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DIGITAL SCRAMBLING FOR SHUTTLE COMMUNICATION LINKS: DO DRAWBACKS OUTWEIGH ADVANTAGES?[†]

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ABSTRACT

Digital data scrambling has been considered for communication systems using NRZ symbol formats. The purpose is to increase the number of transitions in the data to improve the performance of the symbol synchronizer. This is accomplished without expanding the bandwidth but at the expense of increasing the data bit error rate (BER).

Models for the scramblers/descramblers of practical interest are presented together with the appropriate link model. The effects of scrambling on the performance of coded and uncoded links are studied. The results are illustrated by application to the Tracking and Data Relay Satellite System (TDRSS) links. Conclusions regarding the usefulness of scrambling are also given.

1. INTRODUCTION

In the communication links of the Space Shuttle, as in many other communication systems, data clock timing is extracted from the data transitions in the received signal. When NRZ baseband signaling format is used, long data streams of 0's or 1's may be encountered. This can result in the loss of data clock synchronization.

More than one appraoch may be considered for increasing the data transition density. One approach is using biphase signaling format. This scheme provides frequent data transitions at the expense of increasing the bandwidth by roughly a factor of two over NRZ signaling. Biphase signaling has the same BER performance as NRZ and is used in the Shuttle links when no bandwidth constraint is present.

An alternate approach which does not increase the bandwidth is digital data scrambling [1]. This provides a data transition density close to 50%. In the presence of channel noise, however, scrambling increases the data BER and may degrade the overall system performance.

For both of the above methods, coding may or may not be additionally used to improve the performance of the system. In the following sections we study the effects of scrambling on uncoded and coded communication links. We then attempt to weigh the benefits gained by scrambling against the price that has to be paid to obtain them (in terms of increased signal power to achieve the requried BER performance).

In Sec. 2 we describe the model for a link that employs scrambling. In Sec. 3 we introduce the models for the scramblers and descramblers of interest. We then analyze the effects of scrambling on the link BER performance in Sec 4. In Sec. 5 we illustrate the results of Sec. 4 by applying them to the TDRSS links. Conclusions are presented in Sec. 6.

2. LINK MODEL

Figure 1 depicts the model of a modern communication link employing digital scrambling/descrambling. In the transmitter the data may or may not be convolutionally encoded and interleaved. After scrambling PN-spreading may be introduced. In the channel, the transmitted waveform is corrupted by additive white Gaussian noise of power spectral density level N_0 (one-sided). The received waveform is despread (if applicable), demodulated, matched-filtered, hard-limited, descrambled, and deinterleaved and Viterbi decoded if appropriate.

Since the descrambler creates closely spaced multiple symbol errors from one channel symbol error, an interleaver is placed after the encoder to randomize the placement of symbol errors into the decoder. The hard-limiter after the matched filter is necessary for the operation of the descrambler. The Viterbi decoder therefore must operate on hard-limited symbols, on which its

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performance is poorer than, for example, an 8-level-quantized symbols as frequently used in practice.

3. SCRAMBLER AND DESCRAMBLER MODELS

The scramblers and descramblers of interest here belong to the family of self-synchronizing scramblers/descramblers. They recover from the bit errors introduced by the noise in the channel [1].

Digital scramblers/descramblers achieve two goals both of which improve the performance of the bit synchronizer: (1) they introduce frequent transitions in the channel signal, (2) they increase the period of periodic source sequences (an all-0 or all-1 sequence is periodic with period 1). The scrambler consists of two elements: a "basic scrambler" and an associated "monitoring logic" [1].

The basic scrambler or descrambler is a shift register circuit. It consists of a linear sequential filter with feedback paths for the scrambler and feed-forward paths for the descrambler. The mathematical representation of a scrambler (or descrambler) takes the form of a polynomial. The polynomial $h_m(x) = x^m + c_1 x^{m-1} + \ldots + c_{m-1}x + c_m$ is called the tap polynomial of an m-stage (m delay elements) scrambler. The tap constants for the scramblers considered here are either 1 (presence of a tap) or 0 (its absence). For the successful operation of the scrambler the tap polynomial has to be "primitive" over the binary field [1]. We shall see shortly that for practial purposes this will translate to the few simple but effective realizations shown in Figure 2.

The basic scrambler changes the period of the input, say period of length s, to the least common multiple (LCM) of s and 2^m-1 for all but one of the initial states of the scrambler where it remains s. At this point comes the role of the monitoring logic.

The monitoring logic consists of counters, storage elements and incidental logic. The monitoring logic detects the presence of the output data sequence that has period s and adds a '1' at intervals to break that periodicity [1]. The minimum output period then becomes LCM(s,2^m-1).

There are two main considerations in the choice of the number of stages and taps in the basic scrambler. First, a suitable choice for m gives 2^m-1 which is prime. The minimum output period would then be $s(2^m-1)$ for an output of period s. Second, since it is generally true that on the average the descrambler multiplies the channel errors at its input by w(h), where w(h) is the number of non-zero terms in the tap polynomial [1], it is important to use the minimum number of taps possible. Moreover, since this minimum number increases for larger values of m [2], it becomes necessary to use a scrambler with a smaller number of stages.

From the tables of primitive polynomials [2] we find that the scramblers that meet the above requirements correspond to the polynomials

$$h_3(x) = x^3 + x^2 + 1 \qquad (1)$$

and

$$h_5(x) = x^5 + x^3 + 1 \qquad (2)$$

or their reciprocals (over the binary field). The reciprocals are $h_3'(x) = x^3 + x + 1$ and $h_5'(x) = x^5 + x^2 + 1$ respectively. The basic scramblers and descramblers corresponding to (1) and (2) are shown in Figure 2. The alternate center taps which correspond to the realization of the reciprocal polynomials are shown dotted.

The 3- and 5-stage scramblers presented herein have values of 2^m-1 equal to 7 and 31, respectively, which are prime yielding good performance with periodic inputs. These scramblers are also the only 3- and 5-stage realizations with the minimum number of taps possible.

4. EFFECT OF SCRAMBLING ON LINK BER

In what follows we associate the term bit error rate (BER) with the output of the decoder, and use symbol error rate (SER) with the error rate at the input or output of the descramblers. For uncoded links BER and SER are equivalent.

4.1 Calculation of SER at Descrambler Output

Here we describe how an SER at descrambler input is mapped into an SER at descrambler output. We first concentrate on the basic descrambler then discuss the impact of the monitoring logic.

For an m-stage basic descrambler the states at m+1 points in the descramblers are significant in evaluating the output SER. For the 3-stage descrambler these are indicated in Figure 2 by $s_i,\ldots,s_{i-3}$. Only those states which have a connection to the output can actually cause an output symbol to be in error. The approach to obtain the output probability of symbol error is to examine all possible symbol patterns occupying $s_i,\ldots,s_{i-3}$ and determine if each pattern causes an output error. We then add the probabilities of occurrence of the patterns that lead to an output error. After examining $2^4 = 16$ patterns we have at the output of the 3-stage basic descrambler (for both of the possible realizations)

$$\mathrm{SER} = 3(1-p)^3p+3(1-p)^2p^2+(1-p)p^3+p^4 \tag{3}$$

where p is the input SER. Similarly we have at the output of the 5-stage descrambler (both realizations)

$$\mathrm{SER} = 3(1-p)^5+9(1-p)^4p^2 + 10(1-p)^3p^3+6(1-p)^2 p^4+3(1-p)p^5+p^6 \tag{4}$$

Equations (3) and (4) can be simplified by expanding the different terms. After simplification we find that the two equations yield the expression

$$\mathrm{SER} = 3p - 6p^2 + 4p^3 \tag{5}$$

Equation (5) describes how the SER at the input of a 3- or 5-stage descrambler is translated into an SER at its output. It is interesting to note that at small value of input SER, the basic descrambler produces 3 output errors per input error, and 3 is the number of non-zero coefficients in the 3- and 5-stage descramblers used.

Now, how is the output SER of the basic descrambler affected by the monitoring logic? It has been shown [1] that for relatively infrequent channel errors, say for SER less than one over a few multiples of the number of stages, the monitoring logic has negligible effect on the SER at the output of the basic descrambler. For higher levels of input SER (closer to 0.5) the output of the basic descrambler tends to become completely garbled (output SER very close of 0.5). The effect of the monitoring logic in that case is of no significance.

In Figure 3 we illustrate the effects of scrambling and subsequent descrambling on BER = SER for an uncoded link. Carrier and clock recovery are assumed perfect and for an unscrambled link the BER characteristics are given by 0.5 erfc($\sqrt{E_b/N_0}$). The required increase in E_b/N_0 to offset the effect of scrambling depends on the desired BER performance. Typically, for BER = 10^{-5} the required increase in E_b/N_0 is 0.5 dB. The degradation due to scrambling when other degradation sources are present in an actual system are discussed in Sec. 5.

4.2 Calculation of Coded BER

For the coded case the results are quite different. We first assume that the channel is Gaussian and that in the absence of scrambling the Viterbi decoder would work on an 8-level-quantized symbol at the output of the matched filter. The results of simulation reveal that the BER at the decoder output is strongly affected by the presence of scrambling/descrambing (and the necessary hard-limiting). This is seen in Figure 4 where a rate 1/2 constraint length 7 code has been used.

There are two components that contribute to the significant degradation of BER performance of the coded link. There is an effective loss of 2.2 dB in E_b/N_0 due to the necessary hard-limiting (as opposed to operation on 8-level-quantized signal) [3]. There is also the degradation due to the increase in the SER at the input of the decoder due to the descrambler. To understand the contribution of each of these factors, we have drawn in Figure 4 a hypothetical curve that depicts a situation where hard-limiting is used on an unscrambled link. This curve (curve c in Figure 4) is separated by 2 dB from curve a. The difference between curves c and b is due to the descrambler. This difference is largest (up to 2.5 dB) at smaller values of E_b/N_0. In that region, the Viterbi decoder is very sensitive to any increase in SER at its input. As E_b/N_0 increases beyond 6 dB, the symbol errors at the decoder input become infrequent. As a result, the degradation in its output BER due to the increase in its input SER becomes less noticeable. At a typical 10^{-5} BER the degradation in E_b/N_0 due to scrambling is 3.7 dB. The degradation in the performance of the coded links of an actual system, where other sources of performance degradation are present, is discussed in the following section.

5. EXAMPLE: APPLICATION OF SCRAMBLING TO TDRSS LINKS

The model of a typical TDRSS return link follows closely the general link model presented in Figure 1. We shall discuss here the case where no radio frequency interference (RFI) disturbs the link.

Figures 5 and 6 show the results of simulation for the link using the simulation package LinCsim developed by LinCom Corporation for the NASA Goddard Space Flight Center. The results for a typical uncoded and coded return links of the single access S-band service (SSA) are shown in Figures 5 and 6 respectively. The results given reflect the presence of actual system disturbances such as imperfect carrier and clock recovery, and different signal distortions like gain and phase imbalance and data asymmetry etc. [4]. The figures give the BER performance as a functin of delta uplink (user satellite to TDRS) CNR for BPSK at the maximum rate of 12 M symbols/sec. In each curve the nominal CNR is the CNR that yields the design BER of 10^{-5}. Each figure shows three curves: (a) unscrambled link and 50% data transition density, (b) unscrambled and 10% data transition density, (c) scrambled (hence 50% transition density) link. In obtaining these curves the effects of the other system disturbances have been appropriately averaged out [5]. For both figures the BER performance degrades as we go from curve a to b to c. In the uncoded case the degradation of 10^{-5} BER in the scrambled case exceeds the degradation in the unscrambled case with 10% transition density by 3.2 dB.

The above results are in close agreement with the general results of Sec. 4. It is worth noting, however, that in the TDRSS the rms timing error of the symbol synchronizer at 10% transition density is less than 1% of the symbol duration at the values of E_b/N_0 of interest [5]. This explains the relatively small degradation between curves a and b in Figures 5 and 6. It should be noted also that the curves of Figure 5 should not be compared to the curves of Figure 6. This is because of the differences in the nominal CNR's and averaging techniques used [5].

6. CONCLUSIONS

We have seen from Secs. 4 and 5 that the major drawback of digital data scrambling is the degradation in the overall BER performance of the communication link. This degradation is quite significant for coded links.

If the symbol synchronizer is capable of operating at most of the reduced data transition densities encountered (without a large degradation in the overall BER and bit slip rate) then scrambling should not be used. If we cannot make this assertion, perhaps because of the possibility of very low transition densities, then for uncoded links 0.5 dB is a very reasonable price to pay for stable symbol synchronization. For coded links, on the other hand, the large degradation in BER due to scrambling suggests that we rephrase the problem. Should we improve symbol synchronization by scrambling at a price of about 3.5 dB, or by simply raising the SNR by a comparable amount? The answer to this question depends on the required BER performance and the characteristics of the particular symbol synchronizer at hand. It is apparent, though, that scrambling is not well suited for coded links.

ACKNOWLEDGEMENT

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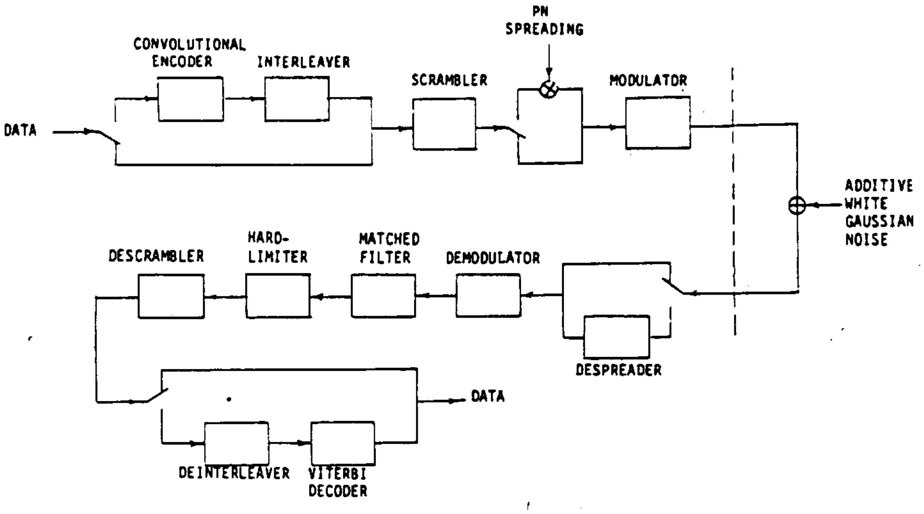

Figure 1. LINK MODEL.

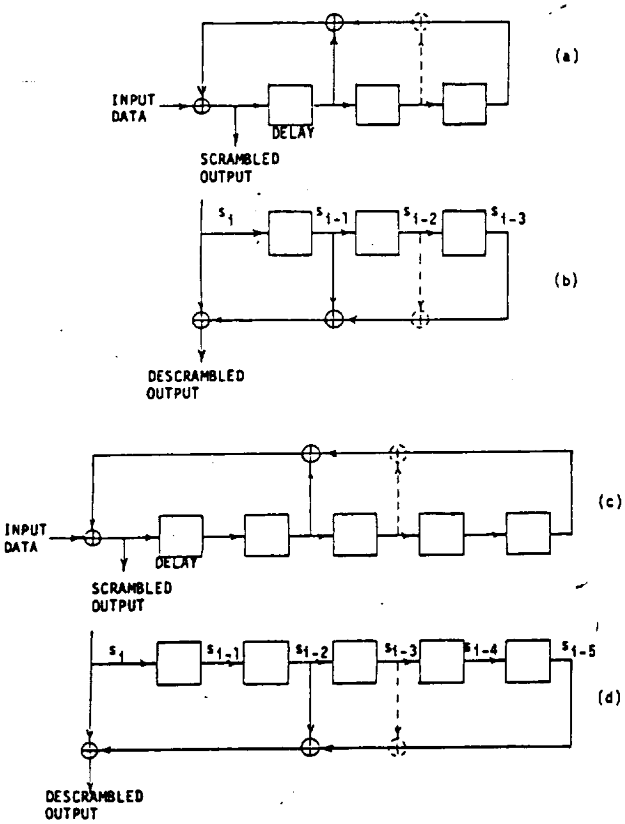

Figure 2. THREE AND FIVE STAGE SCRAMBLERS AND DESCRAMBLERS WITH MINIMUM NUMBER OF TAPS. (A) 3-STAGE SCRAMBLER; (B) CORRESPONDING DESCRAMBLER, (C) 5-STAGE SCRAMBLER; (D) CORRESPONDING DESCRAMBLER (SHOWN DOTTED ARE ALTERNATIVE CENTER TAPS FOR ALTERNATIVE REALIZATIONS.)

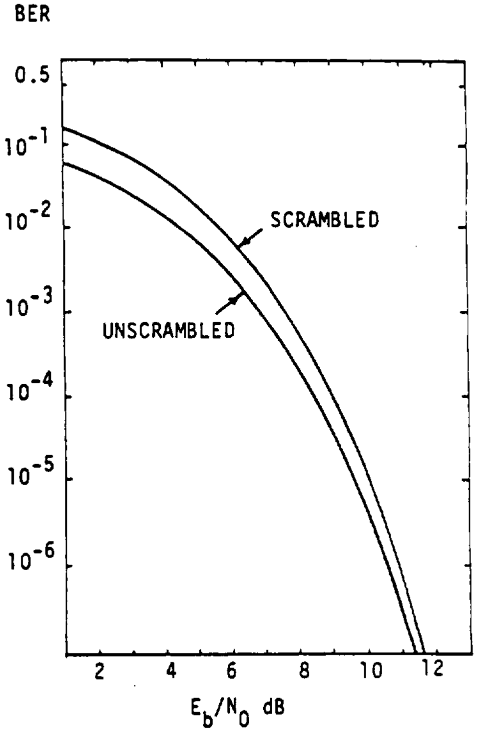

Figure 3. COMPARISON OF BER AS A FUNCTION OF E_b/N_0 IN SCRAMBLED AND UNSCRAMBLED CASES--UNCODED LINK; PERFECT CARRIER AND CLOCK RECOVERY.

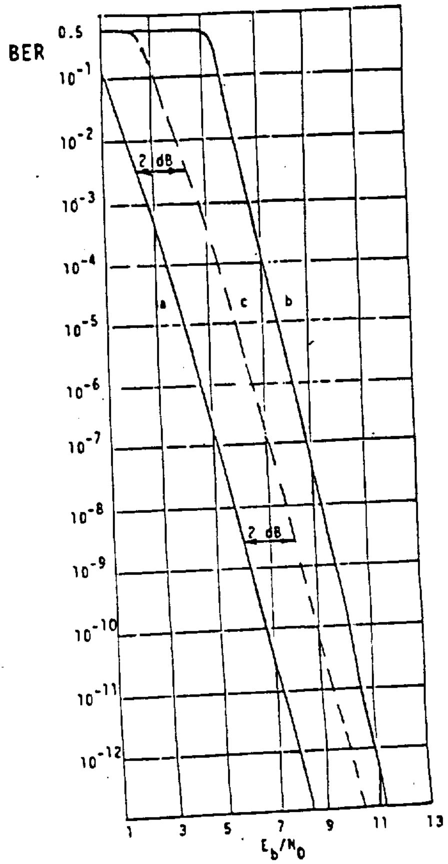

Figure 4. COMPARISON OF BER AS A FUNCTION OF E_b/N_0 FOR SCRAMBLED AND UNSCRAMBLED CASES--RATE 1/2, CONSTRAINT LENGTH 7 CODING; PERFECT CARRIER AND CLOCK RECOVERY.
CURVE A: UNSCRAMBLED
B: SCRAMBLED (AND HARD-LIMITED)
C: UNSCRAMBLED BUT HARD-LIMITED

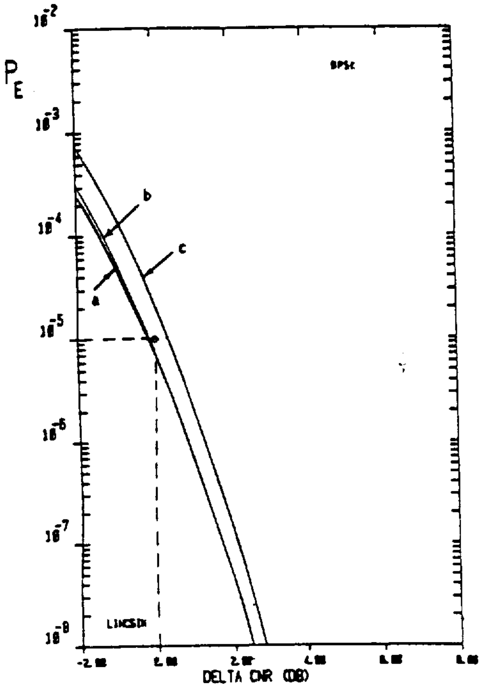

Figure 5. BER PERFORMANCE FOR A TYPICAL UNCODED TDRSS RETURN LINK. (A) UNSCRAMBLED, 50% TRANSITION DENSITY; (B) UNSCRAMBLED, 10% TRANSITION DENSITY; (C) SCRAMBLED.

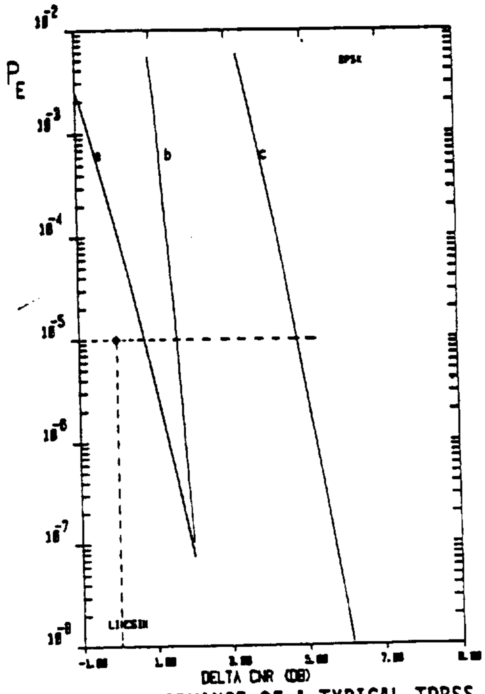

Figure 6. BER PERFORMANCE OF A TYPICAL TDRSS LINK CODED AT RATE 1/3 (CONSTRAINT LENGTH 7). (A) UNSCRAMBLED, 50% TRANSITION DENSITY; (B) UNSCRAMBLED, 10% TRANSITION DENSITY; (C) SCRAMBLED.