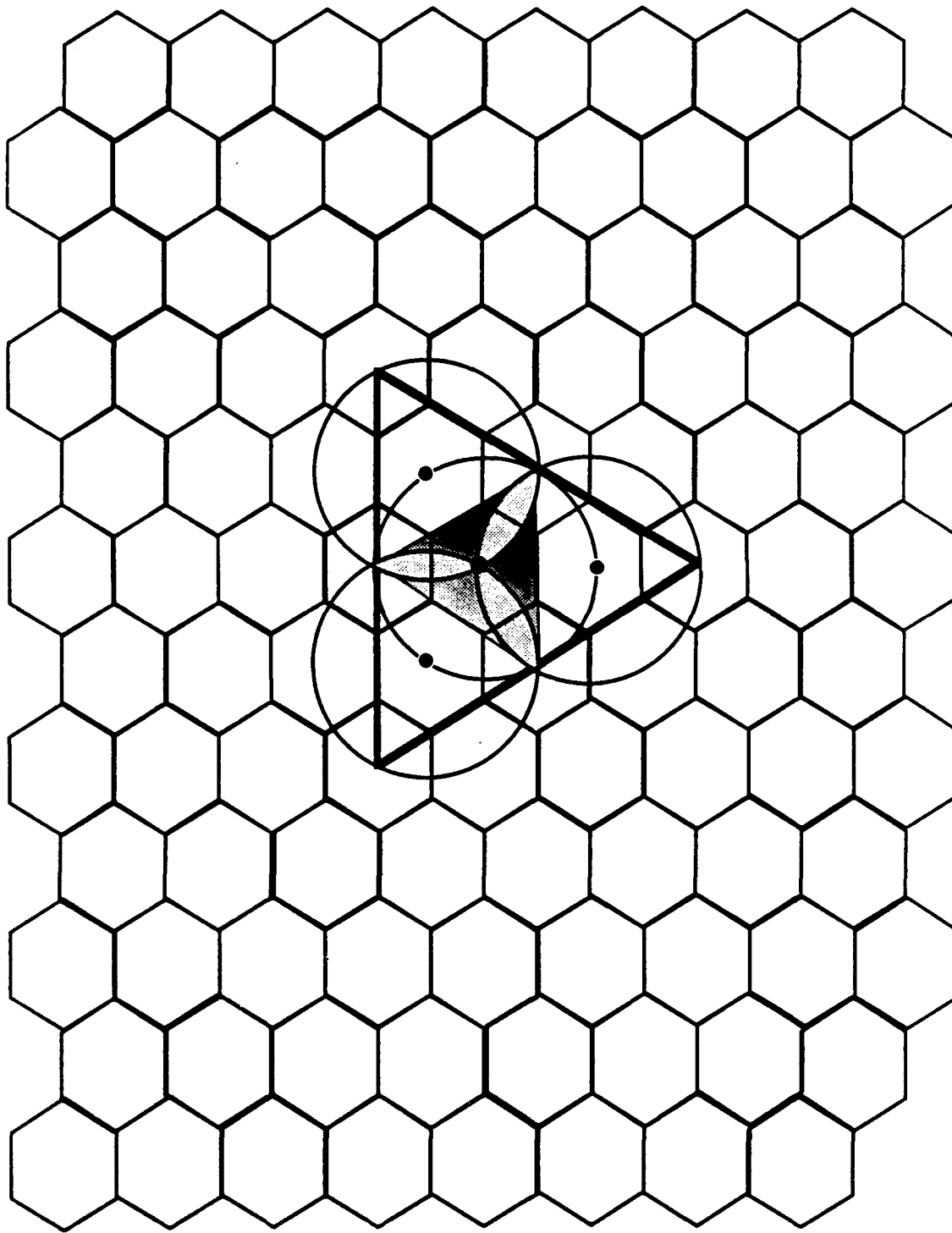


Figure 6-1. Two-Thirds Population of Hexagonal Cells Assuming at Least Double Coverage

Figure 6-1 represents only one level of the three level approach. Figure 6-2 shows the full three-level geometry. The sites marked with "X" serve only low-level users; the sites marked with "O" serve low and medium level users; and the filled sites serve all three levels. As shown in figure 6-2, the triangular cells are conveniently nested so that each large cell contains four intermediate cells, and each intermediate cell contains four small cells.

The "radius" of each cell type is twice that of the next smaller type. The LOS range D (i.e., the "radius") is related to aircraft height h by the equation

$$D = \sqrt{2hR_e k} \quad (2)$$

where R_e is the Earth's radius, and k is taken to be $4/3$; k takes into account bending due to the nonuniform index of refraction of the atmosphere. Due to the square root factor each cell type has a minimum height four times that of the next smaller type. If the cell size is chosen properly the heights served by the three tiers are

1.	low:	1,125 ft - 4,500 ft
2.	intermediate:	4,500 ft - 18,000 ft
3.	high:	18,000 ft - 72,000 ft

The size of the small cells is such that the radius of the small circles is about 40 nmi. Note that since antenna heights are likely to be at least 100 ft the actual LOS distance may be larger. However, this fact is neglected, and ground antenna height is used to provide a small margin of error for nap-of-the-earth propagation. The small triangles have area equal to 2080 sq. nmi. The U.S. can be covered by about 1300 cells (or 1100 if Alaska is omitted). Only one fourth of these cells (about 325) are necessary to provide blanket coverage from 4500 ft to 72,000 ft.

The boundaries of the cells are presented as if they were quite precise, when actually the boundaries are very "fuzzy". In particular the upper limit of each cell is determined primarily by the level at which interference due to frequency reuse becomes intolerable. This clearly depends on the frequency reuse pattern. An attempt was made to arrange it so that an aircraft at the top of a cell can see at least two cells such that it is within LOS of those cells and such that all other cells using the same frequencies are well over the horizon. It is preferable, but not necessary, that the reuse pattern have a "convenient" relationship with respect to the hierarchy of cell sizes. One promising pattern is shown in the figure 6-3. The cells labelled "A" reuse the frequency used in the center of the circle. The larger circle represents the LOS range of the highest aircraft deemed to be in that cell. An aircraft at the point labelled "B" is within LOS of the central cell but is well over-the-horizon with respect to all other cells using the "A" frequency.

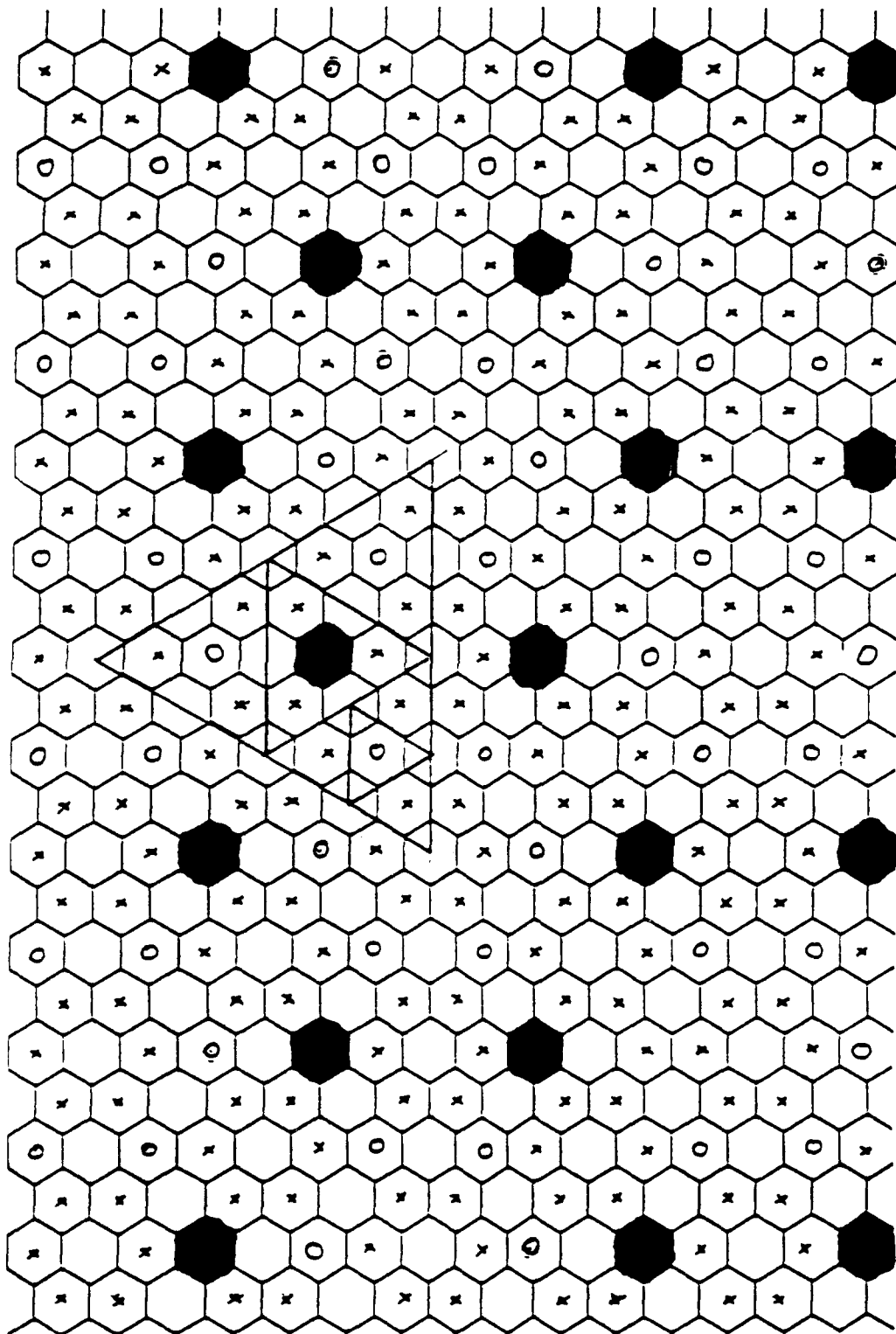


Figure 6-2. Nesting of Three-Sized Triangles

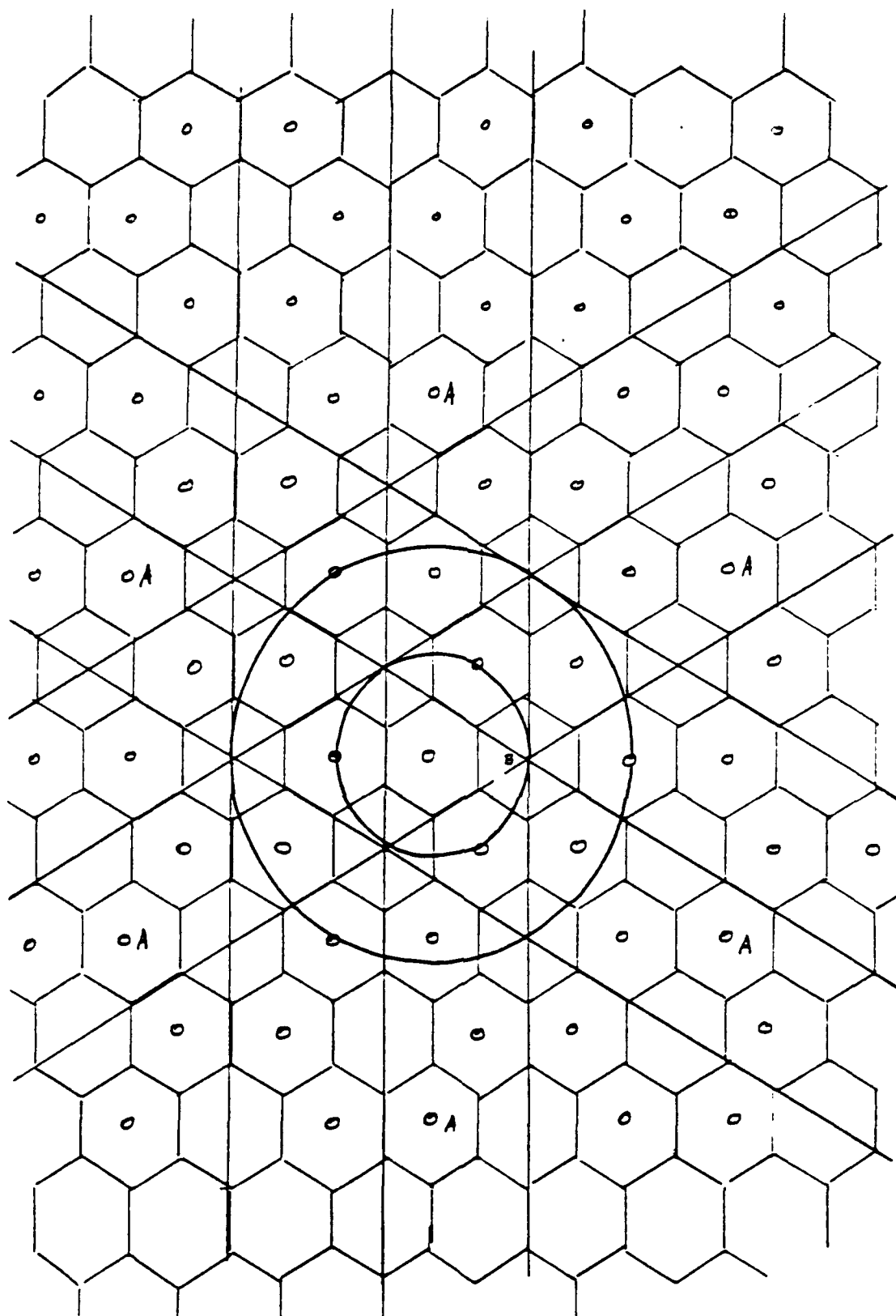


Figure 6-3. Frequency Reuse Relationships for Cells with Double Coverage

That is the main principle one tries to use to control S/I. The interference levels at point B, based on range alone (using $1/R^2$ propagation), would be intolerable. Later (see section 7) using propagation models it was verified that the over-the-horizon propagation losses are great enough. If the frequency reuse pattern shown in the figure 6-3 works, then only eight frequencies are needed for each level. Thus, there are at most 24 service frequencies which need to be scanned.

The work done to quantify the propagation losses and to relate those losses to the resulting S/I levels led to the realization that at least eight frequencies are needed at each level, or at least 24 service frequencies need to be scanned. Additional frequencies may be needed because of terrain conditions that prevail in a given region (see section 7). The propagation modeling results can also be related to requirements on the performance of the modulation technique chosen for voice and data communications.

SECTION 7

CTAG FREQUENCY REUSE

7.0 INTRODUCTION

This section confirms the need for eight frequencies at each of the three cellular layers of section 6. This analysis is due to W. J. Wilson [20] with computational support and guidance from C. C. Li and R. I. Millar, respectively.

7.1 BACKGROUND

The purpose of this exercise is to determine the most efficient frequency reuse pattern for CTAG. Recall that one of the basic principles of cellular communications is frequency reuse. The most efficient system is the one which allows a given frequency to be reused the most times within a given geographical area. This criterion is equivalent to the criterion of reusing a frequency within the shortest possible distance. High frequency reuse helps the cellular approach in two ways. First, high efficiency means that a small number of frequencies can be used as service frequencies, which simplifies and speeds up the cell hand-over problem. Second, high reuse means that more of the limited number of available frequencies can be assigned to each cell, thus increasing overall system capacity.

Technically, the reuse problem consists of determining the minimum distance between transmitters such that a receiver is close enough to one and far enough from all the others so that the signal-to-interference (S/I) ratio is high enough to allow adequate communications performance. In some ways the air-ground (A-G) problem encountered by CTAG is easier than ground-ground (G-G) problem faced by cellular mobile radio. In the mobile case, all links are assumed to be over-the-horizon (OTH) and separations are based on r^{-4} (r = range) propagation models. The airborne situation can be arranged so that the desired link is always line-of-sight (LOS) while the interferers are OTH.

This approach may at first seem simple. One needs only to find the horizon distance for a given cell, and ensure that the cell's frequency is reused just beyond that distance. However, the situation is not so clear cut. The situation on the boundary between LOS and OTH is really rather blurry due to diffraction, refraction, and scattering effects. Also, the locations of the boundary varies due to the local relief of the earth (i.e, it is not as smooth as a billiard ball). Thus, receivers which are just above and just below the radio horizon with respect to a transmitter may receive signals of similar strength. Therefore, one must allow for a margin of error. Luckily, there are a number of models which can be used to estimate how large the margin must be.

7.2 CELL STRUCTURE

Before proceeding much further the proposed cell structure is reviewed. The cells consist of a nested set of three sizes of equilateral triangles. The smallest set serves users at

the lowest levels, the medium size triangles serve the next higher users, and the largest set serves the highest users. They are nested in such a way that each larger triangle contains exactly four of the next smaller triangles. The sizes of the service volumes are shown in table 7-1 below:

Table 7-1 Service Volume Sizes

<u>Largest Distance</u>	<u>Altitude Range</u>
40 nmi	1125 ft - 4500 ft
80 nmi	4500 ft - 18,000 ft
160 nmi	18,000 ft - 72,000 ft

The "largest distance" is meant to mean the distance between the center of the triangle (the location of the transceiver) and any one of the corners. This distance also happens to be the distance to the centers of the three nearest neighbors. This last feature allows the three neighbors to take over servicing a cell if its transceiver should fail, thus providing emergency backup. (Note that the triangular pattern can also be thought of as a traditional hexagonal pattern in which only two thirds of the cells are populated).

The distances and heights mentioned in table 7-1 are based on the assumption that radio waves experience refraction, which causes them to bend around the earth according to the 4/3 earth model. That is, the LOS is roughly equivalent to what one would get by assuming the radius of the earth is 4/3 its actual value. In what follows, one also assumes that the ground-based antennas are situated at the tops of 100 ft high towers.

7.3 REQUIRED SIGNAL-TO-NOISE RATIO

Another ingredient in the determination of frequency reuse is the required signal-to-noise ratio (SNR). The noise here is primarily due to other interfering (undesired) CTAG signals. It is assumed, for simplicity, that this noise is Gaussian.

As a compromise between maximizing the transmitted bits/hertz and maximizing the resistance to noise, differentially encoded quadrature phase shift keying (DQPSK) has been chosen as the signal modulation type. Standard textbooks show that this type of modulation requires a SNR of about 7 dB to provide a bit-error probability of 10^{-2} . This bit-error probability is assumed to be acceptable for the chosen Code Excited Linear Prediction (CELP) voice digitization technique.

7.4 FREQUENCY REUSE PATTERNS

There are an infinite number of reuse patterns that can be used to tessellate a plane earth. Here, one is interested in only those involving small numbers of frequencies. Some of these are listed in table 7-2 below. Note that there are two types of patterns depending on whether the number of nearest frequency reusers is 3 or 6.

Table 7-2 Frequency Reuse Pattern Data

	<u>Number of Frequencies</u>	<u>Size of Reuse Pattern (cells)</u>
6-Fold Reuse Patterns	2	2
	6	6
	8	8
	14	14
3-Fold Reuse Patterns	4	8
	7	14
	13	26

The ones of most interest for present purposes use 6, 7, or 8 frequencies and are shown in figures 7-1 to 7-3. Note that these figures represent possible configurations for a particular type link at a particular altitude range. There is no requirement that the different levels use the same patterns, or that uplinks use the same patterns as downlinks (although it might be convenient).

Some important characteristics of these patterns are: 1) the distance between a cell and the nearest cells to reuse its frequency (center-to-center); 2) the distance from the center of one such cell and the closest corner of one of the others; and 3) the number of such cells. These properties are listed in Table 7-3. The numbers are normalized so that the distance from the center of a cell to its own corners is 1.

Table 7-3 Frequency Reuse Pattern Characteristics

Number of Frequencies	Center-to-Center Distance	Number of Neighbors	Center-to-Corner Distance
6	3	6	2
7	$\sqrt{7}$	3	2
8	$2\sqrt{3}$	6	$\sqrt{7}$

The significance of this table lies in the last column. Consider a ground-to-air link where the airborne user is at the corner of a cell. The distance to the transmitter is denoted as 1 unit. When the receiver is at the bottom of the cell it is barely above LOS (that is how the cell size was chosen) and it is well beyond LOS for any other cell using the same frequency for all 3 patterns. Therefore, the S/I ratio is expected to be large. However, at the top of the cell the situation is different. Here, for the 6- and 7-frequency patterns, the receiver is also within LOS of at least one competing transmitter. This is so because the top of the cell is

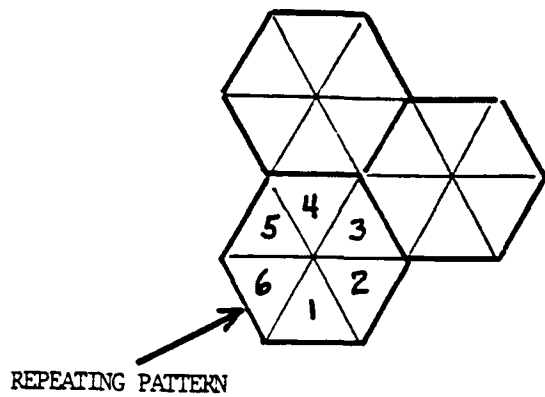


Figure 7-1. 6-Frequency Pattern

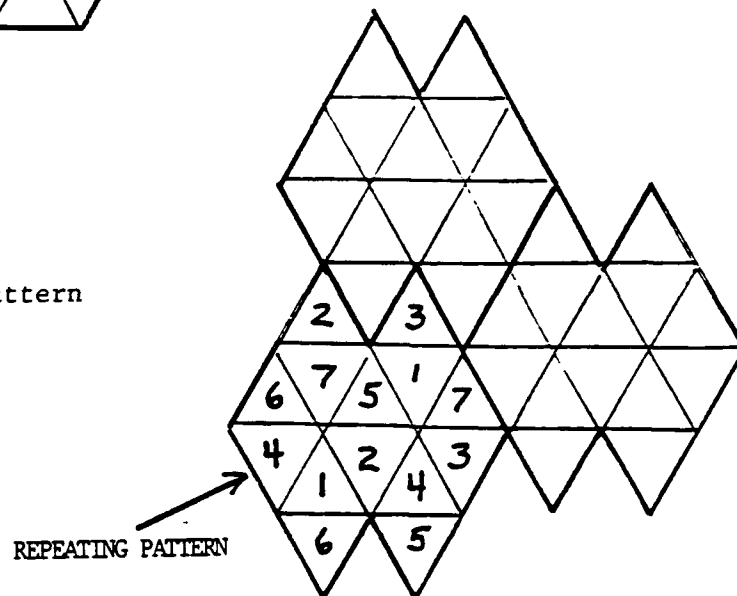


Figure 7-2. 7-Frequency Pattern

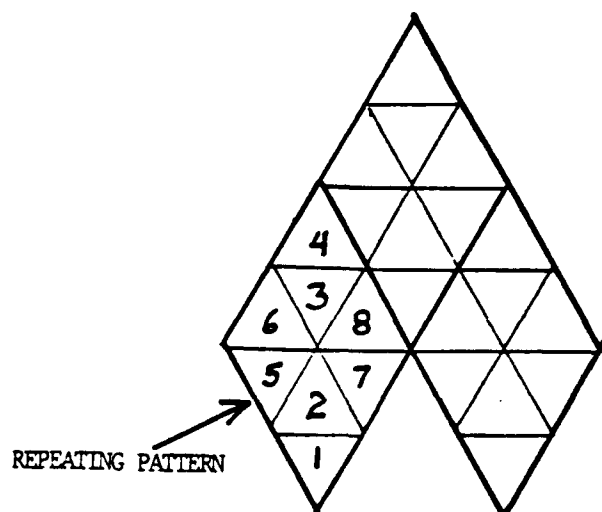


Figure 7-3. 8-Frequency Pattern

defined as the altitude where the effective LOS is double. In the next subsection on propagation, it is shown that the distant signal suffers some excess path loss due primarily to two ray multipath effects. This loss, coupled with the 6 dB S/I difference due to the two-to-one range ratio, may be enough to increase the S/I to an acceptable level; however, there may not be much margin for error. It might be more prudent to consider the 8-frequency pattern.

The situation for air-to-ground links can be even worse. Here, an airborne transmitter at the bottom of a cell may have to compete with interference from a source at the top a neighboring reuse cell. For the 6- and 7-frequency cases, both links are just over the horizon and suffer similar excess path losses, thus the interfering signal may be within 6 dB of the desired signal, which is probably not acceptable. Thus, for downlinks it may be mandatory to chose a pattern with at least 8 frequencies. The detailed properties of the different approaches are given in the next section.

7.5 PROPAGATION EFFECTS

In order to make a good estimate of the optimum frequency reuse patterns, one needs to have a good estimate of the propagation loss near and beyond the radio horizon. There are a number of techniques for making such estimates. There are computer programs by Longley-Rice and by Johnson-Gierhart based on semi-empirical models. There are at least two techniques described by Bullington in his well-known 1957 paper in the Bell System Technical Journal [21]. One of these is based on a nomograph and works only beyond the horizon. The other method is based on a graph which uses Fresnel zone clearance as its main input. One final technique employed is a two-ray multipath model which can be used for LOS links at low grazing angles. This model takes into account such factors as the (complex) reflection coefficient of the earth, divergence due to the earth's curvature, and the average roughness of the earth. It is based on methods described in CCIR report 1008 [22].

As discussed in the previous section, the most interesting locations to consider propagation effects are at the tops and bottoms of the various cells. Thus, attention is focused on links where the aircraft are at 1125 ft, 4500 ft, 18,000 ft, and 72,000 ft. In each case, a graph showing the excess path loss versus distance, with altitude held fixed, has been constructed. Excess path loss is the loss over and above the free space loss factor proportional to r^2 .

The four graphs (figures 7-4 to 7-7) show the estimates of the excess path loss for the various models superimposed. They all assume that the frequency is 125 MHz and make similar assumptions (where applicable) about the roughness of the earth (~10 m), the type of earth (dry ground), etc. In all cases, the ground antennas are assumed to be elevated 100 ft above the ground. It is gratifying that all the techniques seems to agree with one another in a general way. The Longley-Rice model seems to give somewhat high estimates of the loss, while the Bullington graphical technique estimates low values. The Bullington nomograph and the Johnson-Gierhart model agree quite well; and the two-ray model seems to agree with the latter two in a general sense. In what follows the Johnson-Gierhart values are used as the

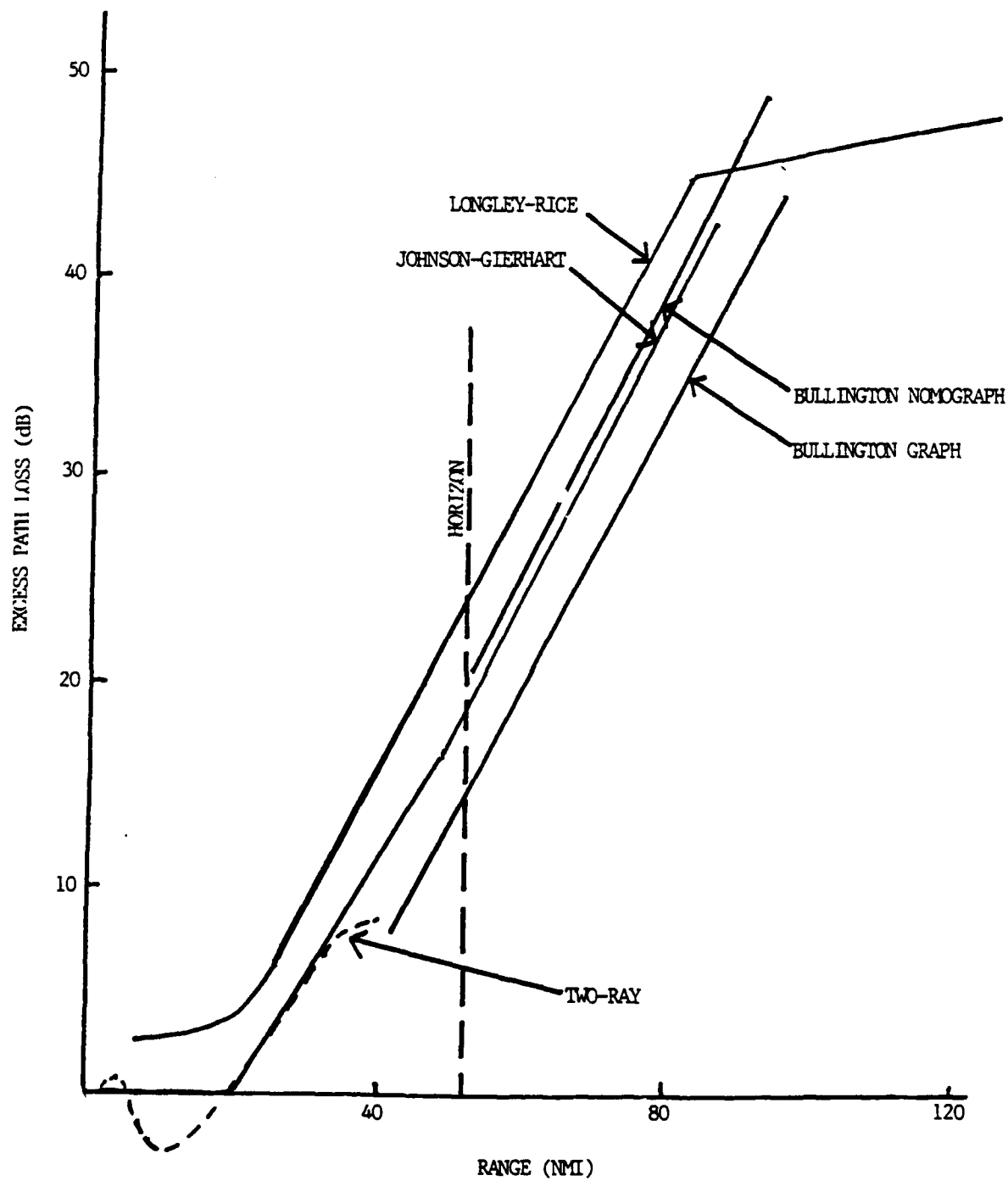


Figure 7-4. Excess Path Loss at 1,125 ft.

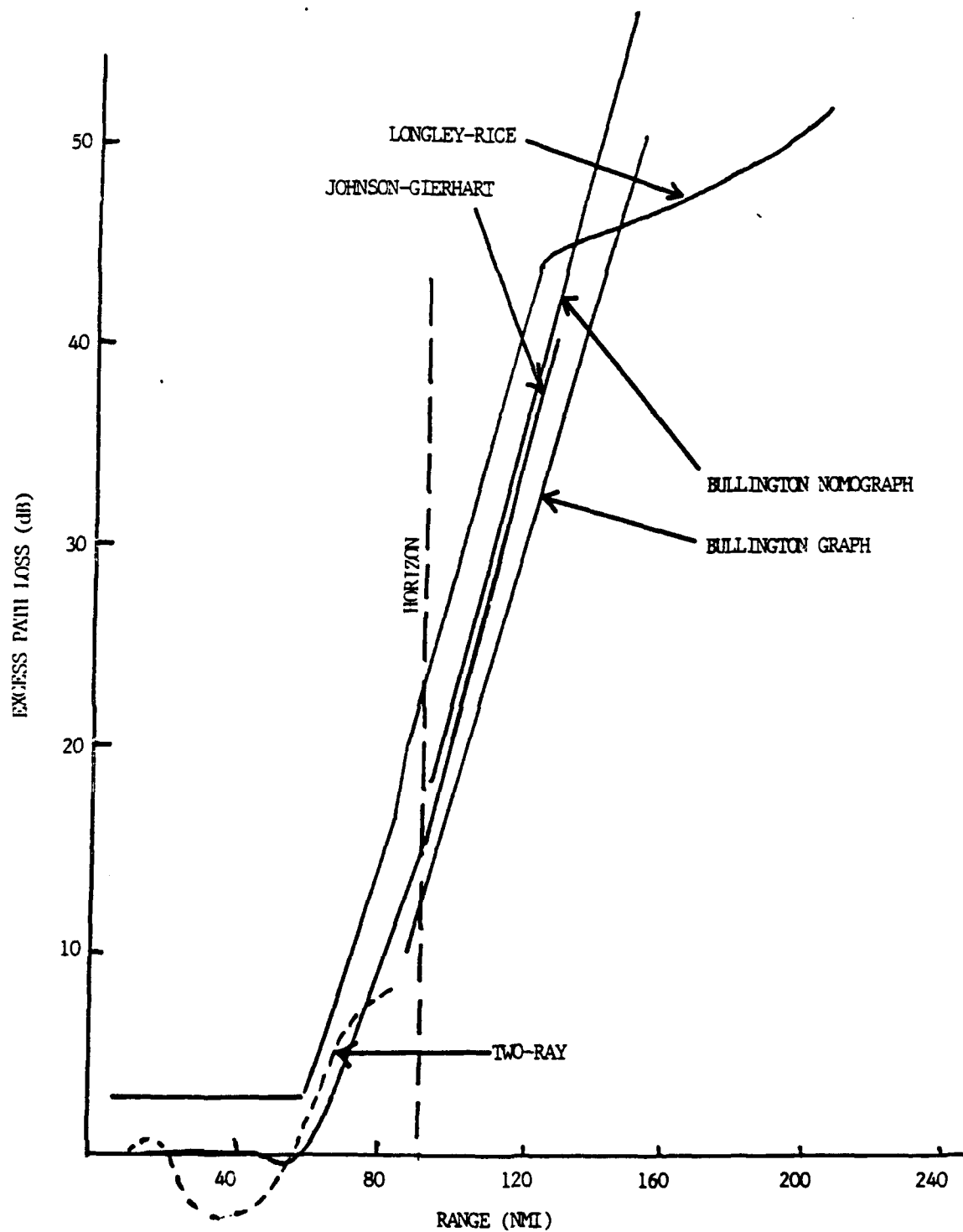


Figure 7-5. Excess Path Loss at 4,500 ft.

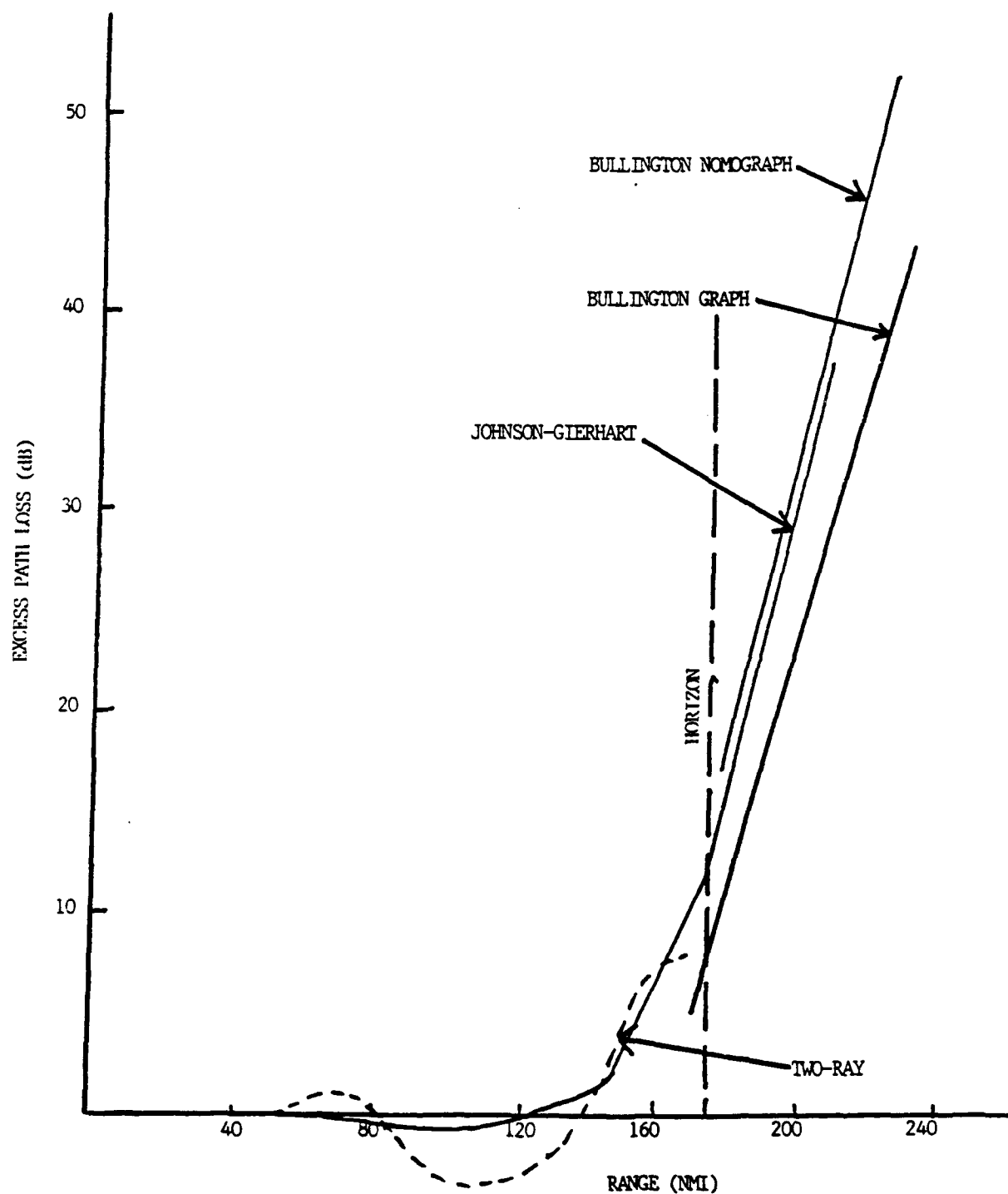


Figure 7-6. Excess Path Loss at 18,000 ft.

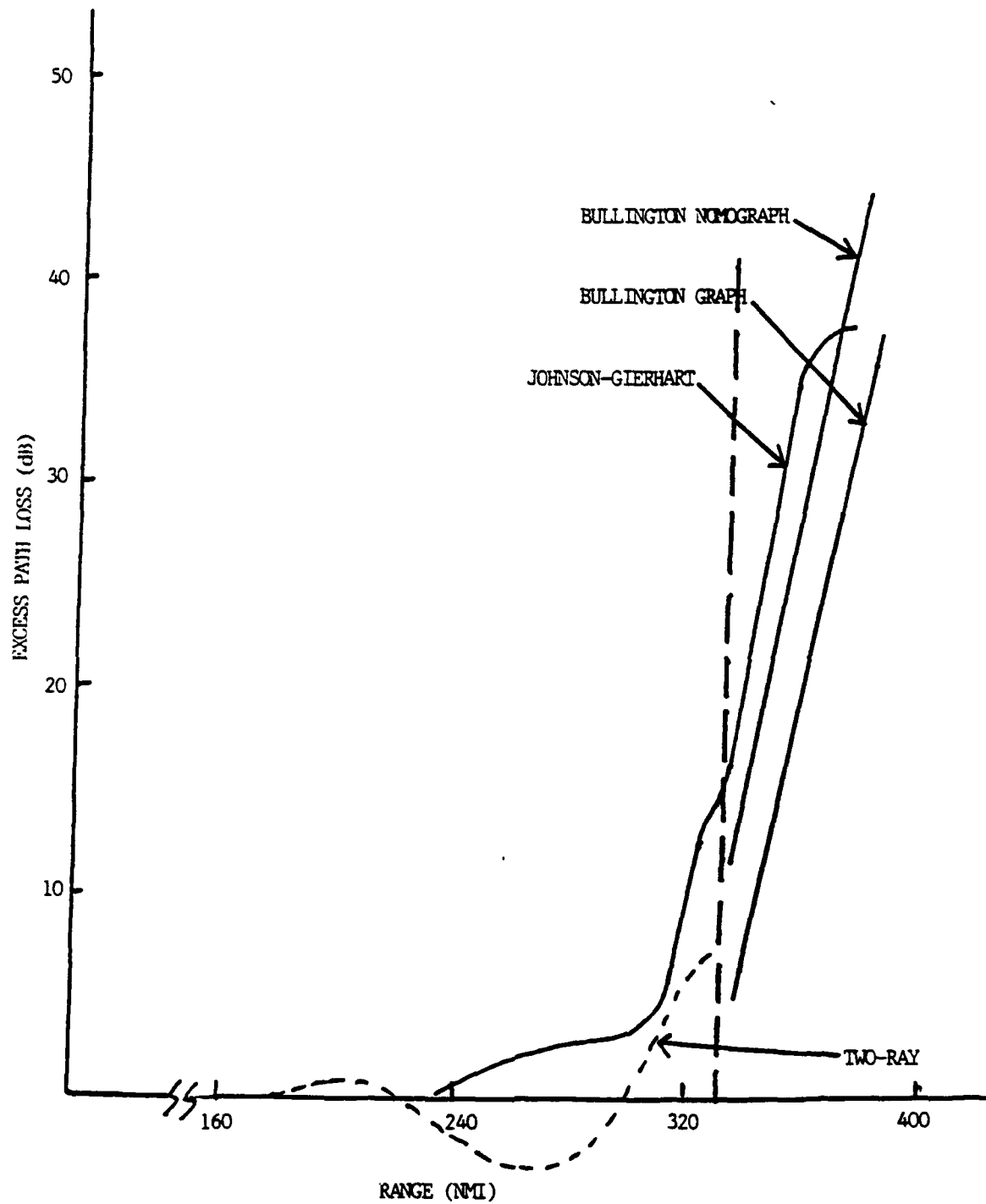


Figure 7-7. Excess Path Loss at 72,000 ft.

best overall estimate of the excess path loss. It is interesting to note at this point that nowhere in the graphs is there any region displaying anything which could be interpreted as r^{-4} propagation!

The information on the graphs can now be used to estimate the S/I ratios at various locations. Table 7-4 shows the estimates of S/I for uplinks, where the receiver is located in the "corner" of a cell, either at the top or the bottom. The interference is due to the constellation of the nearest ground transmitters reusing the same frequency. Table 7-5 shows estimates of S/I for downlinks where the desired transmitter is at the bottom corner of a cell and there is one airborne interferer in the top corner of a reuse cell.

Table 7-4 Uplink S/I Ratios

			Reuse Patterns		
			8	7	6
	Range	Altitude			
Low cell	40 nmi	1125 ft	36 dB	33 dB	31 dB
		4500 ft	30 dB	16 dB	16 dB
Middle cell	80 nmi	4500 ft	36 dB	34 dB	33 dB
		18000 ft	43 dB	12 dB	12 dB
High cell	160 nmi	18000 ft	36 dB	37 dB	35 dB
		72000 ft	41 dB	20 dB	20 dB

Table 7-5 Downlink S/I Ratios

			Reuse Patterns		
			8	7	6
	Range	Altitude			
Low cell	40 nmi	1125 ft	20 dB	4 dB	4 dB
Middle cell	80 nmi	4500 ft	36 dB	2 dB	2 dB
High cell	160 nmi	18,000 ft	40 dB	14 dB	14 dB

One sees from these tables that the S/I ratios provided by the 8-frequency patterns are all very high with respect to the 7 dB required. On the other hand, the ratios provided by the 6- and 7-frequency patterns are in some cases deficient. This is particularly true in the case of the downlinks. Even for the uplinks the ratios can be as little as 12 dB or 16 dB at the top of the lower levels. While these ratios may seem high compared to the required 7 dB, they do not provide much margin for the effects of irregular terrain, unusual propagation behavior, etc. Extra margin should also be provided to allow for the fact that in the real world antennas cannot always be placed at the centers of a grid of perfect triangles. The slopes of the excess loss curves are quite steep and, as a result, losses can change by up to 5 dB due to a 10 nmi change in airborne position. A prudent person would probably choose the 8-frequency patterns for both uplinks and downlinks at all three levels.

7.6 FREQUENCY MANAGEMENT

Having decided that the 8-frequency reuse patterns are to be used, one now investigates whether or not one can allocate frequencies for use by CTAG in an environment where frequency usage has to be shared with other users (i.e., the old AM radios). As a minimum, four frequencies per cell must be provided, one each for up and down service links and for up and down voice links.

There must be 24 frequencies which are unique to CTAG for the 8 service channel uplinks at each of the three levels. These must be available so that airborne users can monitor the quality of the links at each frequency anywhere within the system without interference from other users.

One technique for allocating frequencies is the following. Assume that there are 720 frequencies available; the exact number is not important. Divide these frequencies among the cells so that each of the 24 cell types has 30 frequencies associated with it. One of these frequencies must be one of the 24 CTAG-unique frequencies. The other 29 can be chosen by some criterion such as good IMP properties, etc. If there were no other users of the frequency band, all 29 frequencies could be used by CTAG. Due to use by AM radios, many of the 29 possibilities in each cell will not be available in a particular geographic region. All that is required for a minimum CTAG network, however, is that in every cell at least 3 out of the 29 are available. One of these three will be assigned as the service downlink frequency, the other two will be assigned to the voice channels. To determine whether this is possible would require a survey of current frequency assignments.

If a CTAG network operated in this way, each cell would have to broadcast, in its service channel uplink, the identity of the frequencies of service channel downlink. (There are plenty of bits in the uplink message to do this.) In other words, the service up and downlink frequencies would not be paired in any unique way. When, and if, AM radio usage is reduced so that fewer AM allocations are required, they can be shifted over to usage by the CTAG voice channels.

As a final note, we point out that it might be beneficial to set aside some extra frequencies for service uplinks beyond the 24 already mentioned. A total of 30 might be a good number. The extra frequencies could be used to fill in coverage in difficult areas where terrain or siting problems cause gaps.

7.7 SUMMARY

In this note it has been shown that it may be possible to implement a CTAG network based on frequency reuse patterns using 8 service frequencies at each of 3 levels. The method requires only 24 (or maybe 30 to be extra prudent) unique CTAG-only frequencies. There is considerable latitude in distributing the remaining frequencies to cells. The calculations were based on a perfectly spaced triangular array of antenna sites; however, the 8-frequency pattern approach could probably tolerate antenna replacement errors in the 5 to 10 nmi range without much (if any) degradation in performance.

SECTION 8

OPERATIONAL PROCEDURES

8.0 INTRODUCTION

This section describes CTAG operational concepts from the points of view of the pilot/crew, the aircraft terminal, the CTAG ground system and the controller.

8.1 CELLULAR HANDOFF

A review of current mobile cellular telephone channel allocation, call setup, and cell handoff procedures reveals that, although the switch hardware may be adequate for CTAG (but see Volume 3), the software processes will probably be entirely different[23]. For example, the requirement for voice transmission initiation time for A-G service is 250 ms, continuous pilot access to NAS facilities is required, and a service availability of 0.99999 must be achieved[24]. These types of requirements were not a consideration for the current mobile telephone system.

Due to the short transmission initiation time and the requirement for continuous pilot access, it appears that call set-up will occur once per flight (when the radio is turned on and while the aircraft is on the ground). Therefore, the bulk of the processing requirement will consist of directing frequency changes/cell-cell hand-offs. The cell-cell handoff procedures is an area where the current mobile telephone system is experiencing a problem that is bothersome for them, but which could be disastrous for CTAG. The following paragraphs describe the procedures and problems experienced, and postulate a possible solution for CTAG.

8.1.1 Current Cellular Telephone HandOff Procedures and Problems

After a call is established to a mobile telephone subscriber, the radio channel must be monitored for quality, and when the quality deteriorates below a predetermined threshold, the call must be transferred to a cell which can provide improved reception/transmission. When monitoring the channel, the central controller knows nothing about the mobile unit (location, speed, direction of travel) except received signal level on the voice channel in use, and the cell providing the channel. When the signal level drops below a predetermined threshold, the central controller then monitors that frequency at each of the adjacent cells and begins the procedure to assign the mobile a channel in the cell with the best received signal.

The problem with this procedure is that the cell boundaries are statistical averages and are not clearly defined by the transmit/receive patterns. These "fuzzy" cell boundaries, dead spots, skips, etc., cause the controller to sometimes assign a mobile to a distant cell. When this happens, the mobile can experience problems such as crosstalk (hearing other people on the channel in use) and can cause a great deal of interference as transmissions occur on or near other frequencies in use in/near the cell where the mobile is physically located. It appears that this situation occurs much more often than is admitted by the service providers. Some estimates are that 10-25% of the cell handoffs are in error. In addition to causing a

great deal of interference, these errors may also add a considerable processing burden to the central processor. Even though the actual cell switching action is very quick, several seconds of monitoring and processing may have occurred prior to the actual switch action. In most instances where a cell handoff error occurs, another handoff (hopefully to the "right" cell) will be required. Note that it is theoretically possible for a mobile traveling a fuzzy cell margin between two transmitters to experience repeated handoffs between the two (measured data for this effect has not yet been discovered). Proposals to cure this problem have primarily consisted of trying to determine the physical location of the mobile with respect to the cells. The use of ranging information as well as signal strength for handoff decisions has been considered, but as far as is known, has not been implemented.

8.1.2 CTAG Cell-Cell HandOff Concepts

It is apparent that CTAG cannot experience errors during cell hand-offs comparable to those of the cellular telephone system. For example, if a high flying aircraft were to be erroneously assigned to a low altitude cell, the aircraft could possibly "see" several other low altitude cells where the assigned frequency could be reused. Obviously, transmissions from the aircraft could cause considerable interference, which, in turn, could compromise flight safety.

Any solution postulated for solving the CTAG cell-cell handoff problem, must ensure that the correct decision is always made when assigning a new cell and frequency/channel. Note that there may be more than one "correct" decision. A "correct" decision is one that continues to provide acceptable quality communications for the aircraft and does not cause unacceptable interference with other mobiles or cells -- "acceptable quality" and "unacceptable interference" will be defined later.

The postulated solution to always ensuring a correct decision is based on four major assumptions: 1) dedicated service channels will be assigned to each cell and will always be transmitting; 2) the aircraft radio will periodically scan the service channels and will be capable of rank ordering the received signal based on quality (parameters to be determined); 3) the CTAG Ground Master Switch (CGMS) (see Volume 3) will be provided aircraft location and altitude from ATC ground facilities; and 4) the cell site providing service to the aircraft will monitor the assigned voice channel and report degradation to the CGMS. With input of all these parameters, it appears that technically the CGMS could make the correct decision all the time. However, the control algorithms should allow the decision to be made based on inputs from the aircraft and cell site only (since a separate communications path, which could be interrupted, would be used to obtain the location data). Depending on signal parameters monitored and reported by the aircraft radio, it appears that the correct decision could be made most of the time. However, reporting aircraft location to the CGMS may provide other benefits such as allowing the CGMS to predict the next cell hand-off location which could lead to much shorter decision/set-up time.

It is obvious that this area will require considerable attention during the establishment of an architecture and design for the CTAG system. Further thoughts on the ground system data flow are provided in [25]. It appears that modeling/simulation of the communications network would be very helpful.

8.2 HOW DOES CTAG WORK?

This subsection responds to the question "How does CTAG work?"[26] by stepping through both the human interactions and the automatic information flow necessary for entering the system, cell handoff and controller handoff. The essential ideas presented in the following figures, figures 8-1, 8-2, and 8-3 should be attributed to W. J. Wilson and J. L. Ramsey.

8.3 MESSAGE TRAFFIC REQUIREMENTS FOR ROUTINE CELLULAR HANDOFF IN CTAG

This subsection addresses the messages that must be exchanged between various components of the proposed CTAG system during a routine cellular handoff [27]. By "routine" one means that the aircraft or "user" and its associated controller are already participants in the system. Before the handoff they are connected to each other via three elements: a cell and a ground switch associated with that cell which in turn will be called the "old cell" and "old switch", respectively, and a second, not necessarily distinct ground switch called the "controller's switch." The old switch serves two functions: 1) it controls and monitors the activity and parametric assignments of the cell(s) it serves; and 2) it transfers data passing through its constituent cell(s) to other relevant switches. The controller's switch transfers data going to or coming from the controller to other relevant switches. The switches in the CTAG system are mutually interconnected through a ground-based communications network. The cellular handoff procedure maintains connectivity between the same aircraft and controller, but via a different cell which will be called the "new cell", and a switch called the "new switch". The new switch may or may not be distinct from the old switch and/or the controller's switch.

The path through the cell and the switches that connect an aircraft with its controller is called a "voice/data circuit", or, more simply, a "circuit". In addition to the cell, old switch, and controller's switch, a circuit is also defined in terms of several cellular parameters. Two of these cellular parameters are: 1) a frequency-pair assignment chosen from the set of frequency pairs allocated to the cell; and 2) a particular specification of the 20 ms time slots used for uplink and downlink transmissions, chosen from the set of five possibilities available for periodic access times of 100 ms. (See section 9 for details of a TDMA design example alluded to here.) The frequency-pair/time slot assignment is called the "cellular channel" associated with the circuit. Finally, each circuit is given a "local ID" number ranging from 1 to 16 that is unique to each aircraft using the same cellular channel. A controller can thus access as many as 16 aircraft through the same cellular channel. If more than 16 aircraft were to be connected to a given controller using the same cell, a second cellular channel assignment would be required. The CTAG architecture allows a controller to access all the aircraft under his jurisdiction via several cells concurrently: in fact, interoperability with the current ATC system requires the controller to be able to communicate with both cellular-equipped and current, non-equipped (VHF analog voice) users at the same time in a manner that is transparent to current users of the system.

Entering the System

IN THE AIRCRAFT - THE PILOT	THE TERMINAL	CTAG SYSTEM	AT AIR TRAFFIC CONTROL CENTER - THE CONTROLLER
1. Turns on the terminal 2. Enters initializing info such as Flight Phase: Terminal ☒ TRACON ☐ Enroute ☐ Flight ID #: _____ (alpha/numeric) Aircraft ID#: _____ Present Controller _____ 13. Is given an indication such as voice channel connection indicator light or a canned message that voice channel has been established.	3. Scans all cells and chooses "best" cell. 4. Transmits entered data on downlink service channel. 6. Makes round-trip ranging adjustment. 7. Enters voice channel. Acknowledges voice channel assignment by responding on M/E* portion of assigned voice channel. 12. Receives confirmation that voice channel has been established.	5. Starts to set up a voice channel on entered cell. Connects cell to controller, if not already connected. Transmits voice channel and local ID # assignment on uplink service channel. 8. Receives aircraft response and sends data informing controller of new entrant. New entrant ID # displayed at control center. 10. Receives acknowledgement. 11. Informs aircraft on M/E* portion of uplink voice channel that connection to controller is complete	9. Acknowledges receipt of new entrant.

*Maintenance/Emergency

Figure 8-1. Entering the System

Cell Hand-off

IN THE AIRCRAFT - THE PILOT	THE TERMINAL	CTAG SYSTEM	AT AIR TRAFFIC CONTROL CENTER - THE CONTROLLER
		<i>Performs background processing between cellular hand-offs in order to determine the next cell through which the link should be switched whenever a cell hand-off is required. These steps include:</i> - Scanning list of reported cells and other relevant information which is received periodically from terminal on M/E* portion of voice channel - Choosing best cell that is a. connected to present controller, if good enough; b. otherwise, applies, "best cell criteria" 1. Determines when a cellular hand-off is required. 2. Transmits on uplink voice channel the new cell assignment. 4. Transmits on new cell's uplink service channel - ranging information, the new voice channel and the local ID # assignment. 6. Connects controller to new cell if new designated cell is not currently connected to controller. (Keeps connection to old cell.) 7. Directs terminal on M/E* portion of old voice uplink to switch to new voice channel.	
	3. During time allocated to other voice channels, tunes to new cell. Initiates round trip ranging procedure. 5. Stores round trip ranging adjustment on new cell. Reports on M/E* portion of old voice channel "ready to transfer". 8. Sends acknowledgement of switching assignments as last message on M/E* portion of old voice channel. 9. Then switches to new assignment within __msec of sending acknowledgement in 8.		

*Maintenance/Emergency

Figure 8-2. Cell Hand-off

Controller Hand-off

IN THE AIRCRAFT - THE PILOT	THE TERMINAL	CTAG SYSTEM	AT AIR TRAFFIC CONTROL CENTER - THE CONTROLLER	
			Old Controller	New Controller
16. Is given an indication such as display of new controller ID or a canned message that a controller hand-off has occurred.	6. During time allocated to other voice channels, tunes to new cell. Initiates round-trip ranging procedure. 8. Stores round-trip ranging adjustment for new cell if required. Reports on M/E* portion of old voice channel confirmation of assignment in any case. 14. Sends message acknowledging the termination of the previous assignment on M/E* portion of old voice channel. 15. Then switches to new assignment.	4. Establishes new voice channel assignment. Finds from data base all cell connections to new controller. Uses present cell, if new controller is also currently connected. Otherwise either matches a cell on list reported by A/C, or designates a new voice channel on current cell. Procedure similar to hand-off. 5. Transmits intention to switch controller. Transmits controller identity, new cell assignment (if required) on M/E* channel of current voice uplink. 7. Transmits on new cell's uplink service channel - ranging information, the new voice channel and the local ID # assignments. 9. Sends indication to old controller that link to new controller is ready to be activated. 13. Directs terminal to switch to new voice channel.	1. Informs new controller of desire to hand-off by transferring relevant data. 3. Informs CTAG of impending controller hand-off. Identifies Aircraft ID # and new controller.	2. Accepts transfer.
			10. Completes transfer of relevant data to new controller. 12. Informs CTAG to complete transfer.	11. Acknowledges receipt of data.

*Maintenance/Emergency

Figure 8-3. Controller Hand-off

There are two principal reasons for making a routine cellular change. The first is that there is a hierarchy of cellular networks that correspond to whether the aircraft being serviced are flying at low, medium, or high altitudes. As an aircraft changes altitude, it may become appropriate for the CTAG system to reassign the connectivity between the aircraft and its associated controller from a cell in one hierarchy to a cell in an adjacent (in altitude) hierarchy. The second reason for making a change is that the aircraft is flying out of the service region of the old cell or is experiencing poor communications quality due to interference on his particular cellular channel assignment, and must make a cellular change in order to maintain reliable communications. For either reason, at this point in the CTAG system design it has not yet been determined whether the cellular handoff process should ordinarily be originated by the aircraft or by the ground switch. In order to minimize the amount of message traffic needed at the time of a cellular handoff, it would probably be preferable for the ground switch to initiate handoffs whenever possible. Certainly, however, there would be situations (such as an inordinate amount of interference at the aircraft on the old cellular frequency) that would have to be recognized initially by the aircraft. The communication requirements would, of course, depend on whether the aircraft or the switch first determined the need for making a cellular transition.

Figure 8-4 shows the steps involved in making a routine cellular handoff. First, a request for a cellular handoff is initiated by either the aircraft or the old switch. The CTAG system then has to prepare a circuit for connecting the aircraft and the same controller in some new cell. The amount of message traffic required for this second step depends on whether a tentative new cellular assignment has already been determined (probably by the old switch) or whether the designation of the new cell is made only after the cellular handoff request has been received. Following the definition of a new circuit assignment, the actual process of handing over the aircraft from the old cell to the new cell can take place. This third step requires various messages to be exchanged between the aircraft and the old and new cells as well as messages between the old and new switches if the two switches are different. Finally, the system has to update various relevant data records regarding the new status of the system following the transition to the new circuit assignment.

The message traffic requirements associated with a routine cellular handoff can be more readily estimated by separately considering each box shown in figure 8-4. Many of these requirements depend on the specific details of the handoff process for a particular transition, such as whether it is the aircraft or the old switch that initiates the request for the cellular handoff, whether the aircraft or the switch is responsible for determining which cell should be the new cell, what information is required to make that determination, how and when that information is communicated to the element that designates the new cell, whether a tentative new cellular designation has been made prior to the request for a cellular handoff, and so forth. Nevertheless, one can outline some of the message traffic requirements on the basis of certain reasonable assumptions, and can predict what changes in these requirements would take place if the assumptions were to be changed.

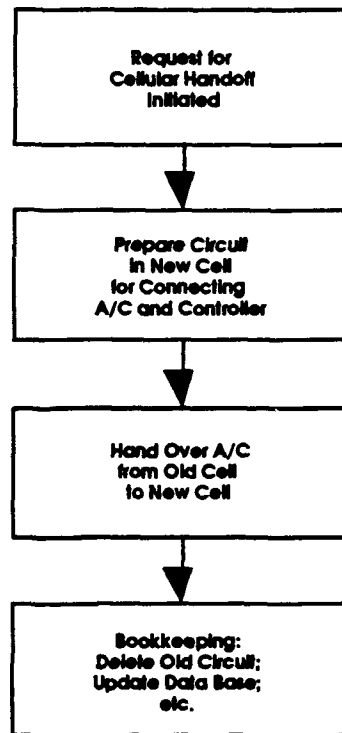


Figure 8-4. Procedure for Routine Cellular Handoff

For example, suppose that the old switch is ordinarily responsible for making cellular assignments and for originating cellular handoffs. The aircraft could also request a handoff if it were experiencing poor communication quality, but this would be a secondary mode of initiating the handoff process. The message traffic requirements corresponding to the first box in figure 8-4 would then be modest. Usually no data transfer would have to take place, since the switch would determine when a handoff was required. Only in the relatively infrequent cases when the aircraft sensed the need for a cellular change would a message be sent; this would consist of a single message from the aircraft to the old switch relayed through the old cell.

Figure 8-5 shows the steps required to prepare a circuit in the new cell for connecting the aircraft with its controller. The first issue is whether a tentative new cell has already been designated at the time a cellular handoff is requested.* Of course, no message transmissions would be required if this task had already been completed, or if the old switch already had the information from the aircraft that it would need to perform the cellular selection process. The only situation for which data exchange would be necessary would be when the old switch did not already have the requisite data available. The amount of data to be exchanged could be substantial. The switch would have to notify the aircraft, via the old cell, to provide the relevant information needed to make the proper selection; the aircraft would then comply by sending the data to the old switch through the old cell.

Once the new cell has been selected, the remaining generic steps in the process of setting up a circuit in the new cell are for the old switch to inform the new switch of the pending handoff, for the new switch to connect to the controller and to make the appropriate cellular assignments if the controller is not already connected, for the new switch to assign a local identity (ID) number for the incoming aircraft, and for the new switch to send back the cellular channel and local ID number assignments to the old switch so that the old switch can communicate this information to the aircraft via the old cell. All this is shown in figure 8-5. The information content of the message from the old switch to the new switch would contain the actual (not local) ID number of the aircraft, and the ID number of the corresponding controller. If the controller were already connected to the new cell, a cellular channel assignment corresponding to that controller would have already been established, and all the new switch would have to do would be to make a local ID number assignment uniquely defining the incoming aircraft and to communicate the relevant information to the old switch. That information would consist of the cellular channel parameters and the local ID number assignments as a minimum, and should probably contain the actual ID numbers of the incoming aircraft and the associated controller for verification by the old switch.

If the controller were not already connected to the new cell, a circuit for connecting the incoming aircraft with its controller would have to be prepared. The new switch would reserve a cellular channel assignment (a frequency pair and a time slot designation) for the incoming controller, and would send a message to the controller's switch that the new switch should henceforth be connected to the controller via the controller's switch. The new cell would then begin to broadcast uplink messages from the entering controller. This would provide the mechanism for connecting the aircraft to the new cell. However, the new cell would not receive any downlink messages at this time. The aircraft would still be

* It is assumed here that the ground system (i.e., network of switches) performs the calculation required to determine the tentative new cell. A similar, but obviously different discussion would apply if the aircraft instead were the element in the CTAG system to make these calculations.

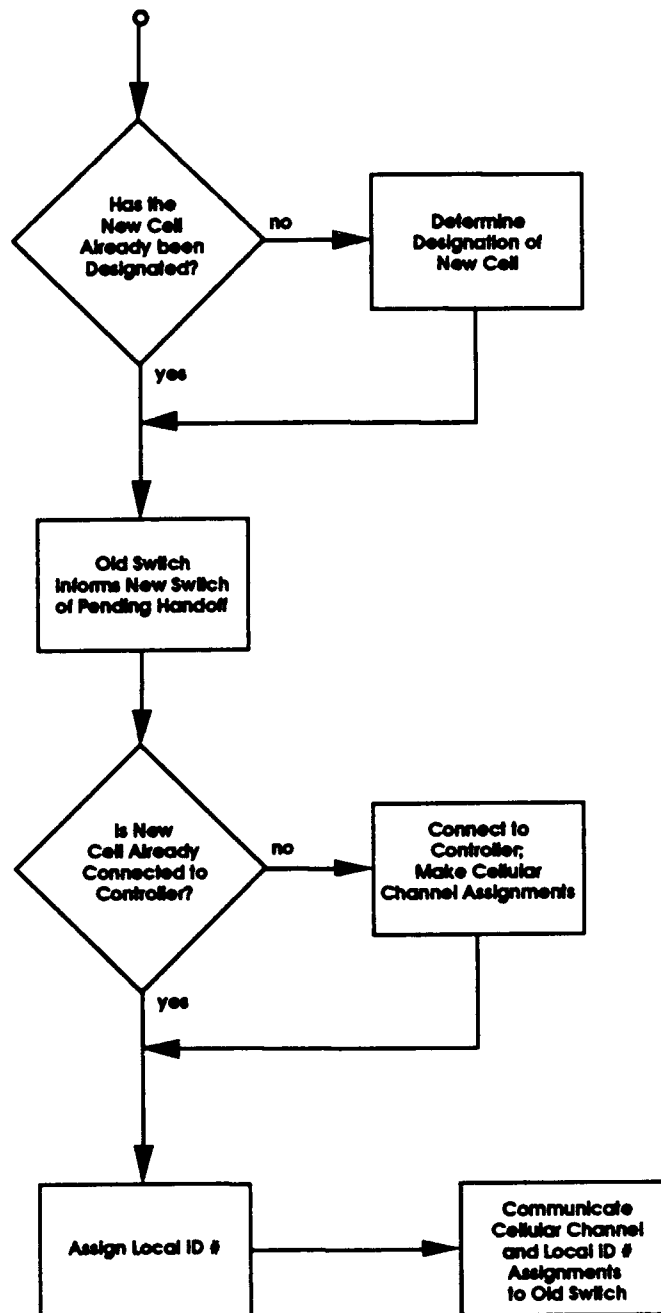


Figure 8-5. Circuit Preparation in New Cell

transmitting its downlink messages through the old cell, and would continue to do so until the cellular handoff procedure had been completed at the aircraft. Only then would the new cell start to receive downlink messages.

Once a circuit has been prepared in the new cell, the actual process for making the cellular transition at the aircraft can proceed. Figure 8-6 shows some of the details of that process. Most of the steps in this process require some messages to be exchanged. First, the old switch directs the aircraft to transfer to the new cell via a message sent through the old cell. That message includes, as a minimum, the cellular channel parameters and the local ID number assignments for the aircraft in the new cell, and, of course, either (or both) the local or actual ID number corresponding to the aircraft. The aircraft then sends a round trip timing (RTT) request message to the new cell via the service channel of the new cell. This step is necessary in order for the aircraft to be able to adjust its message transmission timing relative to the timing of the new cell, so that messages originating from the aircraft on the new voice/data circuit will arrive at the new cell at the proper time. Included in the RTT request

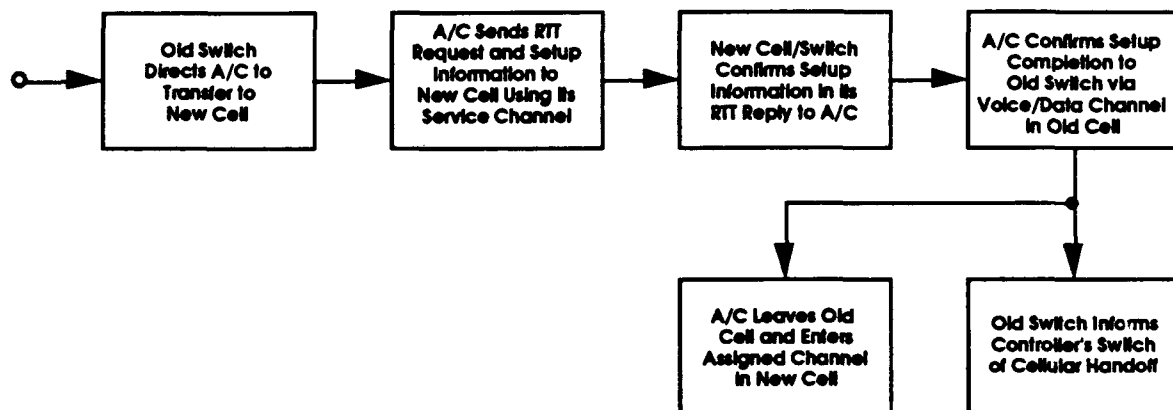


Figure 8-6. Procedure for Cellular Transition at the Aircraft (A/C)

message is the relevant setup information: the actual ID number of the aircraft, and the cellular channel parameters and local ID number assignments corresponding to the new cell. The new cell responds by transmitting a RTT reply message on its service channel to the aircraft, indicating the time of arrival of the RTT request message, and confirming that the new-circuit setup parameters received from the aircraft were indeed the parameters that were assigned by the new switch during the setup process for the new cell. The aircraft then sends a message to the old switch, via the voice/data circuit in the old cell, indicating that the cellular handover process has been coordinated with the new cell, and that the aircraft will henceforth communicate with its controller via the new cell. This message is the last message that will be sent by the aircraft to the old cell. The aircraft will then adjust its timing

if necessary to be commensurate with the timing of the new cell, and will enter the newly-established circuit that uses the new cell. Meanwhile, the old switch will inform the controller's switch of the cellular handoff in order for the controller to be able to continue to communicate with the aircraft without perceptible interruption. The message must contain, as a minimum, the actual ID number of the aircraft, the identification of the new cell (or new switch) to which the aircraft has been assigned, and the local ID number corresponding to the new cellular assignment. It is not necessary to provide information regarding the new cellular channel assignments (frequency pairs/time slots), since that information is only used by the new switch or new cell.

To fully complete the cellular handoff process, the data bases at the relevant switches have to be updated. Many of the steps involved in this bookkeeping function require no message exchange, since they are internal to the switches themselves. Data only has to be transmitted from one switch to another when that data is required for the proper functioning of the receiving switch.

For example, figure 8-7 shows the bookkeeping functions that take place at the old switch. First, of course, the aircraft is removed from its channel assignment in the old cell. This merely means that the local ID number corresponding to the aircraft is deleted from the assignment records at the old switch. Next, the switch determines whether any aircraft other than the departing aircraft are connected to the controller via the old cell. If there are, no further action is required; if not, however, the old switch sends a message to the controller's switch indicating that fact and informing the controller's switch that the cellular channel assignment for that controller at the old cell is being released. The next consideration is whether the new cell is controlled by the same switch as the new cell. This situation might occur, perhaps, when a particular switch controls cells in two altitude-adjacent hierarchies. If so, the switch updates relevant entries in its local data bank concerning the connectivity of the aircraft and its associated controller, but this action requires no message transmission between various elements of the CTAG system. However, if the new cell is controlled by a different switch, the old switch transfers relevant information concerning the aircraft from its data bank to the data bank in the new switch. This information might include a listing of the cells (service channels) currently visible to the aircraft, possibly also including an estimate of the communication quality expected on each of the visible service channels, or of the distance of the aircraft to some or all of the visible service channels, and the information might further include identifying information such as the actual ID number of the aircraft, an ancillary identifying ID number such as an airline flight number, or a reiteration of the controller to whom the aircraft is connected. Once this information has been sent to the new switch, the old switch will then erase the information from its own data bank. This last step, of course, requires no message transfer.

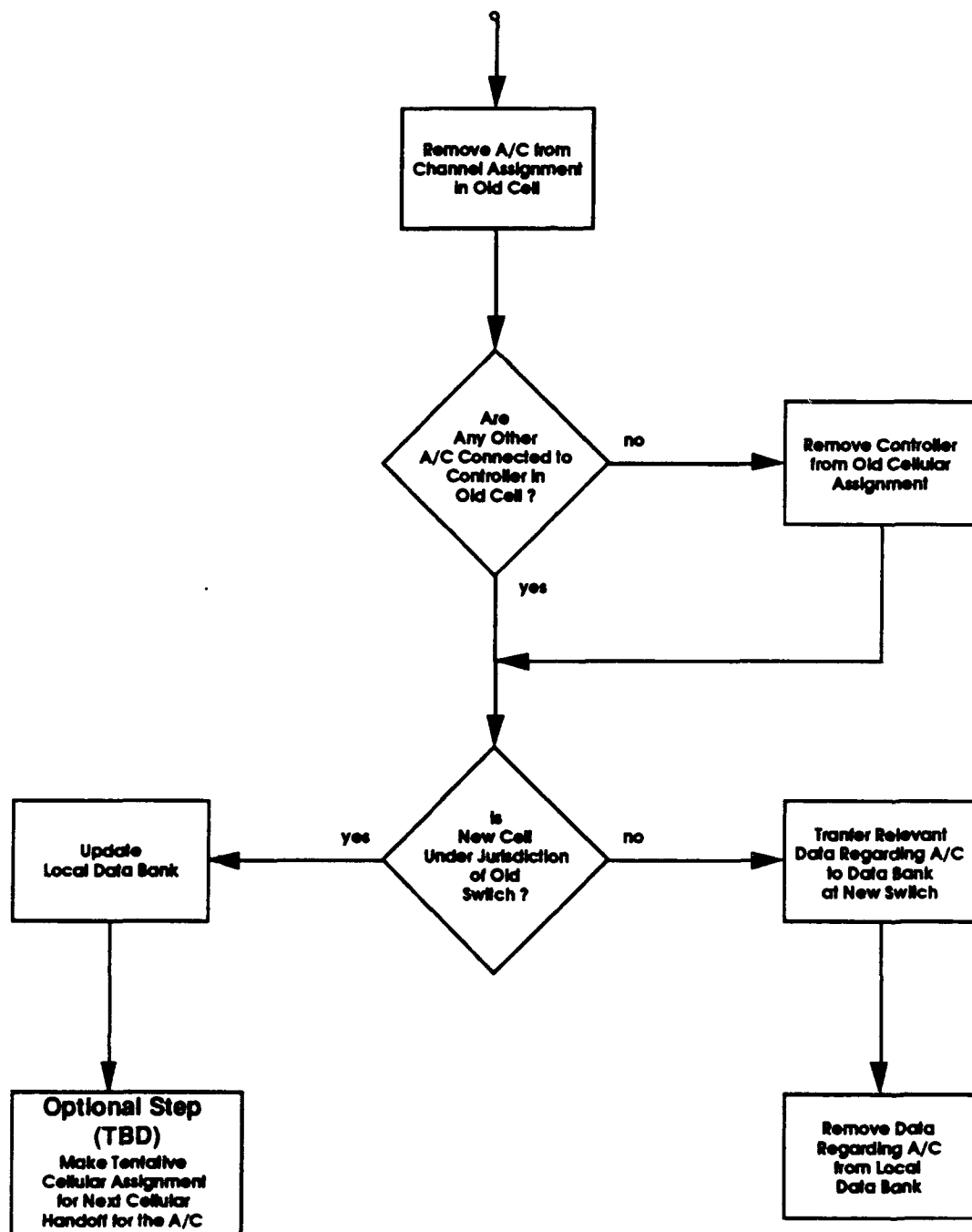


Figure 8-7. Bookkeeping Functions at Old Switch (A/C = aircraft)

SECTION 9

TDMA EXAMPLE DESIGN

9.0 INTRODUCTION

This section contains the results of a preliminary effort to define a TDMA solution to the CTAG problem. The ideas incorporated in this plan are due to J. L. Ramsey and W. J. Wilson [28].

9.1 ASSUMPTIONS

Before describing the architecture in detail certain basic assumptions that were made are listed:

1. There are separate up and downlink frequencies in 25 kHz channels.
2. A/A connectivity is achieved by ground relay and under the control of the air traffic controller.
3. At most, M aircraft share a voice channel with a controller in a cell. M is currently assumed to be 16. Contention is eliminated through (enforced) discipline. A user who wishes to break in can activate a "call waiting" feature. There is also an emergency break-in feature.
4. Voice is digitized at 4.8 kbps (perhaps using the Code Excited Linear Prediction (CELP) [4] approach). It is assumed that the voice will be acceptable provided the bit error rate is less than 1%. No error correction coding is applied to the voice bits.
5. There are 24 service channels which may need to be monitored.
6. The modulation is assumed to be some form of quaternary signaling (perhaps Aviation QPSK) using 20 kbaud, or 40 kb/s instantaneous data rate.
7. Data which is transferred in order to provide network maintenance, emergency access, cell handover, etc., is protected with an $r=1/2$ rate code. A Golay (20,9) code is currently assumed but this is subject to change.
8. Synchronization and a start symbol are assumed to consume 1.5 ms per transmission (i.e., 60 bits).
9. Knowledge of absolute time is unnecessary in the air and on the ground. When in a cell, an airborne radio slaves itself to the timing associated with that cell. Oscillators with frequency accuracy of 10^{-6} are assumed so as to keep frequency offsets comparable to the maximum Doppler shift.

10. Radios must be able to change frequencies and change from receive to transmit in at most 1 ms.

Most of these assumptions can be relaxed in one way or another; however, they apply to the particular architecture described herein.

9.2 FRAME STRUCTURE

As shown in the figure 9-1 the basic unit of time is 100 ms. Each 100 ms period is divided into five 20 ms time slots. A basic voice circuit consists of a frequency channel pair and an associated time slot pair. An airborne platform will typically transmit on a frequency (f_1) in one slot per period and receive on a different frequency (f_2) in the next time slot. The time allocated to the remaining three slots can be used to scan for other usable service channels.

The downlink voice time slot is divided into two subchannels: The maintenance/emergency channel (M/E), and the voice/data (V/D) channel. The M/E channel is used in a "round-robin" fashion by the 16 airborne users on the voice circuit. The V/D channel is used by the current speaker (if any). Each downlink subchannel has its own sync and header, since different users may use the two subchannels.

The uplink voice time slot is also divided into M/E and V/D subchannels. However, the uplink is always transmitted by a single ground station so that separate syncs are not required. The uplink header contains M/E information and a separate part associated with the V/D link.

The service circuit uplink has a 100% transmit duty factor. Each time slot contains a sync and an information portion in each time slot. Voice is never transmitted on the service circuits.

The service downlink consists of a sync, an information portion, and a substantial guard time (4 ms). The guard time is to allow for a round trip propagation delay of 320 nmi (each way).

9.3 KEY PROCEDURES

To allow the reader to appreciate the various features of the architecture workings of a few key procedures are described.

9.3.1 Net Entry

When an airborne radio enters a new cell it must first "check in" on the service channel associated with that cell. How the cell is chosen will be described below. To check in the radio receives an uplink message on a service circuit and responds on the downlink associated with that circuit using the perceived timing associated with that cell (i.e., its transmission will be delayed by a one-way propagation delay). The downlink message will

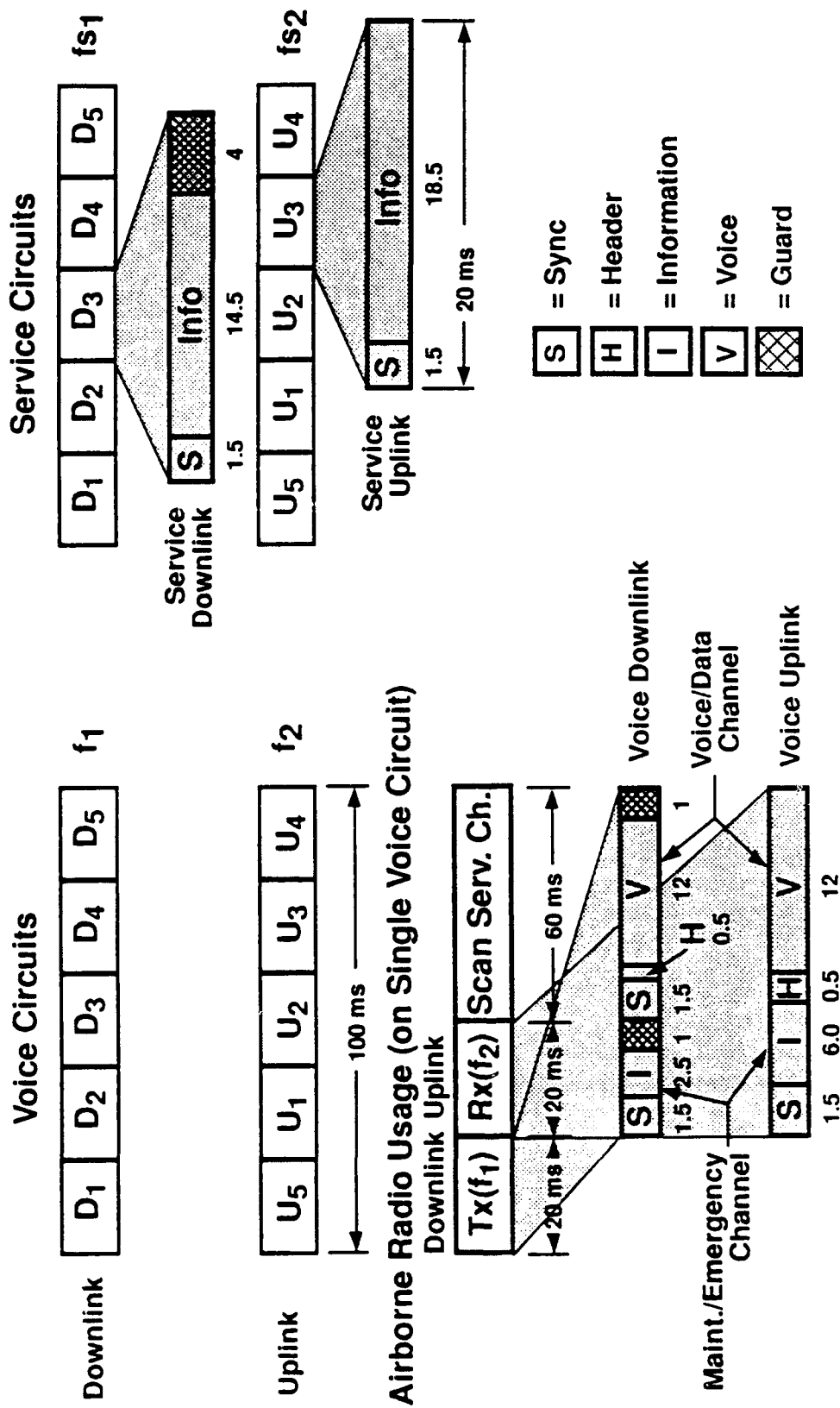


Figure 9-1. TDMA Example Design Architectural Organization

contain information identifying the user (perhaps a 24 bit identifier used in Mode-S, tail number and/or flight number) and (if available) the "address" of the controller to whom he is connected.

An uplink message will be returned to the new user. The voice circuit information will include

- (1) uplink voice frequency
- (2) downlink voice frequency
- (3) voice time slot assignment
- (4) repeat of the user's ID information for verification
- (5) a temporary ID number (1 to 16)
- (6) time offset information.

The temporary ID number is a number from 1 to 16 which is assigned to the user for as long as it remains in a particular cell. On the ground this nibble of information will be associated with the more extensive user ID information which was originally transmitted.

The time offset information tells the user how "late" his message on the service channel was at the ground station. The user must transmit "early" by a related amount when he transmits on the voice circuit. Because his transmit slot comes before his receive slot this transmit time shift will not cause a conflict. The purpose of this offset is to ensure that the signals from all users arrive at the ground receiver with no overlap (without having to allow for excessively large guard times). Note that in the V/D downlink a generous 1 ms guard time is allowed for time compensation errors.

9.3.2 Circuit Maintenance

When no V/D communication is taking place on a voice circuit there is a small amount of traffic required to maintain connectivity among all users. This occurs on the M/E subchannel. Each airborne user is allocated the M/E subchannel in the voice downlink channel for one time interval out of 24 in which to report to the ground station. The interval assignments are as shown in figure 9-2. The intervals labelled "E" are for emergency access. Recall that each interval is 100 ms so that each user reports every 2.4 s.

The M/E downlink information includes the following:

- (1) message type (Maintenance or Emergency)
- (2) user ID, slot number (1 to 16)
- (3) request to talk (used for the "call waiting" feature)
- (4) increment/decrement time
- (5) channel quality information

The message type information indicates whether the user has declared an emergency. Emergency procedures are described in subsection 9.3.5. The user ID information is redundant since only one user at a time can use each M/E subchannel. The call waiting bit

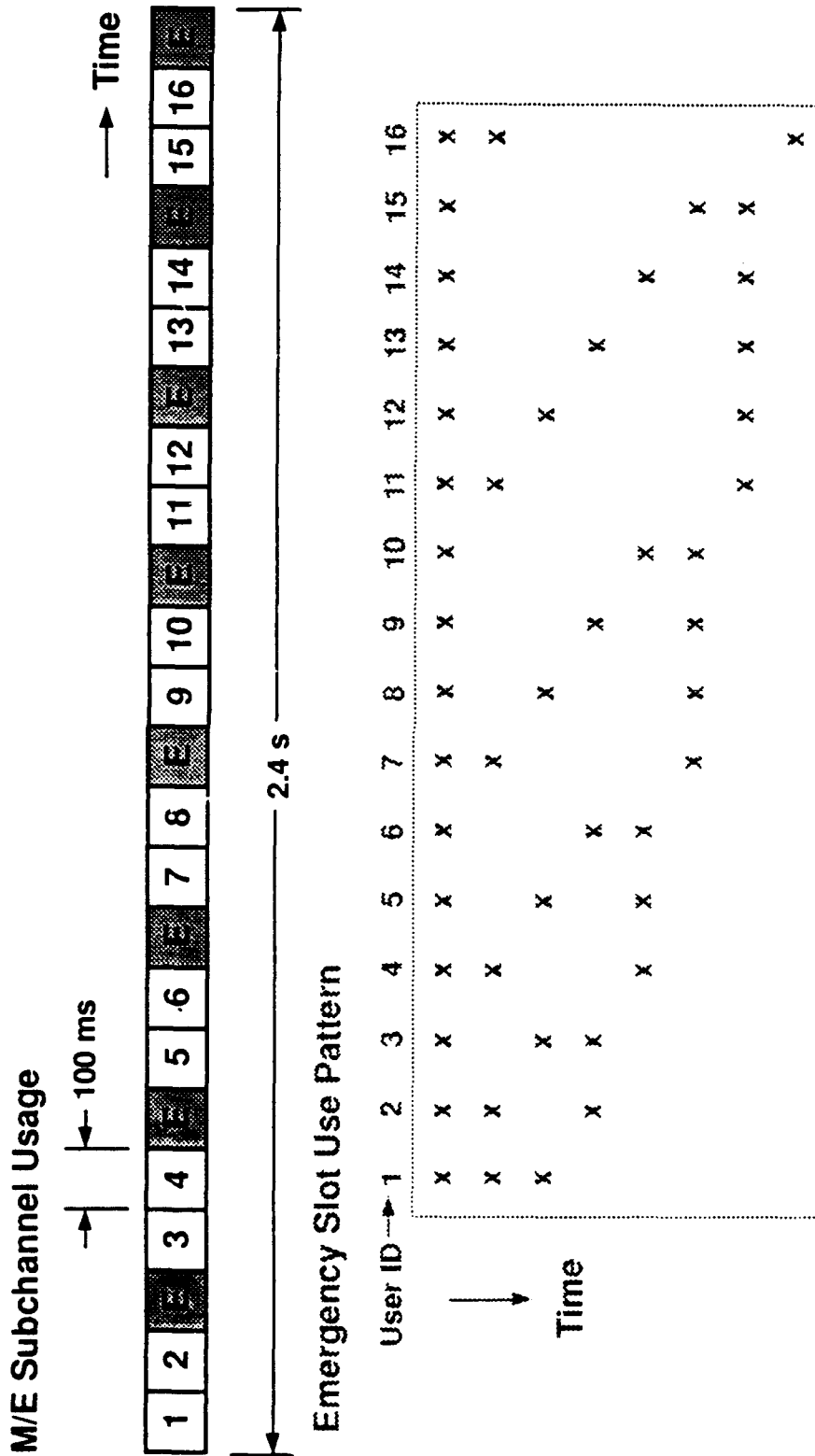


Figure 9-2. Maintenance/Emergency Organization

can be used to alert the controller that another user wishes to use the downlink. The increment/decrement information indicates whether the user's transmit timing has been adjusted since the previous update (see below for time adjustment description).

Finally, the channel quality information includes an estimate of the quality of the uplink service circuit as perceived by the airborne user. This estimate may, for instance, be based on the number of errors corrected by the error correction code. The user may also indicate to the ground the number of cells whose service channels are better than the current one.

The M/E uplink information includes the following:

- (1) message type
- (2) user ID, slot number
- (3) talk/don't talk
- (4) increment/decrement
- (5) channel change information

If the uplink voice circuit is being used by the ground user (or to relay another airborne user's speech) the "don't talk" signal will be given. Under those conditions the user will not normally be allowed to transmit in the V/D subchannel. If push-to-talk (PTT) is activated the "call waiting" signal will be activated in the next available M/E slot, and the controller can be made aware of the existence of a potential speaker.

The increment/decrement message can be sent to each user at 2.4 s intervals to adjust transmit timing so that messages arrive at the ground at the correct time. Note that time can probably be measured to an accuracy of at least one fourth of a symbol, or about 10 μ s. Whenever signal arrival times start to wander they can easily be corrected so that the 1 ms guard time is very generous. Also, note that both the ground and the airborne radios can accurately determine the range to each user since the original offset and the subsequent increments and decrements can be remembered. Range accuracies of one or two miles should be achievable.

The channel change information may simply be an indication to initiate channel (cell) change procedures on a service circuit. The decision to change could be based on the uplink quality (and the known existence of better channels), downlink quality, and/or link range.

9.3.3. Voice Communications

Whenever an airborne user wishes to speak he simply waits for a period of silence and activates PTT. His digitized voice will occupy the V/D subchannel of all subsequent slots in the circuit. The ground station, upon receiving this signal, will relay the message to all other users. The ground radio will also change the "talk" indicator to the "don't talk" indicator on the M/E subchannel for each of the other users. Thus, the other users can monitor the conversation but cannot normally break in.

The ground controller always has complete control of the communication network. If he should activate PTT, his message would replace that of the original airborne speaker; and the previous speaker will also receive the "don't talk" indicator on the M/E channel.

If an airborne user wishes to speak while another is already talking he can activate PTT and a "call waiting" signal will be sent in his M/E time slot. This call waiting message will be put in a queue with any other call waiting messages and the controller will receive some appropriate indication. Since the controller controls the network he may select a new user to access the V/D subchannel.

Note that the V/D subchannel is fairly simple. Each 20 ms time slot contains a 1.5 ms sync message, 0.5 ms header, and 12 ms of voice bits. The header is just 20 bits long. If a (20,9) Golay code is used, this is only 9 information bits.

These bits include:

- | | |
|-----------------------|----------|
| (1) routine/emergency | (1 bit) |
| (2) user ID | (4 bits) |
| (3) voice/data | (1 bit) |
| (4) undefined | (2 bits) |
| (5) parity check | (1 bit). |

The voice/data bit indicates whether the ensuing message is 4.8 kbps voice or coded data of some sort.

9.3.4. Cell Monitoring/Cell Handover

Every airborne user is always connected by a voice circuit to a particular cell site. As it flies from place to place the cell will have to change in order to maintain connectivity. This is accomplished by cell monitoring.

Suppose, for instance, that there are a total of 24 different uplink service channel frequencies that blanket the entire service area using some appropriate frequency reuse pattern. Every airborne user will monitor the activity on one of these channels during each 100 ms time interval during the slots not allocated for transmitting or receiving on the voice circuit. It will take 2.4 s to update all the channels. Note that the approximately 60 ms available is more than enough to monitor two complete time slots during each interval no matter what the time offset between the different cell site clocks.

The quality of each channel can be estimated, perhaps, by keeping track of the number of errors corrected by the error correcting code. This measure is not dependent on knowing the information which was actually sent. The quality of the service channel of the currently-occupied cell is reported to the ground station via the M/E subchannel, along with an indication of the number of other service channels deemed to be of better quality. The ground station can develop its own measure of link quality by monitoring the error correction statistics of the M/E downlink.

These two qualities, plus the known range of the airborne radio, can be combined by some to be determined (TBD) algorithm to ascertain when a cell handover is imminent. When this is determined the uplink M/E is used to tell the user to dump its quality information via a specified service circuit. The information downloaded includes a list of the

"best" quality service channels and their (numerical) qualities. (Alternately, this information might already be incorporated in the routine downlink M/E report). Using this information the ground station instructs (via the service circuit) the user to interrogate the two or three most likely handover candidates. To interrogate, the user performs a round trip timing procedure (see net entry) and measure the range to each site. This range is reported to the ground station, which chooses the most appropriate new cell. In a final uplink service message the identity of the new service channel and the time to switch over is revealed.

The entire handover procedure may take one or two seconds (from the time of the indication of channel degradation to the new channel indication). It is assumed that this is fast enough to track actual changes in the RF environment. Note that after the new cell is determined, but before the handover actually takes place, the ground connections will have to be prepared so that there is no interruption in service. This might add one or more seconds to the total handover time.

9.3.5 Emergency Communications

When an airborne user feels it is warranted, he may declare an emergency by, for instance, activating a special switch on his radio set. Then he simply activates PTT and the message will be transmitted with a special emergency header. In addition, he will indicate an emergency in his allocated M/E slot and in a number of the special emergency slots (see figure 9-2).

If no other user is "on the line" the emergency user captures the circuit and his emergency status is made known to the controller. If someone is already speaking the existence of an emergency will be indicated to the ground via the M/E subchannel. The ground radio can then remotely shut off all non-emergency traffic using the "don't talk" indication in the uplink M/E channel.

To guarantee that two emergency messages, which happen to originate at exactly the same time, do not constantly conflict and prevent either from being received, there are two mechanisms provided. First, each such user has his own unique M/E subchannel slot. Secondly, each user will have a unique pattern of three emergency slots (based on ID number) which are guaranteed not to conflict more than twice. Thus, at least one user will always get the circuit in times of emergency. Normally, emergency access time will be less than 300 ms if there is already a (nonemergency) user on the air and there is no multiple emergency situation. If no one is on the air, access time is less than 100 ms.

In case of multiple emergency messages there are a number of possible solutions. One possibility is to provide "emergency call waiting". Another possibility is to quickly assign a new voice circuit to the second emergency speaker. It is not clear to the study team how air traffic controllers or pilots would like to resolve this issue.

The above is a rough outline of what appears to be a viable architecture for TDMA CTAG. Many details have not been spelled out; however, there is enough information to elicit some feedback from the reader on the basic soundness of the concept and how this example design might be improved.

9.4 LINK SYNCHRONIZATION

In the above TDMA architecture, uplink and downlink messages are sent in 20 ms time slots. Each message consists of a synchronization (acquisition) preamble followed by the information or data content of the message. Assuming both the sync and data portions of the message are transmitted using QPSK modulation at a 20 kbaud rate (corresponding to an instantaneous 40 kb/s data rate in transmission), 60 bits, corresponding to 30 bauds, is devoted to the sync preamble.

Given the signal to noise ratio (SNR) required to achieve some specified level of performance) such as a 10^{-2} binary error rate (BER) during the data portion of the message, one of the open questions was whether the 1.5 ms sync preamble is sufficiently long to support that same standard. This subsection addresses that question. It is shown that, for a 1.5 ms preamble, the sync is approximately 9.5 dB stronger than the data [29]. A 1.0 ms preamble would therefore be about 7.7 dB stronger than the data. The resulting 0.5 ms might more usefully be redirected toward increasing the data content that can be communicated in CTAG messages.

To begin, consider the SNR required for acceptable communication performance in the data portion of CTAG messages. We assume that a 10^{-2} BER is required in the data portion of CTAG voice messages. Moreover, for the (20,9) Golay code proposed for the data portion of CTAG data messages, a 10^{-2} BER yields a code word error probability of 0.4×10^{-4} . Figure 14-6 of reference [30] indicates that for an ideal differentially coherent detector of QPSK, a SNR of about 8.0 dB (E_b/N_0 of 11.0 dB) is required.

Next, consider the SNR required for the synchronization portion of CTAG messages. A detection probability $P_D = 1 - 10^{-4} = 0.9999$ is commensurate with a Golay code error probability of 10^{-4} in the data portion of CTAG data messages. If the preamble detector for CTAG messages were sampled at the 20 kHz baud rate over a 5 ms uncertainty period, 100 samples would be taken. For a message false alarm rate of 10^{-5} , a per sample false alarm rate $p_f = 10^{-7}$ is required. In reference [31] it is shown that for an idealized detector, a single-pulse SNR of 16.3 dB is required for $P_D = 0.9999$ and $p_f = 10^{-7}$. Recall that a 1.5 ms sync preamble consists of 30 bauds. If a baud SNR $E_b/N_0 = 11.0$ dB were required for acceptable CTAG performance in the data portion of CTAG messages, as indicated above, this would correspond to a single-pulse baud SNR of

$$25.8 \text{ dB} = \text{SNR (baud)} + 10 \log_{10} 30 \text{ b} = 11.0 \text{ dB} + 14.8 \text{ dB} \quad (3)$$

for the synchronization portion of CTAG messages. This exceeds the required amount by 9.5 dB. A 1.0 ms sync preamble, consisting of 20 bauds, would produce a single-pulse SNR exceeding the required amount by about 7.7 dB.

SECTION 10

FDMA COMPARISON

10.0 INTRODUCTION

A TDMA system architecture for CTAG and the procedures required for net entry, circuit maintenance, cell monitoring, cell handover and emergency communications is described in section 9. Those procedures, except for some minor modifications, could also apply to an FDMA architecture [32].

Modifying assumptions 6 and 8 of subsection 9.1 by:

- 6'. Each voice and service channel is a separate 5 kHz signaling channel with an 8 kb/s instantaneous data rate.
- 8'. Synchronization consumes 7.5 ms per transmission (60 bits), although as shown by Ramsey in subsection 9.4, it can be considerably shortened.

As in TDMA, contention for a voice channel is eliminated except for the PTT discipline among the aircraft using the same transmission slot. Although the M aircraft sharing a voice "circuit" with a controller share a single FDM channel pair, the uplink voice channel carries information directing which one of the M aircraft terminals is permitted to transmit on the downlink voice channel.

A single FDM voice channel pair is used for all aircraft connected to a cell which are sharing a voice circuit with a controller. As shown in figure 10-1, the downlink channel is divided into two TDM subchannels: the V/D subchannel and the M/E subchannel.

An airborne user is given a dedicated time slot assignment on the M/E channel which, using Wilson's M/E subchannel usage map, he can access under normal conditions every 2.4 s and under emergency conditions every 300 ms. He uses these accesses to request from the controller use of the V/D subchannel (i.e., the voice circuit). The header portion of the voice uplink identifies the airborne user permitted to use the V/D downlink.

In this architecture, like in the TDMA design, initial synchronization of the voice downlink is achieved by monitoring the service channel uplink and maintained by monitoring the voice channel uplink. No timing correction is needed since sufficient guard times (5 ms) to prevent adjacent time slot overlap is provided for both the M/E and V/D subchannels.

The uplink voice channel transmissions are continuous but are formatted to provide a synchronization preamble every 100 ms. Reception of the preamble is used to provide a timing marker for the downlink. The header contains M/E data to control use of the downlink.

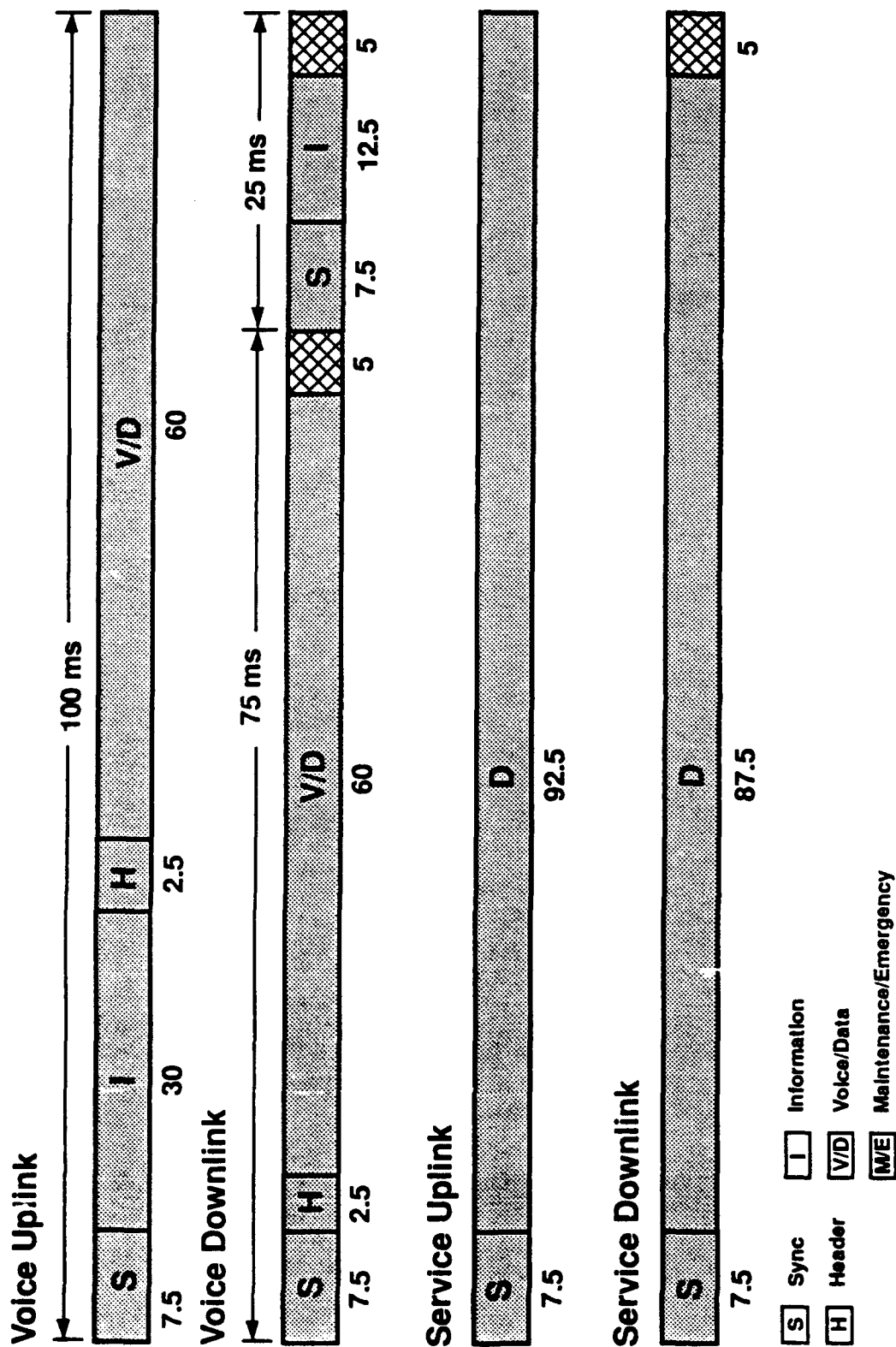


Figure 10-1. Alternative FDMA Organization

There is a single uplink and a single downlink service channel per cell which are shared by all cell participants. The uplink service channel transmissions are continuous and contain a synch portion, transmitted every 100 ms, and a data portion. The downlink channel timing is synchronized to the uplink but has an uncertainty proportional to the propagation distance between the cell and the airborne user. A 5 ms guard time prevents overlap of transmissions from different airborne users in adjacent time slots.

The following question comes to mind -- are there any advantages of the FDMA architecture versus the TDMA architecture? Since this FDMA design parallels the TDMA design one would expect few differences. For the same system capacity the total bandwidth required is the same. The time to access a new cell would increase since there are 1/5th as many accesses on the downlink service channel. However, one access every 100 ms seems sufficient. More importantly, access to the voice downlink is the same. Assuming both designs use the same modulation and coding techniques, they both require the same E_b/N_0 , but the peak power required in the FDMA design would be 1/5th that required in TDMA. Another advantage of FDMA is that in that design the aircraft radios don't have to synchronize as precisely (i.e., RTT) to their respective cells.

In the TDMA design, transmit and receive time slot assignments do not overlap. Therefore the radio is either transmitting or receiving, but never doing both simultaneously. In the FDMA design, the radio is simultaneously participating on a voice uplink channel (receiving) and a voice downlink channel (transmitting). In addition, the FDMA radio must concurrently monitor the quality of the service channels of nearby cells. As a result, the FDMA radio requires one transmitter, two receivers and either two or three synthesizers depending on whether the receiver scanning the service channels can share a common synthesizer with the transmitter. The TDMA design requires one transmitter, only one receiver and only one common synthesizer.

LIST OF VOLUME 2 REFERENCES

9. Panter, P. F., *Modulation, Noise, and Spectral Analysis*, McGraw Hill, New York, 1965.
10. Schwartz, M., Bennett, W. R., and Stein, S., *Communication Systems and Techniques*, McGraw Hill, New York, 1966.
11. Reed, T. A., "CTAG Airborne and Ground Radio Price Estimates," D093-M-603, Internal Memorandum, The MITRE Corporation, 27 August 1991.
12. Gilhousen, K. S., Jacobs, I. M., Padovani, R., Viterbi, A. J., Weaver, L. A., and Wheatley, C. A., "On the Capacity of a Cellular CDMA System," *Special Issue on Digital Cellular Technology, IEEE Trans. Vehicular Technol.*, May 1991.
13. Goodman, D. J., "Trends in Cellular and Cordless Communications," *IEEE Communications Magazine*, June 1991, pp. 31-40.
14. Taylor, J. T., and Omura, J. K., "Spread Spectrum Technology: A Solution to the Personal Communications Services Frequency Allocation Dilemma," *IEEE Communications Magazine*, February 1991, pp. 48-51.
15. Casewell, I. E., "The Provision of GSM Cellular Radio Environments within Passenger Aircraft Operating Over Europe," *5th Intern. Conf. Mobile Radio and Personal Commun.*, Univ. of Warwick, Coventry, U.K., 11-14 December 1989.
16. Millar, R. I., Department D050, The MITRE Corporation, private communication.
17. Wickwire, K. H., "CTAG Message Generation," D095-M-490, internal memorandum, The MITRE Corporation, 14 June 1991.
18. Millar, R. I., "Cell Structure and Frequency Reuse in Cellular-Trunked Air/Ground (CTAG) Radio Communications," D050-M-050, internal memorandum, The MITRE Corporation, 17 April 1991.
19. Wilson, W. J., "Solution to the CTAG Cellular Problem," D053-M-1024, internal memorandum, The MITRE Corporation, 23 May 1991.
20. Wilson, W. J., "CTAG Frequency Reuse Patterns and Propagation Effects," D053-M-1454, internal memorandum, The MITRE Corporation, 15 October 1991.
21. Bullington, K., "Radio Propagation Fundamentals", *The Bell System Technical Journal*, Vol. XXVI, No. 3, pp. 593-626, May 1957.
22. International Radio Consultative Committee (CCIR), "Reflections from the Surface of the Earth", Vol. V, REport 1008, pp. 89-95, 1986.

LIST OF VOLUME 2 REFERENCES
(Concluded)

23. Davis, R. W., "Cell Hand-Off Procedures for CTAG Radio Channels", D059-M-2111, internal memorandum, The MITRE Corporation, 9 May 1991.
24. Jain, G. P., "FAA National Airspace System Architecture," Department F085 briefing, The MITRE Corporation, 6 February 1991.
25. Leiter, M., "CTAG Ground System Data Flow," D053-M-1361, internal memorandum, The MITRE Corporation, 16 August 1991.
26. Leiter, M., "How Does CTAG Work?," D053-M-1318, internal memorandum, The MITRE Corporation, 23 July 1991.
27. Ramsey, J. L., "Message Traffic Requirements for Routine Cellular Handoff in CTAG," D053-M-1276, internal memorandum, The MITRE Corporation, 3 July 1991.
28. Wilson, W. J., "Rudiments of CTAG TDMA Architecture," D053-M-1218, internal memorandum, The MITRE Corporation, 31 May 1991.
29. Ramsey, J. L., "The Relative Strengths of the Sync and Data Portions of a Prospective CTAG Message Format," D053-M-1243, internal memorandum, The MITRE Corporation, 13 June 1991.
30. Stein, S., and Jones, J. J., *Modern Communication Principles*, McGraw Hill, New York, 1967.
31. Robertson, G. H., "Normal Error Model Analysis Charts," published privately by author, Mountainside, New Jersey, May 1977.
32. Leiter, M., "Strawman FDMA Architecture," D053-M-1270, internal memorandum, The MITRE Corporation, 2 July 1991.

APPENDIX 1

Briefing on Trellis Coded Modulation

by M. Leiter

Integrated Modulation and Coding

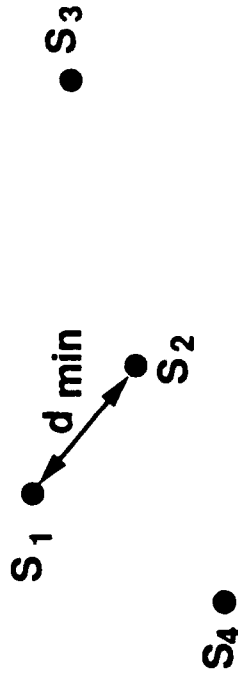
- Generally, modulations by themselves:
 - If more bandwidth efficient are less power efficient
 - If more power efficient are less bandwidth efficient
- Conventional codings in general improve power efficiency at expense of bandwidth efficiency
- Trellis-coded modulation (TCM) improves power efficiency without increasing bandwidth
- Eb/No improvement is not as large as in conventional coding schemes
- Complexity and processing delay increases.

Trellis-Coded Modulation

- An efficient modulation for band-limited channels
- Coding gain without bandwidth expansion

Approach

- Start with M-ary signal set ($M = 4$)



- Error performance is proportional to $d_{\min}^2$, where $d_{\min}$ is the Euclidean Distance to closest neighbor
- Approach is to increase number of signals in set and add coding so that $d_{\min}$ is increased

Outline of Example

- Baseline signal set is 4-level ASK (Amplitude Shift Keying)
 $I = 2 \text{ bits}/T^*$ (bandwidth efficiency) and $d_{\min}^2 = 16.8$
- Increase signal set to 8-level ASK
 $I = 3 \text{ bits}/T$ and $d_{\min}^2 = 4$
- Apply rate $2/3$ trellis coding to 8-level ASK set, so that
 $I = 2 \text{ bits}/T$ and $d_{\min}^2 = 36$
- Define asymptotic coding gain as ratio of $d_{\min}^2$ values:

$$G = \frac{(\text{ } d_{\min}^2 \text{) 8-ASK with trellis coding}}{(\text{ } d_{\min}^2 \text{) 4-ASK}} = \frac{36}{16.8} = 3.31 \text{ dB}$$

* Symbol duration

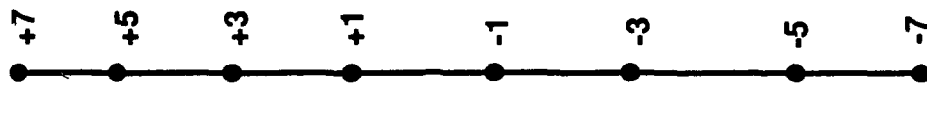
MITRE

4-Level ASK vs. 8-Level ASK

Equivalent average power, $\bar{P}$

$$\bar{P}_4 = \frac{(6.15)^2 + (2.05)^2}{2} = 21$$

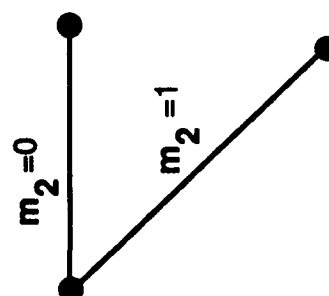
$$\bar{P}_8 = \frac{7^2 + 5^2 + 3^2 + 1^2}{4} = 21$$



$$d_{\min}^2 = (6.15 - 2.05)^2 = 16.8$$

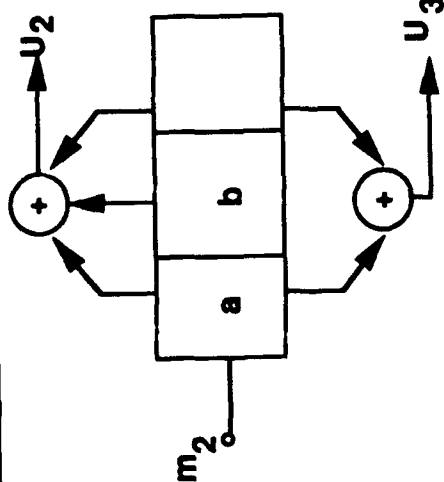
$$d_{\min}^2 = (7 - 5)^2 = 4$$

MITRE

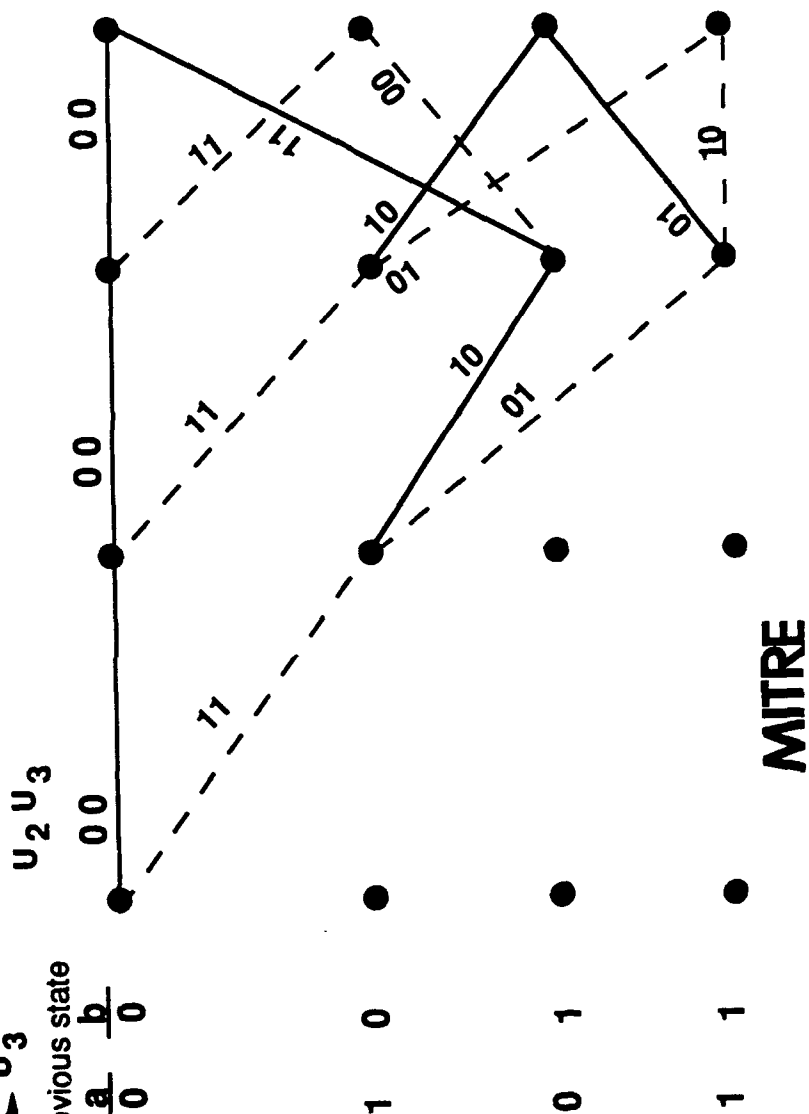
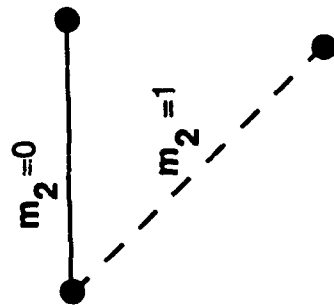
[illegible]

Trellis Diagram

$R = 1/2$ (code rate)
 $K = 3$ (constraint length)



previous state
 $\frac{a}{b}$
 (initial) 0 0

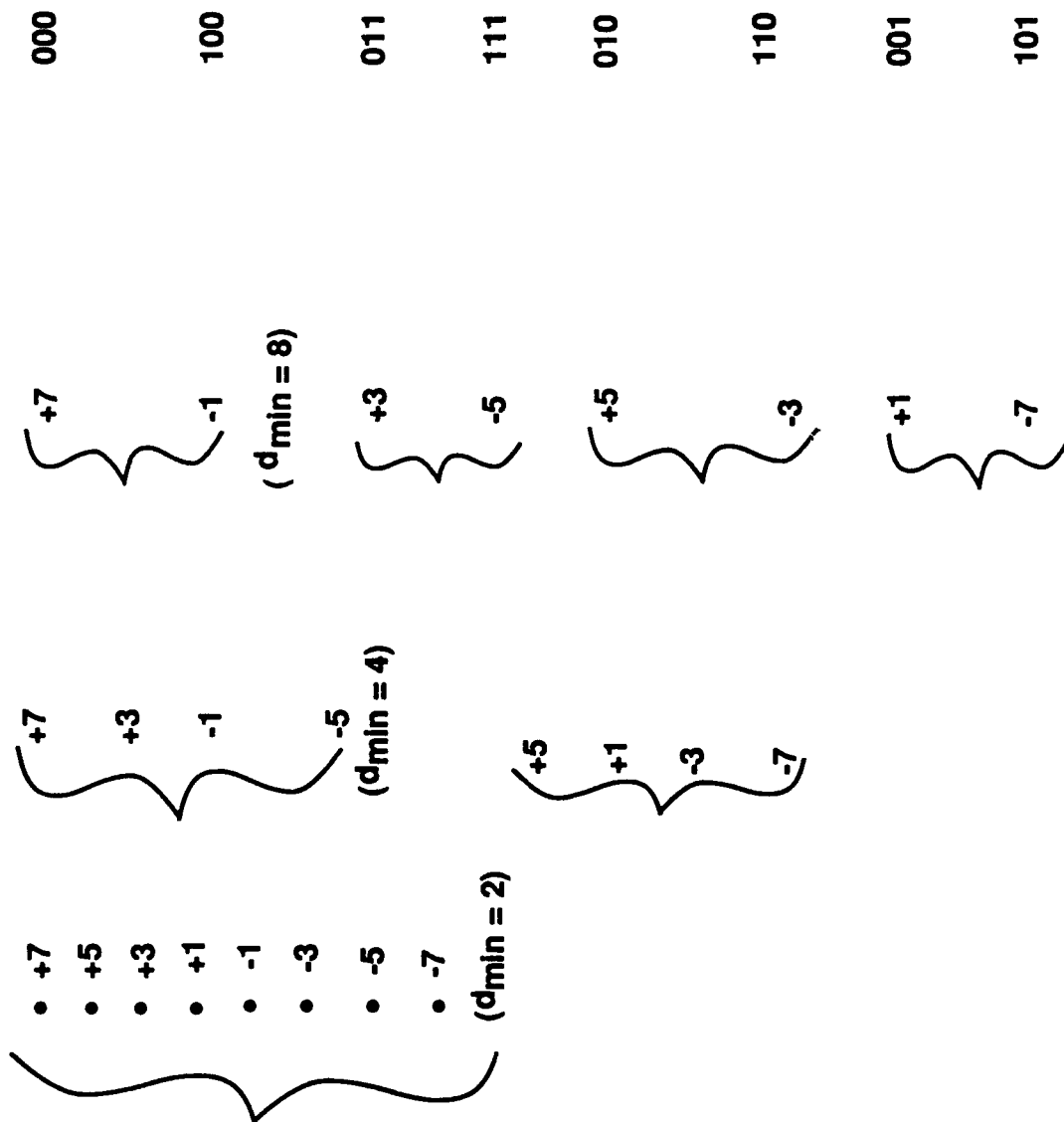


Euclidean Distance Expansion

- Relate codeword symbols U_1 U_2 U_3 to 8-level ASK signal set
- Choose so that
 - Parallel branches have maximum Euclidean distance
i.e., 000 and 100; 011 and 111; 010 and 110;
001 and 101
- Transitions, diverging or merging, have next largest Euclidean distance, e. g.,
 - 000 and 100 with 011 and 111 ($m_2=0$, then 1)
 - 011 and 111 with 010 and 110 ($m_2=1$, then 0)

MITRE

Partitioning of 8-Level ASK



MITRE

Compare $d_{\min}^2$ for An Error Event

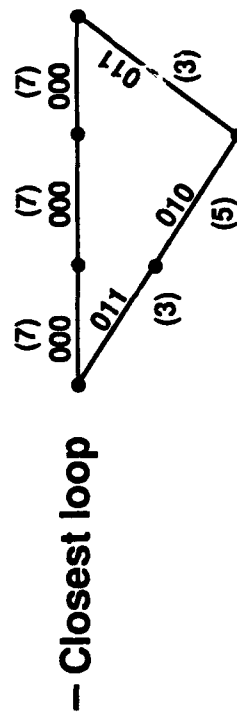
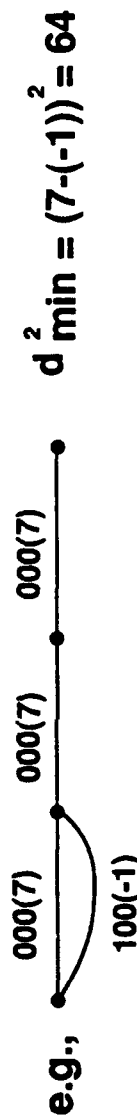
- 4-ary ASK

Closest neighbor

$$d_{\min}^2 = (6.15 - 2.05)^2 = 16.8$$

- 8-ary ASK trellis coded

– Two possibilities for one error
– Parallel branch



$$d_{\min}^2 = (7-3)^2 + (7-5)^2 + (7-3)^2 = 36$$

$$\min d_{\min}^2 = \min \{64, 36\} = 36$$

MITRE

Comparison of Bandwidth and Power Efficiency of Coherent QPSK/4-OQAM with and without Coding

(Additive White Gaussian Noise)

Case	Bandwidth Efficiency (b/s/Hz)	Power Efficiency Eb/No (dB) required for BER		
		10-3 (coding gain)	10-4 (coding gain)	10-6 (coding gain)
Without coding	2.0	6.8 (0.0)	8.4 (0.0)	10.5 (0.0)
With trellis-coded modulation	2.0	5.3 (1.5)	6.2 (2.2)	7.7 (2.8)
With conventional rate 2/3, K=3 convolutional code	1.33	4.5 (2.3)	5.6 (2.8)	7.3 (3.2)
With conventional BCH (31,16) code, hard decision	1.03	5.9 (0.9)	7.0 (1.4)	8.4 (2.1)
With conventional BCH (127,64) code, hard decision	1.00	5.1 (1.7)	5.7 (2.7)	6.6 (3.9)

APPENDIX 2
Development Work Breakdown Structure
by T. A. Reed

Development Work Breakdown Structure

Element Number	Item
1	Cellular Trunked Air Ground (CTAG) Radio System
1.1	Ground Equipment
1.1.1	Receiver/Transmitter
1.1.1.1	Hardware
1.1.1.2	Software
1.1.2	Antennas
1.1.2.1	Hardware
1.1.2.2	Software
1.1.3	Exciter
1.1.3.1	Hardware
1.1.3.2	Software
1.1.4	Switching Equipment
1.1.4.1	Hardware
1.1.4.2	Software
1.1.5	Backup Equipment
1.1.5.1	Hardware
1.1.5.2	Software
1.2	Airborne Equipment
1.2.1	Commercial Radio
1.2.1.1	Hardware
1.2.1.2	Software
1.2.2	Civil Radio
1.2.2.1	Hardware
1.2.2.2	Software
1.3	Training
1.3.1	Equipment
1.3.2	Services
1.3.3	Facilities
1.4	Peculiar Support Equipment
1.4.1	Organization/Intermediate
1.4.2	Depot
1.5	Systems Test & Evaluation
1.5.1	Development Test & Evaluation
1.5.2	Operational Test & Evaluation
1.5.3	Mockups
1.5.4	Test Facilities
1.5.5	Test and Evaluation Support

**Development Work Breakdown Structure
(Concluded)**

- 1.6 System/Project Management
 - 1.6.1 System Engineering
 - 1.6.2 Project Management
- 1.7 Operation/Site Activation
 - 1.7.1 Contractor Technical Support
 - 1.7.2 Site Construction
 - 1.7.3 Site Conversion
- 1.8 Common Support Equipment
 - 1.8.1 Organization/Intermediate
 - 1.8.2 Depot
- 1.9 Initial Spares
 - 1.9.1 Ground Equipment
 - 1.9.2 Airborne Equipment
- 1. 10 Data
 - 1. 10.1 Technical Publications
 - 1. 10.2 Engineering Data
 - 1. 10.3 Management Data
 - 1. 10.4 Support Data

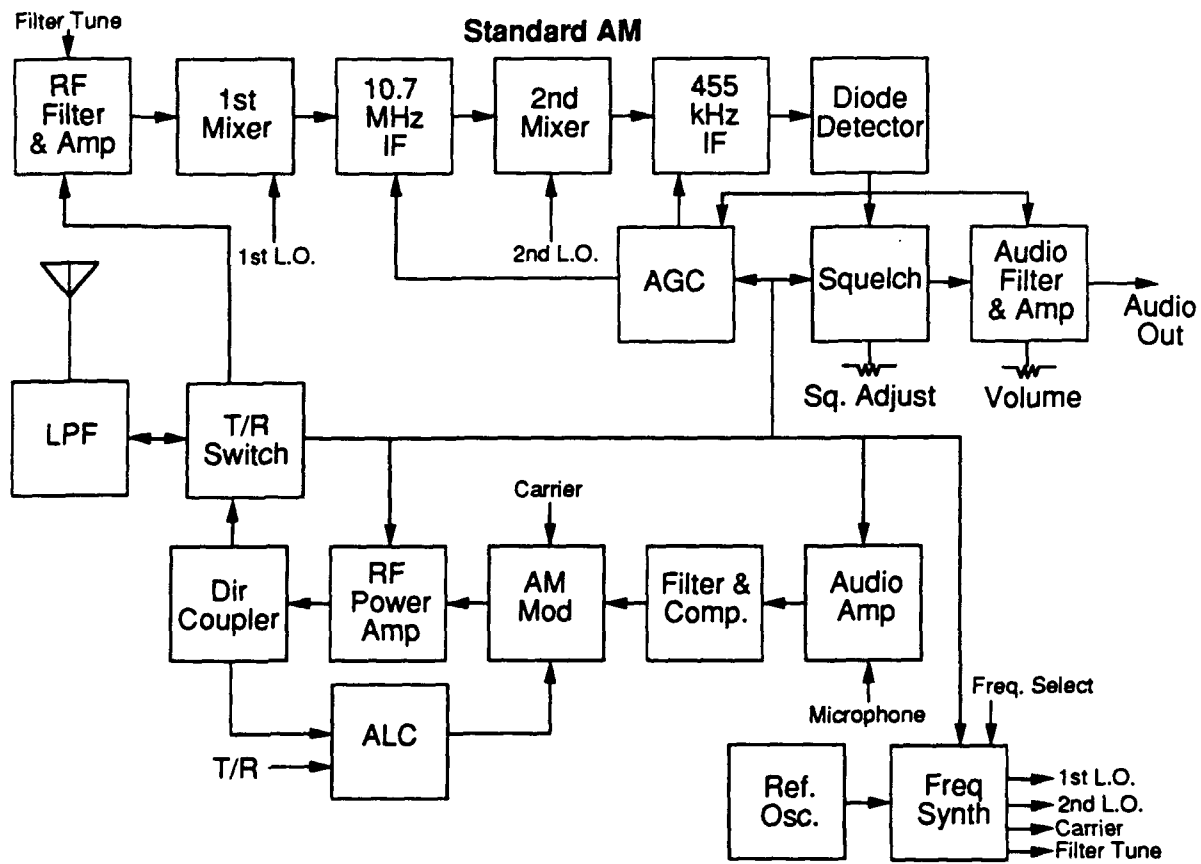
Production Work Breakdown Structure

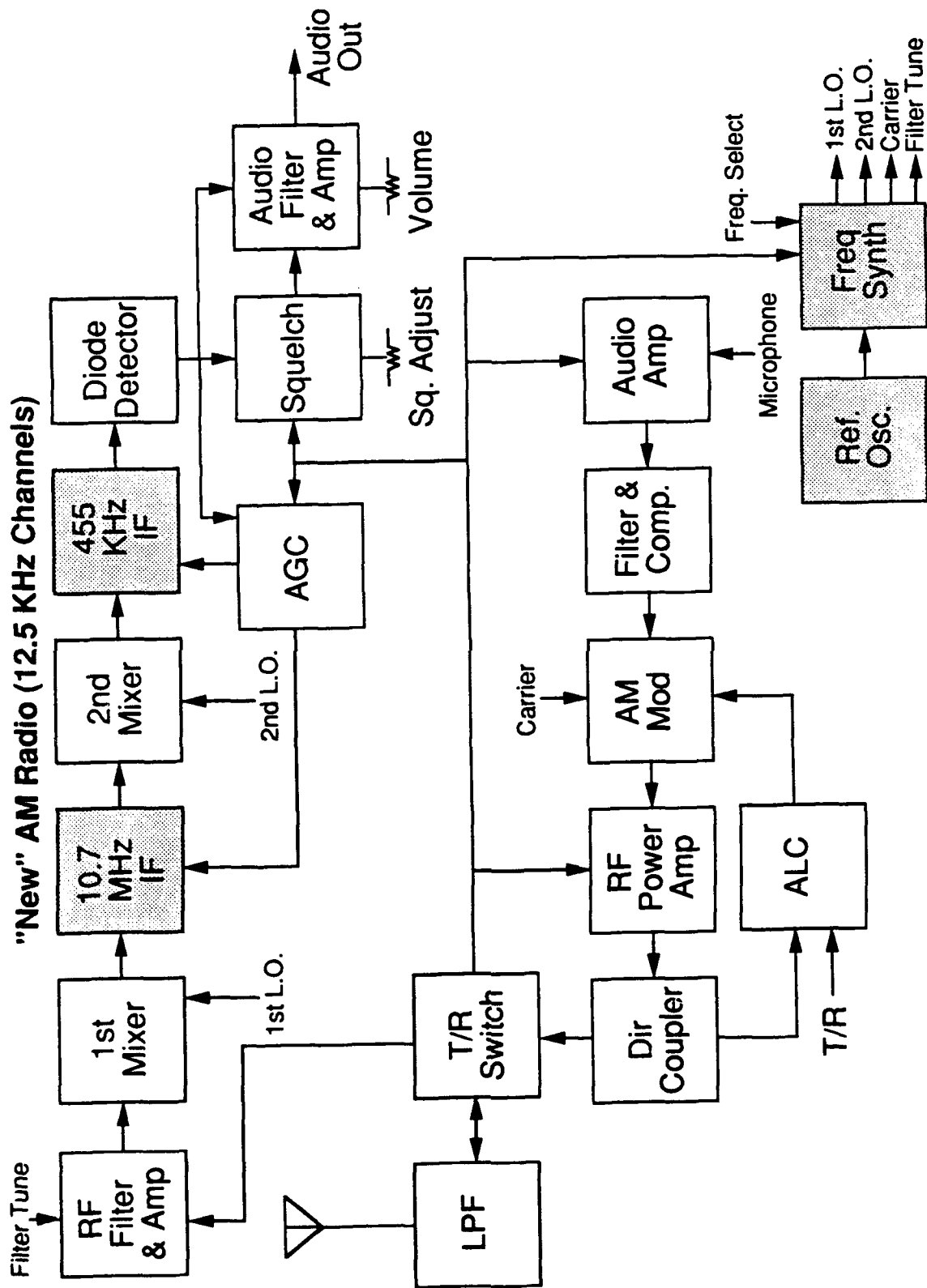
Element Number	Item
1	Cellular Trunked Air Ground (CTAG) Radio System
1.1	Ground Equipment
1.1.1	Receiver/Transmitter
1.1.1.1	Hardware
1.1.1.2	Installation
1.1.1.2.1	A-Kits
1.1.1.2.2	B-Kits
1.1.2	Antennas
1.1.2.1	Hardware
1.1.2.2	Installation
1.1.2.2.1	A-Kits
1.1.2.2.2	B-Kits
1.1.3	Exciter
1.1.3.1	Hardware
1.1.3.2	Installation
1.1.3.2.1	A-Kits
1.1.3.2.2	B-Kits
1.1.4	Switching Equipment
1.1.4.1	Hardware
1.1.4.2	Installation
1.1.4.2.1	A-Kits
1.1.4.2.2	B-Kits
1.1.5	Backup Equipment
1.1.5.1	Hardware
1.1.5.2	Installation
1.1.5.2.1	A-Kits
1.1.5.2.2	B-Kits
1.2	Airborne Equipment
1.2.1	Commercial Radio
1.2.1.1	Hardware
1.2.1.2	Installation
1.2.1.2.1	A-Kits
1.2.1.2.2	B-Kits
1.2.2	Civil Radio
1.2.2.1	Hardware
1.2.2.2	Installation
1.2.2.2.1	A-Kits
1.2.2.2.2	B-Kits

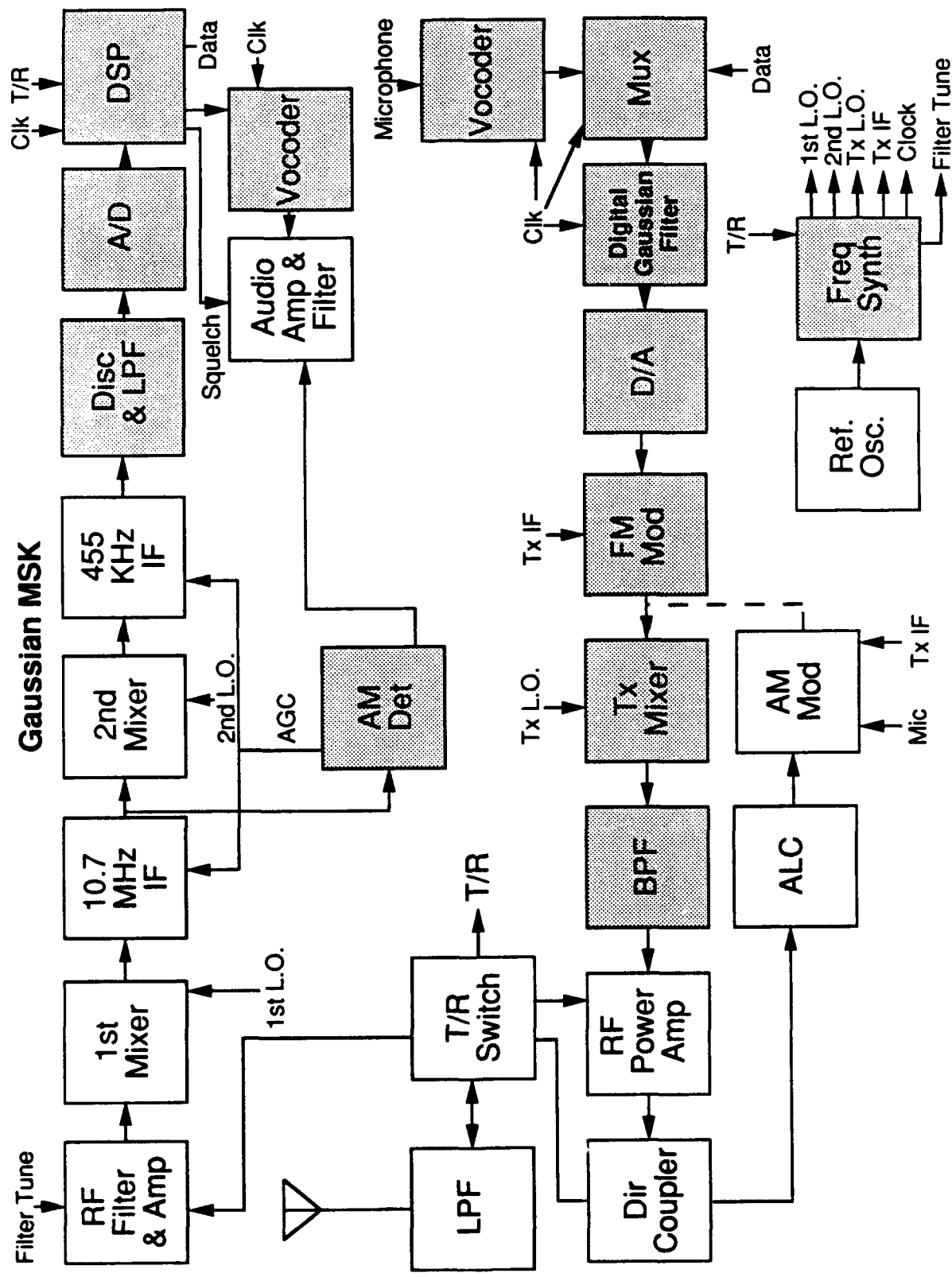
**Production Work Breakdown Structure
(Concluded)**

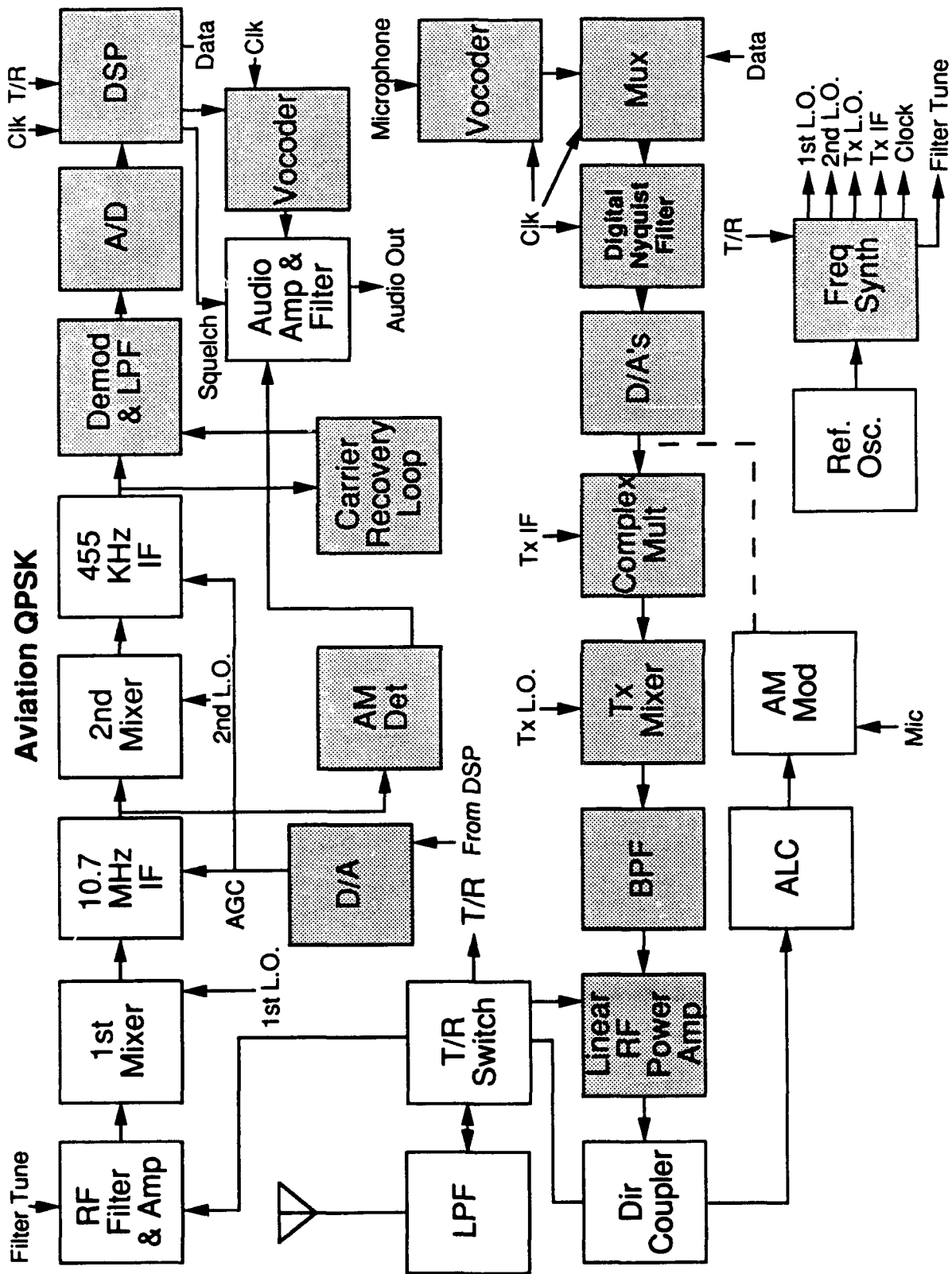
1.3	Training
1.3.1	Equipment
1.3.2	Services
1.3.3	Facilities
1.4	Peculiar Support Equipment
1.4.1	Organization/Intermediate
1.4.2	Depot
1.5	Systems Test & Evaluation
1.5.1	Development Test & Evaluation
1.5.2	Operational Test & Evaluation
1.5.3	Mockups
1.5.4	Test Facilities
1.5.5	Test and Evaluation Support
1.6	System/Project Management
1.6.1	System Engineering
1.6.2	Project Management
1.7	Operation/Site Activation
1.7.1	Contractor Technical Support
1.7.2	Site Construction
1.7.3	Site Conversion
1.8	Common Support Equipment
1.8.1	Organization/Intermediate
1.8.2	Depot
1.9	Initial Spares
1.9.1	Ground Equipment
1.9.2	Airborne Equipment
1. 10	Data
1. 10.1	Technical Publications
1. 10.2	Engineering Data
1. 10.3	Management Data
1. 10.4	Support Data

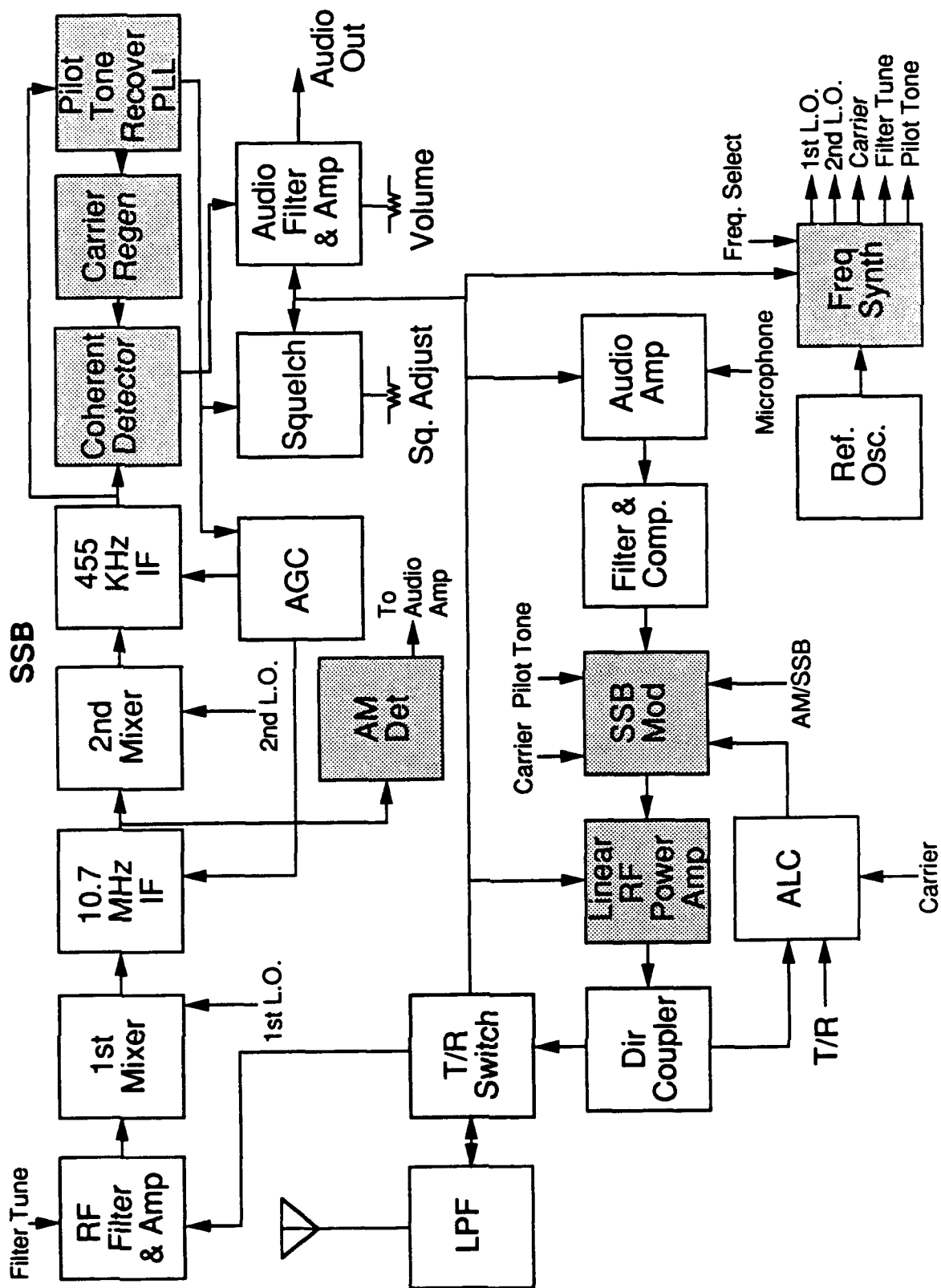
APPENDIX 3
Candidate Airborne Block Diagrams
by D. K. Snodgrass

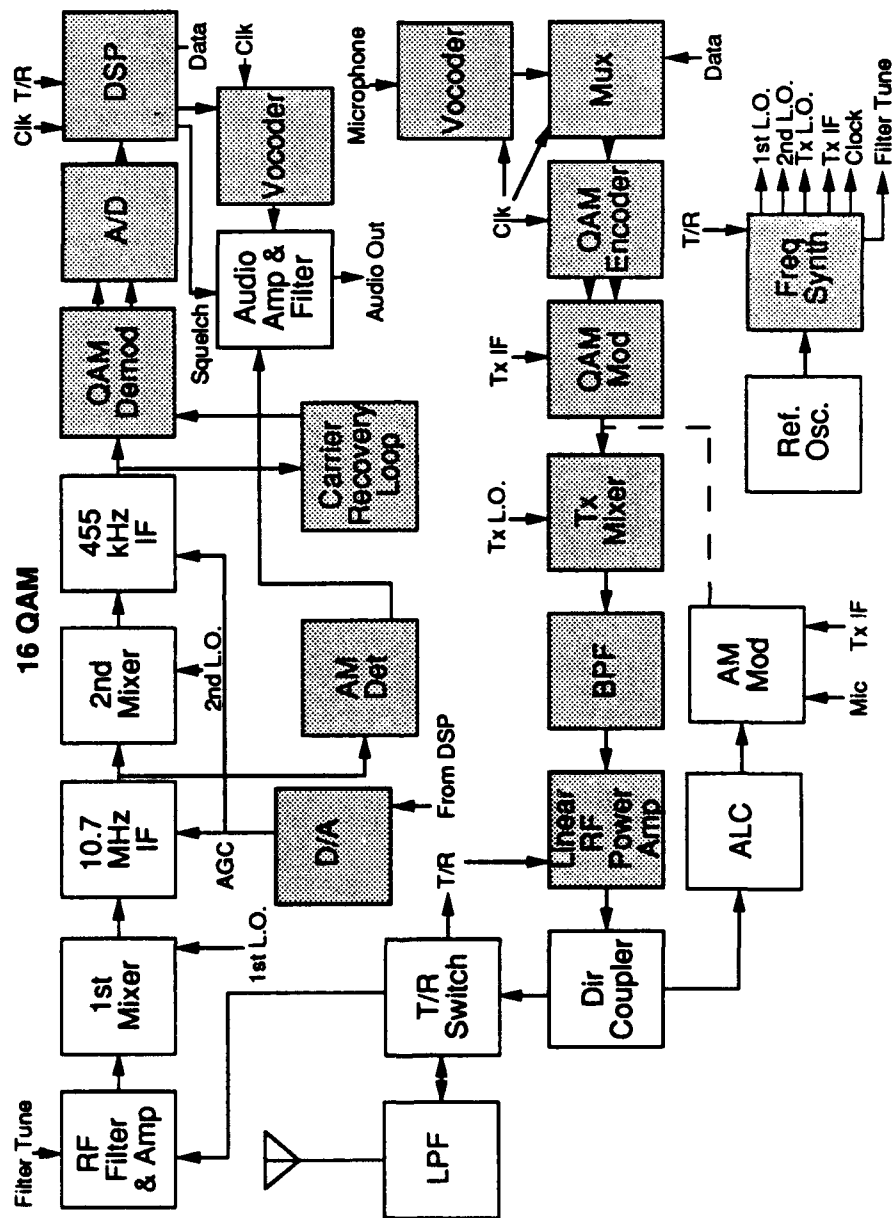










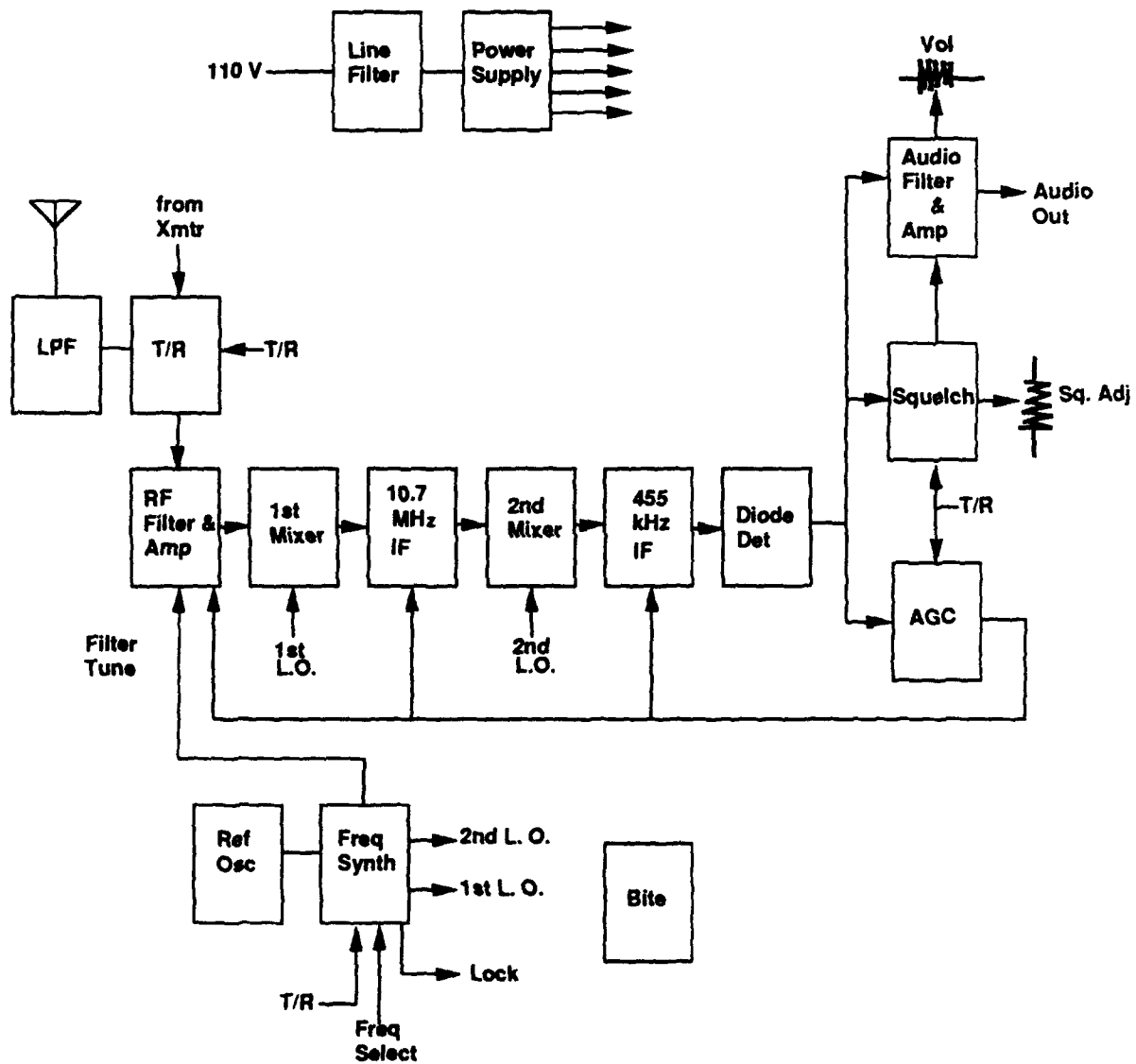


APPENDIX 4

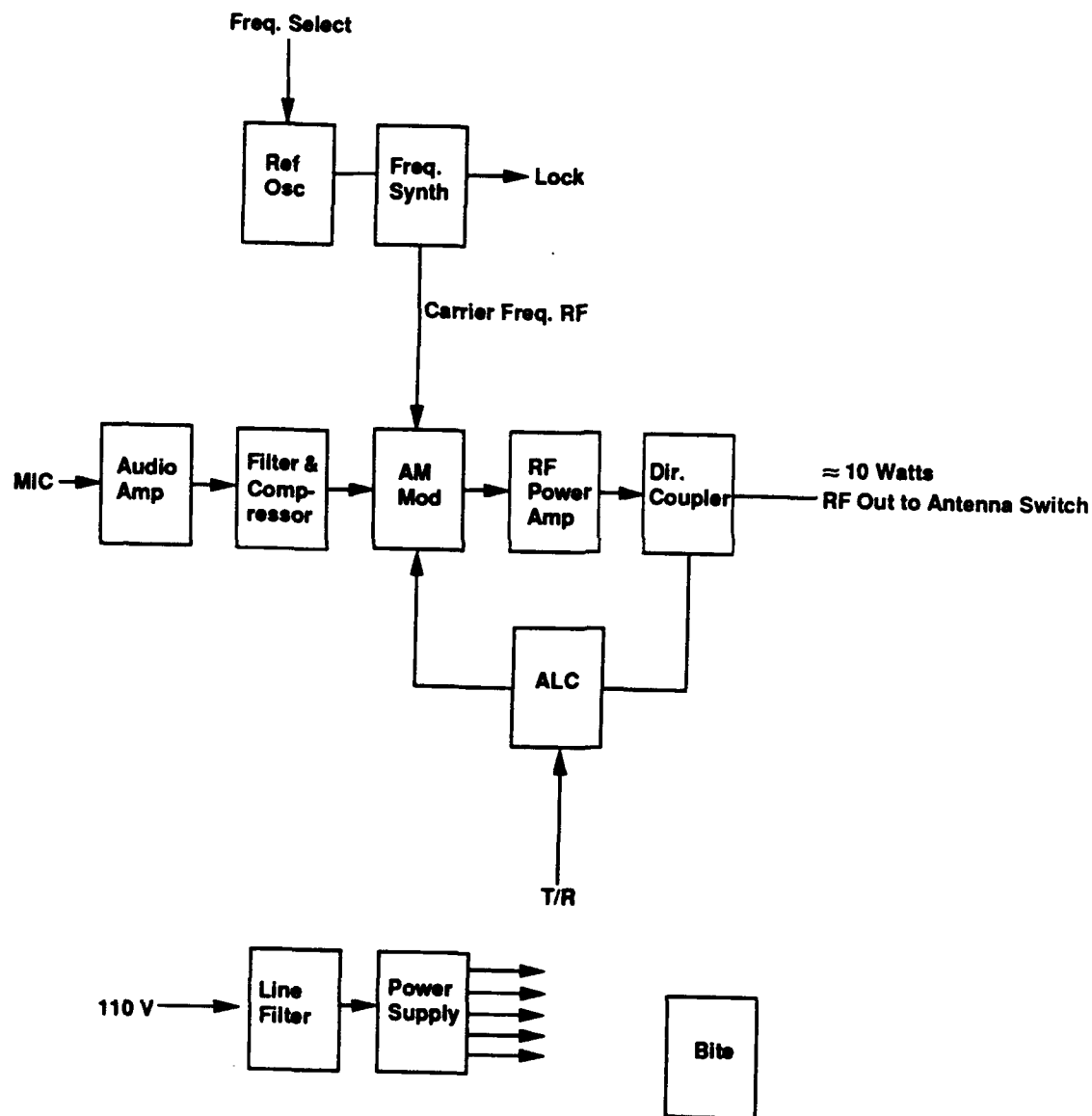
**Block Diagrams Used in Cost Estimates
for Ground Radios**

by D. K. Snodgrass

Standard AM & Narrowband AM Receiver



**Standard AM &
Narrowband AM Exciter**



New AM Radio 12.5 kHz Channel Spacing

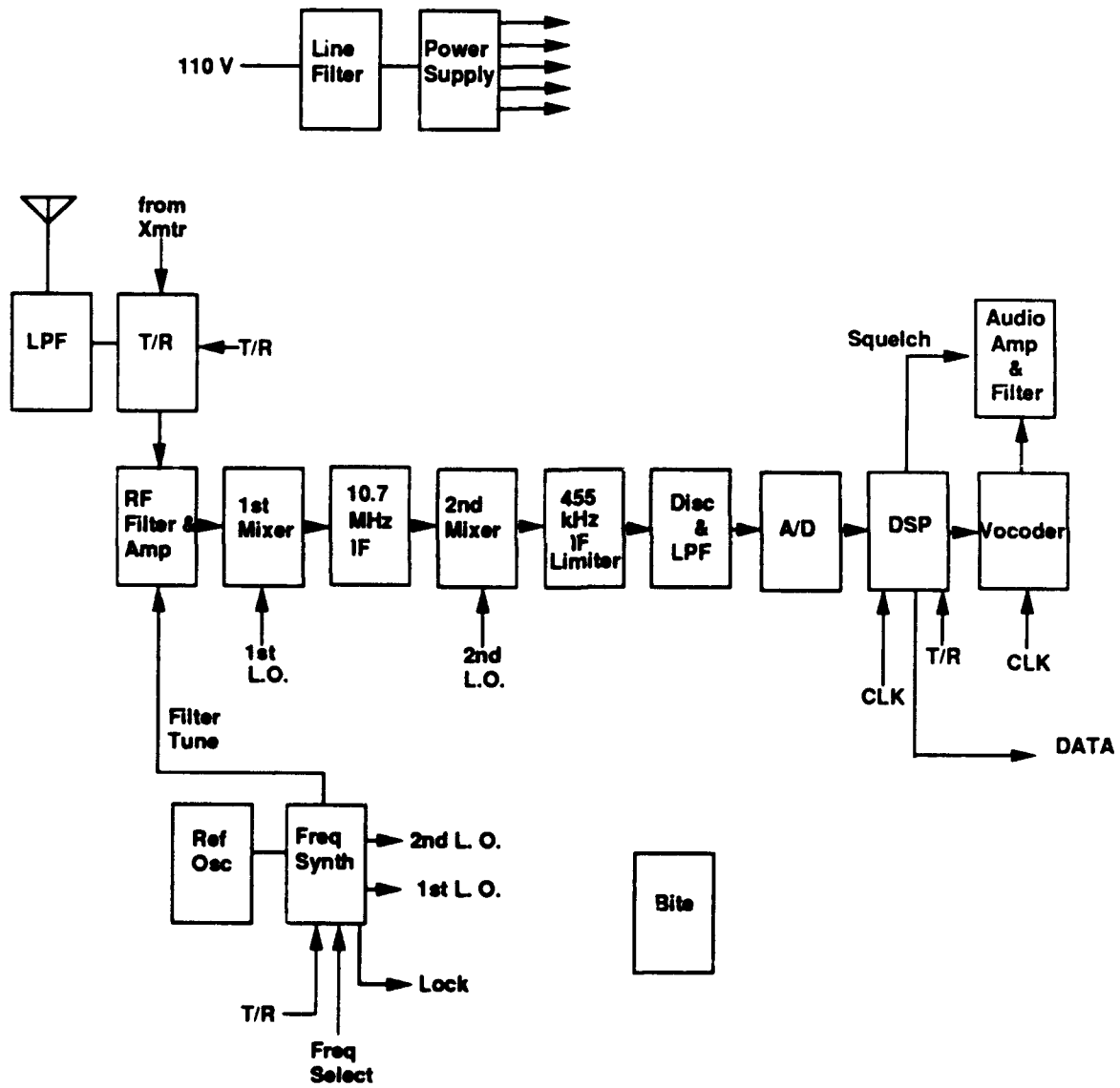
Same block diagram as "old" AM radio.

10.7 MHz IF Filter and 455 kHz 2nd IF filters have narrower bandwidth and better selectivity (more sections) to allow closer channel spacing.

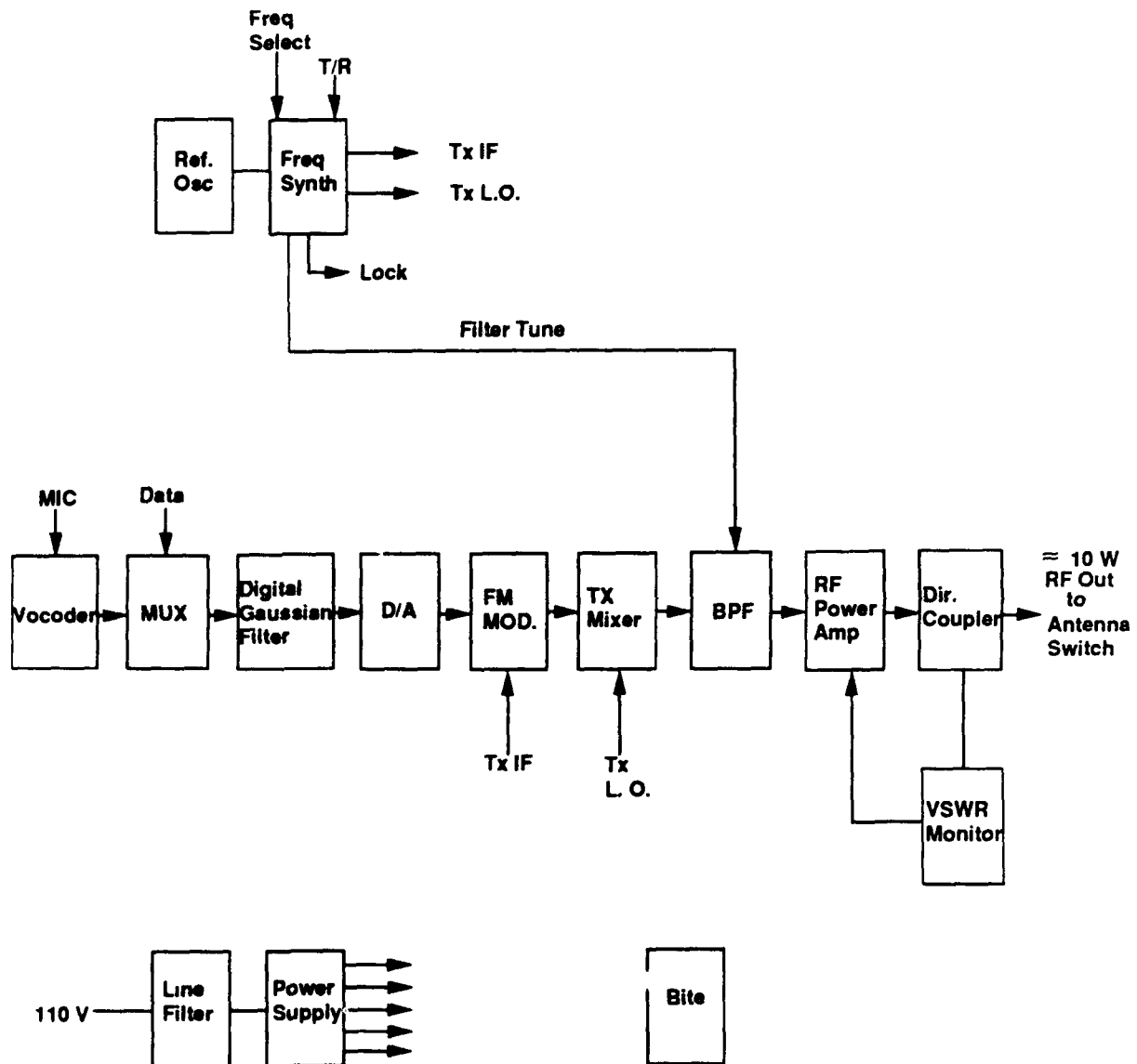
Synthesizer operates with a 12.5 kHz reference and has better phase noise characteristics. Reference is more stable than old radio ($\sim \pm 5\text{ppm}$). Second L.O. is also required to be more stable - may have to be locked to references.

To be backward compatible with old system, a second AM detector may be necessary.

GMSK Receiver



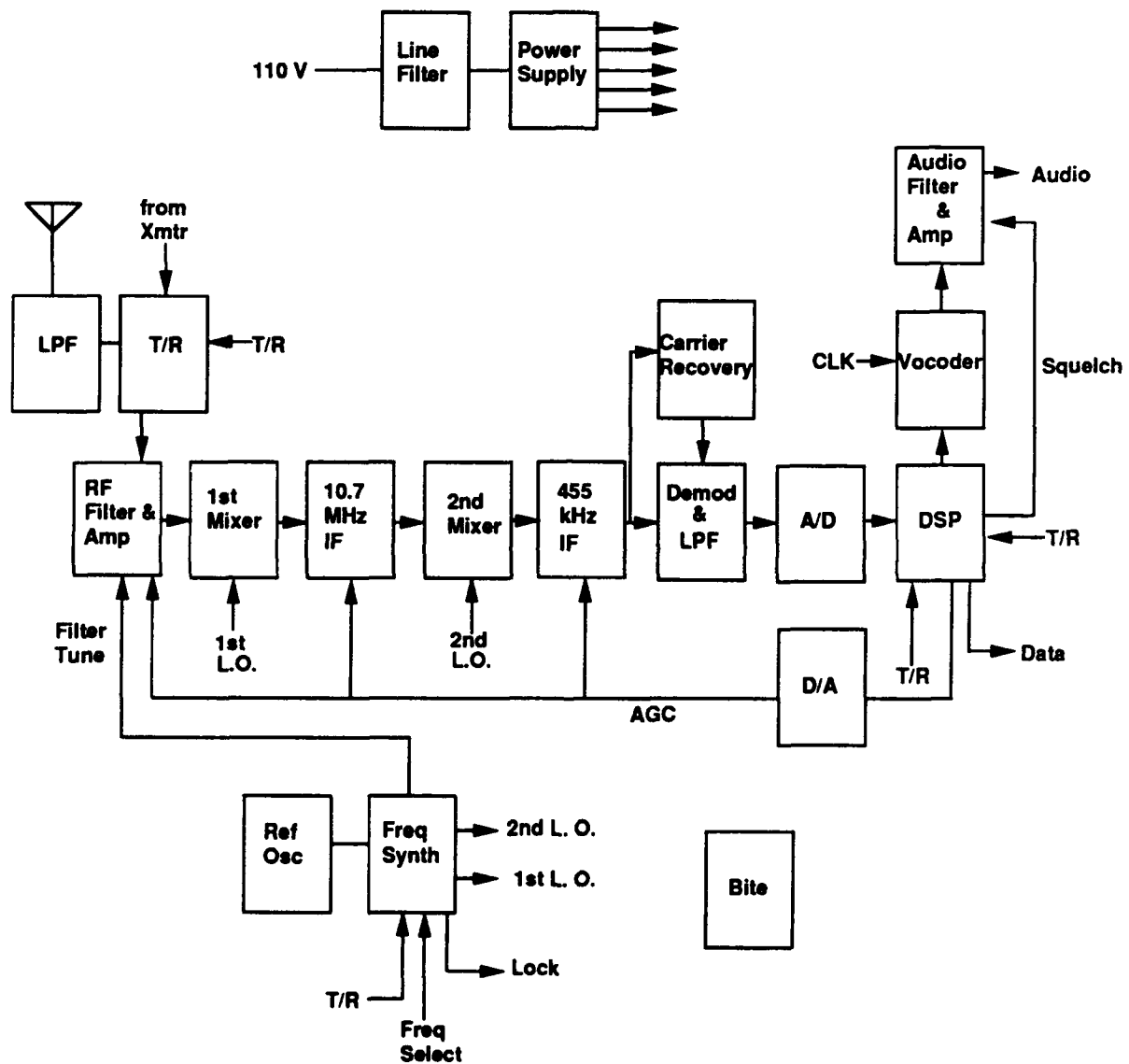
GMSK Exciter



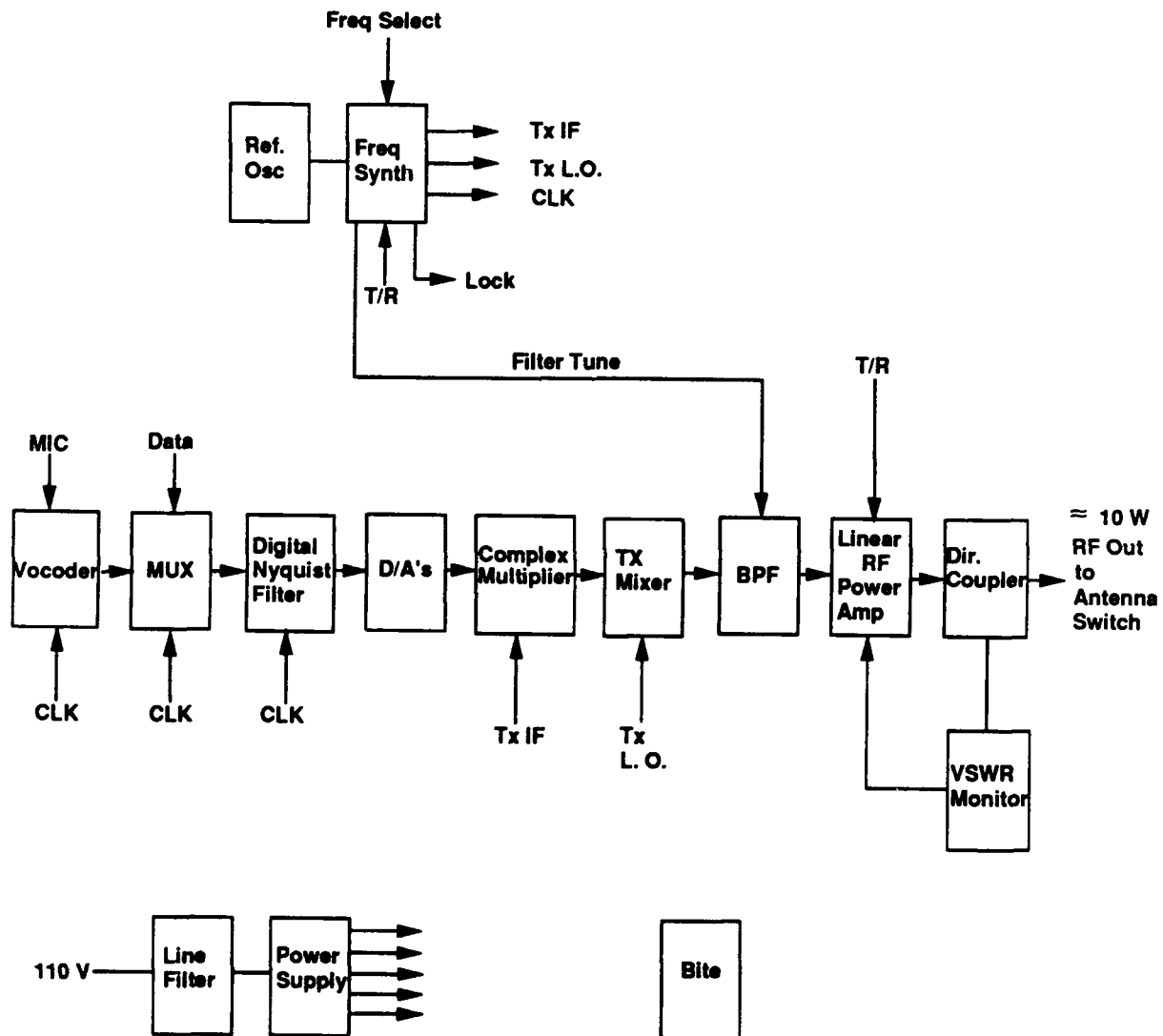
GMSK

- 1.) Receiver IF filters have constraints on group delay as well as bandwidth and selectivity.
- 2.) Bit timing, matched filtering, data decisions and squelch function are all in block labeled DSP.
- 3.) RF power amp can be nonlinear - GMSK is constant envelope.

Aviation QPSK Receiver



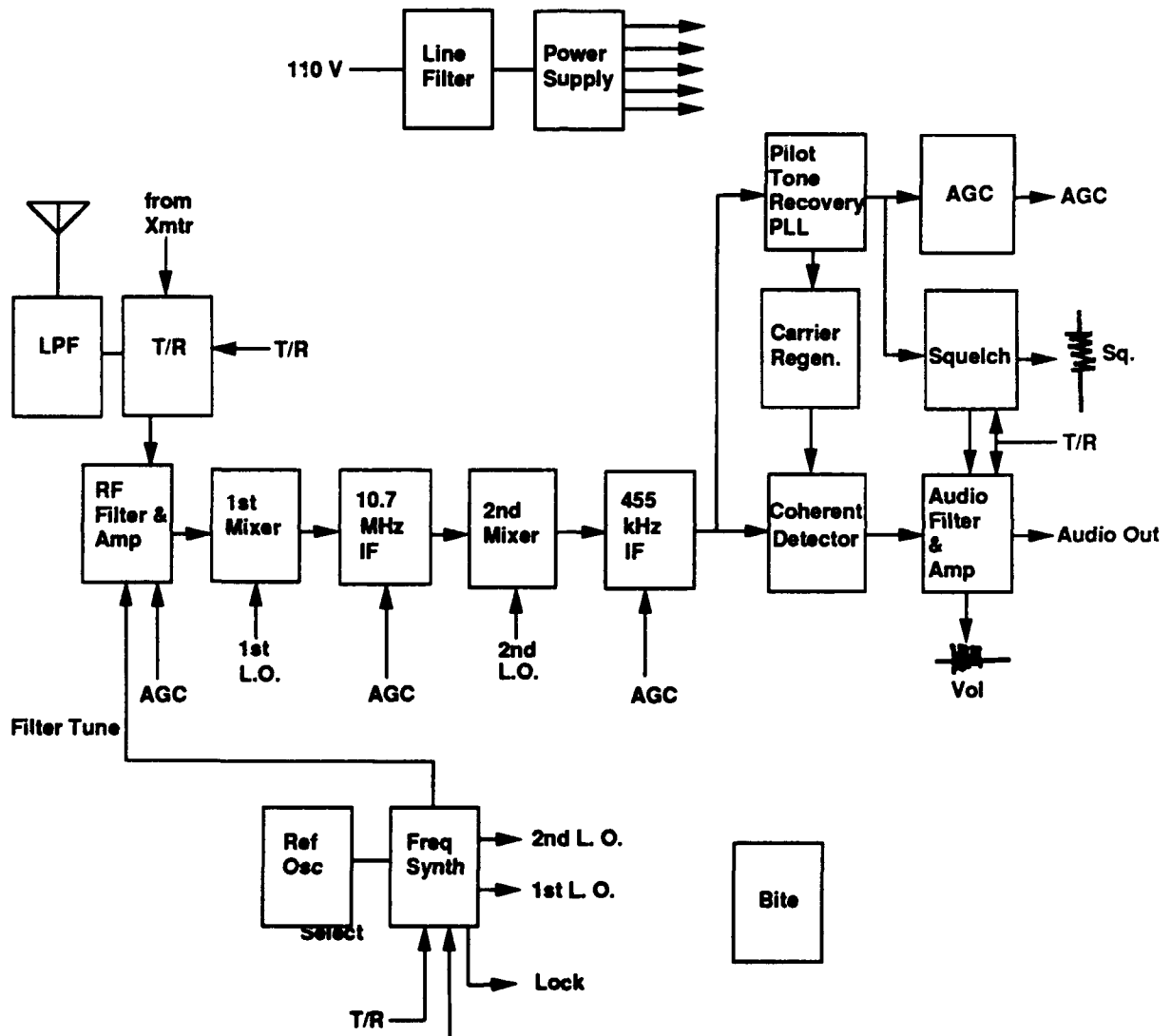
Aviation QPSK Exciter



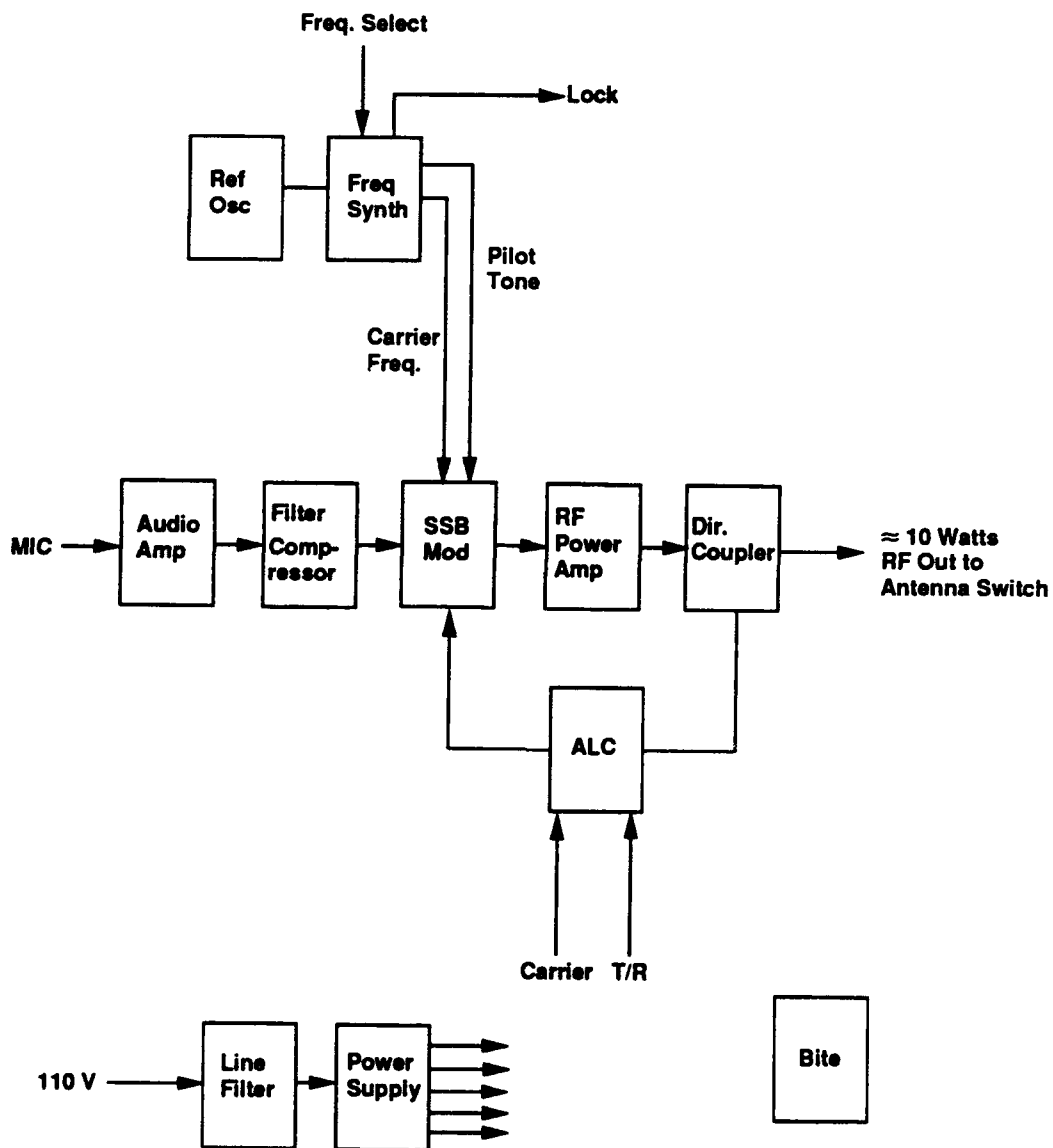
Aviation QPSK

- 1.) Receiver IF filters have constraints on group delay as well as bandwidth and selectivity.
- 2.) Bit timing, matched filtering, data decisions and squelch function are all in block labeled DSP.
- 3.) RF power amp must be fairly linear.
- 4.) Receiver linearity?

SSB Receiver



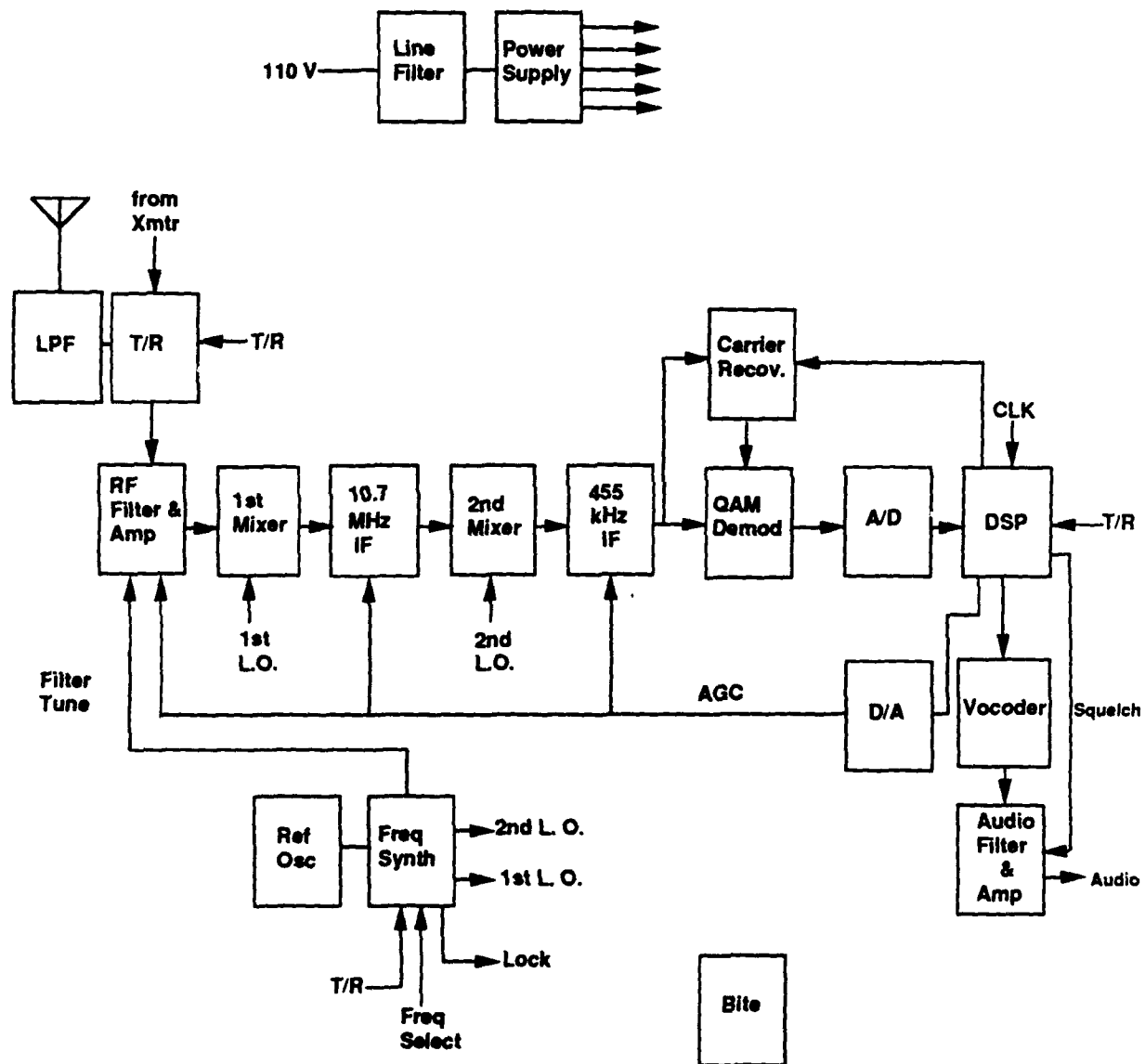
SSB Exciter



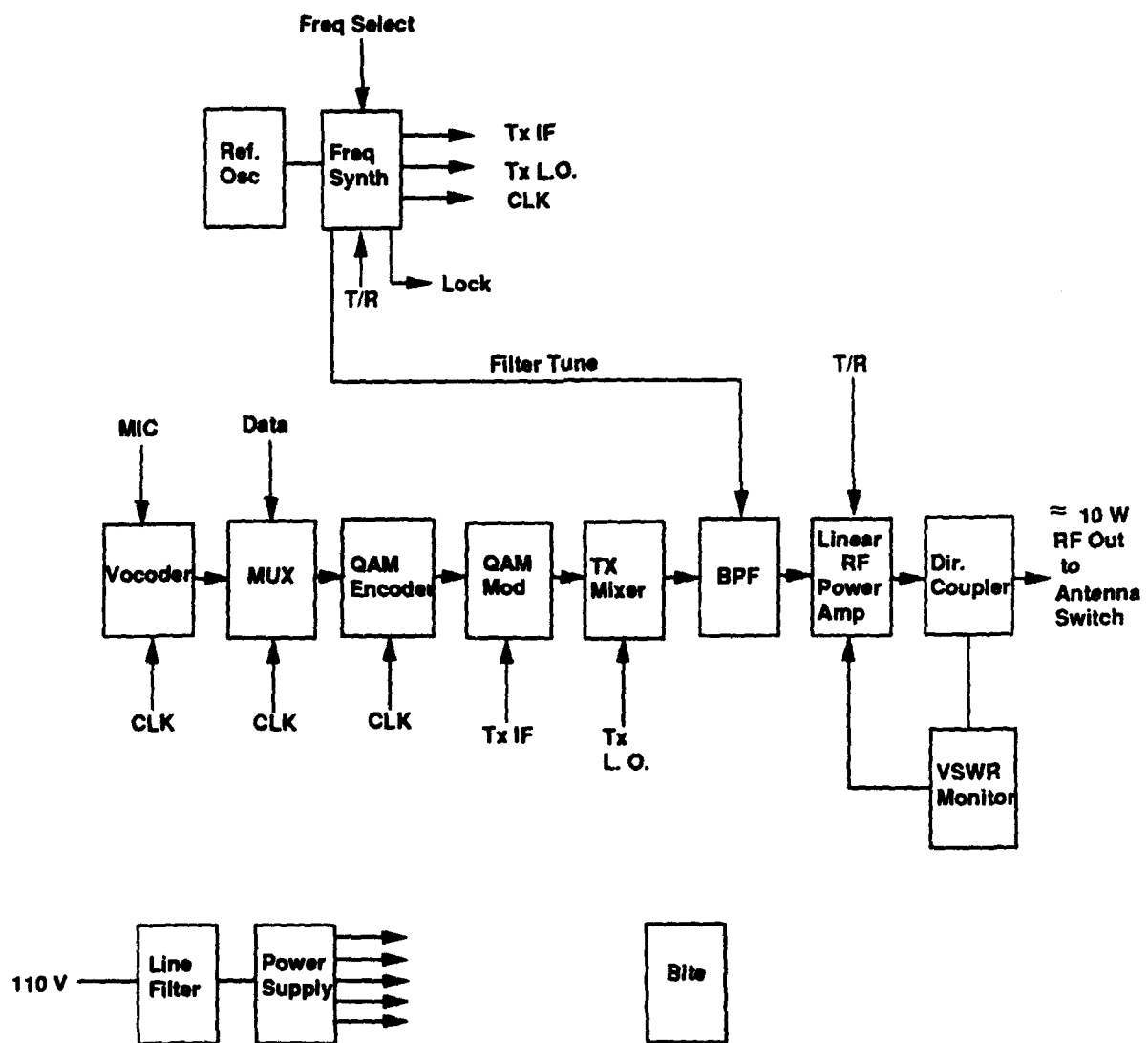
SSB

- 1.) 10.7 and 455 kHz IF filters very narrow and with very sharp selectivity to achieve channel spacing.
- 2.) RF PA must be very linear - probably most stringent linearity requirements of all systems considered.
- 3.) Pilot tone recovery and SSB modulation both relatively complex signal processors.

16 QAM Receiver



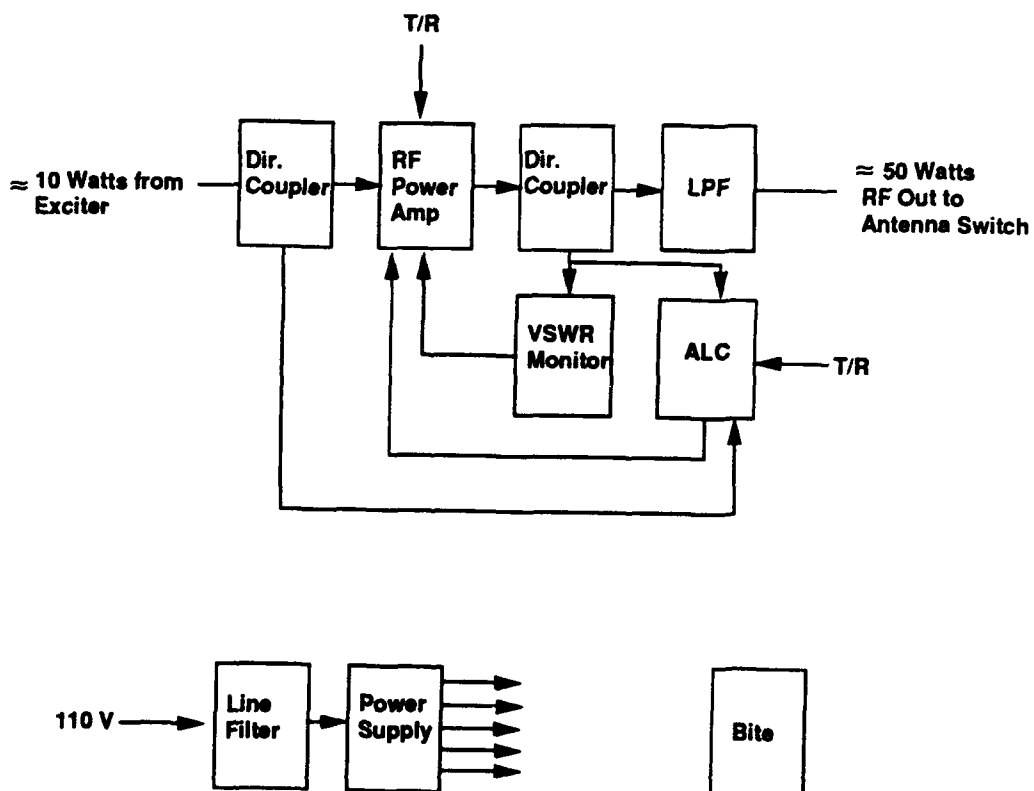
16 QAM Exciter



16QAM

- 1.) Receiver IF filters have constraints on group delay as well as bandwidth and selectivity.
- 2.) Bit timing, matched filtering, data decisions and squelch functions are all in the block labeled DSP.
- 3.) RF power amp must be linear.
- 4.) Receiver must be linear.

RF Power Amplifier



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-Hocquenghem
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

TBD - To Be Determined
TCM - Trellis Coded Modulation

VOLUMES 1 AND 2 GLOSSARY
(Concluded)

TDM - Time Division Multiplexed
TDMA - Time Division Multiple Access
TRACON - Terminal Radar Approach Control
Tx - Transmitter

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

WBS - Work Breakdown Structure

VOLUMES 1 AND 2 DISTRIBUTION LIST

A010

R. D. Haggarty
C. J. Whiting

A030

R. W. Jacobus

D050

R. A. McCown
R. I. Millar
E. A. Palo
E. N. Skoog
W. J. Wilson

D053

C-H. Chen
C. H. Harris
M. Leiter
J. L. Ramsey

D057

A. J. Graff
A. S. Margulies
B. E. White (10)

D059

R. W. Davis
H. Gong
M. L. Kuras
R. D. Sakamoto
G. R. Strohmeyer

D090

L. S. Metzger

D093

N. D. Hulkower
R. A. Pomponi

D095

R. G. Bland
G. H. Naditch
K. Wickwire

D104

T. A. Reed

F010

J. J. Fearnside
R. M. Harris

F040

L. G. Culhane
R. A. Rucker

F080

R. Braff
D. J. Chadwick
A. A. ElSawy
J. S. Matney
R. J. Ravera

**VOLUMES 1 AND 2 DISTRIBUTION LIST
(Concluded)**

F085

L. del Cid (25)
K. L. Crocker
J. E. Dieudonne
S. M. Elnoubi
R. L. Richards
A. J. Steger

F087

J. C. Moody, Jr.

F088

C. A. Shively
M. J. Zeltser