ERROR BEHAVIOUR IN HIGH SPEED CHANNEL LINKS

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Abstract: *Channel coding is a standard method of improving a system's energy efficiency in digital communications; its practice does not extend to high-speed links. Increasing demands in network speeds are placing a large burden on the energy efficiency of high-speed links and render the benefit of channel coding for these systems a timely subject. The low error rates of interest and the presence of residual inter symbol interference (ISI) caused by hardware constraints impede the analysis and simulation of coded high-speed links. This framework provides a deeper insight into joint error behaviors in high-speed links, extends the range of statistical simulation for coded high-speed links. Finally, based on the performance of standard binary forward error correction and error detection schemes is evaluated, from which recommendations on coding for high-speed links are derived. The work presented serves as the foundation for future investigations in the use of ECC in these systems. Scaling of integrated circuit technology has continually increased the data processing capabilities of integrated circuits in these systems. The work described in these is shows that it may be possible to use coding techniques to share the burden of combating errors, while increasing the throughput of the link or improving its energy-efficiency. An experimental setup was created for characterization of link channel properties and performance gains from different codes. Four codes, specifically Hamming, BCH, Fire, and SEC-DED codes, are implemented and analyzed with various configurations (i.e. different block sizes, data rates, and detection or correction). Most significantly, it is discovered that detection and retransmission of even the simple codes implemented in this project.*

Keywords: *Communication systems, integrated circuit inter-connections, intersymbol interference (ISI).*

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1. INTRODUCTION

Practice of constraining the data stream in order to mitigate the effects of the communication channel on the received signal, commonly referred to as channel coding, is a fundamental technique in digital communications that is responsible for some of the most dramatic improvements in the modern communication standards. while channel coding is employed in most of today's communication systems, both wireless and wire line, in order to improve on the speed/reliability/energy efficiency of the system, the technique remains unexploited in a ubiquitous class of communication systems, namely the high-speed backplane and chip-to-chip interconnects. The increasing network speeds place a large burden on high-speed links, which fail to keep up with the scaling trends. The underlying problem is the bandwidth-limited nature of the backplane communication channel, exacerbated by severe complexity and power constraints. Despite several recent efforts the topic of channel coding for high-speed links remains largely unexplored due to a lack of suitable analysis and simulation frameworks. The residual inter-symbol interference (ISI), coupled with noise and other circuit impairments, significantly obscures the performance picture and renders both the theoretical and computational approaches more arduous. The problem of estimating the performance of a coded high-speed link is further exacerbated by the low error rates of interest. We apply the analysis and techniques used in communication system design to the unique problems posed by the high-speed, channel-limited link design. By analyse the specific properties of the high-speed link system. There is a constant struggle to keep up with the increasing demands in various applications requiring high-speed chip-to-chip interconnects, such as network routers and processor-memory interfaces. To increase data rates while maintaining reliability, new advances must be made in the techniques used for data transmissions. Modeling the high-speed link as a system with additive white noise and ISI, as makes it possible to describe the error correlation in terms of two fundamental quantities: the systems error region and the channel's sign signature. The error region corresponds to the set of values in the ISI distribution that are responsible for the majority of errors. While the error region is determined by the combined noise and the magnitude of the coefficients forming the channel's pulse response, the channel signature is specified by the signs of those coefficients. The analysis shows how these quantities conceptually decouple the complex problem of accounting for the effect of a real-valued channel on error behaviour and provide a missing insight into error correlation in a high-speed link. While current statistical simulation techniques for high-speed links ignore error correlation between symbols, shows that a direct extension of the independent-errors approximation improves the estimate's accuracy by up to five orders of magnitude for the error rates of interest. The approach exploits the physical properties of high-speed links, particularly the nature of the ISI, which limits the range of the error correlation. It relies on accurately capturing the short-term error correlation within no overlapping blocks of symbols and assumes independence. This model has proved helpful for modeling and analysing behaviours of communications circuits. However, as data rates increase, the effects of noise need to be taken into account.

2. REVIEW OF SYSTEM MODEL

A simplified model of a high-speed link is shown in Figure 1. The bit stream, which can be coded or uncoded (unconstrained), is modulated to produce the equivalent symbol stream and transmitted over a communication channel. The system employs PAM2 modulation with detection performed on a symbol-by-symbol basis with the decision threshold at the origin. The transmitter and receiver may contain equalizers, in which case the channel's impulse response may contain residual ISI. The two main mechanisms that account for the most significant portion of the residual ISI in high-speed links are dispersion and reflection. In addition, residual interference may also include co-channel interference, caused, for instance, by electro-magnetic coupling. As accounting for co-channel interference involves the same set of mathematical tools as accounting for the ISI, the remainder of the paper focuses on the effects of the ISI. The quantity of interest is the received signal at the input to the decision circuit at time, denoted and expressed as

$$Y_i = Z_i + N_i \qquad (1)$$

Where denotes the received signal in the absence of noise and is the noise term. Specifically, denoting the channel's pulse response by, where represents the length of the pulse response and is associated with the principal signal component, and letting denote a sequence of transmitted symbols, then

$$Z_i = \sum_{j=-k}^{m} X_{i-j}\ h_j \qquad (2)$$

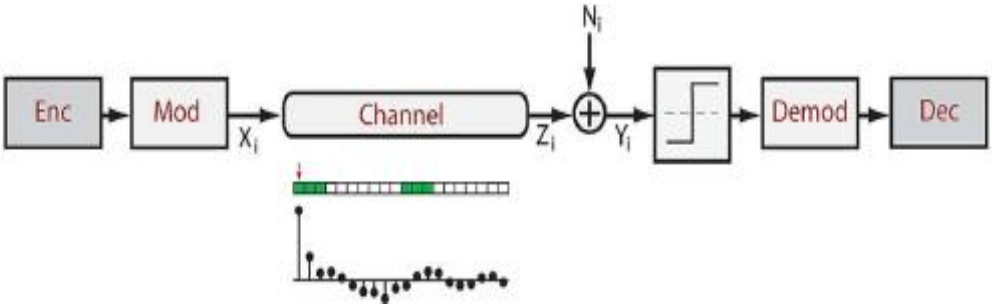


Figure 1: Simplified model of a high-speed link. Transmit / receive equalization is reflected on the symbol-spaced pulse response.

3. ERROR BEHAVIOR IN SYSTEMS WITH NOISE AND ISI

In the system of Figure 2 an error at the receiver occurs if the noise and ISI couple to bring the received signal over the decision threshold. It follows that the marginal symbol error probability for the symbol is given by

$$p_i = P\left(\{Y_i < 0 \mid X_i = 1\} \cup \{Y_i > 0 \mid X_i = -1\}\right) \quad (3)$$

Assuming an unconstrained symbol stream, the marginal symbol error probabilities are equal that is for all symbols. The quantity, which becomes the relevant figure of merit, is entirely determined by two factors, namely the channel pulse response, and the probability distribution of the noise. Efficient methods of computing the marginal error probability are described in among others. In a coded system with ISI, this picture changes in two important ways. Due to constraints on the symbol stream, the marginal error probabilities are no longer equal across different symbols. An efficient method of computing for different symbol locations in a codeword is described in which focuses on systematic binary linear block codes. However, the performance of a coded system cannot be expressed through marginal error statistics alone, but is instead dependent on the joint error behaviour. For instance, the performance of a -error correcting linear block code is typically expressed through the word error rate (WER), given by the probability of observing at least errors in a codeword. The following development shows that the complex relation between the ISI and the joint error behaviour can be greatly elucidated by decoupling the effects of the magnitude and the signs of the channel's pulse response. Understanding the effect of system's *error region* and channel's *sign signature* on error correlation lends a deeper insight into the behaviour of codes and the shortcomings of common simulation techniques in high-speed links. Further, an analysis of *correlation distance* in high-speed links paves the way for a more reliable simulation approach.

Error Correlation in High-Speed Links

In practical channels, the direct link between the channel signature, error region and joint error behaviour holds only asymptotically. For instance, in the worst-case-dominant conditions, the problem reduces to the nesting properties of, while in the limit of large noise, the effect of any channel correlation vanishes as errors become independent. However, both the channel signature and the error region play an important role in determining the joint error statistics. An illustration of the effect of channel signature on error correlation in a realistic high-speed link is shown in Figs. The communication channel of Figure 2 is a standard 802.3ap B32 channel operating at 10 Gb/s. Single tap decision-feedback and three-tap zero forcing equalizers are used, yielding an error rate of. The channels of Figure 2 are obtained by altering the signature of the original channel, which preserves the marginal error behaviour, but alters the joint error statistics. Margining by 36 mV widens the error region, thus increasing the error rate to and rendering the higher-order error events observable through Monte Carlo simulation. The resulting joint error statistics are shown in for a block of ten consecutive symbols.

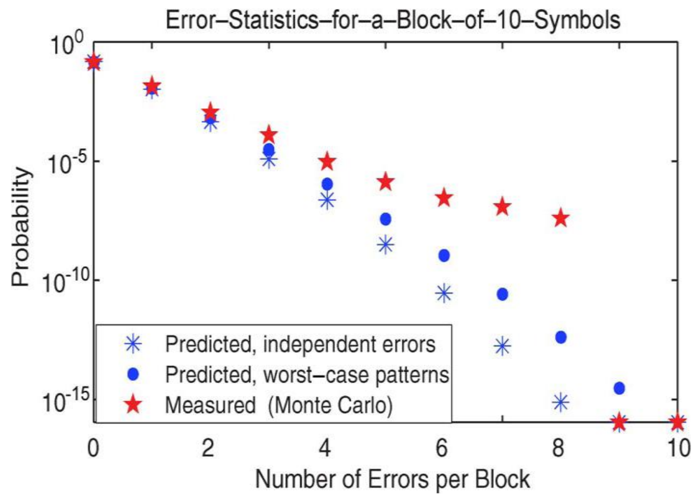


Figure 2: Error statistics for channel

In particular, it is interesting to consider the benefit of focusing on the *largest* interference coefficients so that the error hinges on the occurrence of the resulting worst-case ISI. The relevant error region becomes associated with the worst-case ISI computed relative to the largest interference coefficients, and includes any amount of deviation caused by the remainder of the channel's pulse response. Identifying the worst-case-dominant conditions in a high-speed link is primarily useful from the standpoint of pattern elimination, that is, the use of code constraints to prohibit error-causing symbol patterns in a high speed link. This idea is further explored. The worst-case dominant conditions are, however, of limited use in improving the performance estimation of high-speed links. In particular, while accurately accounting for the effect of the worst-case ISI on joint error behaviour is computationally tractable, the error correlation due to secondary. Unlike the maximally-correlated channel (Channel B), the original channel (Channel A) does not nest in the sense described in the previous section, neither considering the worst case patterns formed by the entire channel pulse response, nor those formed by the dominant interference coefficients only. However, both channels show a significant increase in the frequency of the higher-order error events compared to the independent- errors assumption. This behaviour is analogous to the example of Figure 2 and is due to the size of the error region, which is made sufficiently large to generate Monte Carlo estimates. Due to the limitations of the Monte Carlo method, it is difficult to infer the degree and type of error correlation associated with the randomly generated signature (Channel C). The presence of a handful of strong interference coefficients in the previous example is due to the dispersive nature of the high-speed link channel and the presence of signal reflections. In general, the pulse response of a typical high-speed link can contain several clusters of strong interference coefficients, separated by coefficients of significantly weaker magnitudes. This suggests that a viable method of deriving intuition about the error behaviour from the channel pulse response consists of considering the error correlation caused by these dominant interference coefficients separately.

4. MODULE EXPLANATION

Module 1

Designing the system model, in that we are simulating the channel impulse model, along with corresponding inter symbol interference distribution A simplified model of a high-speed link is shown in paper here, the bit stream, which can be coded or uncoded (unconstrained), is modulated to produce the equivalent symbol stream and transmitted over a communication channel. The system employs PAM2 modulation with detection performed on a symbol-by-symbol basis with the decision threshold at the origin. The transmitter and receiver may contain equalizers, in which case the channel's impulse response may contain residual ISI. The two main mechanisms that account for the most significant portion of the residual ISI in high-speed links are dispersion and reflection. In addition, residual interference may also include co-channel interference, caused, for instance, by electro-magnetic coupling (crosstalk). As accounting for co-channel interference involves the same set of mathematical tools as accounting for the ISI, the remainder of the paper focuses on the effects of the ISI. The quantity of interest is the received signal at the input to the decision circuit at time, denoted and Yi expressed as

$$Y_i = Z_i + N_i$$

Z_i → denotes the received signal in the absence of noise

N_i → denotes the noise term

In a coded system with ISI, this picture changes in two important ways. Due to constraints on the symbol stream, the marginal error probabilities are no longer equal across different symbols. An efficient method of computing for different symbol locations in a codeword is described in, which focuses on systematic binary linear block codes. However, the performance of a coded system cannot be expressed through marginal error statistics alone, but is instead dependent on the joint error behaviour. For instance, the performance of a -error correcting linear block code is typically expressed through the word error rate (WER), given by the probability of observing at least(t+1) errors in a codeword. The following development shows that the complex relation between the ISI and the joint error behaviour can be greatly elucidated y decoupling the effects of the magnitude and the signs f the channel's pulse response. Understanding the effect of system's error region and channel's sign signature on error correlation ends a deeper insight into the behaviour of codes and the shortcomings of common simulation techniques in high-speed links. Further, an analysis of correlation distance in high-speed inks paves the way for a more reliable simulation approach

Module 2

Generating equalized pulse response for various channels named as Channel A, channel B. To illustrate the effect of extending the error region beyond the worst-case ISI, consider the equal-magnitude, all-positive channel. The corresponding worst-case sequence, given by p=1 1 1 1 1 1 cannot be nested, implying that it is impossible for two symbols to both be affected by the worst-case ISI unless separated by at least l-1 symbols Suppose that for some sufficiently large , , where happens to be such that only the worst-case ISI causes significant error, as illustrated. Compared to the assumptions that the ISI affects distinct symbols independently, the higher-order error events become significantly less likely. Consider next the case where the system parameters (e.g. noise, threshold margin) are changed so that, where as shown in above figure. By allowing the error-prone sequences to deviate from by one symbol, it becomes possible to nest two error-prone sequences.

5. STATISTICAL SIMULATION FOR CODED HIGH-SPEED LINKS

For an arbitrary system with ISI, fully specifying the joint error probabilities for all symbols in a codeword is computationally intractable due to the size of the resulting state space. The same holds even if the code constraints on the symbol stream are ignored and the codeword is replaced by a block of consecutive, independently transmitted symbols. For this reason, it is common practice to account for the ISI only through marginal error statistics while discounting its effect on error correlation.

However, considering error events on distinct symbols to be independent frequently yields large inaccuracies in the performance estimate, as demonstrated in the previous sections. Rather than ignoring the error correlation altogether, accounting for short-term correlation within a codeword is both computationally tractable and yields superior performance estimates. A simple statistical method of estimating the effect of short term error correlation is described below. The method also provides direct means of trading off computational requirements for accuracy and enables computationally tractable code-space explorations. A set of numerical examples illustrates the proposed simulation approach and completes the previous discussion of the effect of error region and channel signature on error correlation. The results point to the inadequacy of biased Monte Carlo techniques in accurate high-speed link simulation. In particular, it is shown that the joint error behaviour of a specific high-speed link channel at high error rates need not be indicative of its behaviour at low error rates. Thus, without an adequate method of “unbiasing” the performance estimate, biased Monte Carlo techniques should not be used for the accurate simulation of coded high-speed links.

Proposed Simulation Method

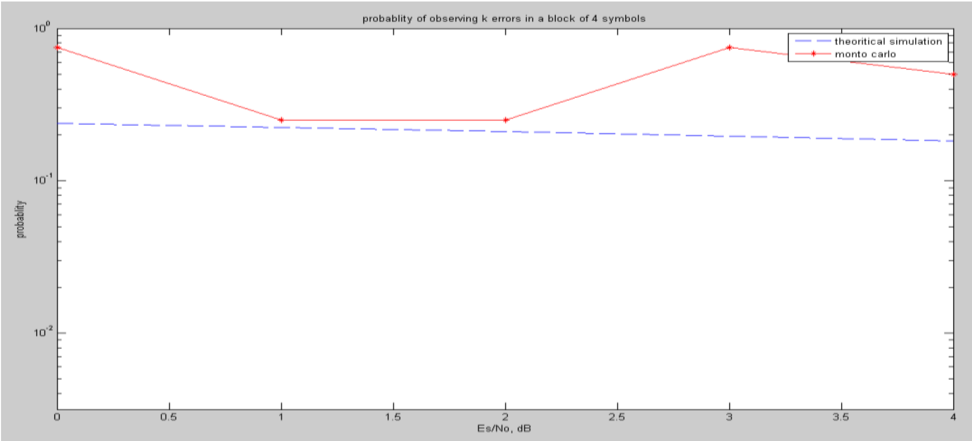
Based on the physical properties of high-speed links, the previous section develops the motivation for focusing on short-term error correlation in simulation of coded high-speed links. While the independent-errors assumption is by default incapable of capturing any error correlation, the following simple extension provides means of capturing varying degrees of short-term error correlation and thus drastically improves the accuracy of the joint error estimates. The approach consists of subdividing a codeword into non-overlapping blocks of consecutive symbols, accurately computing the error statistics for each block, and combining the results assuming the errors across distinct blocks to be independent. Effectively, this replaces the "independent errors" approximation by the "independent blocks" approximation. Although transmitted symbols in separate blocks need not be independent in a coded symbol stream, as the blocks form parts of a larger codeword, shows that it is relatively difficult for a code to achieve consistent pattern-eliminating properties. It follows that the underlying symbol constraints in a coded system likely have little direct effect on the marginal and joint error statistics prior to decoding.8 However, more significant inaccuracies may arise from the error behaviour at the boundaries between blocks, as at least one symbol in each block is affected by the ISI from the preceding blocks. The quality of this approximation for a given codeword length improves with a decreasing number of blocks, which yields a direct method of trading off computing speed for accuracy. To accurately compute the joint error statistics in each block, it is convenient to shorten the channel pulse response by removing the portion of the response tail that creates negligible error correlation. The effect of the tail ISI is treated as mean-distortion and added to the noise term. Based on the above approximations, the performance of a coded high-speed link is estimated as follows. Subdivide the codeword of length into blocks of lengths, where the number of blocks and the corresponding block lengths are chosen based on implementation convenience. For each of the blocks, the error statistics can be accurately computed by considering the possible symbol patterns that affect the corresponding received symbols. Specifically, for the block, it suffices to enumerate all possible symbol patterns of length, where denotes the length of the shortened channel's pulse response, and compute the ISI affecting each symbol in the block. For an uncoded symbol stream, the number of underlying symbol patterns equals

Then, the probability of observing errors in the block, denoted by, is computed considering the possible error patterns and taking into account the noise. Given the partial error statistics for all and, it remains to compute, that is, the total probability of observing errors in a codeword of symbols where This is achieved by considering all compositions of into parts, that is, the possible vectors, where and The number of possible compositions is given by and the corresponding probability is given by

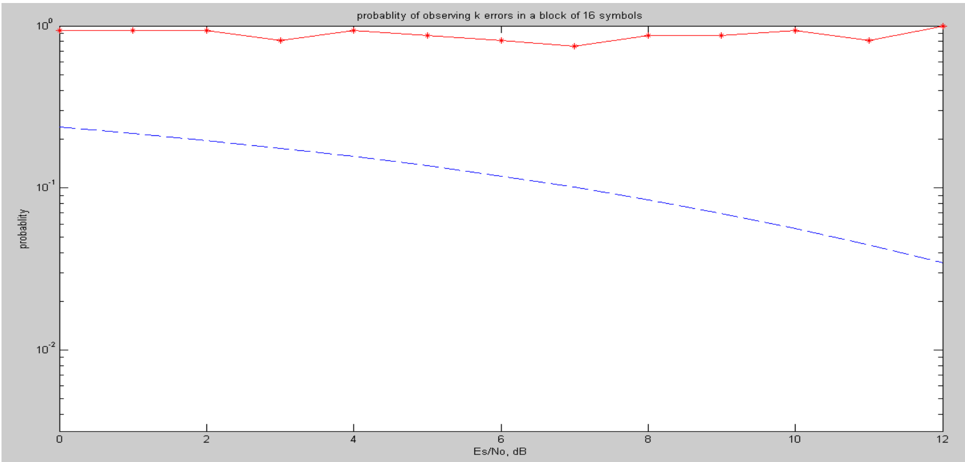
$p_m = \sum_{\substack{all\ compositions \\ (m_1,......m_k)}} p^{\sim(1)}(m_1)p^{\sim(2)}(m_2)......p^{\sim(k)}(m_k)$ in addition, if the error statistics are equal across the blocks, which occurs if and the symbol stream is considered to be unconstrained, the ordering among the blocks does not need to be considered. The problem therefore reduces to dealing with a partition of into integers. Finally, given the codeword error statistics , the performance of a -error-correcting code, for example, is given by For the high-speed link channel of letting yields the block error statistics of for blocks of[top] and [bottom] symbols. As expected, the results match closely the statistics captured through Monte Carlo simulation. Applying the proposed simulation technique to a codeword of symbols and discounting the code constraints results in performance estimates. At error rates of interest, the estimates based on block sizes of n=4,6,8,10 and symbols yield improvements of four and six orders of magnitude, respectively, over the independent-errors approximation. Though both estimates still fall short of capturing the full extent of error correlation for a system operating under these conditions, the proposed estimation method provides a simple and powerful alternative to the independent-errors approximation. Finally, for practical codeword lengths, the computational complexity of the above method is determined by the shortened channel length, as the number of possible symbol patterns of length is typically large. Based on the block size, the runtime for the previous example is on the order of one minute on a 1.8 GHz processor with 2 GB of memory, for codeword lengths of up to 100 symbols. Pre computing the block-wise statistics further reduces the runtime and allows for the use of larger blocks in systematic code-space explorations.

6. SIMULATION RESULTS

Analyzing the error statistics for 4 symbols



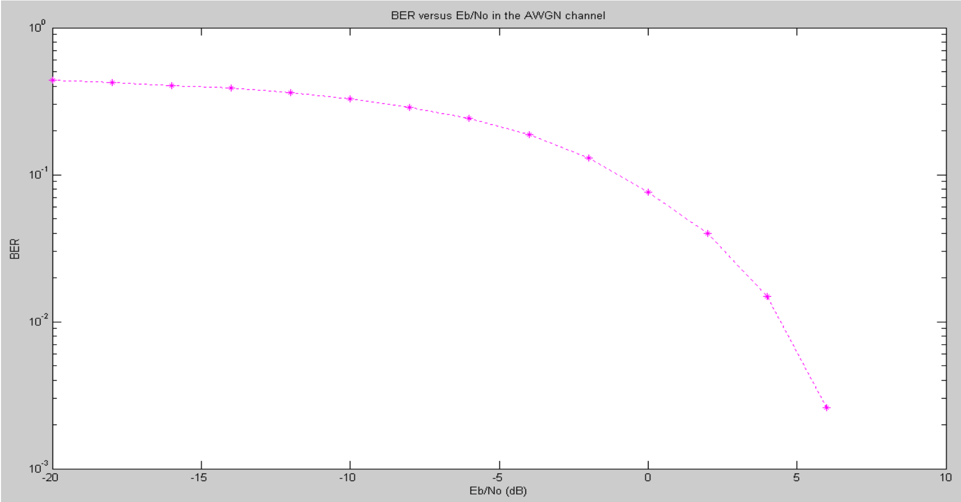
Analyzing the error statistics for 16 symbols



Hamming

The ECC functions described in this application note are made possible by Hamming code, a relatively simple yet powerful ECC code. It involves transmitting data with multiple check bits (parity) and decoding the associated check bits when receiving data to detect errors. The check bits are parallel parity bits generated from XORing certain bits in the original data word. If bit error(s) are introduced in the codeword, several check bits show parity errors after decoding the retrieved codeword. The combinations of these check bit errors display the nature of the error. In addition, the position of any single bit error is identified from the check bits. The Hamming codeword is a concatenation of the original data and the check bits (parity).

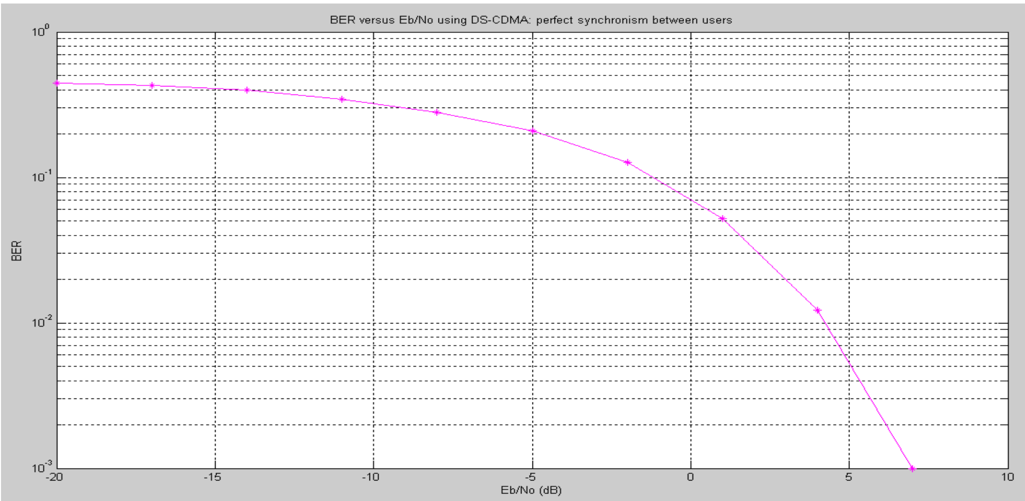
Error Behaviors in the channel using Hamming ECC code



Bose-Chaud-huri-Hocqenghem(BCH) AND Fire codes

A Bose-Chaudhuri-Hocquenghem (BCH) error correction circuit and method including storing normal data and first parity data in a memory cell array, the normal data and first parity data forming BCH encoded data; generating second parity data from the stored normal data; comparing the first parity data with the second parity data; and checking for an error in the normal. A Bose-Chaudhuri-Hocquenghem (BCH) error correction method comprising.

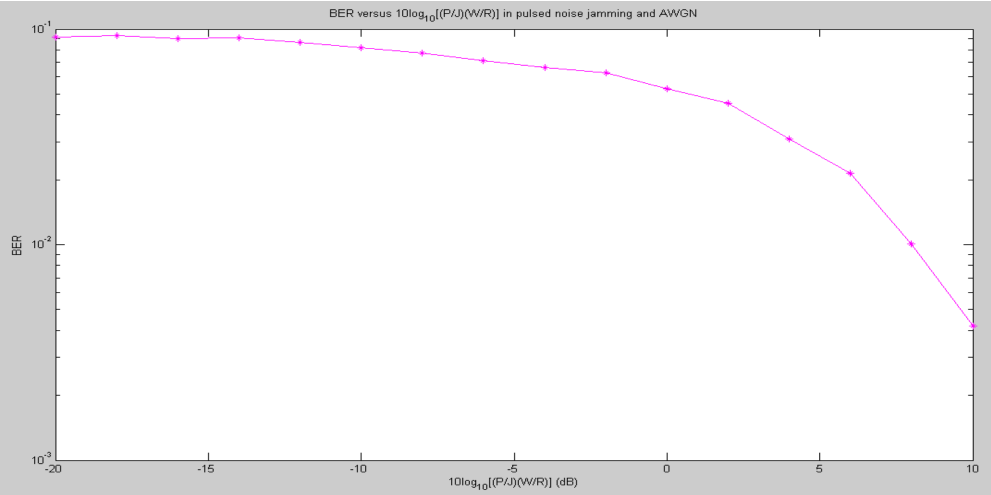
Error behavior in the channel using BCH& Fire codes



Automatic repeat request (ARQ)

Automatic Repeat request (ARQ), also known as Automatic Repeat Query, is an error-Control method for data transmission that uses acknowledgements (messages sent by the receiver indicating that it has correctly received a data frame or packet) and timeouts (specified periods of time allowed to elapse before an acknowledgment is to be received) to achieve reliable data transmission over an unreliable service. If the sender does not receive an acknowledgment before the timeout, it usually re-transmits the frame/packet until the sender receives an acknowledgment or exceeds a predefined number of re-transmissions.

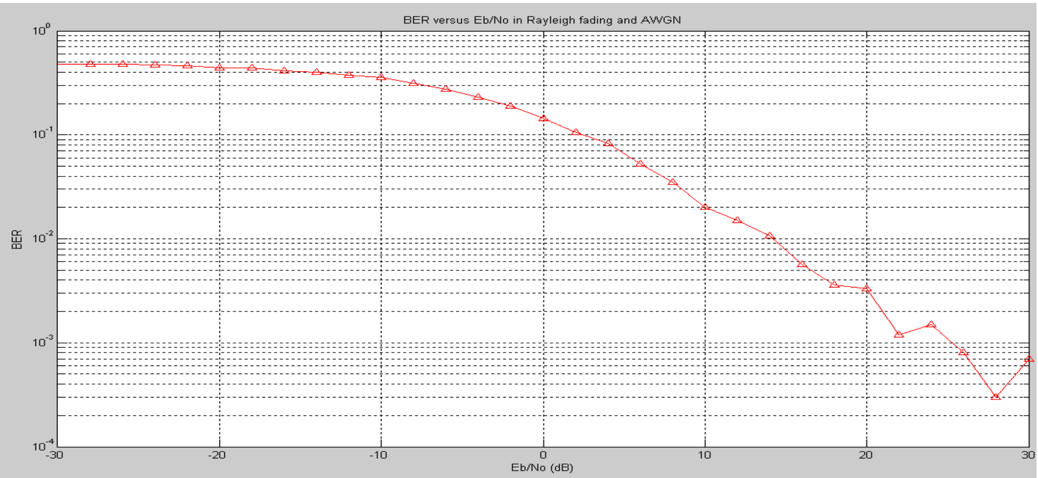
Error behavior in the channel using ARQ error control



SEC-DED with ARQ

To improve system reliability, a designer may wish to provide an automatic error detection and correction circuit. One such example is the data communicated from the microprocessor to peripheral memory devices. This document describes a flow-through method for doing data SECDED with a ARQ.

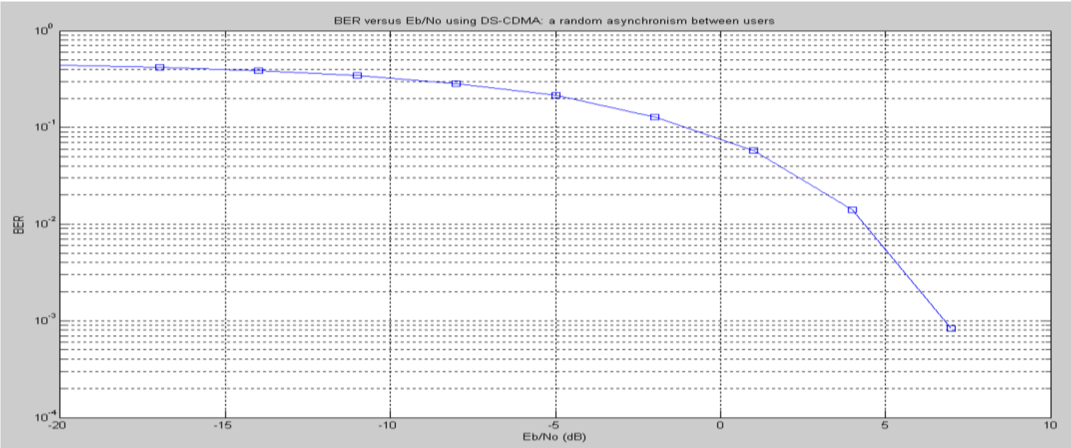
Error Behavior in the channel using SEC-DED with ARQ



Hamming with ARQ

Hamming product codes combined with type-II hybrid automatic repeat request (HARQ), for on-chip interconnects. Input flit width and the number of rows in the product code message are investigated for their impact on the number of wires in the link, codec delay, reliability, and energy consumption.

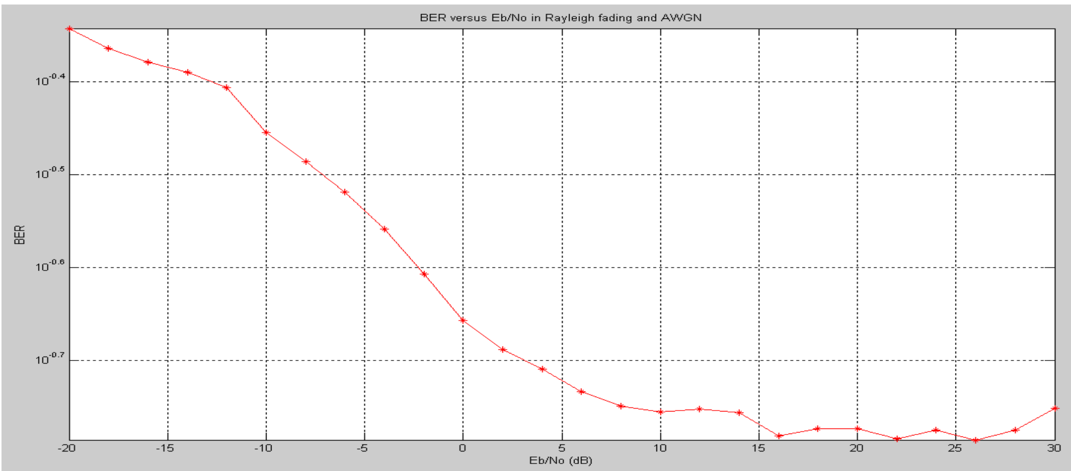
Error Behavior in the channel using Hamming with ARQ



PAM (Pulse Amplitude Modulation)

Pulse-amplitude modulation, acronym PAM, is a form of signal modulation where the message information is encoded in the amplitude of a series of signal pulses. Example: A two bit modulator (PAM-4) will take two bits at a time and will map the signal amplitude to one of four possible levels, for example −3 volts, −1 volt, 1 volt, and 3 volts. Demodulation is performed by detecting the amplitude level of the carrier at every symbol period. Pulse-amplitude modulation is widely used in base band transmission of digital data, with non-base band applications having been largely superseded by pulse-code modulation, and, more recently, by pulse-position modulation.

Error behavior in the channel using PAM



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