ECM/ECCM EFFECTS ON VOICE TRANSMISSIONS

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Summary. - An evaluation methodology for conventional and ECCM voice communications is presented, wherein intelligibility of the received message rather than error rate or signal-to-noise ratio is the quantity measured. This allows the engineer to include the psychoacoustic phenomena of a human listener in his system design considerations.

Analyses have been performed which allow transformation of speech articulation test results into data more meaningful to the communications engineer. Since message intelligibility is established after baseband reconstruction of the voice signal, this method is universally applicable to most voice transmissions. It is insensitive to the nature of the medium, modulation, and interference sources.

Examples are presented showing applications of these guidelines to the design of frequency hopping radios. Tests run on a simulator confirm the analyses. A sample tape is available to demonstrate some of the effects.

Introduction. - The transfer of digital information in modern telemetry and communication systems can be measured against well-defined performance criteria. However, voice transmissions - whether in analog or digital format - must ultimately be evaluated by the human listener. While signal-to-noise ratios and bit error rates can be quite useful, the real measure of performance for voice communications is the intelligibility of the received message. The psychoacoustic characteristics of the human listener are essential considerations in an overall evaluation.

Basic work performed in this area in 1949 by Miller and Licklider [1] outlined the effects of continuous noise and pulsed noise on voice intelligibility. Pollack [2, 3] extended the investigation of pulsed noise interference on speech further, and Hogan and Hanley [4] reported on the interference effects of multiple voices. While these studies brought to light effects important to the electronic communications field, they have remained largely in the domain of psychoacoustic specialists.

This paper provides the transition from psychoacoustics to electronics; factors impacting on intelligibility are transformed from audio to RF. Guidelines are established for design and evaluation of ECM and ECCM systems. More importantly, a method is presented which is applicable to most voice transmissions, whether analog or digital, military or commercial, UHF or K-band.

Background. - Miller and Licklider [1] provided the basic studies on voice intelligibility in the presence of noise and applied their results to multiplexed signals. Subjects listened to voice recordings during which time interference was introduced. The subjects were graded on the number of words heard correctly and the results were averaged to yield a percent value of intelligibility for a specified type and level of interference.

Three different types of interference were used: 1) continuous noise, 2) repeated signal drop-out periods, and 3) pulsed noise. Figure 1 shows the relationship between word articulation (also referred to as intelligibility) and audio signal-to-noise ratio. Figure 2 shows articulation contours for speech-time fraction versus interruption rates. To understand Figure 2, consider 0.1 interruptions per second and an 0.8 speech-time fraction. This corresponds to a voice transmission for 8 seconds followed by a 2-second period during which there is no sound. At this low rate it is no surprise that about 80% of the words are intelligible.

An interesting phenomenon occurs for interruption rates above 10 per second. An 0.8 speech-time fraction now means that voice is heard for 80 milliseconds, followed by a 20-millisecond “dead time”. For rates between 10 and 100 per second, interruptions occur several times during most words, allowing at least a portion of every phoneme to be heard. This allows the human listener to understand more words and a higher level of intelligibility results.

Above 100 interruptions per second, the curves start to return to their original values at lower rates. However, another effect begins above 1000 interruptions per second. At this rate the interruptions are too fast for the middle ear to respond well and the speech signal is smoothed to essentially its uninterrupted form, thus resulting in very high levels of intelligibility.

Figure 3 shows the effects of periodic and aperiodic pulses of noise added to the voice signal. The main difference between Figure 3 and Figure 2 (no noise) is the deterioration of intelligibility at high interruption rates. Miller and Licklider explain that the strong noise pulses (9 dB stronger than signal for the graph shown) are low-pass filtered by the ear, thereby spreading the noise energy out over a larger portion of signal than the pulse actually occupies. Also, the similarity of the data for both random and regular interruptions allows the use of either set of curves for most purposes.

In contrast to the investigation of multiplexed signals by Miller and Licklider in 1949, research was also performed which pertained to other communication methods of interest. Typical of such efforts is the work of Hogan and Hanley [4] relating voice intelligibility phenomena to conferencing. In their work, the masking properties of simultaneous voice signals were investigated.

RF Effects on Intelligibility. - The work presented in this paper emphasizes the impact of modern radio communications on voice intelligibility. Interruption and masking phenomena can be introduced into a communications link in a number of places (modulation, transmission medium, demodulator hardware, etc.) Quality of the received voice signal (a measure of the system throughput) can be analyzed using psychoacoustics.

The phenomenon of fading has dramatic effects on intelligibility of voice transmissions when the fades are of sufficient depth to cause communications "drop out". For many types of systems, this can be associated with thresholding effects, causing loss of lock and/or synchronization. The effect of the fade in the audio signal is to cause pulses of "no signal". These fades can thus be interpreted in terms of the intelligibility curves shown in Figure 2. AGC response characteristics may also increase receiver sensitivity and require consideration of Figure 3, since noise may be substituted for signals.

Such interruptions can be introduced into a system in several ways. The natural phenomenon of fading due to changes in the propagation path is well known, particularly for tropospheric scatter communication and skywave propagation in the lower frequency bands (e.g. MF and HF). Other causes are related to localized propagation or implementation problems. Multipath and antenna nulls fall into this category. In dynamic situations (ships and aircraft, for example) such fades cannot always be "designed out" by clever placement or pointing of antennas. Performance prediction for such systems has previously been speculative.

For conventional narrowband signals in the presence of continuous noise, Miller and Licklider's continuous noise intelligibility curve (Figure 1) is transformed to RF by means of a detector transfer function plot. Such a transformation process is illustrated in Figure 4. The audio intelligibility curve is shown in the lower left corner of the figure. Audio intelligibility versus baseband SNR is plotted in that curve. The lower right corner shows a graph illustrating three different transfer functions for various detectors. These transfer functions allow baseband SNR to be converted to RF SNR for a specific type of detector. The upper right corner shows a composite graph which plots audio intelligibility as a function of RF SNR. Note that the linear transfer characteristic of coherent detection has not introduced any changes in the intelligibility curve. However, the curve for FM detection shows significantly different performance. The preference for FM detection of high fidelity music as compared with AM detection is illustrated by the increased intelligibility of the FM Curve.

ECM Effects on Narrowband Signals. - Before discussing Electronic Counter Measures (ECM) effects on voice intelligibility, a brief description of basic ECM techniques is in order. The ECM threat can be considered as consisting of three distinct components: the jamming waveform, the jamming power level, and the relative geometry. The jammer may be free to select all three within certain constraints. The jamming waveform can be optimized against the victim communications system. The jamming power can be maximized within the constraints of mobility and prime power availability. The geometry is mission sensitive and often influenced by considerations of physical vulnerability of the jamming installation.

Jamming waveforms may be selected to provide either jamming or deception. Jamming results in the introduction of sufficient interfering signal power to render the desired signal unusable by virtue of poor intelligibility or an excessively high bit error rate. Deception is practiced by causing erroneous messages to be accepted. This requires the enemy to generate messages in an acceptable format, either by synthesis or through record/ playback techniques. If successful, both jamming and deception approaches are detrimental to the efficient execution of military operations.

Many jamming threats could be effective against a particular communications system. Some of these are listed in Table 1; the particular threat of concern will depend very much on the signal(s) to be protected. As the signal structure is changed to reduce its vulnerability to jamming a different threat may become more effective and must be analyzed. It must be assumed that the enemy will have sufficient intelligence information about the communications systems so that he can design an optimum jammer. Conversely, the antijam (AJ) communication system design must anticipate every type of jamming signal which the enemy can deploy. The solution will be limited by the cost of implementation as well as by satisfying other constraints.

Jamming signals can be divided into several major categories: simple manual and semi-automatic brute force jamming systems, spoofers, and followers. Spoofers try to transmit replica signals to preempt the acceptance of legitimate communications signals. A fully automatic, fast response, look-through follower jammer attempts to cancel the advantage of certain ECCM approaches by virtue of its speed of response. A variety of jamming waveforms are shown in Figure 5. To illustrate some of the more specialized jammers, a frequency hopping ECCM signal is shown as well as special waveforms designed to counter it. For other communications signals, which will be mentioned later, comparable jamming waveforms can be postulated.

TABLE 1. JAMMING THREATS

Narrow Band Noise/CW	Covers a single narrow band communications channel
Partial Band Noise	Covers several communications channels and guard channels
Multiple Carriers	Covers several communications channels only
Wide Band Noise	Covers part or all of a communications band
Narrow Band Pulses	Covers a single digital data channel
Wide Band Pulses	Covers several digital data channels
Swept Frequency	Covers several channels; appears as pulse jammer to each channel
Fast Follow Look-Through	Intercepts signal and responds immediately on the same frequency
Repeater	Records and plays back signals in an attempt to deceive
Replica/Captured Equipment	Can deceive or jam a single channel

Let us now consider the effects such jammers have on conventional narrowband signals. For example, one might expect jammer strategy to make use of wideband noise, swept frequency, or pulse techniques against an AM or narrowband FM radio. Such approaches would give the jammer an advantage in peak power, or afford him the capability of covering several different communications channels at the same time with a single equipment. Interference caused by a noise jammer can be interpreted in terms of the intelligibility curves presented in Figure 4. The interference is continuous, and its level is determined by relative bandwidths and geometry involved. For instance, if a 10 dB stronger noise jammer spread its power over a bandwidth four times (6 dB) greater than the bandwidth of an AM radio, a receiver equidistant from the transmitter and the jammer, would expect a -4 dB SNR at RF. This results in roughly 8% voice intelligibility.

For non-continuous interference (such as a pulsed jammer) the curves presented in Figure 3 are used, provided the jammer overpowers the signals. The interruption rate and speech-time fraction are the repetition rate and the off-time of the jammer, respectively. It is, of course, possible that other factors could come into play to diminish the effective speech-time fraction. For example, AGC loop time constant or amplifier recovery time could be significant. Such effects must be considered on an individual basis.

Another example of non-continuous interference is the swept frequency jammer. Such a jammer can cover several channels simultaneously by rapidly sweeping its RF output. The sweep rate of the jammer becomes the average interruption rate and the speech-time fraction (STF) is determined by

$$S.T.F. = 1 - \frac{BW_{SIG}}{BW_{JAM}} \tag{1}$$

If a swept frequency jammer much stronger than the signal were to sweep across 10 signal channels at a rate of 1000 times per second, the interruption rate in one channel would be 1000 per second and the speech-time fraction would be 0.9. Figure 3 shows that this would result in about 65% intelligibility.

ECCM Approaches. - Techniques most commonly associated with Electronic Counter Counter Measures (ECCM) operation are spread spectrum modulations. Four basic techniques are pseudo-noise modulation, frequency hopping, chirp modulation, and time hopping. A short discussion of these spread spectrum techniques can be found in Appendix A. Table 2 lists some of the general characteristics of the basic spread spectrum modulations. Each has different advantages and disadvantages for a specific application. Two or more of these techniques are often combined to solve a particular communications problem.

Effects of the ECCM implementation on voice intelligibility are a significant consideration. An anti-jam modem must certainly function in the absence of jamming with minimum intelligibility degradation. For example, PN modulation does not degrade performance of the unjammed communications link, but frequency hopping may. The hopping capability is commonly provided by indirect frequency synthesizers to reduce size and cost in comparison with direct synthesizers. A penalty for those reductions is a much longer switching (and settling) time. The need to blank the transmission during this switching period can introduce discontinuities in a voice signal transmitted over such a link. The effects of these interruptions can easily be appraised using Figures 2 and 3.

Mutual interference in multi-net operation is another example of possible degradation due to ECCM techniques. Consider two frequency hopping radios located near each other operating in different nets. Where conventional narrowband radios would use different channels, FH radios could use different hopping sequences which would make use of the same set of frequencies. Although driven by different codes, the hopping radios could simultaneously occupy the same frequency. Normal designs will cause the probability of

TABLE 2. SPREAD SPECTRUM TECHNIQUES

Pseudo-Noise Modulation

- Low Peak Power Density
- Easily Implemented with LSI Technology
- Requires Good Propagation Medium
- Requires Contiguous Spectrum
- Bandwidth Limited by Power, Cost

Frequency Hopping

- Can Cover Wide Bandwidth
- Not Restricted to Contiguous Frequencies
- Can Often be Performed with Radio Synthesizer
- Instantaneous Power Density is Higher than PN

Chirp (Swept FM)

- Wide Bandwidth has been Demonstrated
- Little Doppler Sensitivity
- Requires Contiguous Spectrum
- Vulnerable to Special Detectors/Jammers

Time Hopping

- Natural for use with TDMA
- Good Near-Far Performance
- Compatible with Analog or Digital Modulation
- Forces Jammer Towards CW
- Inexpensive
- Requires Peak Power

overlap to be quite low, but as the number of nets in operation increases, so will the probability of overlap. Such overlaps will cause increased levels of interference in the received voice signal. The effects of such occurrences can be analyzed with the previously presented intelligibility curves, by considering the average interruption rate and the speech-time fraction.

ECM Effects on ECCM Signals. - The combined effects of ECCM and ECM techniques are of major concern in anti-jam (AJ) communications. The factors discussed previously must be re-evaluated, since interactions can cause the total effect to be different from the sum of the parts.

In order to make the speech intelligibility curves useful for communication engineers, translation to RF transmission frequencies is essential. This is facilitated by categorizing signal and jamming waveforms as either continuous or switched transmissions. Specific examples of both types are presented in Table 3, which lists a number of possible signal and jammer configurations. While the Table is not meant to be all-inclusive, it does succeed in showing typical signals and the types of interactions resulting from them. For example, in the trivial case of a narrowband noise jammer used against a narrowband signal, both the signal and jammer are continuous waveforms. As indicated in the legend, this type of interaction dictates use of the intelligibility curves presented in Figure 4.

TABLE 3. SIGNAL/JAMMER INTERACTIONS

Jammers \ Signals	Narrow Band				Wide Band		
	Analog		Digital		Digital		
	AM	FM	PSK	FSK	PN	TH	FH
Narrow Band Noise/CW	1	1	1	1	1	3	3
Partial Band Noise	1	1	1	1	1	3	3
Multiple Carriers	1	1	1	1	1	3	3
Wide Band Noise	1	1	1	1	1	3	3
Narrow Band Pulses	2	2	2	2	2	4	4
Wide Band Pulses	2	2	2	2	2	4	4
Swept Frequency	2	2	2	2	2	4	4
Fast Follow Look-Through Jammer.	1	1	1	1	1	4	4
Repeater	1	1	1	1	1	4	4
Replica/Captured Equipment.	1	1	1	1	1	1	1

Type 1:	Continuous Signal +	Continuous Jammer	Use Figure 4
Type 2:	Continuous Signal +	Switched Jammer	Use Figure 3
Type 3:	Switched Signal +	Continuous Jammer	Use Figure 3
Type 4:	Switched Signal +	Switched Jammer	Use Figure 3

As an example of interaction between a switched jammer and a continuous signal, consider a swept frequency jammer interfering with a PN-PSK signal. Assume that the jammer is sweeping a 50 MHz bandwidth while the PN spectrum occupies 10 MHz within that region. As illustrated in Figure 6, the jammer sweeps the full 50 MHz band in a period of 50 ms (a repetition rate of 20 Hz). This means that the signal under consideration is jammed for a 10 ms period out of every 50 ms. The interruption rate of the signal channel is 20 Hz and the speech-time fraction is 80%. If the jammer's power is much stronger than the signal power during the interference pulse, the intelligibility curve shown previously in Figure 3 applies. For a 20-Hz interruption rate and 80% speech-time fraction, the intelligibility of the resultant baseband voice signal would be on the order of 95%. Note that if the jammer's repetition rate had been on the order of 1 KHz, the resultant intellibibility of the voice signal would have been reduced to roughly 50%.

On the basis of signal intelligibility, the 50 ms sweep time used for this hypothetical jammer is the least effective repetition rate that could have been selected. Disregarding other considerations, the intelligibility curves clearly show that a more optimum jammer strategy would be to implement a faster sweep of the 50 MHz band, if possible. Alternately, a slower sweep would also be more effective.

Continuous jamming of discontinuous signals can be the cause of interruptions, too. Partial band (continuous) noise jams a frequency hopping ECCM signal in this way. Any jammer covering a fraction of the total transmitted bandwidth (e. g. partial band, narrow band, CW, etc.) yields an average interruption rate (IR) slower than the hopping rate (HR). Figure 7 shows the conversion, which follows the equation

$$\text{I.R.} = \frac{BW_{JAM}}{BW_{SIG}} \times \text{H.R.} \qquad (2)$$

Equation 1, which relates speech-time fraction and bandwidth ratio, and Equation 2 can be combined to yield

$$\text{I.R.} = \frac{1}{1-\text{S.T.F.}} \times \text{H.R.} \qquad (3)$$

This equation gives the performance of partial band jamming of an FH signal when plotted on Miller & Licklider's curves (Figure 8). Speech-time fraction indicates a specified ratio of signal and jammer bandwidths, as given in Equation 1.

In a much different type of waveform interaction, consider a pulse jammer used against a frequency hopped signal. Both the signal and the jammer exhibit switched waveforms, and a different set of transformation rules must be used in order to apply the baseband intelligibility data to derive meaningful RF design principles. The effects of periodic noise pulses caused by such pulsed jammers can be seen in Figure 9 for one pulse per hop. The duty cycle of the pulse determines the speech-time fraction. Thus the locus of points for jammers of this type is given by a vertical line for the hop rate used.

The response of ECCM techniques such as frequency hopping to a fast follow look-through jammer provides another example of ECM/ECCM interactions. For geometries which introduce small propagation delays (relative to the jammer's response time) a relationship between speech-time fraction and hop rate can be plotted as in Figure 10. Speech-time fraction is the portion of time spent on one frequency before a follow jammer's signal arrives at the receiver. STF is proportional to hop rate, resulting in logarithmic curves on the semi-logarithmic axes of Figure 10.

The conclusion can be drawn that a hop rate of about 1000 hps or more would be necessary to provide substantial improvement against a follow jammer with slow response time. Realistically, jammers may respond in less than 100 μs, thus pushing the required hop rate to over 10, 000 hps.

The geometry dependence of a fast follow jammer is illustrated in Figures 11 and 12. In Figure 11 the geometry of the fast follow jammer problem is defined. Contours of constant additional propagation delays are ellipses, where a line joining the transmitter and receiver forms the major axis of the ellipse. To simplify the mathematical treatment of this problem, jammer positions can be taken on the minor axis of the ellipse, thus introducing equal path differentials along the two segments of the signal path through the jammer. The differential time delay of the jamming signal can then be calculated as the total propagation delay along the path through the jammer, plus the jammer response time, minus the propagation delay from the communications transmitter to the receiver. Thus, for a given jammer response time, various geometric relationships will define differential time delays. These in turn correspond to fractions of a hop frame which are successfully received. Figure 12 illustrates the geometry dependence of a fast follow jammer's successfulness, for several assumed jammer response times and distances.

Signal/Jamming Simulator. - A simulator, built to experimentally verify the previously discussed analytical results, is shown in Figure 13. The simulator is configured with a flexibility that allows convenient adjustment of various interference parameters. Both continuous and periodic or aperiodic repetitious interference can be added to an audio signal. Interruption rates from 1 Hz to 100 Hz are provided and blanking/jamming duty factors from 1% to 30% can be selected.

While a built-in noise generator is the usual interference source, it is possible to use other signals for interference. This is of interest in simulating the effects of multinet operation or conferencing.

Another flexibility of the RCA simulator allows the input and/or output to be either recorded or “live” voice signals. Input signals can be provided by a microphone or tape recorder; output signals are available via the loudspeaker, headphones, or for recording. This is convenient for creating standard test tapes and also for simulator-overlay testing. Standard test tapes can be created by using the simulator to suitably modify a speaker’s voice signal while he reads through the selected test material. Simultaneous recording of the reader’s voice and the simulator’s output are made. These then become the sources for use during actual testing, where the only difference in the two tapes is due to the simulated interference.

Simulator-overlay testing is another valuable tool. While rhyme tests and phonetic speech tests can provide useful and convenient data, the results do not answer all questions. A pilot, whose life depends on rapid, intelligible communications, might like to listen to the effects various jammers have on his radio messages. Such effects can be measured by using the simulator as an overlay to recordings made in the field. Another possibility exists for creating multiple, independent interference effects (e. g. conferencing and jamming, simultaneously) by using the simulator repetitively.

A block diagram which illustrates the simulator operation is shown in Figure 14. The heart of the simulation methodology lies in characterizing the interference. This can be shown by some examples. Consider the use of a pulsed CW jammer against a voice signal transmitted by a PN-PSK spread spectrum system. The input J/S ratio and the amount of processing gain determine the interruption noise level, while the PRF and duty factor of the jammer determine the interruption timing. The background noise level can also be set appropriately to simulate the thermal noise SNR.

In another example, a narrowband or partial band noise jammer is used against a slow frequency hopping signal. The interruption timing is determined probabilistically, using the jammer and signal bandwidths and the number of hopped frequencies. Noise levels during the interruptions and background noise can of course be individually adjusted. This will be demonstrated by means of tape recordings which simulate communications provided by a slow frequency hopping radio in the presence of a partial band noise jammer covering 30% of the band. Three different hop rates will be simulated in the following order:

1. 1 hop per second
2. 100 hops per second
3. 20 hops per second
4. 20 hops per second with added background noise

The recordings clearly point out how parameter selection can play a critical part in voice intelligibility, in view of a specific jamming model.

Conclusion. - The primary result of the work reported in this paper is to bring psychoacoustics and voice intelligibility to the attention of communication engineers. It has been customary in the past to design systems for acceptable signal-to-noise ratios and/or acceptable bit error rates. While these criteria are acceptable for many types of information, the transmission of voice under various interference conditions bears the basic requirement that a human listener must be able to understand the received signal. Thus it is a natural and logical step to transform the psychoacosutic phenomena into forms more useful to communication engineers.

Utilization of the criteria presented here enables modern communication systems design and evaluation to be carried out in a more meaningful way when voice transmissions and nonstationary interference are involved. The transmitted information may be in analog or digital format, the frequency of transmission may be in the UHF or K-band frequency range, yet the criteria presented here can be applied. This universal applicability is the result of measuring performance at the system output, rather than at an intermediate way point. Thus the system can now be evaluated in totality, making use of the known characteristics of human hearing and interpretation.

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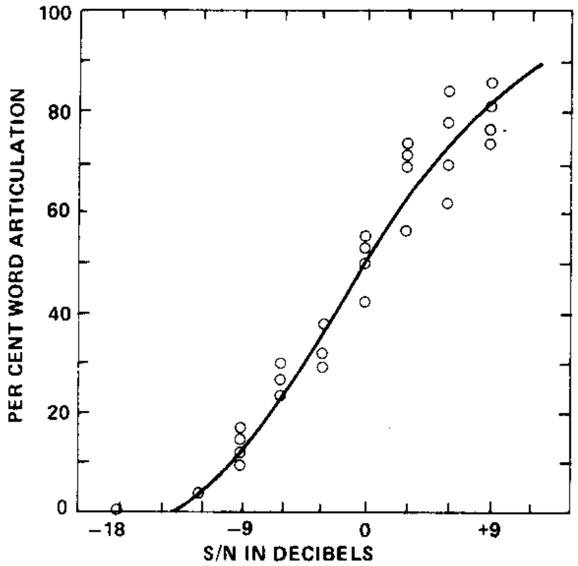

Figure 1. Word Articulation for Speech in the Presence of Noise(Ref. 1)

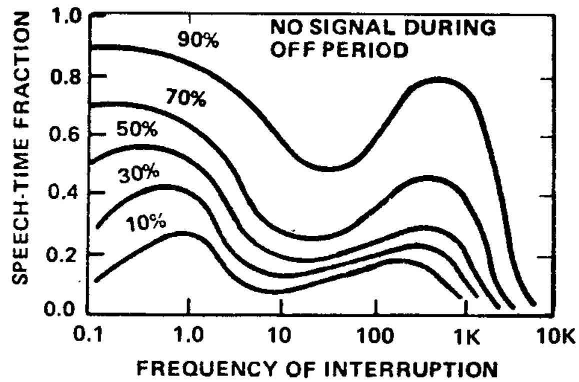

Figure 2. Constant Intelligibility Contours for Interrupted Speech (Ref. 1)

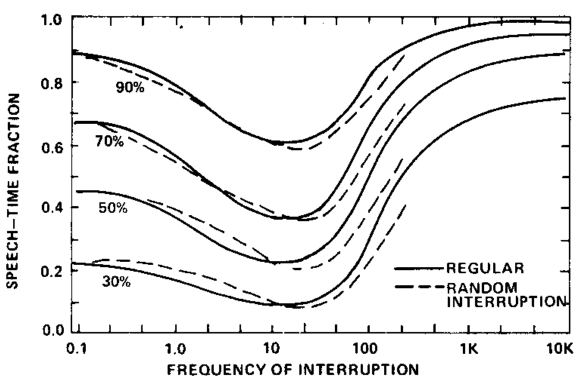

Figure 3. Constant Intelligibility Contours for Speech Interrupted by Noise, SNR = -9 db (Ref. 1)

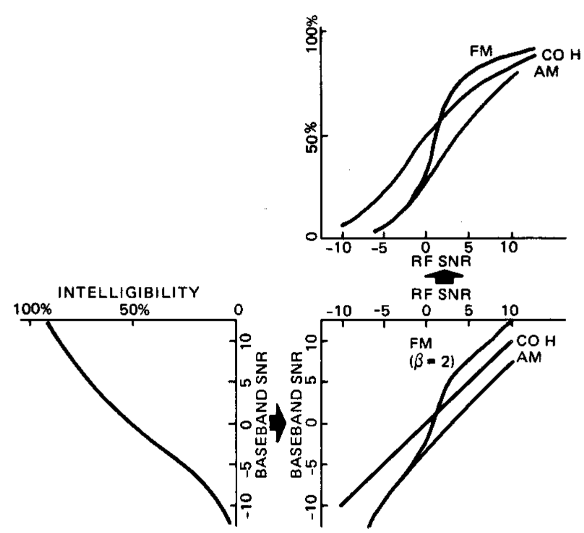

Figure 4. Transformation of Intelligibility Curves

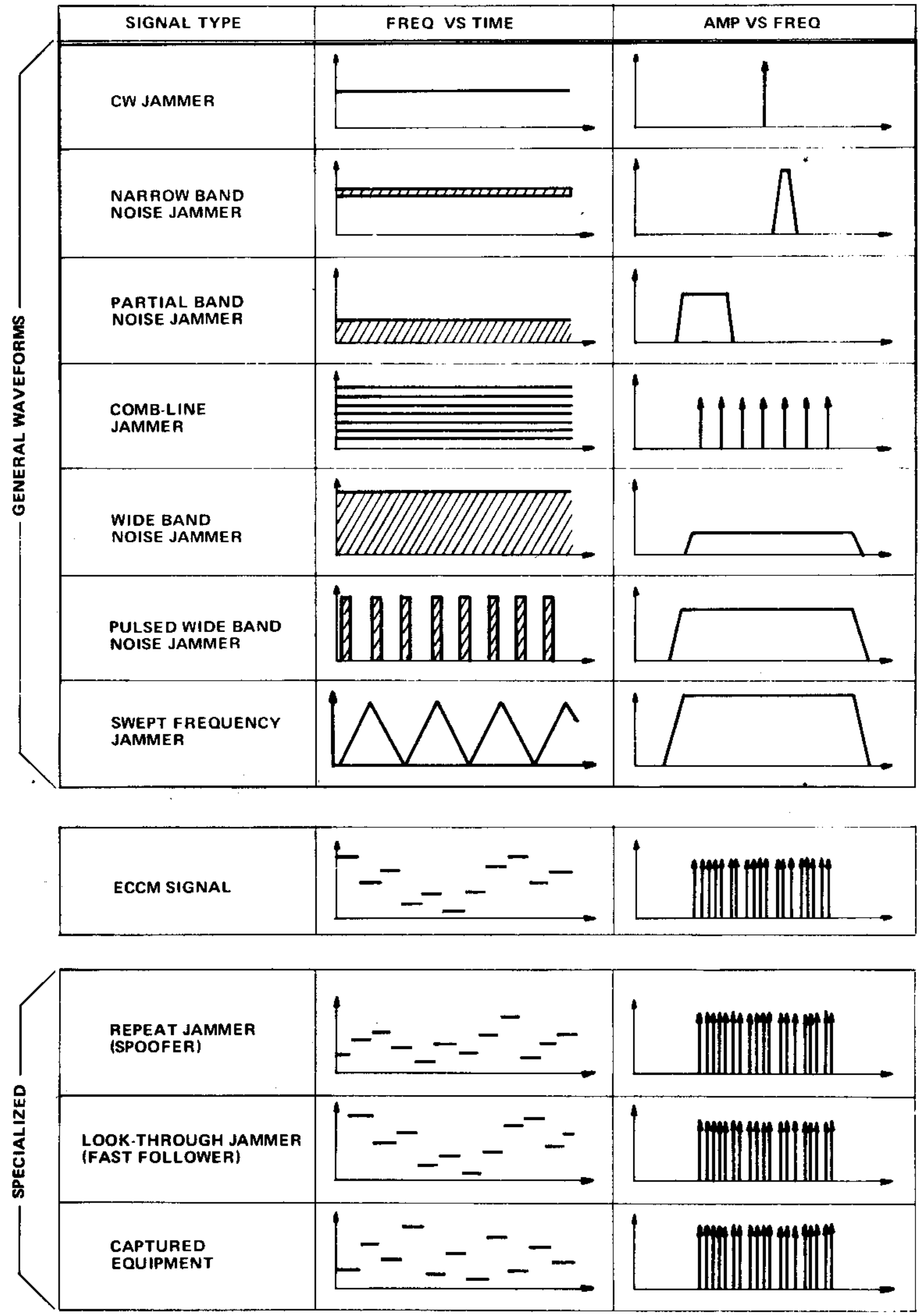

Figure 5. Jammer Threats

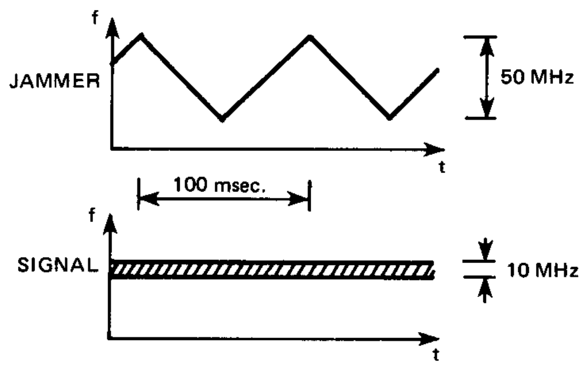

Figure 6. Swept Jamming of PN Signal

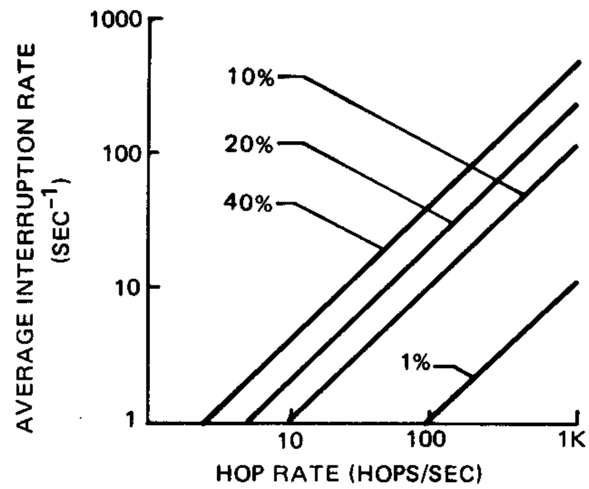

Figure 7. Interruption Rate for Fractional Band Jammers

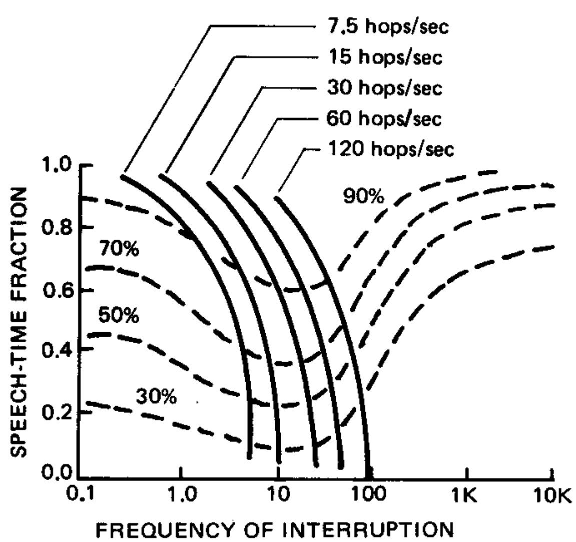

Figure 8. Performance of Partial Band Jamming of FH Signal

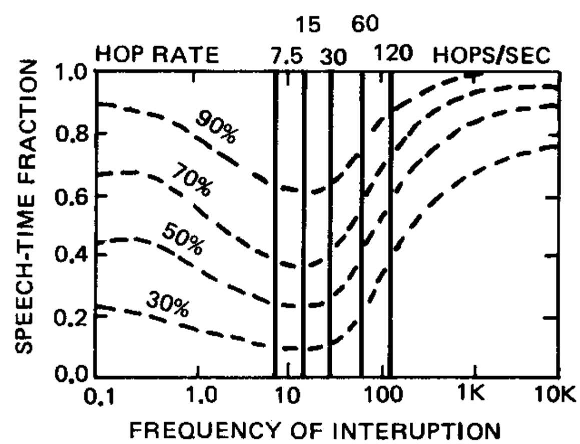

Figure 9. Pulse Jamming Effectivess

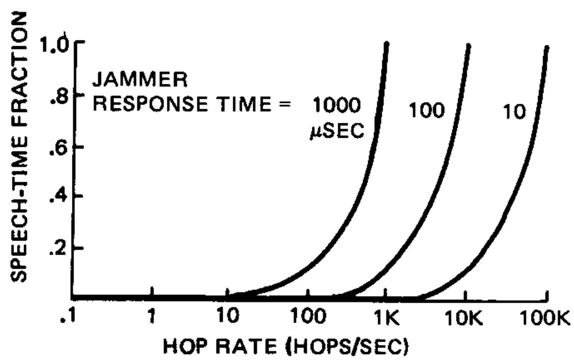

Figure 10. Fast Follow Jammer and FM Signal Interaction, for Small Propagation Delays

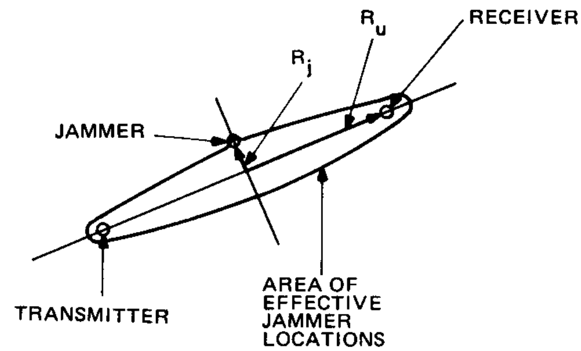

Figure 11. Fast Follow Jammer Geometry

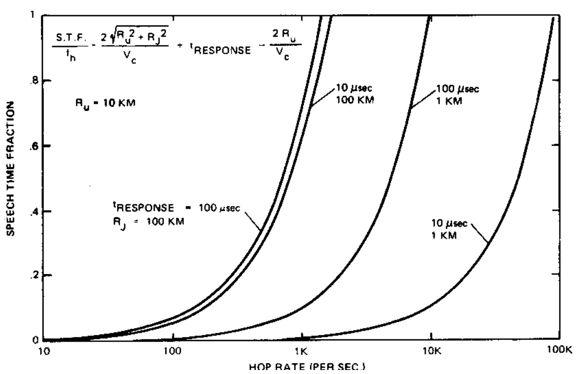

Figure 12. Fast Follow Jammer Effectiveness, including Geometry Dependence

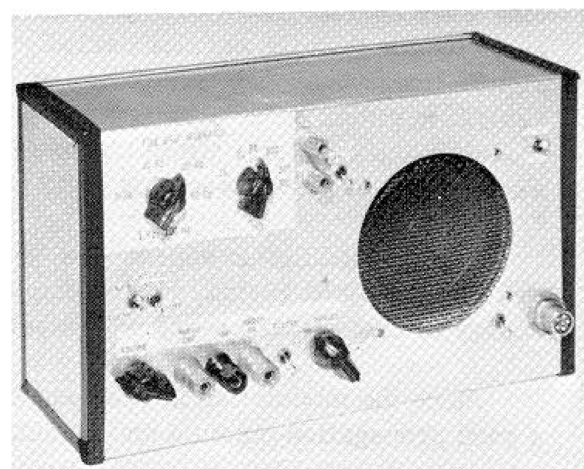

Figure 13. Audio Interference Simulator

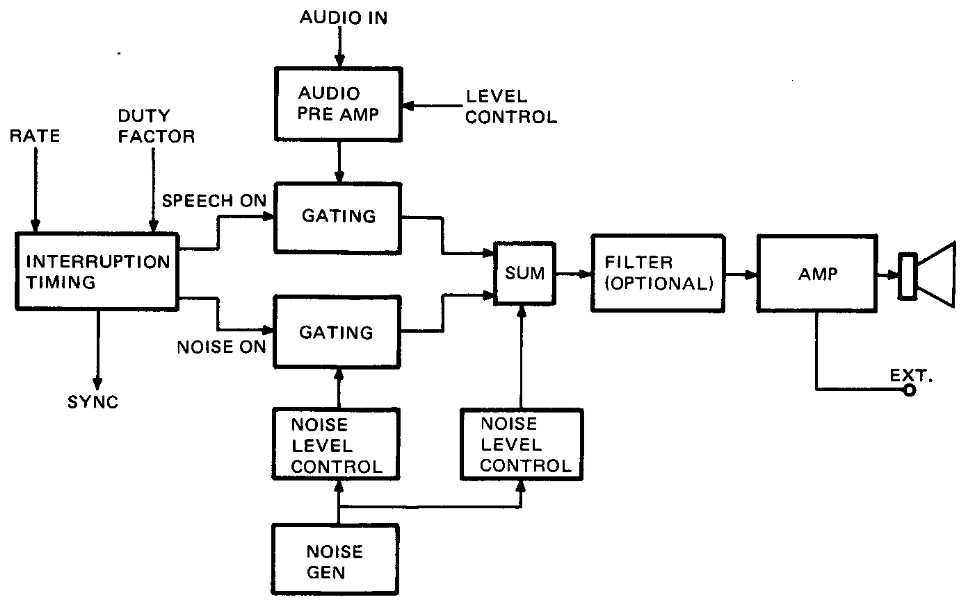

Figure 14. Simulator Block Diagram

APPENDIX A.

Pseudo-Noise Modulation. - Pseudo-noise or pseudo-random noise, also known as direct sequence modulation, is illustrated in Figure A1 which shows a sine wave carrier and a code pattern with a basic clock period T. This is generally much longer than the carrier period. The code pattern can be generated from a simple linear sequence generator, or from a cryptographically secure code generator. In either case, a binary sequence is obtained which is used to phase modulate the carrier. While biphase modulation is illustrated, quadraphase modulations are also becoming quite common.

Special modulation approaches, such as offset keyed quadraphase modulation or minimum shift keying, can be employed to achieve rapid fall-off of sidelobe energy to avoid interference with other signals in the band.

Since the modulation is coherent over a wide bandwidth, it generally requires a good propagation medium and a contiguous spectrum.

Frequency Hopping. - The basic concept of frequency hopping is illustrated in the frequency-time diagram of Figure A2, where the signal is transmitted on frequency F1; after a period of T microseconds the transmitter switches from F1 to F2, and then to F3, and subsequently to F4, and then to F5, etc.

In actual use, the transmitter may hop over several hundred frequencies and thus cover a wide spectrum. These frequencies do not have to be contiguous, so they can be spread over a wide band and can avoid other communications signals in the band. This is illustrated with an actual spectrum analyzer photograph, where 100 MHz is covered with a number of randomly spaced frequencies. While the instantaneous power density is the same as for a non-hopping signal, the average power density is low.

Chirp Modulation. Figure A3 illustrates examples of chirp modulation. Chirp is well known in the radar community, where it has been used for many years for high resolution pulse compression radars. It has also been used in FM CW altimeters to measure aircraft altitude accurately. The modulation is basically a swept frequency signal, which can take the form of an up slope or a down slope chirp. In some cases combinations are used. In the up slope chirp example, the frequency of the transmitter is increased linearly from frequency F1 to frequency F2 over a time interval T. Conversely, the frequency could be decreased from F2 to F1 over the same interval. The spectrum of the chirp signal is generally quite flat as shown. For very large time-bandwidth products, such as 1000 or greater, the spectrum appears to be almost rectangular. This has the advantage of minimum out-of-band radiation, while maintaining a flat or noise-like spectrum within the band of interest. As with pseudo-noise modulation, chirp requires a contiguous spectrum and is therefore subject to the same inband mutual interference as pseudo-noise modulations.

RCA has built equipment for use in space on the Apollo 17 mission which had an 11% bandwidth at several HF and VHF frequencies. The chirp modulation can be randomized to defeat special detectors/jammers by using pseudo-random combinations of up slope and down slope chirps.

Time Hopping. Figure A4 illustrates an example of time hopping. Pulses are transmitted at a low duty cycle, thus requiring high peak power. However, this is inherent in time division multiple access (TDMA) systems. The unique characteristic of time hopping is that the next pulse will occur at an unpredictable time, unless the coding algorithm is known. It may be viewed as a pseudorandom pulse position modulation. When multiple users operate on the same channel, the apparent duty cycle will increase. All users must be synchronized and avail themselves of the same pseudo-random algorithm to avoid self-jamming. The anti-jam protection of time hopping arises from the fact that the jammer cannot jam any one user consistently, unless he resorts to a high duty cycle (CW) jamming signal.

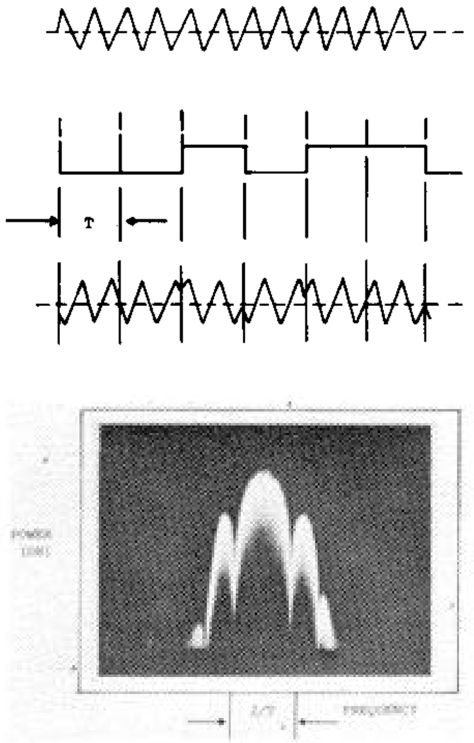

Figure A1. Pseudo-Random Noise Modulation

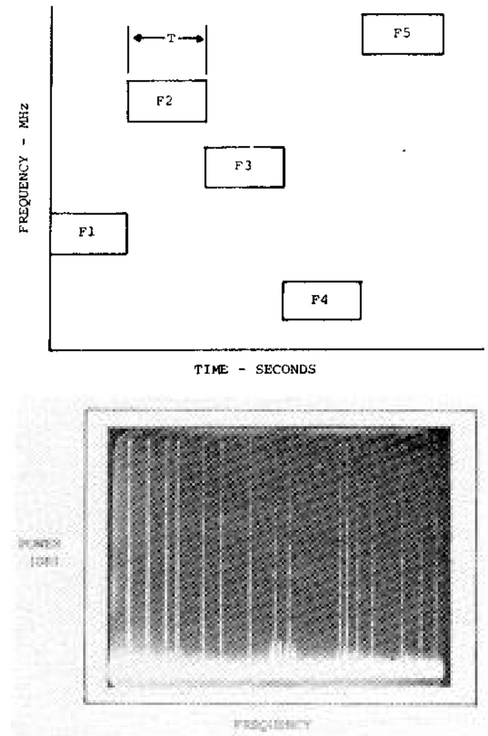

Figure A2. Frequency Hopping

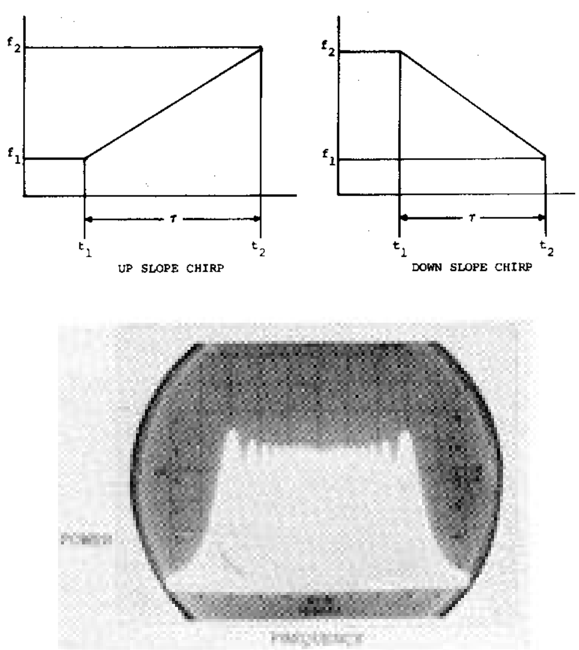

Figure A3. Chirp Modulation

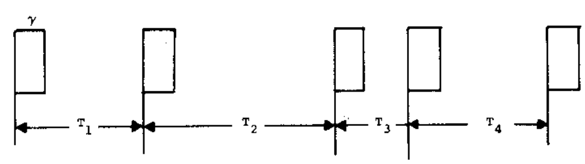

Figure A4. Time Hopping