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ELECTROMAGNETIC COUNTER-COUNTER MEASURE (ECCM) TECHNIQUES OF THE DIGITAL MICROWAVE RADIO

JAMES E. BARTOW
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MAY 1982

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The Digital Microwave Radio will provide an ECCM capability in a new multichannel radio for tactical and strategic LOS radio relay applications. It will incorporate a null/beam steering antenna, direct sequence and frequency hopping spread spectrum techniques and forward error correction coding. In addition it will feature adaptive bit rate control and power output control. A modular approach will enable all various combinations of techniques to be used in a number of applications.

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ELECTROMAGNETIC COUNTER-COUNTER MEASURE (ECCM) TECHNIQUES OF THE DIGITAL MICROWAVE RADIO

by James E. Bartow

1. INTRODUCTION. A number of ECCM techniques are included in the advanced concepts of the Digital Microwave Radio (DMR) which is being designed to replace the army tactical Radio Relay Set AN/GRC-144 and to provide a new multichannel radio capability for Defense Communications System (DCS) line-of-sight (LOS) applications. The DMR will be modular in design so as to provide several configurations to meet specific needs of path length, channel capacity, ECM environment, set-up time, etc., at a minimum cost and with maximum equipment and circuit reliability. One configuration of the DMR is shown in figure 1. The ECCM features are necessary because of the EW threat facing LOS radios. If we were to go to war with present tactical communications equipment we would find that our transmissions were disrupted by enemy ECM. Present military line-of-sight microwave radios are not designed to provide ECM resistance. The enemy will attempt to block radio reception with massive jamming, electronic deception and weapons, aided by direction-finding equipment. Radio relay systems are clearly vulnerable to the enemy threat. The specific degree of vulnerability is determined by modulation characteristics, antenna patterns and built-in ECCM. All communications radiations are susceptible to enemy detection. (See reference 1.) Tactical LOS multichannel radio is used to provide interconnection between major headquarters and command elements. Specifically, radio relay equipment is used at the brigade, division, corps, and army level, and is used to interconnect tactical elements to the DCS. It provides user paths for high speed data and teletype, point-to-point and common-user telephone service, trunking, and access to commercial telephone facilities and the military's automatic voice network. Communication systems can be disrupted by jamming or by physical destruction. Integrated electronic intercept, direction-finding, and electronic jamming, are designed to prevent us from coordinating and directing our weapons by exploiting the vulnerability of our command and control systems. The enemy will attempt to severely disrupt tactical and strategic communications during critical battle periods.

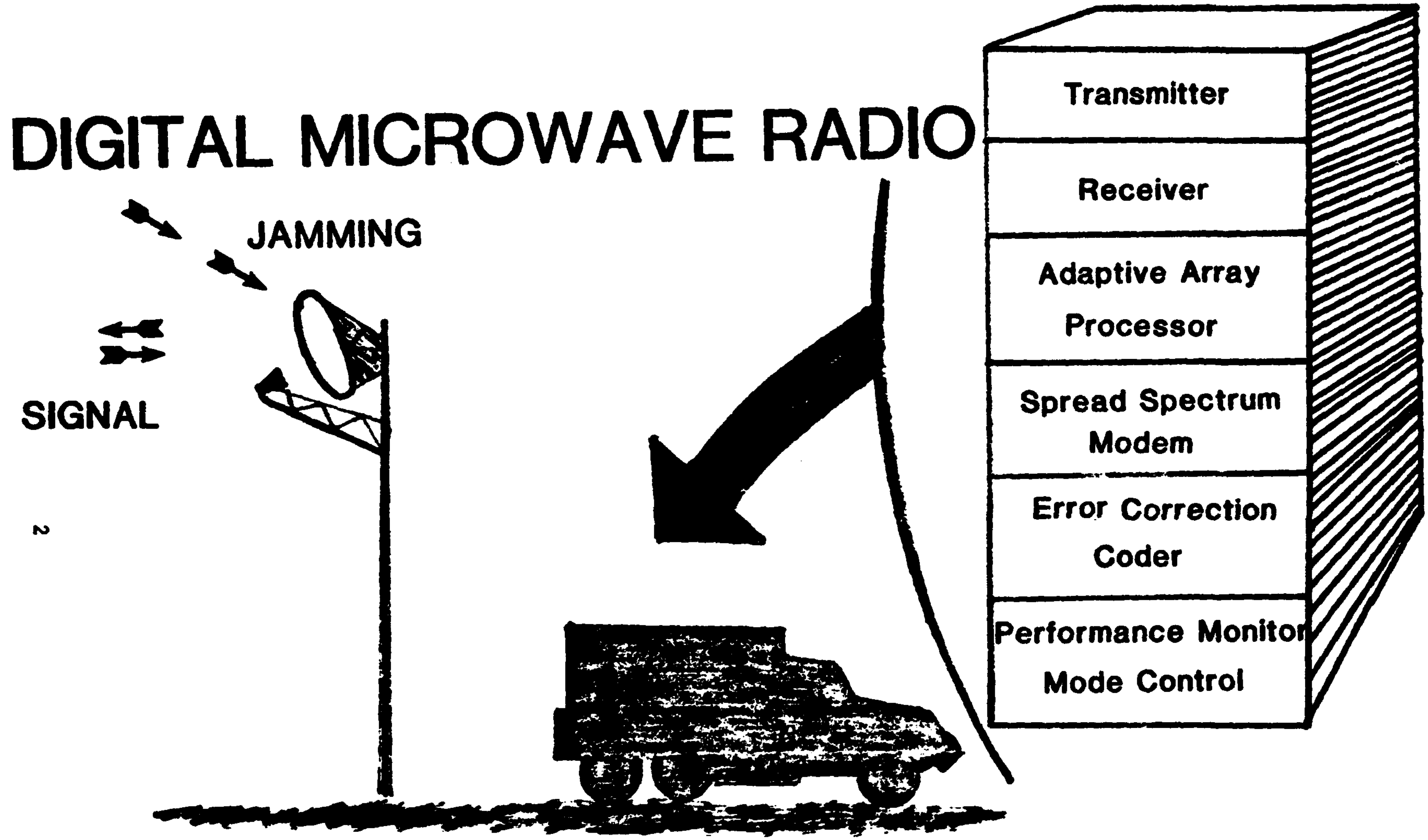


FIGURE 1 - Digital Microwave Radio - Artist's Concept

The enemy may depend on barrage jamming of entire radio band to keep numerically inferior allied forces from coordinating their technologically superior weapons and command and control systems. Key communication centers at battalion, brigade, and division and army levels may be disrupted with spot jamming (specific channels). Interference signals will arrive in our microwave antenna sidelobes and in the main beam. Through a combination of airborne direction-finding (DF) and ground DF stations, jammers can be targeted on communication nodes. After detection priorities are established for jamming, command and control systems receive first priority. Command posts and communications centers receive second priority. The threat to radio relay communications facilities is obvious.

2. DMR SYSTEM. Techniques available to solve this problem are antenna discrimination against undesired signals, bandwidth expansion to reduce the effective jammer energy density, and coding to permit error correction. We will provide graceful degradation by varying the data rate, trading it off for added anti-jamming (A/J) protection when necessary. Finally, the radios will be modularized so that they can be tailored for different EW environments, and so that radios or networks can be rapidly reconfigured. (See reference 2.)

The ECCM performance will be obtained by use of a spread spectrum modem, coding techniques, a null steering antenna, and the use of adaptive techniques such as variation of output power, channel capacity, and routing procedures to match the environment. By employment of a selected group of these techniques as modular combinations of equipments, varying levels of ECM threats can be accommodated in an optimum manner.

Figure 2 shows the system block diagram of the DMR illustrating the interconnection of the major transmit and receive subsystems. Antenna discrimination is achieved through a combination of antenna nulls directed at jammer arrival angles and low antenna sidelobe response. The antenna system interoperates with the spread spectrum modem and coding equipment in a manner which provides the necessary ECCM performance.

Included in the DMR system design will be considerations of alternate routing and automatic re-routing of channel groups. Means will be provided to reduce the voice channel capacity or bit rate when the jamming environment becomes intolerable. The dropping of low priority channel groups in order to provide increased protection for higher priority groups is a technique to be considered. The system design may also employ frequency or space diversity both to overcome propagation effects and to minimize jamming effectiveness. Channel equalization techniques may also be incorporated to optimize the demodulation performance in the presence of multipath or other propagation effects. Other techniques may be incorporated which will overcome the weaknesses of present designs and avoid the choice of circuit designs which may prove to be vulnerable to sophisticated attack.

Spread spectrum techniques include Direct Sequence (DS) modulation by pseudo-noise sequences and Frequency Hopping (FH) of the information spectrum and error correction coding. Error correction coding of the information bits is a powerful bandwidth expansion technique because it adds redundancy in a carefully chosen pattern to facilitate minimization of errors in detection. The discrimination against the jammer as the result of error correction coding is generally greater than the bandwidth expansion factor.

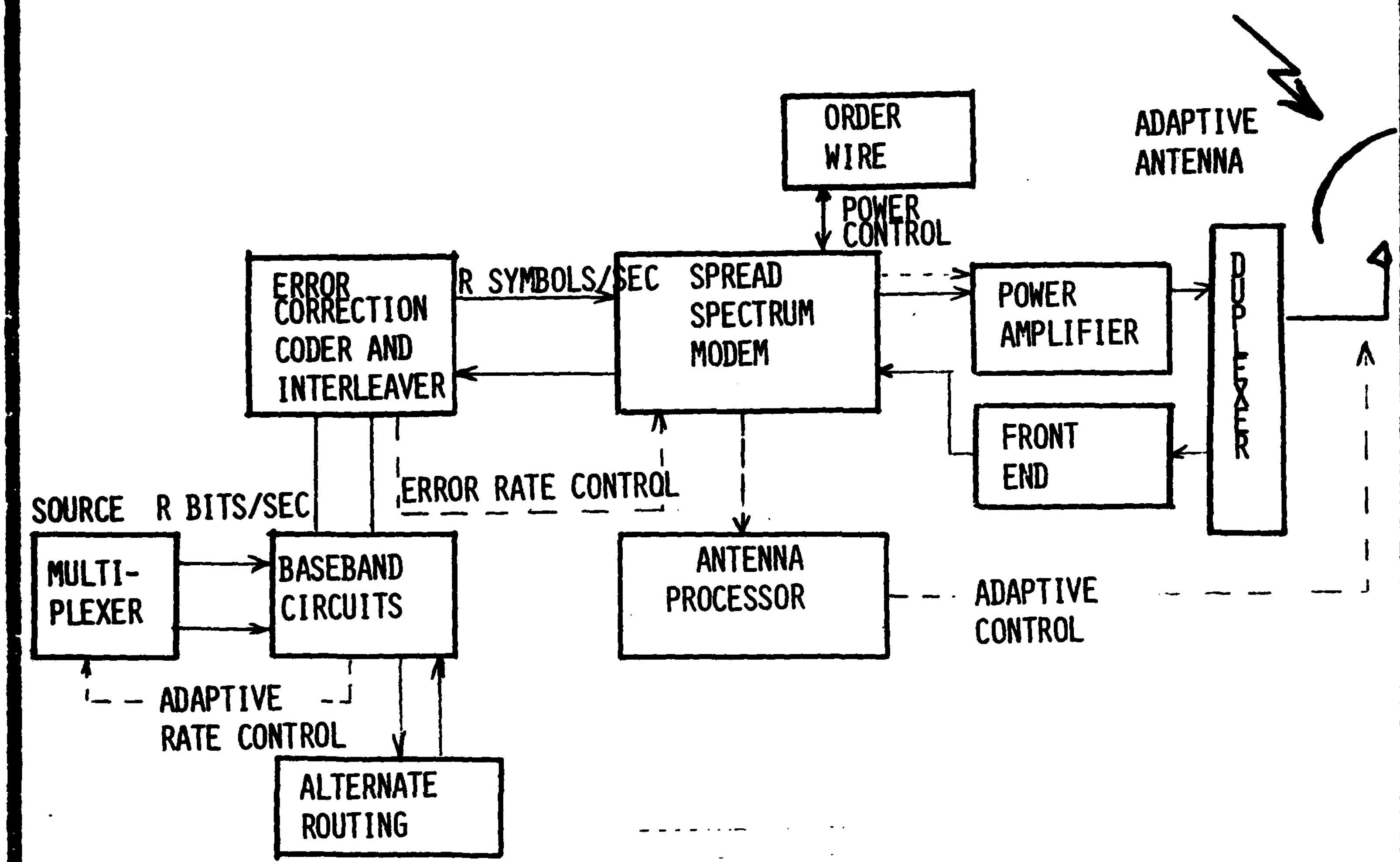


Figure 2. Block Diagram of the Digital Microwave Radio.

The code rate, which is defined as the ratio of information bit rate to the bit rate of the sum of information and redundant code bits, is the reciprocal of the bandwidth expansion factor. It is important to select efficient and practical error correction decoders and minimize decoding delays. Only a fraction of the total increase in bandwidth can be realized with error correction coding techniques. The remainder of the bandwidth expansion must be provided by simpler and less powerful techniques.

Pseudo noise (PN) sequence modulation in the Direct Sequence technique increases the bandwidth by a factor equal to the number of PN chips per information bit. Against continuous jammers this technique provides a jammer discrimination factor approximately equal to the bandwidth expansion ratio, W/R. The autocorrelation function of the PN sequence over one bit interval determines the spread spectrum processing gain and the jammer discrimination.

The effect of pulse jammers on the DS system can be reduced to nearly the same as continuous jammers of the same average power through the judicious application of interleaving and the error correction coding used for initial bandwidth expansion. As in the coding system, the DS spread spectrum is also application limited by practical considerations. Because the synchronization time for acquiring the PN sequence at the receiver is proportional to the bandwidth expansion factor, very large expansion factors may mean a long synchronization time. With large spread ratios, many other users in the band may suffer interference. These difficulties can be overcome, at a cost of some performance loss, by obtaining some of the bandwidth expansion with a frequency hopping technique. Frequency hopping requires special synthesizers and filter banks. Large bandwidth expansion in a microwave radio relay application can best be achieved with a hybrid system which includes a combination of error correction coding, direct sequence modulation, and frequency hopping.

The bandwidth expansion is limited by RF bandwidth restrictions and interference considerations, and by the minimum data rate. It is desirable, therefore, to achieve as much of the jammer discrimination from the antenna system as possible.

The factors which must be considered in providing jammer discrimination by means of the antenna system include:

- Location and quantity of jammers and their power levels
- Jammer modulation techniques and strategies
- Multipath fading
- RF components differential delay and amplitude distortion
- Transmitter to receiver coupling
- Mast wind motion and weight limitations
- Antenna reflector blockage, asymmetry and surface tolerance
- Overall radio system costs

Because the spatial distribution of main beam jammers varies with time, antenna nulling of these jammers requires some form of adaptation. Adaptive algorithms for this purpose include power inversion, reference and decision directed Least Mean Squares, random search, Gram-Schmidt orthogonalization and others. Each of these algorithms provides certain performance, implementation, and cost factors to be considered in a system design.

The spread spectrum modem in the DMR will be a hybrid incorporating error correction coding, direct sequence modulation, and frequency hopping. Some of the considerations in the design and development of this DMR subsystem include

- processing gain
- performance as a function of jammer modulation type
- pulse jammer performance
- emission bandwidth and spectral shaping
- transmission system control - overhead bit rate
- means of incorporating alternate routing.
- detection of spread modulation, coherent or incoherent
- method of generating the frequency-hop signals
- frequency hopping rate
- data rates to be transmitted
- interoperability with the antenna and coding system
- frame and multiplex signal structure protection against jammer attack
- quality measure requirements and outputs required for antenna nulling
- system cost

Error correction coding in the DMR provides efficient bandwidth expansion. Coding in conjunction with interleaving is essential in order to combat pulse jammers. The analysis and evaluation of jammer strategies with respect to coding is critical since weaknesses in the coding approach might allow intelligent jammers to more than offset the bandwidth expansion gain. Partial frequency band jamming must, in particular, be considered. On the other hand a properly designed coder/interleaver system offers the potential for greatly reducing the effectiveness of pulse jamming and of eliminating transient weaknesses in the remainder of the ECCM radio. Some of the major factors to be considered in the coder/decoder design are

- degree of bandwidth expansion realizable with practical decoder design
- interleaving vs. burst error codes for protection
- coding gain against background noise
- signal delay through the coder and interleaver

The DMR design will incorporate the three techniques effort into a modularized adaptive system.

We have begun exploratory development of a null steering antenna, a spread spectrum modem, coding equipment and a system design effort. These efforts are being accomplished concurrently and will provide the technology development necessary for us to proceed with advanced development of the digital microwave radio set in fiscal year 1983. Included in this effort are an analysis of the threat and calculations of the ECCM performance of the modem, coding equipment, antenna, and overall radio system. We are postulating optimum jammer strategies against each chosen technique and examining potential weaknesses of these techniques. We will incorporate alternative designs, additions, modifications and improvements and determine the performance improvement resulting therefrom. This effort will continue through the exploratory development phase. Among other system considerations we have or will analyze are graceful degradation, frequency and space diversity, orderwire design, routing techniques, adaptive bandwidth, power and bit rate control. We must analyze various modulation, processing, spreading, antenna nulling, coding, synchronization and framing techniques. Computer based systems analysis may be used to determine the weakness or vulnerability to jamming threats of the proposed techniques.

3. <u>NULL STEERING ANTENNA</u>. The null steering antenna development will provide techniques to null main beam jammers and reduce the effectiveness of side and back lobe jammers. It must be designed to be compatible with spread spectrum and coding techniques. The antenna will be designed for duplex operation. An antenna will be designed to operate in the 4.4-5.0 GHz band, see figure and an antenna with minimum component change, in the 14.4-15.35 GHz band. Because of program funding limitations, only the 4.4-5.0 GHz design will be fabricated and tested on this exploratory development effort. The antenna will be designed for a main beam gain of 30 dBi at C-band and 40 dBi at Ku band with 0 dBi side and back lobes and will have a maximum sail area of 15 square feet. The antenna shall weigh 300 pounds or less so that it can be supported by a lightweight tactical quick-erection mast. The C-band antenna will be a parabolic reflector with offset multi-mode feed horns. A phased array approach is under consideration for Ku band. Various types of jammers and levels of jamming have been included in the analysis of the proposed techniques. Among the technical areas requiring analysis and judgment are IF versus RF processing, propagation effects, implications of coding and modem design on the antenna, acquisition techniques, bandwidth requirements, self interference, reference signal requirements, polarization effects, diversity techniques and system transient response time. See Figure 3.

The antenna technique chosen for the DMR in the 4.4-5.0 GHz band is a parabolic reflector with an offset feed. See figure 4. A multi-layer, multi-mode feed horn is used, with a side lobe canceller located near the focus. The antenna system uses a monopulse technique to provide sum and difference beams, which are used to form a null in the direction of a jammer in the main beam. One of the features of the antenna system is a look ahead capability whereby

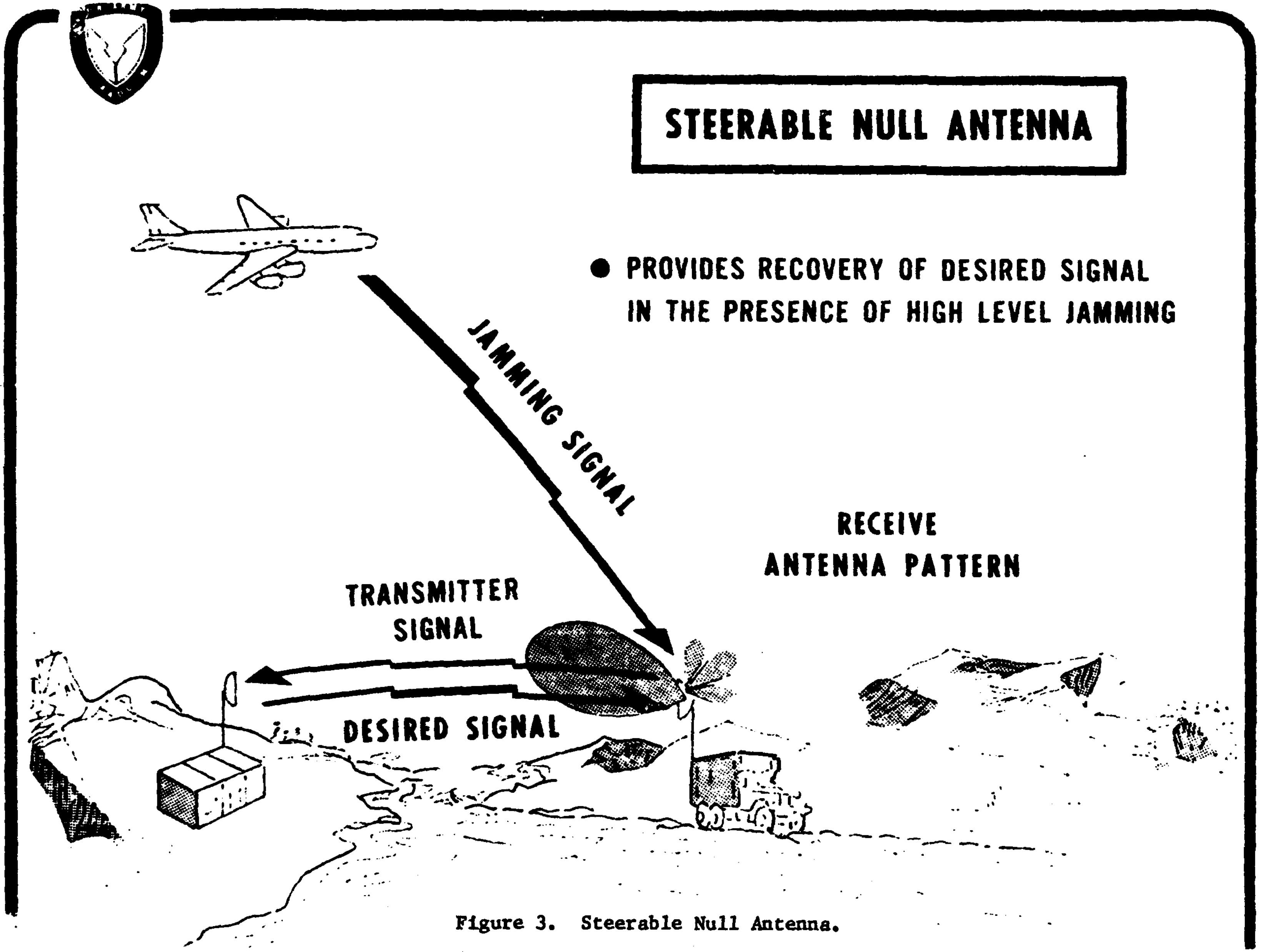


Figure 3. Steerable Null Antenna.

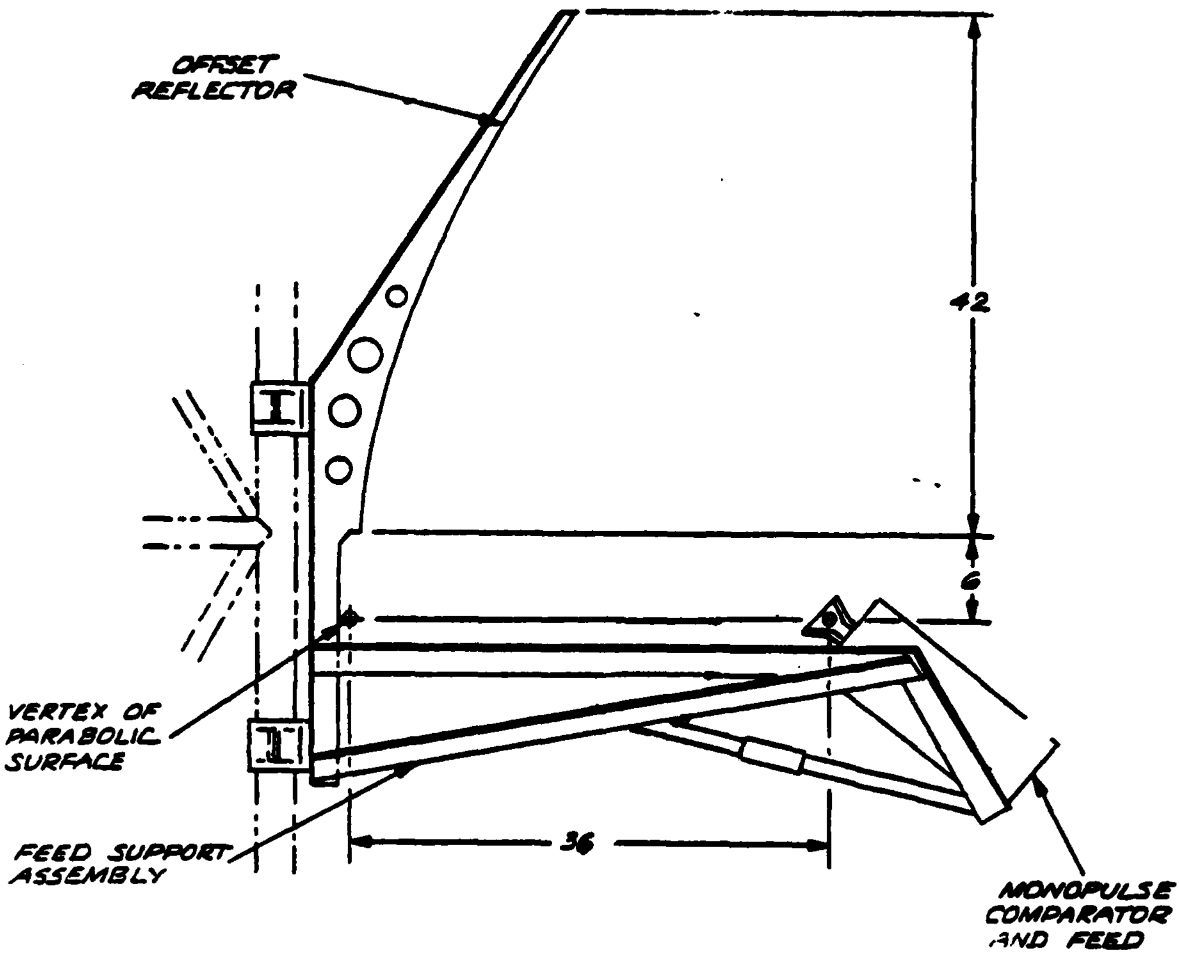


Figure 4. Parabolic Reflector with Offset Feed.

the next hopping frequency is examined and weighting networks are adjusted prior to the actual shift to the frequency. In order to provide duplex operation a split band approach is employed whereby transmission is limited to the upper half (or less) of the band in one direction and to the lower half (or less) of the band for transmission in the return direction. In addition to its null steering capability, the antenna will provide beam steering to adjust the direction of transmission and reception to correct for mast movement under wind conditions. (See reference 3.)

The more critical areas to be addressed in the antenna design include the requirement for full duplex operation with the frequency hopping modulation, the need to maintain low side lobes while forming a main beam null, achieving the performance for all postulated jammer waveforms, and angle tracking the desired signal during mast motion and jamming.

The Steerable Null Antenna System (SNAS) design is shown in Figure 5. This design incorporates main beam and near in sidelobe adaptive null steering, using least mean square (LMS) criteria, with direction of arrival of the desired signal, reference signal and look ahead as discriminants. The rf output of the multiport antenna system drives both the rf weighting element and the reference inputs of the adaptive processor. A channelized implementation of the adaptive processor with "look-ahead" that accommodates the frequency hopping pattern of the modem waveform has been selected. The received signals are dehopped to a constant i-f frequency channel matched to the signal bandwidth (i.e., approximately 10 MHz). Band-limiting enhances the jamming rejection capability of the system and eliminates the need for wideband equalization. The use of "look-ahead," digital weight memory techniques, and rapid adaptation algorithms permits rapid null formation and provides protection against jammers using sophisticated jamming strategies.

The antenna uses a monopulse difference pattern that is capable of electronic steering with the aid of the modem to provide the necessary discriminant between the communication and jamming signals as well as compensating for antenna motion.

A low sidelobe monopulse pattern is used for nulling main-beam jammers and a low gain auxiliary antenna is used to optimize null performance in the near sidelobe region.

The Steerable Null Antenna System includes a beam steering signal tracking loop that maintains the antenna boresight during sway and tilt by closed loop control of a beam steering network. The beam steering loop makes use of both the array processing gain and modem gain in deriving amplitude and phase beam-steering control signals.

A main-beam processor loop makes use of frequency hop information from the modem to "look-ahead" and develops nulling weights for the upcoming hop frequency while nulling with another weight set at the current hop frequency. In addition to the use of frequency hopping to separate the desired signal from the interference, the main-beam processor uses a spatial discriminant between desired signal and jammer which permits nulling in the main beam during the reception of the desired signal and a jammer on the same frequency.

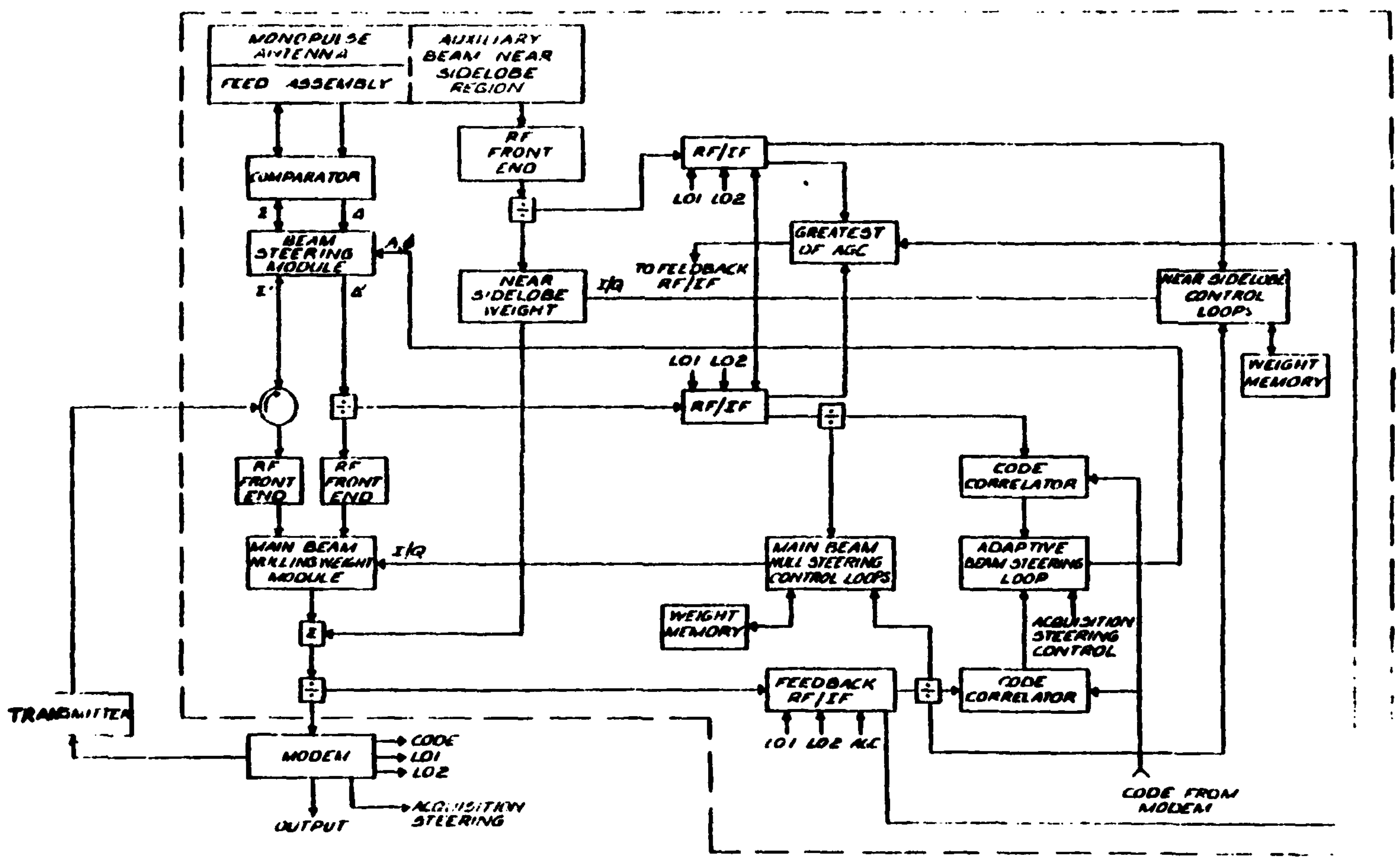


Figure 5. Steerable Null Antenna System Design.

A sidelobe processor loop is used to cancel a jammer in the near sidelobe region. This processor also makes use of "look ahead" techniques to insure rapid null formation.

The need for a reference signal for proper operation of the null steering antenna is based on the availability of an error signal to use as a criterion for signal to noise optimization.

An excellent error signal in a least mean square (LMS) algorithm is the difference between the received sample upon which a bit decision is to be made and the correct value of that bit decision. When this difference is small, good performance will result. In most applications, minimization of the mean square value of this error gives virtually the same results as minimization of the bit error probability. It should be noted, however, that an error signal which depends on the correct bit decision suggests a circular argument since it is the correct bit decision which our error signal and adaptive processor is trying to achieve. A solution to this dilemma, called decision-directed, simply assumes that the bit decision is correct. A second solution, called reference-directed, generates an error signal only when a known bit has been sent and received. Decision-directed LMS algorithms have application when jamming is not a threat. When jamming is present, it is possible for the decision-directed error signal to cause the weights to lock on the jammer as a desired signal and cancel the information signal. This likely possibility in the presence of strong jammers precludes the use of decision-directed LMS algorithms in ECCM applications. The reference-directed error signal always contains the correct signal discriminant and thus always leads to correct convergence of the algorithm. The disadvantage of the reference-directed requirement is that some fraction of the transmit power must be devoted to the reference and algorithm updates can be made only during reception of the reference bit.

Adaptation using reference bits rather than reference chips is preferable because it is the bit decision that counts in final system quality and not the chip decision. This factor influences the rate of adaptation and the method of inserting the reference.

Adaptation using reference bits means that the LMS algorithm must adapt at rates slower than the reference bit rate. Tracking of the fading of the information signal and wind fluctuation effects will require that the reference bit rate be much larger than fading and wind-induced channel rates. Since these rates are on the order of a few Hertz, no serious limitations in signal tracking is incurred.

For data rates of 72 kb/s and higher, a reasonable reference bit rate might be 72 kb/s which would reduce system margin by at most 3 dB at the lowest data rate and less at higher data rates. Signal tracking of the reference-directed LMS algorithm would then be on the order of a few hundred Hertz.

The spread spectrum modem has to time-division-multiplex the reference bits into the transmit information stream, synchronize the reference bit generators at transmitter and receiver, and generate the LMS algorithm error signal to be used in the adaptive antenna combiner.

4. <u>SPREAD SPECTRUM MODEM.</u> The spread spectrum modem development will provide modulation and demodulation techniques to reduce the effectiveness of a wide variety of jammer types. The modem will be designed to operate at rates of from 72 kbits per second to approximately 18 Mbits per second in factor of two steps. A modem will be designed to operate at C band also at Ku band with a minimum of change in modules. The modulation technique chosen is Offset Quadra Phase Shift Keying. The basic technique is a hybrid combination of frequency hopping, and direct sequence, spread spectrum. By change in modulation rate, the error rate at various jammer levels can be controlled. In order to accomplish this a continuous monitoring of error rate performance and estimation of jammer environment is required which can be accomplished by the error correction coder. (See reference 4.)

The modulation system must be designed so that it can be synchronized and resynchronized under the maximum jamming environment. The modem will accept coded signals from the error correction coder and deliver a 3-bit quantization representation of the encoded signals to the decoder. The modem must be capable of providing a reference signal to the null steering antenna.

Direct sequence spreading is achieved by multiplication by a binary pseudo-random sequence whose symbol (or switching) rate is many times (i.e., $W/R \gg 1$) the binary data bit rate. The spreading symbol rate is commonly called the chip rate.

With frequency hopping the spreading signal remains at a given frequency for each bit or even for several bits. Thus, instantaneously, the signal is no wider than the data signal (without coding), but it hops to a new frequency which may be anywhere within the spreading bandwidth W. The hopping pattern is usually controlled by a PN sequence.

One difference between the two techniques is that direct sequence spread signals usually are demodulated coherently. With frequency hopping, on the other hand, the path phase shift at each hopping frequency must be determined for coherent detection; hence this modulation is often demodulated noncoherently unless the hopping rate is sufficiently slow relative to the symbol rate which would allow a differentially coherent system to be used.

The spreading sequence in a DS modulation technique is commonly a pseudo-noise (PN) binary sequence with a long period compared to the information symbol interval. The long period insures that the jammer cannot easily determine the PN shift register connections and thereby utilize the same PN signal to obtain a coherent jamming advantage. This approach has two limitations. First, the autocorrelation function over each information symbol interval is pseudo-random itself and occasionally will provide poorer peak-to-average ratios. This means that the spread spectrum gain is somewhat reduced for these poorer autocorrelation functions. Long PN sequences require considerable acquisition time to resolve the path delay ambiguity and align the transmit and receive PN generators. If the path delay is τ seconds and the spreading sequence has a bandwidth B (chip interval of 1/B for binary sequences), there is an ambiguity at the receiver of approximately $B\tau$ chips which must be resolved before communication can begin. A synchronization system with a fixed acquisition probability requires an averaging time per chip to combat background noise. If this averaging time is Δ the total synchronization time is $B\tau\Delta$. This dependence of the total synchronization time on the spread spectrum bandwidth B is a limitation on achievable bandwidth with this approach.

Frequency hopping systems are easier to synchronize than long PN sequence DS systems and are widely used when the spread spectrum bandwidth B is very large. Frequency-hopping technology has an advantage in achievable band spreading of one or more orders of magnitude over direct sequence spreading technology. The FH systems also have the advantage that other users can be accommodated within FH cells which are not used, on a non-interference basis. On the other hand, frequency hopping systems are limited by achievable hopping rate with the available hardware and are vulnerable to tracking if the hopping rate is slow.

Since direct sequence spreading can be coherently demodulated, it is used with coherent data modulation techniques such as binary PSK, QPSK and Offset-QPSK. Frequency-hopping on the other hand, is often used in conjunction with noncoherent modulation formats such as MFSK. When DS is used with more efficient modulation schemes it will operate with a lower E_b/N_0 to achieve the same jamming protection as noncoherent modulation schemes used with FH.

For reasons mentioned above, a hybrid FH/DS spread spectrum modulation technique will be used to exploit the efficiency of DS with the wider band spreading capabilities of FH. A simplifier block diagram of a combined FH/DS Modem is shown in Figure 6. The input to the modulator may be the multiplexer output or the output of a coder.

5. ERROR CORRECTION CODER. The coding equipment development will provide a coding technique which is a random error and burst error correction coder. These coding techniques are to reduce the required E_b/N_o input to 4.5 dB while delivering an output error rate of no more than one error in ten thousand bits. We have analyzed the spread spectrum modem and null steering antenna techniques and developed an error correcting capability to optimize performance of the antenna-modem-coder combination. The coding equipment will be used to estimate the bit error rate of the received data and the severity of the jamming environment. The coder developer has developed an optimum method of introducing interleaving to protect against bursts of errors. We have analyzed the threat, the proposed modem and antenna approaches and the multiplexer interface in order to devise the optimum coding/interleaving technique. (See reference 5.)

In general, spread spectrum processing gains can be achieved by using direct sequence (DS), frequency hopping (FH), or coded sequences (CS). A coded sequence system is one in which a low rate block or convolutional code is used to spread the bandwidth. The bandwidth expansion factor is equal to the inverse of the code rate, that is the code expansion factor ($W/R = 1/r$).

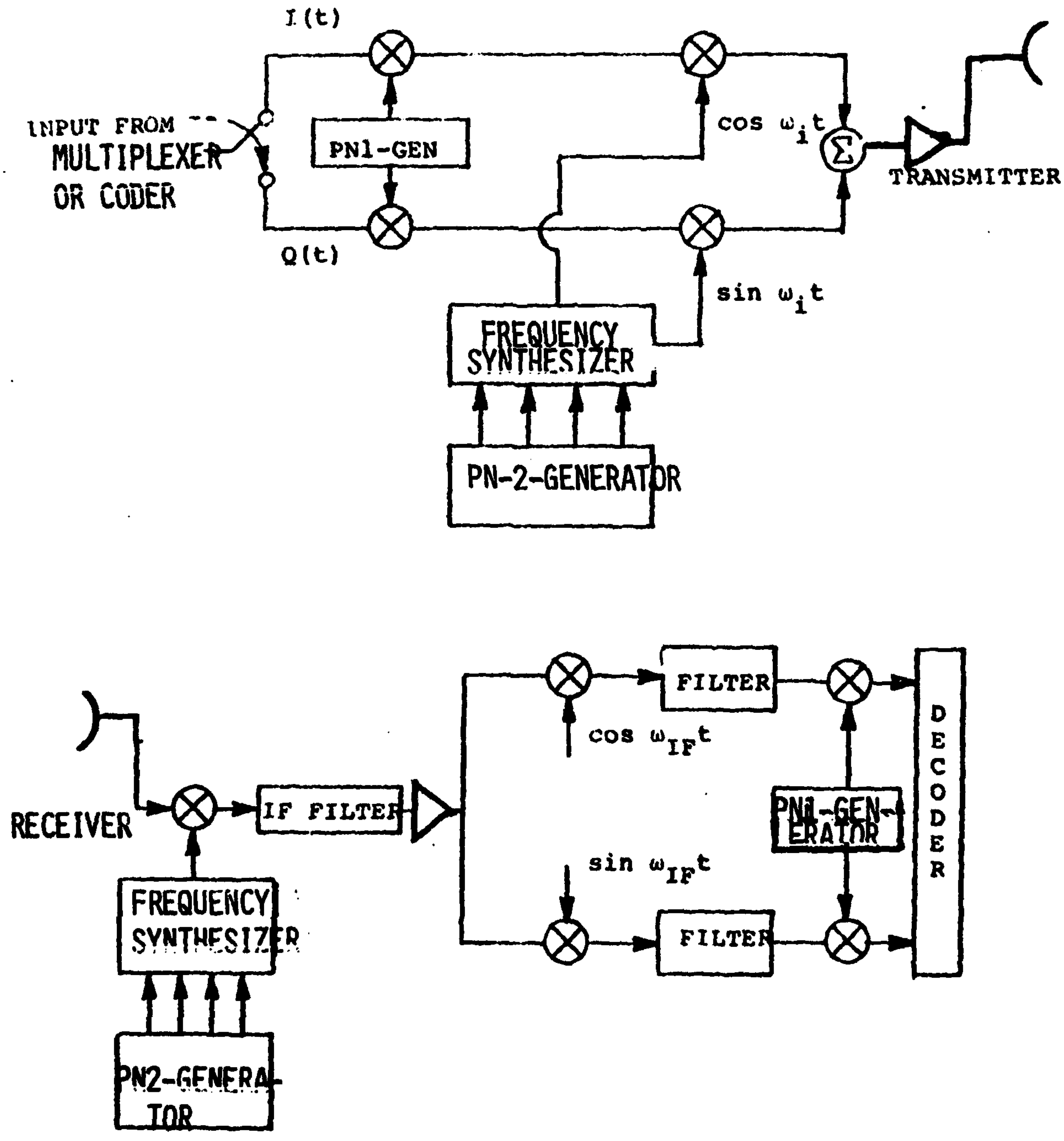


FIGURE 6. Simplified Hybrid FH/DS

For a fixed bandwidth expansion factor W/R and jammer-to-signal power ratio J/S (i.e., fixed E_b/N_0), a convolutionally coded sequence has a lower bit error probability because of its more powerful error correcting capabilities while the frequency-hopped (FH) spread spectrum system has the highest bit error rate. Alternatively if we fix the error rate to $P_b \propto 10^{-5}$, then a convolutional coded sequence will require an E_b/N_0 of 6 dB, a direct sequence spread spectrum system will require an E_b/N_0 of 13 dB. Since E_b/N_0 = (W/R)(S/J), a coded sequence system will require a smaller bandwidth expansion factor than a DS or FH spread spectrum system for fixed jamming-to-signal power ratio J/S. However, if J/S is large the required code rate r = R/W to obtain an E_b/N_0 of 6 dB would be extremely low. For a fixed performance level, decoder complexity relative to DS systems and significant delays introduced by the decoder are disadvantages in this application. For code rates less than about 1/10, the additional performance advantage of the pure coded system is negligible. A good compromise between coded sequences (or coded MFSK) and direct sequence or frequency hopping spread spectrum system are hybrid systems which utilize both coding and spread spectrum. Because direct sequence spread spectrum is limited in bandwidth spreading by hardware constraints and acquisition time, a hybrid system using a combined direct sequence/frequency hopping technique to further spread the signal after coding, achieves a higher bandwidth expansion than would be possible with just direct sequence band spreading.

It already has been established that the jamming margin (maximum tolerable jamming power-to-signal-power ratio) afforded by spread spectrum signals in the presence of wideband jamming is directly proportional to the band spreading factor, W/R, and inversely proportional to the minimum bit energy-to-noise density ratio needed to support a given bit error rate, E_b/N_0. Hence,

$$\frac{J}{S} = \frac{W/R}{E_b/N_0} \quad .$$

If coding is used along with spread spectrum, or instead of spread spectrum, a greater jamming margin J/S can be achieved with an equal band spreading factor W/R, or equivalently, an equal jamming margin with a smaller band-spreading factor.

Pulse jamming is particularly effective against coherent systems. Consider what the effect of pulsed interference can be for an uncoded system. The jamming may be present only a fraction $p < 1$ of the time, but during this time, the noise density level is increased to a level N_0/p Watts/Hz.

This assumes an average power rather than a peak power limitation on the jammer. The noise is intermittent, and hence only corrupts a given transmitted bit with probability p but with higher noise density N_0/p. Clearly the jammer would choose the low duty factor p which maximizes the bit error rate. As an example, if we desire a bit error rate performance on the order of $P_b \simeq 10^{-5}$, stationary noise (or jamming) requires only E_b/N_0 equal to $(W/R)(S/J) \simeq 10$ dB, while with pulse jamming we must have $E_b/N_0 \simeq 45$ dB, an increase in required processing gain (for fixed J/S) of over three orders of magnitude, i.e., 35 dB.

Coding can almost fully restore this 35 dB loss. Spreading causes this to appear at the receiver as wideband noise of density level N_0/p but for a reduced duty factor p. Suppose that we construct a device which randomly interleaves the order of the symbols prior to transmission, but after coding, and puts them back in the right order after reception but before decoding. The deinterleaver which restores the transmitted symbols to their right place in order actually scrambles the jamming pulses into random patterns, allowing the decoder to restore the required low error rate output.

The error correction coder design concept employs a constraint length K=7, rate r = ½ convolutional code with Viterbi decoding. This design meets the requirement of no more than one bit error in 10,000 bits at $E_b/N_0 = 4.5$ dB. As shown in Figure 7, the bit error rate for the selected code with 3-bit soft-decision Viterbi decoding is less than 10^{-5} at $E_b/N_0 = 4.5$ dB when operating over an Additive White Gaussian Noise (AGWG) channel.

In order to maximize the efficiency of the coder-decoder (CODEC), the baseband signal provided by the modem will be the optimum (maximum likelihood) metric. Generation of the optimum decoder input requires estimation of the channel state information. Channel state estimation is performed by the modem, which quantizes the metric to 3-bits before sending it to the CODEC system. Increasing the number of bits per sample to 4 results in only a small improvement in performance while significantly increasing the memory requirement of the deinterleaver and the complexity of the decoder.

The quantized baseband signal from the modem is fed to a pseudorandom convolutional deinterleaver. Interleaving is employed to provide protection against pulse jamming. The coder block diagram is shown in Figure 8.

6. PROPAGATION EFFECTS. Since the DMR will operate in the 15 GHz as well as the 5 GHz frequency band, atmospheric attenuation is a significant factor in designing the system. The radio set will include adaptive techniques which will respond to varying jamming levels to provide the optimum throughput. The radio set will also respond to varying signal levels

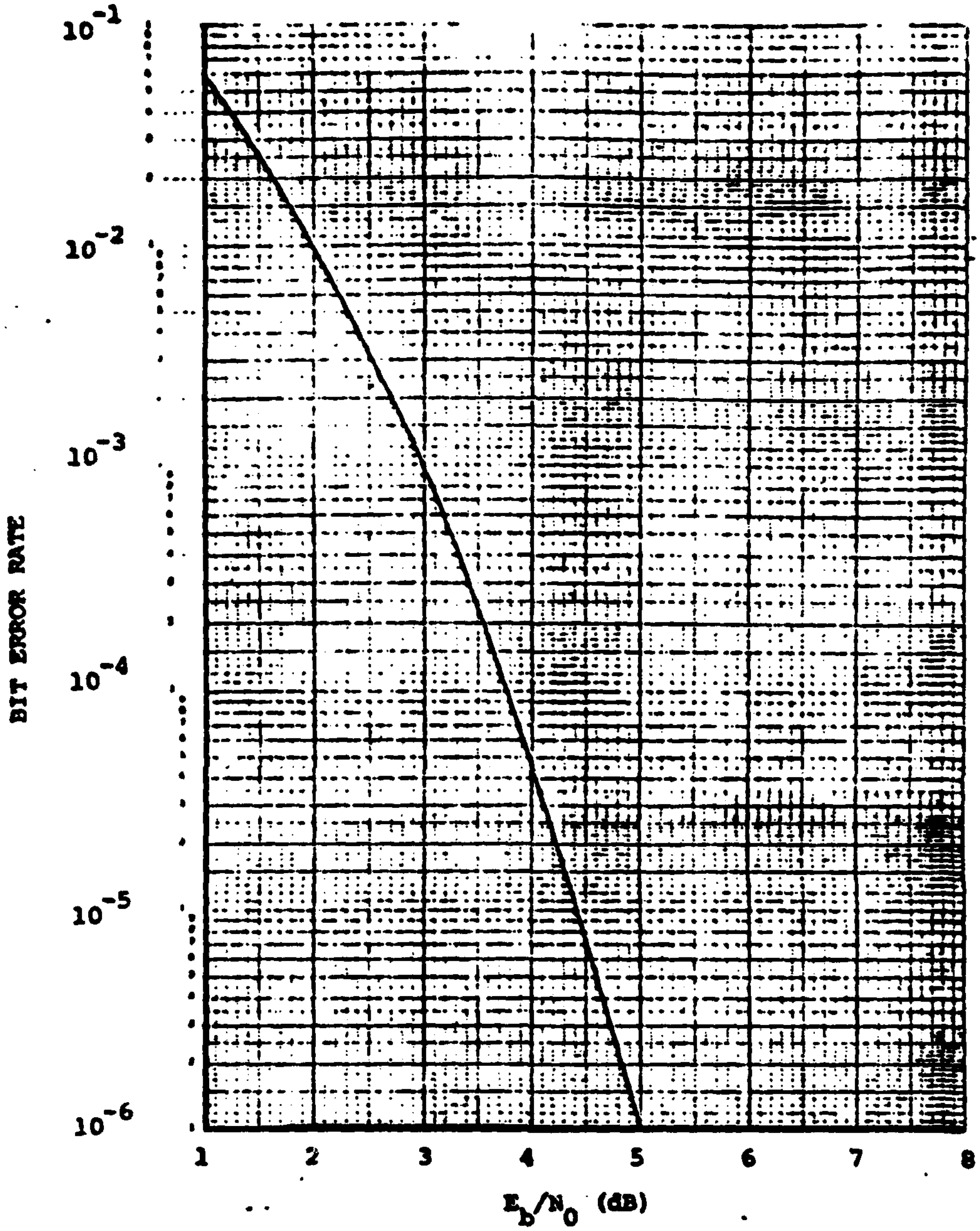
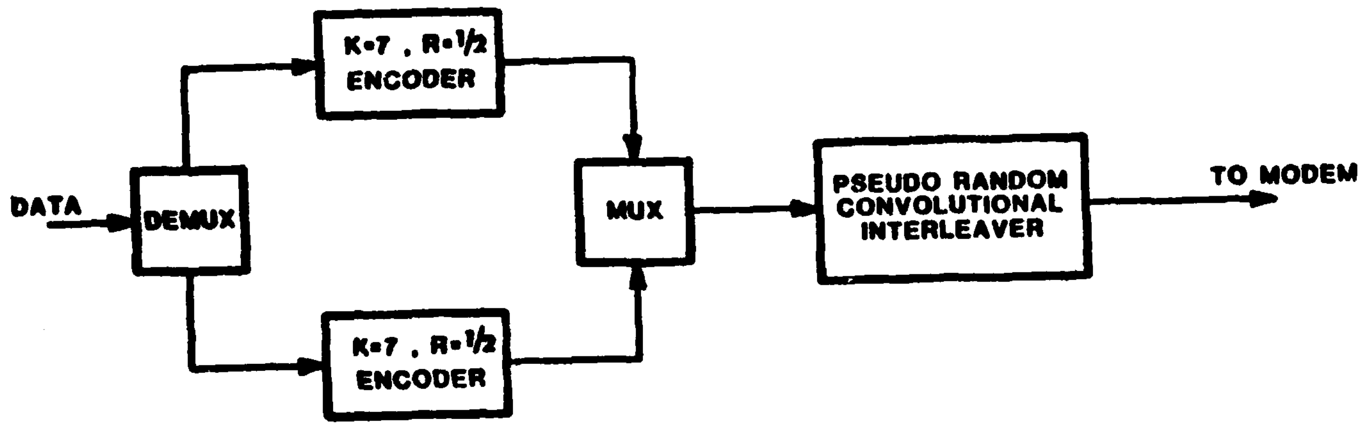
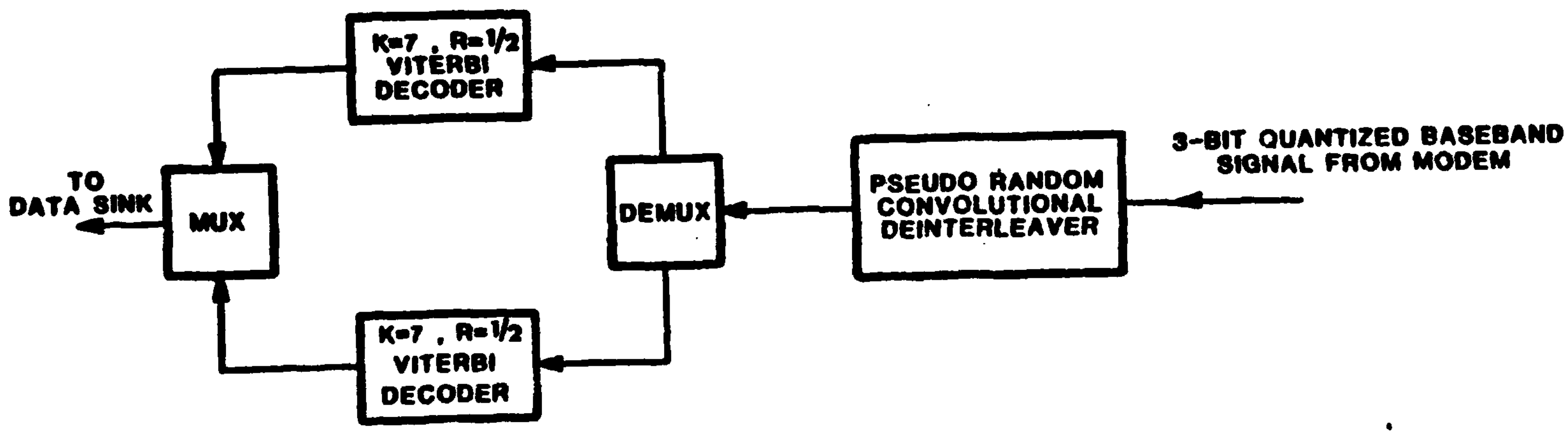


Figure 7. Computer Simulated Performance of a Constraint Length 7, Rate 1/2 Convolutional Code with 3-bit Soft-Decision Viterbi Decoding in Conjunction with BPSK over an AWGN Channel.



(a) ENCODER/INTERLEAVER



(b) DEINTERLEAVER/DECODER

Figure 8. Encoder/Interleaver and Deinterleaver/Decoder Block Diagram.

resulting from rain attenuation conditions along the path. Especially at 15 GHz, the effect of rain attenuation on the desired signal and the jamming signal is a major factor in the system design and in the network performance. The need for wide spectrum occupancy rules out the use of frequencies below 10 GHz in many areas. The primary concern at 15 GHz is the rain attenuation which will be experienced.

The signal received over microwave radio paths also varies with time as a result of irregularities in the refractive index of the atmosphere. This fading is characteristic of multiple path propagation caused by an atmospheric layer of abnormal refractivity located in the transmission path. Fades of 28 dB depth are predicted 0.1% of the time.

The effects of rain and multipath fading are analyzed in Reference 6. 18 dB depth fades may occur 1% of the time. Also note that signals 5 dB above normal may occur 10% of the time and 10 dB above normal about 1.0% of the time. The latter effect may cause an increase in jamming signal level of 5 to 10 dB while not necessarily increasing the desired signal during this period. In fact for other than main beam jamming it may be expected that the periods of enhancement of two signals will be uncorrelated.

Rain in the most significant cause of signal propagation attenuation at 15 GHz. The reduction in received signal will vary from .002 dB/km at a rate of 0.1 mm/hr to 7 dB/km at a rate of 100 mm/hr. The time distribution of rain intensity varies widely with geographic location.

In order to determine the effect of rain on a communications network, a model of the expected rainstorms was formulated. A cylindrical rain cell model is assumed. The diameter of the rain cell will vary with rain rate; for rain rates of 32 mm/hour or more the rain cell diameter will be 30 km or less.

A typical deployment of the DMR assumed in the above reference is shown in figure 9. Path lengths were assumed to be 50 km, nominally, with some shorter. Two jammers were assumed, placed as indicated, approximately 100 km from the network. The effect of rain on both the desired signal and on the jamming signal for the values of rain cell diameter were calculated. In each case the rainstorm passed directly across the communication network. In each case the time each desired signal path was in the rainstorm, the amount of time both jammer paths to any given terminal were disrupted by rain and the rain attenuation on each jammer and signal path were determined. It should be noted that for rainstorms of 30 km or less, there was never a simultaneous reduction in both jammer signals to both terminals of a path. It was only when the storm diameter approached the nominal path length that some jammer signal attenuation was simultaneously experienced from both jammers. Jammer signal attenuations of up to 30 dB were noticed in rare cases. At a storm diameter of 90 km most of the paths in the network

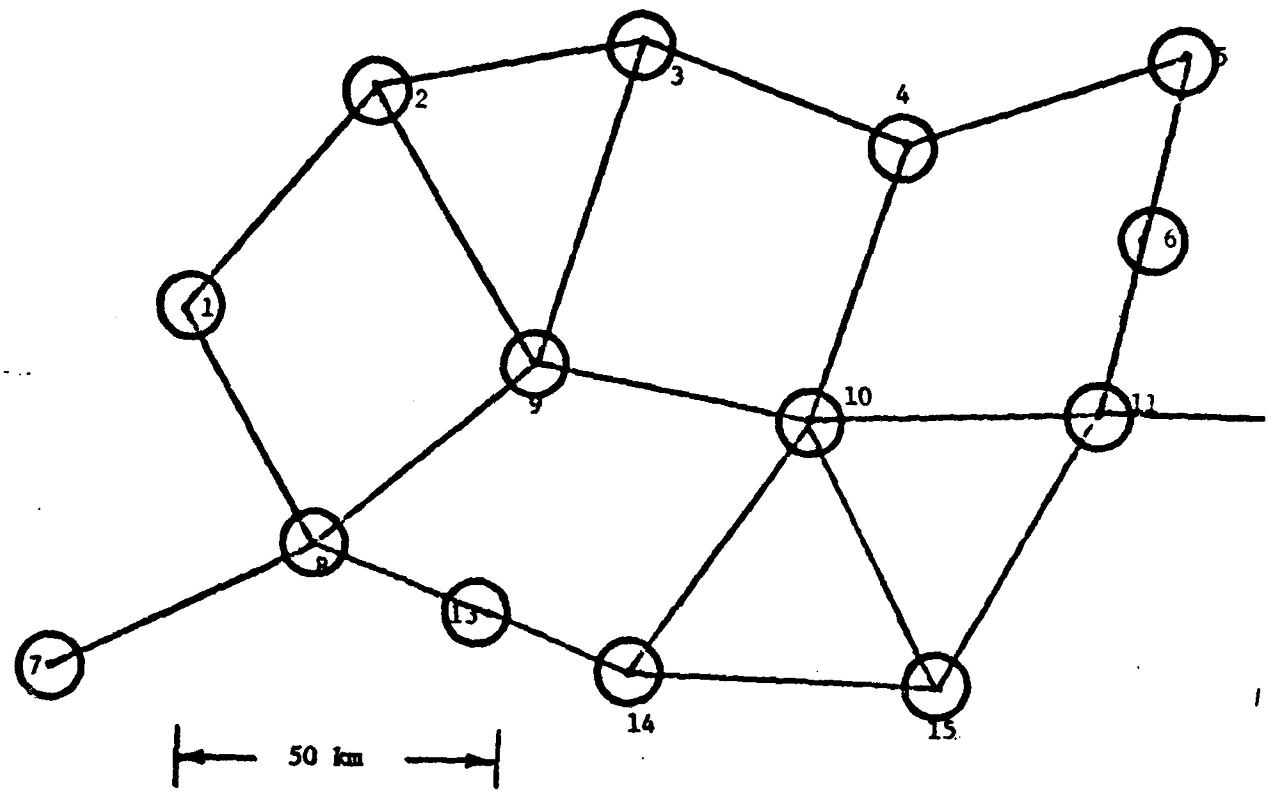


Figure 9. Typical Deployment of the Digital Microwave Radio.

were affected by rain attenuation. However, at this rain rate the maximum attenuation was 15 dB. The 150 km rainstorm enveloped the entire network. However, the rain was so light as to cause only a maximum of 5 dB path attenuation, in those cases. The effect of rain on the network communications is shown in figure 10.

It can be seen that the jammer power received from at least one of the two jammer sources is attenuated very little, compared with the signal. This is a result of the small likelihood of rain cells simultaneously covering a significant portion of widely separated paths.

Figure 10 indicates that the communications system designer would be required to provide 42 dB of margin to compensate for the difference in rain attenuation on the desired and the jamming paths to avoid outages of more than 0.1%. 55 dB of margin is required in order to reduce outages to .03% of the time.

In view of the high values of signal attenuation caused by rain at 15 GHz, alternate routing of signals should be used during periods of heavy rain. The effect of rain attenuation on the parallel combination of direct and alternate route for each path was determined for each rain cell size and rain rate.

The method employed combined the fading effects of rain and multipath on the assumption that these effects would not occur simultaneously. There is evidence to indicate that severe multipath is most likely on clear nights. Therefore, it is reasonable to design radio circuits to operate with fades which occur for the sum of the fading periods of multipath and of rain. Since the jammer attenuation will not be increased any significant amount of time, the curve remains unchanged. Note that during the 10% of the time that the jammer signal may be enhanced by multipath, no rain is likely in the area. Therefore the system margin against rain and multipath should be sufficient to negate this enhancement.

The reduction in combined rain and multipath fade margin as a result of alternate routing is shown in figure 11. It is seen that a 28 dB fade margin (24.5 dB J/S margin) is required for 0.1% outages and a 40 dB fade margin (32 dB J/S margin) is required for .03% outages. The use of alternate routing, therefore, provides from 18 to 23 dB reduction in the required margin to overcome rain attenuation on this jammed communications network.

7. STRATEGIC APPLICATION. In addition to being responsible for its own tactical LOS links, the army is the principal military operator of strategic LOS links for the Defense Communications System. Because of this dual capacity, the design concept for a generic DMR should satisfy both the strategic and tactical needs. We have broadened our DMR system design to incorporate the requirements and design characteristics of a generic DMR for the 1990's time frame, which will meet both tactical and stragegic requirements.

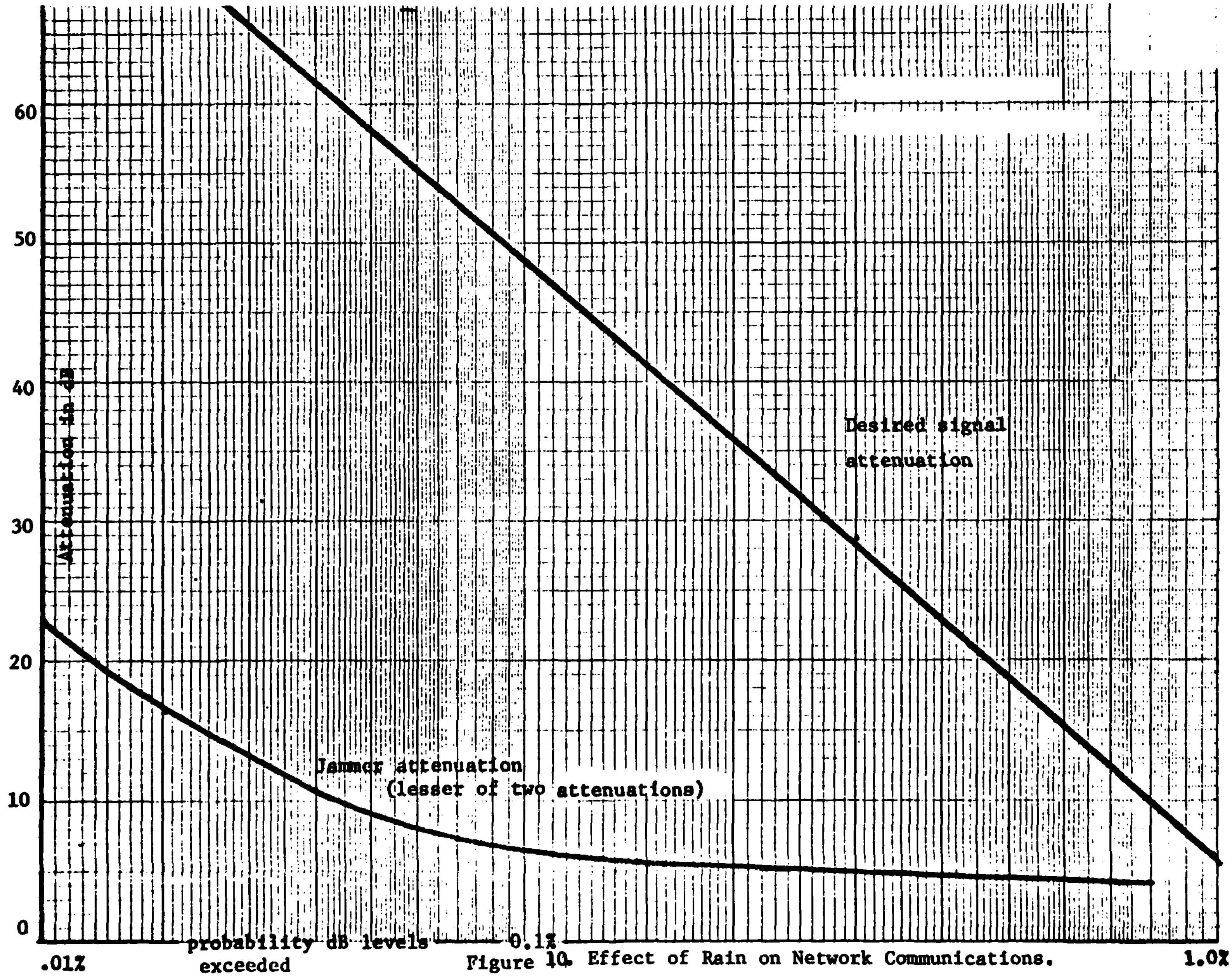


Figure 10. Effect of Rain on Network Communications.

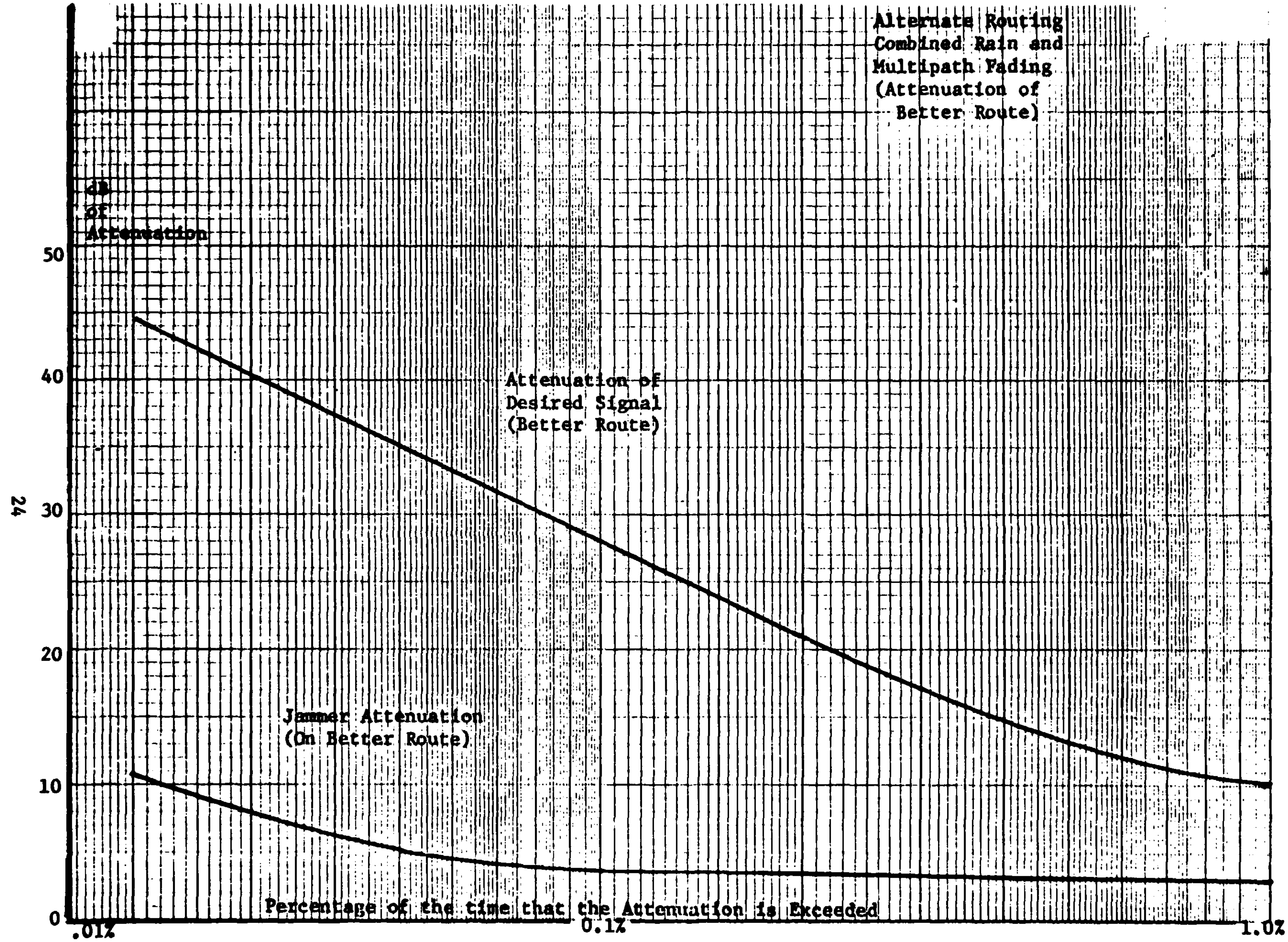


Figure 11. Alternate Routing Combined Rain and Multipath Fading
(Attenuation of Better Route)

The investigation will attempt to maximize aspects of commonality for tactical (division and above) and strategic (fixed plant and a reconstitution requirement) users in order to simplify logistic problems (such as spare parts inventory), control interface characteristics and obtain optimum performance at minimum cost. The analysis will be comprehensive, and include such considerations as interoperability, commonality, modularity, survivability, and electronic counter-countermeasures.

We will develop a design concept that will satisfy the requirements and performance characteristics that were defined as a result of the analysis. The design concept will emphasize commonality, will consider techniques such as building block concepts and interchangeable common modules, and will balance the tactical need for ruggedness versus the strategic need for cost effectiveness without the stringent environmental requirements. The design will consider the feasibility of adaptive techniques that will provide maximum throughput during ideal benign conditions, and will restrict throughput when ECCM needs are dominant. The design concept for the strategic reconstitution radio will reflect the philosophy that (at least initially) it will maximize speed of establishing reasonably reliable communications to critically essential users. The tradeoff will be against full normal throughput and reliability. For the reconstitution radio, reliability of the initially re-established link in the order of 95% is acceptable. The feasibility of a design which allows field augmentation to build up the capability of the reconstitution radio to a full throughput and reliability status, as time and resources permit, will be investigated.

The design will consider the optimum modulation techniques. Attributes such as robustness, spectral efficiency, implementation complexity, and suitability for ECCM techniques will be considered. A summary of the requirements and characteristics of the design concept will be given. An assessment of the technical risk and a base line performance specification will be prepared for the radios in the generic system.

We hope to be able to prepare procurement packages for the advanced development of the DMR during the spring of 1983 and to place an advanced development contract by January 1984. The advanced development contract is expected to take 24 to 30 months to complete. On this basis engineering development could be completed by June 1988 and first production started in January 1990.

We are now considering an additional exploratory development effort to start in FY-82 which would supplement the previously described program. This program is for the development of a Phased Array Distributed Amplifier Antenna (PADAA). The PADAA will be an ECCM microwave low sidelobe antenna with a beam steering capability. This effort will provide the necessary advance in the state-of-the-art at Ku band to form a basis for technology insertion into the digital microwave radio program.

8. <u>CONCLUSION</u>: The Digital Microwave Radio development will provide a new radio set for multichannel tactical and strategic use in the 1990-2010 time period which will have a high degree of protection against jamming. The DMR will be designed in a modular fashion to allow the needed functional building blocks to be assembled to meet a variety of needs. Through the use of alternate routing and adaptive techniques highly reliable multichannel communications will be maintained even under severe environmental stress. The future requirements of both tactical and strategic users can be met by a family of DMR modules, from which can be selected combinations of equipment to meet specific needs, while allowing maximum interoperability and commonality.

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