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# CHANNEL MODELS FOR THE ERROR INJECTOR UNIT

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**13. ABSTRACT** *(Maximum 200 words)*

This report discusses channel modeling for the generation of error patterns to conduct experimentation in RADC's Network Design Laboratory. The interference process and impairments in most real communication channels are such that errors tend to occur in clusters. Channel models based on Markov chains are able to generate error sequences which are typical of the error patterns produced by real channels. Four-state Markov channel models for HF, troposcatter and AUTOVON channels described in the report are considered suitable for demonstration and experimentation. Further research is needed in the area of channel modeling especially in the presence of jamming.

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# I. INTRODUCTION

In classical point-to-point digital communication systems (DCS), a dedicated communication link is established for digital data transmission. Communication over a link is affected by interference processes which are functions of the specific channel in use. The interference processes cause errors in the transmitted digital data stream. In memoryless channels, errors are assumed to be independent of each other and probability of bit error characterizes the DCS performance. However, most real communication channels exhibit memory, i.e., the interference processes and channel impairments are such that errors tend to occur in clusters. Thus, there are error bursts separated by relatively error free periods. The performance of such real communication systems is described in terms of higher order error statistics. Due to this memory, the modeling of channel error behavior is quite involved. However, it is an important problem due to its utility in the performance evaluation of digital communication systems.

More recently, communication networking has come of age. In these networks, communication channels are not dedicated for use by a pair of users but are pooled together to form a network which is shared by many users. The performance of these networks is determined by measures such as throughput, average delay, reliability etc. During the performance evaluation, it is generally assumed that communication network consists of perfect channels and the effect of any interference is ignored. In practice, however, this assumption is not valid since real channels are noisy and are susceptible to other channel impairments. In addition, the situation becomes even worse in military communications due to jamming.

An important step for realistic performance evaluation and experimentation is to develop a communication network model which takes the real channel behavior into account. In order to accomplish this, we need to have communication channel models which generate realistic error patterns. These error patterns can then be used to inject errors in the transmitted digital stream. This process will portray the operation of communication networking more accurately. In addition, it can be used to determine the performance of various communication networking and implementation techniques such as routing and other protocols. In Section 2, we briefly discuss some concepts related to modeling of channels. In Section 3, we present some models for real channels from the literature which can be used to generate error patterns for use in communication network evaluation. In Section 4, a brief discussion is included.

## II. CHANNEL MODELING FUNDAMENTALS

As indicated earlier, an accurate characterization of the error behavior of real communication channels is of fundamental importance in the design, simulation and analysis of communication systems. During communication, errors are caused not only by interference processes such as noise and other channel impairments, but also may be caused by processes such as jamming. Almost all of the channel modeling effort has concentrated on channels without jamming. In this section, we will briefly review this effort. The impact of jamming on channel modeling will be brought up in the last section.

One approach to model communication channels is in terms of randomly time-variant linear filters [1]. The filters are characterized in a symmetric manner in time and frequency domains by arranging system functions in dual pairs. A statistical characterization is carried out in terms of correlation functions for the various system functions. These are obtained for specific communication channels based on physical phenomena. These models are implemented in hardware and/or software for channel simulation. This approach is attractive and intuitively satisfying in that it attempts to model the physical mechanisms causing the errors. These channel simulators, however, are quite bulky and expensive to build. Therefore, this approach is impractical for use in the implementation of a communication network simulator especially when it is desirable to be able to simulate a network with a reasonable size.

One approach that has been quite successful is to work with sample error sequences obtained by transmitting test data on communication channels of interest [2]. In this approach, the actual physical mechanisms causing the errors are not taken into account. The communication channel is considered to be a black box and only the input-output relationship is examined. An analytical representation of the stochastic behavior of the error process is obtained. The error sequence can be processed directly to obtain statistical parameters of the communication channel or it can be used to parameterize a mathematical model which would generate similar sequences. While the main objective of developing these models was for the evaluation of error control techniques, here we are interested in using this class of models for developing an error injector unit. Next, we present a framework for system modeling.

Consider the simplified model of a digital communication channel shown in Figure 1. The model consists of an information source which generates the input sequence $\{x_i\}$. The channel corrupts the transmitted information with communication interference and produces an output sequence $\{y_i\}$. We assume that communication interference is statistically independent of the input sequence $\{x_i\}$. Let $\{e_i\}$ represent the error sequence. For simplicity, we assume that all three sequences are binary. In general, they can be modeled as elements of a Galois Field. The three sequences are related by

$$y_i = x_i \oplus e_i$$

where $\oplus$ is the exclusive OR operation. The error sequence $\{e_i\}$ is a zero-one discrete-time stochastic process which is to be modeled.

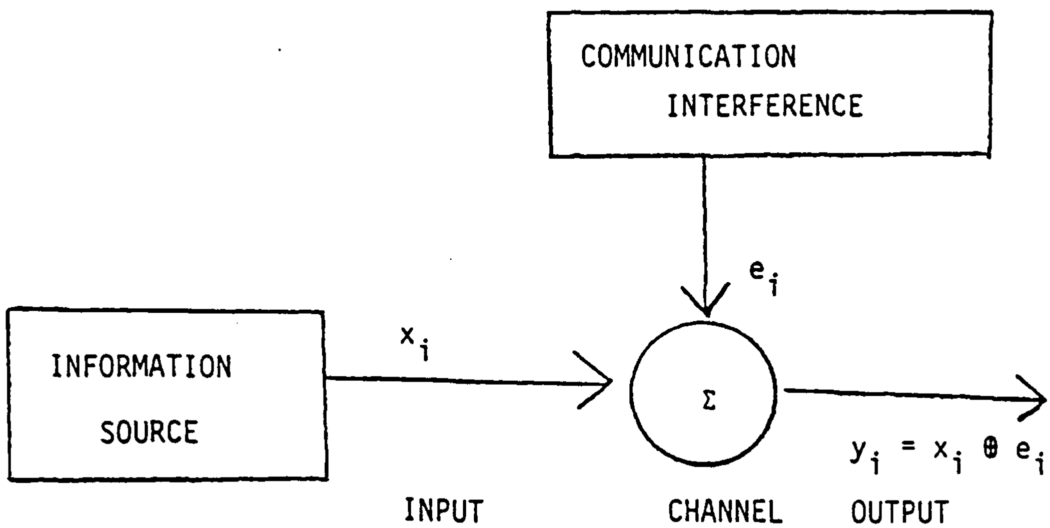


Fig. 1 Communication channel model

Next, we define some concepts which will be useful in our discussion on channel models. As indicated already, $\{e_i\}$ is a binary sequence where a zero indicates an error-free transmission of symbol and a one indicates a symbol transmission with error. It is expected that an error sequence obtained from a well-designed communication system will have many more zeroes than ones and many consecutive zeroes will occur. This motivates us to define a gap which is an error-free interval between two errors. The gap length is defined as the number of error-free digits between two errors, i.e. it is given by the number of zeroes between two ones. Two consecutive errors produce a gap of length zero. Thus, we may define another discrete stochastic process, $\{X_k\}$, representing the lengths of consecutive gaps. We define the unconditional gap distribution (sometimes also referred to as the error-free run distribution) as the probability of a gap of length m or more given a bit in error.

$$P(m) = \text{Prob. } (X_k \leq m \mid \text{a bit in error})$$

$$= \text{Prob. } (1\underbrace{00\ \ldots\ 0}_{m})$$

It is also denoted as $P(0^m|1)$. We define the gap probability as the probability of a gap of length n.

$$p(n) = \text{Prob. } (X_k = n)$$

$$= \text{Prob. } (1\underbrace{0\ \ldots\ 0}_{n}1)$$

Conditional gap distribution and the conditional gap probability are defined in a similar fashion.

$$P(m|n) = \text{Prob. } (X_k \geq m | X_{k-1} = n)$$

$$= \text{Prob. } (1\underbrace{00 \ldots 01}_{n}\underbrace{00 \ldots 0}_{m}|\underbrace{10 \ldots 01}_{n})$$

$$p(m|n) = \text{Prob. } (X_k = m | X_{k-1} = n)$$

$$= \text{Prob. } (1\underbrace{0 \ldots 01}_{n}\underbrace{0 \ldots 01}_{m}|\underbrace{10 \ldots 01}_{n})$$

Another quantity of interest is the probability of m errors in a block of length n, P(m,n). This is used frequently in the validation of channel models.

Mathematical models to represent channel error behavior can be classified into two groups:

i) Descriptive Models: These models attempt to describe the error sequence structure by means of some basic statistics such as gap distributions.

ii) Generative Models: These models attempt to represent a mechanism which would generate error sequences similar to the available channel error sequence.

It is this second class of models that are of interest to us because they produce error sequences which are similar to the typical sequences generated by the type of channel being modeled. These models are usually described in terms of a Markov chain consisting of a finite or infinite number of states. The transitions among various channel states are well defined probabilistically. These states correspond to a variety of error conditions of the channel and the state transitions represent the transitions from good to bad or vice versa. Transitions among the states produce a state sequence which can be mapped to the error sequence, or to the error gap sequence or to a function thereof. These state models can be parameterized using the error data from real channels. Models become more complicated when they are required to represent the channel behavior more accurately. The problem of tradeoff between the model complexity and the accuracy with which a model represnts a channel has not been solved.

Markov characterization of the error sequences was first proposed by Gilbert [3]. He suggested a two-state model consisting of a "good" state G and a "bad" state B as shown in Figure 2. The state G was assumed to be error-free and the probability of error in the state B was h, i.e., in stage G we always have $e_i = 0$ and in state B we have $e_i = 1$ with probability h. After the transmission of each digit, a state transition takes place. Transistion probabilities are small so that the probabilities of staying in the states G or B is large and thus the model attempts to simulate the bursty channel behavior. The mapping from the state sequence to the error sequence is probabilistic. Gilbert's model was a valuable first-step in attempting to simulate the bursty nature of channel errors. The model, however, is limited in its applicability t. represent real channels.

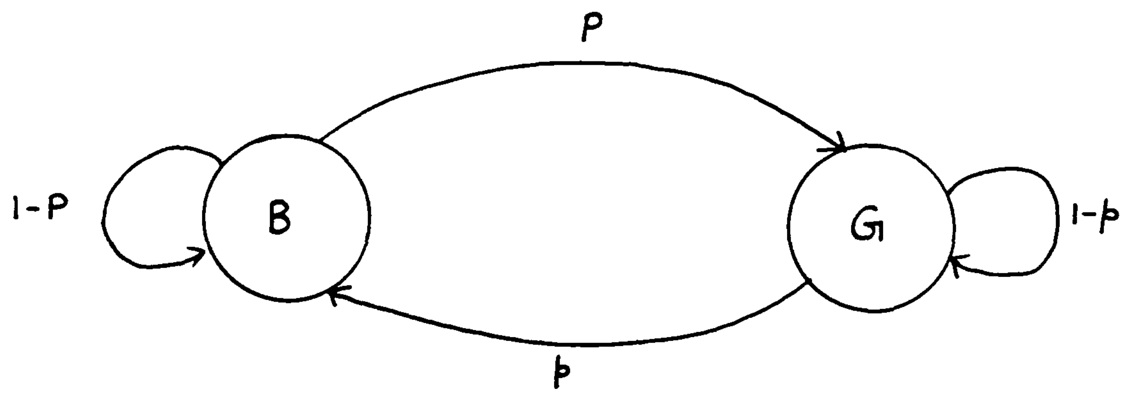


Fig. 2  Gilbert's two states model

Fritchman [4] considered a more general Markov chain model with N states. The state space was partitioned into two groups one with k error free states and the second with (N-k) error states. State transitions occur synchronously with the transmission of symbols over the channel. The Markov chain was assumed to be atationary and the stationary state probabilities were represented by the set $\{p_i, i=1,2,...N\}$. The probability of transition from state i to state j was $p_{ij}$ and $P = [p_{ij}]$ was the transition matrix. A mapping from the state sequence into (0,1), i.e. the channel error sequence, was defined in such a way that the probability of tranmsission among the error states was zero and the probability of transition among the error-free states was also zero.

The above model is analytically interesting but is quite complex to parameterize and use. Also, the gap distribution does not uniquely specify the model due to the multiple number of error states. Therefore, a simpler model with only a single error state was considered. This model and the associated transition probability matrix is shown in Figure 3. In the next section, we present models for some real channels that are based on the Fritchman model.

$$
\left[\begin{array}{cccc|c}
p_{11} & & & 0 & 1-p_{11} \\
 & p_{22} & & & 1-p_{22} \\
 & & \ddots & & \\
 & 0 & & p_{N-1,N-1} & 1-p_{N-1,N-1} \\
\hline
p_{N1} & & & p_{N,N-1} & p_{NN}
\end{array}\right]
$$

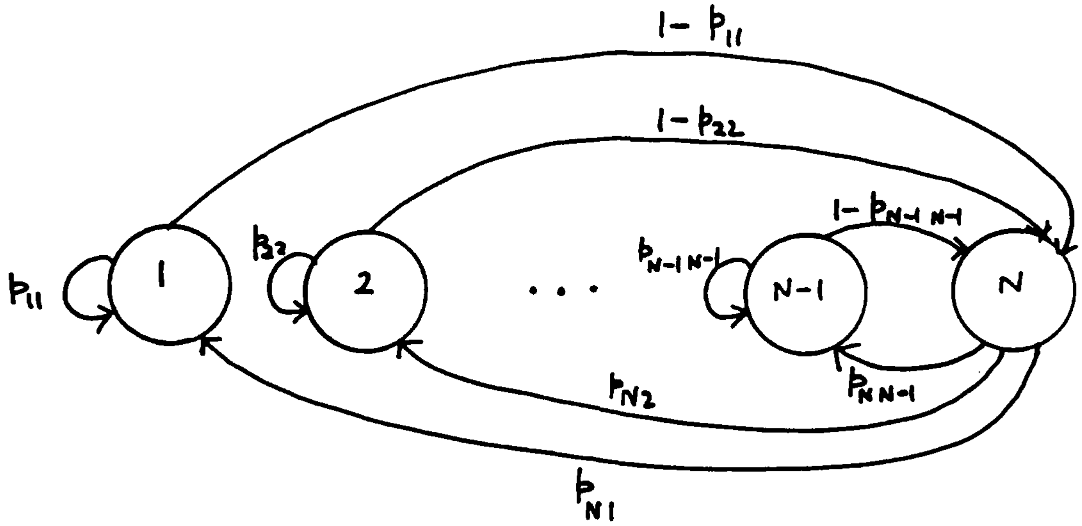


Fig. 3 Fritchman's model with one error state

## III. CHANNEL MODELS BASED ON REAL DATA

In the previous section, it was indicated that channel models based on Markov chains are able to generate error sequences which are typical of the error patterns produced by real channels. Actual data obtained from real channel measurements is used to parameterize the Markov models. Some work along these lines is reported in the literature, i.e., real error data for several channels has been recorded and model parameters have been obtained. Such models can be used to generate error patterns by the error injector unit for networking experimentation. In this section, we briefly describe some models that have been obtained in the literature. It is suggested that these models be used initially in the ROMENET experiments.

### HF Channel Model 1

This model is based on the data obtained on a DCS HF link operating between NAVCOM centers located at Stockton, California and Cheltenham, Maryland [5]. For this set of measurements a three-state model with one error state was found to be sufficient. The model, the associated transition matrix and gap distribution is shown in Figure 4 [4]. The bit error rate (BER) for this model is $2.631 \times 10^{-3}$.

### HF Channel Model 2

This model is based on the data taken from the Naval Electronics Laboratory Center (NELC) and IIT Research Institute HF link between San Diego and Chicago. The parameters of a three-state model were determined [6]. The transition matrix for the model is given below.

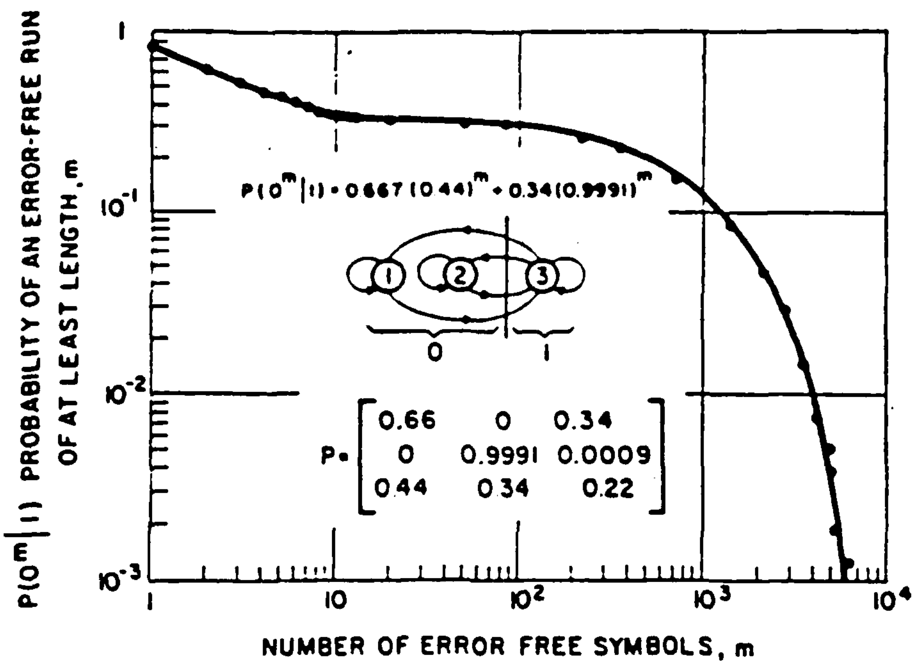


Fig. 4. Gap distribution for the HF channel model 1

$$\begin{bmatrix} .99911 & 0 & .00089 \\ 0 & .73644 & .26356 \\ .36258 & .58510 & .05232 \end{bmatrix}$$

The BER was calculated to be $2.4353 \times 10^{-3}$ and the corresponding measured value was $1.787 \times 10^{-3}$. The gap distribution for this model is shown in Figure 5.

<u>*HF* Channel Model 3</u>

This model is based on the data taken on the same link as the above Model 2 but under different channel conditions. From the data, a four-state model was obtained [7]. The transition matrix for the model is given by

$$\begin{bmatrix} .698 & 0 & 0 & .302 \\ 0 & .9976 & 0 & .0024 \\ 0 & 0 & .99935 & .00065 \\ .639 & .264 & .015 & .082 \end{bmatrix}$$

The calculated value of the BER is $7.34 \times 10^{-3}$ where as the measured value was $7.277 \times 10^{-3}$. The gap distribution is shown in Figure 6.

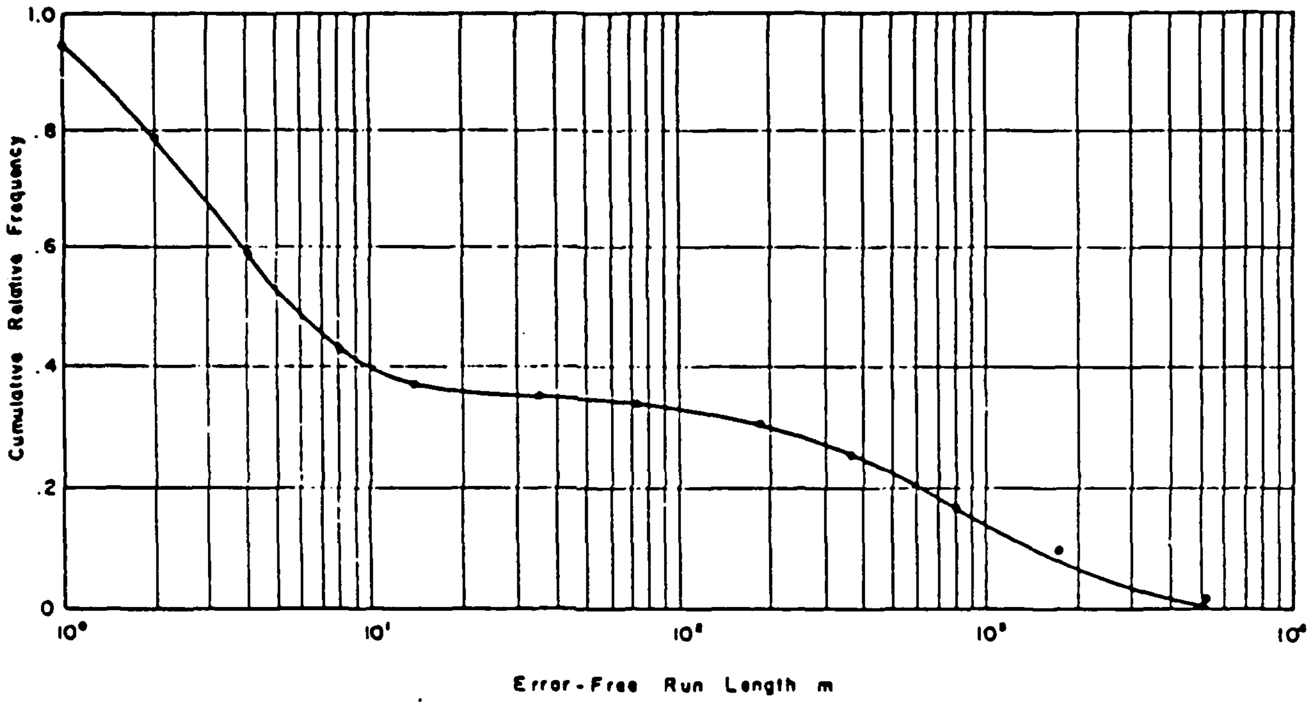


Fig. 5 Gap distribution for the HF channel model 2

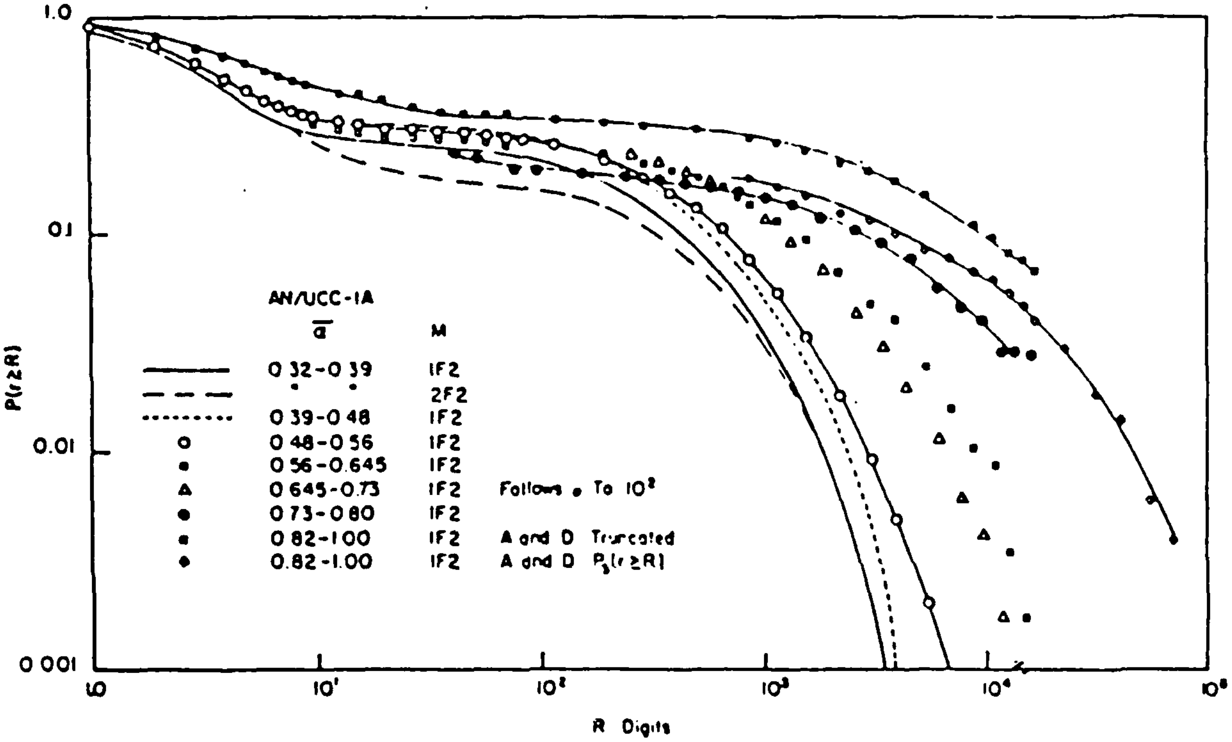


Fig. 6 Gap distribution for the HF channel model 3

## Troposcatter Channel Model 1

This model is based on data collected by the US Army Electronics Command, Fort Monmouth, New Jersey. A four-state model was obtained from this data [8]. The transition matrix is given by

$$\begin{bmatrix} .99959 & 0 & 0 & .00041 \\ 0 & .99634 & 0 & .00366 \\ 0 & 0 & .95802 & .04198 \\ .16632 & .30795 & .48217 & .04356 \end{bmatrix}$$

The measured BER is approximately $10^{-3}$ while the calculated BER is $1.99 \times 10^{-3}$. The gap distribution for the model is given in Figure 7.

## Troposcatter Channel Model 2

This model is based on another run of the error data available from the U.S. Army Electronics Command, Fort Monmouth, New Jersey. Again, a four-state model is used for channel representation [8]. The transition matrix is

$$\begin{bmatrix} .99952 & 0 & 0 & .00048 \\ 0 & .99534 & 0 & .00466 \\ 0 & 0 & .94196 & .05804 \\ .06902 & .25289 & .63308 & .04501 \end{bmatrix}$$

The measured as well as calculated BER are approximately $4.8 \times 10^{-3}$. The gap distribution for the model is provided in Figure 8.

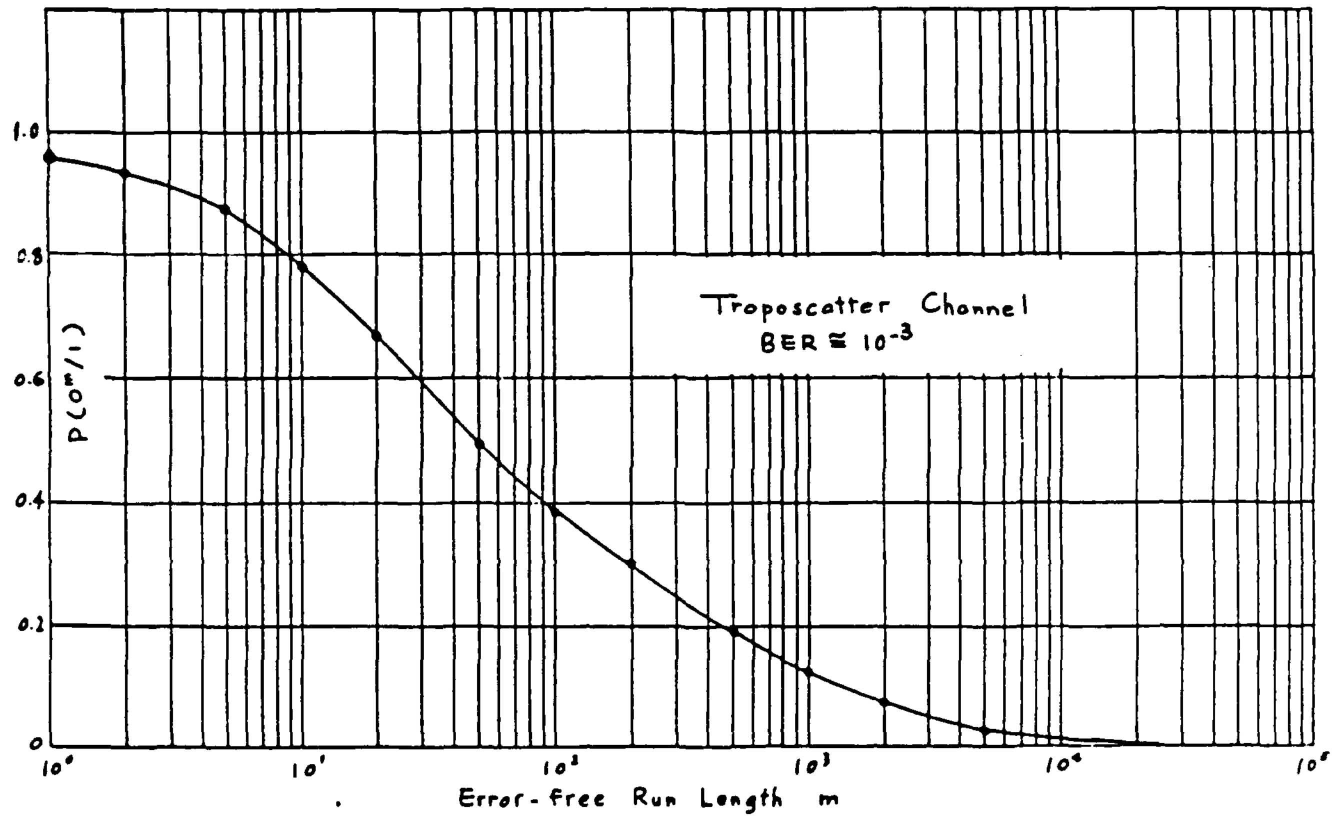


Fig. 7 Gap distribution for the Troposcatter channel model 1

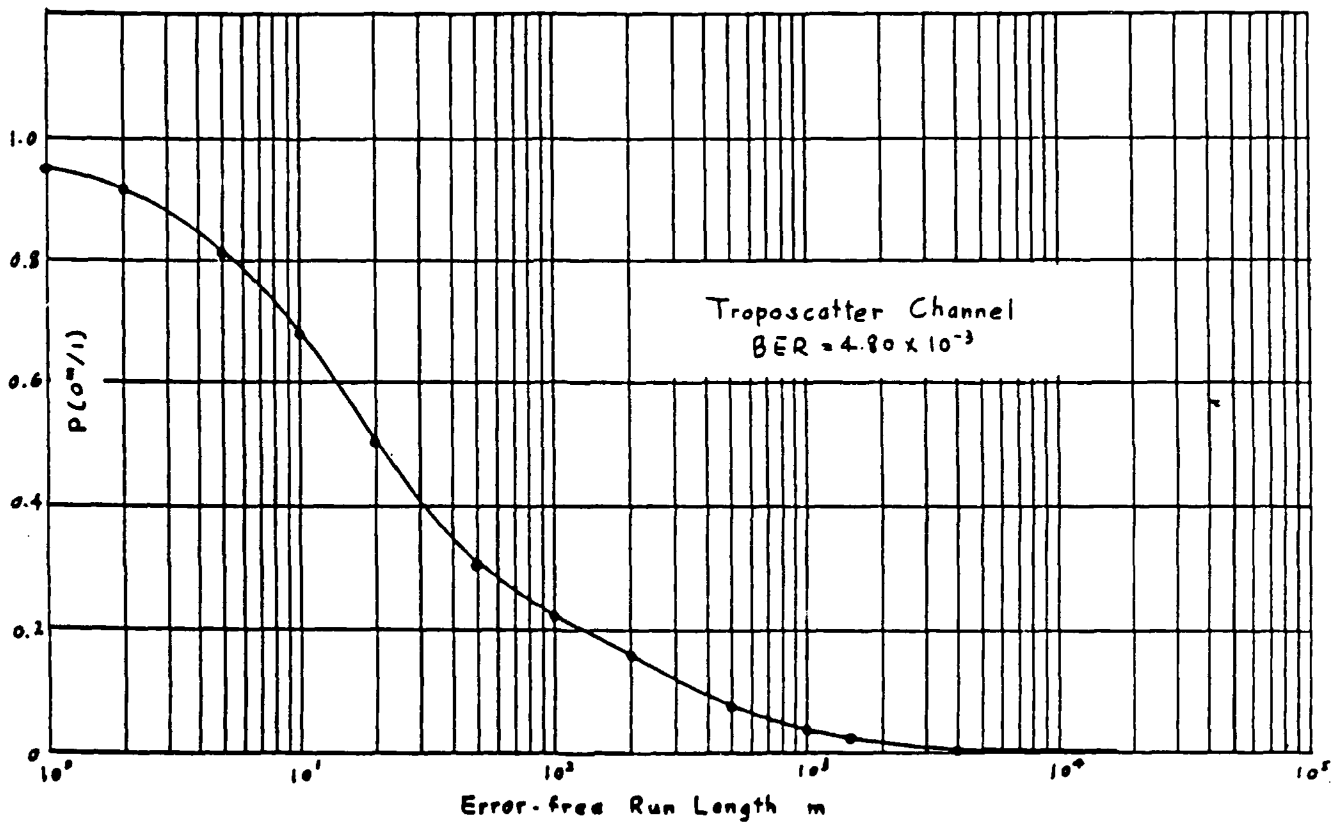


Fig. 8 Gap distribution for the Troposcatter channel model 2

AUTOVON Channel Models 1 and 2

These models are based on error data collected by transmitting telephone calls through the Codex 9600 modem. The phone calls originated at the RADC and proceeded via C-3 conditioned access lines to the Tully, NY AUTOVON switch. From Tully, connections were made to the switches at Pottstown, PA, Arlington, VA, Rockdale, GA and Santa Rosa, CA. For the 4800 b/s AUTOVON data a three-state model was obtained whereas a four-state model was obtained for the 9600 b/s data [9]. The two transition matrices are given below

$$\begin{bmatrix} .9996990 & 0 & .0003010 \\ 0 & .9999974 & .0000026 \\ .3669279 & .0443345 & .5887375 \end{bmatrix}$$

and,

$$\begin{bmatrix} .8656363 & 0 & 0 & .1343637 \\ 0 & .9994334 & 0 & .0005666 \\ 0 & 0 & .9999943 & .0000057 \\ .3668136 & .1796088 & .0640107 & .3895669 \end{bmatrix}$$

The model predicted BER are $5.26 \times 10^{-5}$ and $8.65 \times 10^{-5}$ respectively. The gap distributions are given in Figure 9.

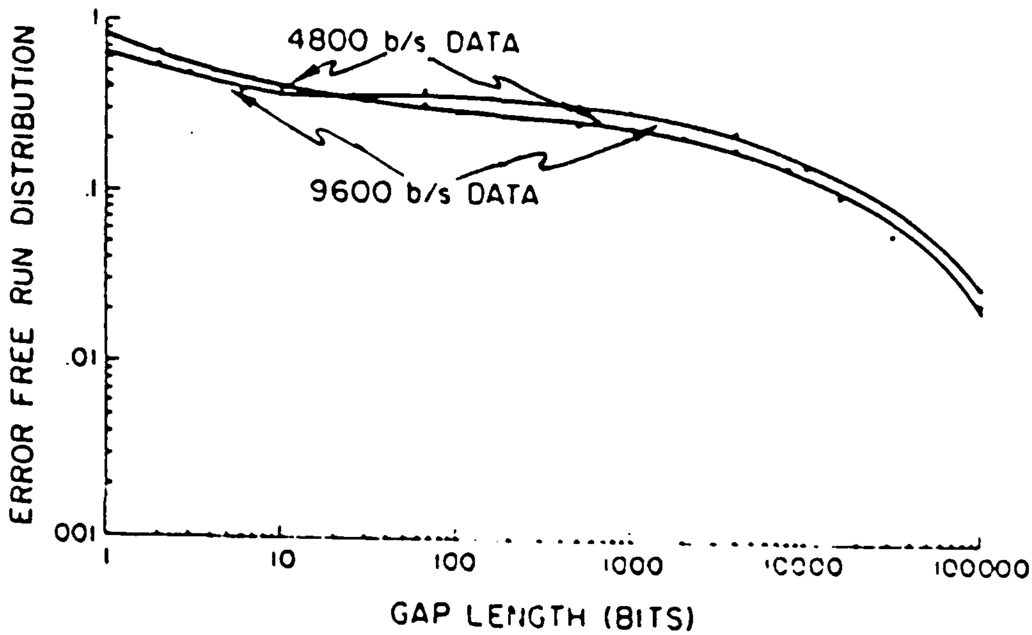


Fig. 9 Gap distribution for the AUTOVON channel

## IV DISCUSSION

In this report, we have discussed channel modeling for the generation of error patterns to conduct experimentation with the ROMENET. These models require the availability of error data to be able to obtain the model parameters. Unfortunately, error data for real channels is not widely available and, therefore, model parameters can only be obtained to a limited extent. Moreover, it appears that error data for channels in the presence of jamming is not even available and, therefore, an accurate model fitting can not be attempted. At this stage, implementation of the error injector unit should be carried out for subsequent demonstration and experimentation with the ROMENET. The channel models described in this report can be used for this task. Further research is needed in the area of channel modeling especially in the presence of jamming.

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