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The research supported by this grant has led to a significantly improved mathematical understanding of the problems associated with communication in a hostile environment. The basic approach has been to apply the techniques and insights of information theory. The results obtained have given insight into how to best design communication systems which must function under severe noise.

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CODING FOR SPREAD-SPECTRUM CHANNELS
IN THE PRESENCE OF JAMMING
(Grant No. AFOSR-83-0296)

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Abstract:

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The long-term goal of this project has been to obtain a basic mathematical understanding of the problems associated with communications in the presence of severe noise, e.g. jamming or fading. Our basic approach has always been to apply the techniques and insights of *information theory* to these problems. In our earliest work in this area, which was devoted solely to the jamming problem, we combined information theory with *game theory*, and obtained many insights about optimal jamming and antijamming strategies for a variety of realistic scenarios (Refs. [1]-[6]). Later, we studied more general models for severe noise (Refs. [7]-[13], and obtained results which we feel shed considerable light on how best to design communication systems which must function reliably in hostile environments.

Details:

In References [1]-[6], we studied many specific spread-spectrum modulation techniques, our goal being to identify the corresponding "worst case" jamming strategy. In some cases, our results have confirmed the

conclusions of other researchers (e.g., in Ref. [2] we gave a rigorous proof of a result first announced by Houston about the worst-case jammer vs. a classical frequency-hopped system), but in many others, our results have been entirely new. We believe our most important results have been our development of an entirely new kind of "anti-jam" strategy involving the *randomization* of certain of the transmitter parameters. This technique was originally described in [2], but its most promising variation appears in [4], and [6], where we introduced the notion of the *random ration-threshold (RRT)*.

The RRT is based on another recent development in the field, Viterbi's *ratio threshold (RT)*, a robust A/J countermeasure which has attracted considerable interest in the military communications community. We discovered several possible weaknesses in the RT technique which can be remedied by a certain kind of parameter randomization. In fact, we proved that the RRT is superior by several dB's to conventional RT vs. many different jamming thresholds.

In reference [7], we embarked on a new direction for this project, and began an abstract study of the problem of reliable communication in the presence of extreme and unpredictable fading. There, using a remarkable recent idea of Posner (IEEE Trans. Communications, April 1983, pp. 509-517), we studied this problem using the techniques of *broadcast coding*. Broadcast coding, which was invented in 1972 by Cover, is a communication strategy which is normally applied to situations in which one individual must transmit information simultaneously to two or more

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receivers over two or more noisy channels. Posner's idea was to apply these results to a single physical transmitter and receiver, for which the transmission conditions are unknown, and to treat the possible transmission conditions as several "virtual" channels, corresponding the possible noise conditions. In this way, when the channel conditions are favorable, a large volume of information can be transmitted (this corresponds to transmitting over one of the "good" broadcast channels), but when conditions are unfavorable, nevertheless it is still possible to transmit critical information reliably, albeit at a slower rate (this corresponds to transmitting over one of the "bad" broadcast channels). In our paper [7], we showed that for a Gaussian broadcast channel (the broadcast channel model most appropriate for deep space and satellite communication), that for low signal-to-noise ratios, the sophisticated broadcast coding strategies devised by Cover and other researchers may not be significantly superior to the much simpler class of "timesharing" strategies. Our student, Eric Majani, has since shown that this same result (broadcast coding is not markedly superior to timesharing) is also true for very noisy binary symmetric channels. Since timesharing is much easier to implement than broadcast coding, this is an important point to know.

We also discovered that a serious study of very noisy broadcast channels requires a thorough understanding of very noisy (ordinary) channels. And although there is some published research on this topic, we found nothing in the literature which is quite what we need. Therefore, in [8], we completed what we feel is the definitive study of very noisy discrete memoryless channels (DMC's). In [8], we defined a class of very

noisy DMC's, where the noise is controlled by a single parameter $\epsilon \geq 0$, which we call the abstract signal-to-noise ratio. We found that DMC's fall into two different categories, one for which the capacity is proportional to ϵ , and the other for which it is proportional to ϵ^2 , for small values of the signal-to-noise ratio ϵ . We have developed algorithms for calculating the constant of proportionality, for both classes of channels. We feel that this paper is the definitive work on very noisy DMC's; in any case, it is just what we needed for our study of very noisy broadcast channels.

In a related study, we made an information-theoretic investigation of the problem of optimal data compression. In [9], we have solved an outstanding problem in this subject, and computed the worst-case behavior of a certain class of quantization algorithms. And while it is too early to say exactly what practical importance this result may eventually assume, it is a nice example of how research in one area (in this case, communication in the presence of severe fading) may lead to results in another (in this case, data compression).

In our final series of papers ([11]-[14]), we investigated the performance of coded telecommunications systems, specifically binary phase-shift-keyed systems in the presence of Gaussian noise, at low signal-to-noise ratios. This is important because without a reliable theory, it is necessary to resort to elaborate computer simulations in order to find the performance at low snr's. We have discovered a reasonably simple formula [12] for the low snr performance that involves the distance spectrum of the code, together with another family of

parameters. Also, in [13] we have identified a simple parameter (the so-called dominant-root) associated with any convolutional code which appears to accurately predict its performance at low signal-to-signal ratios. Extensive computer simulation confirms our belief in the importance of the dominant root; We hope that further research will provide us with a rigorous proof of it.

In summary, the research supported by this grant has led to a significantly improved mathematical understanding of the problems associated with communication in a hostile environment. This research is closely related to what others in this area have done, but contains many unique features (e.g. applications of game theory; tractible models for very noisy channels; the dominant root of a convolutional code). We feel that our results can contribute to greatly enhanced U.S. Communication security.

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(all except [1] acknowledge AFOSR support)

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