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A Systematic Look at Code Performance and System Simulation

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ABSTRACT
The most standard method in improvise a system's efficiency in Digital communication is channel coding but this methods is not been able to extend its features for high speed links. Growing 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. Focusing on the residual ISI and collective noise as the dominant error mechanisms, this paper analyzes error correlation through concepts of error region, channel signature, and correlation distance. 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, and provides a case against the use of biased Monte Carlo methods in this setting. Finally, based on a hardware test bed, 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.
Keywords: Communication systems, Integrated circuit interconnections, Intersymbol interference (ISI).

I. 1 INTRODUCTION

This thesis explores the benefit of channel coding for high-speed backplane or chip-to-chip interconnects, commonly referred to as the high-speed links. High-speed links are ubiquitous in modern computing and routing. In a personal computer, for instance, they link the central processing unit to the memory, while in backbone routers thousands of such links interface to the-speed links are subject to stringent throughput, accuracy and power consumption requirements. A typical high-speed link operates at a data rate on the order of 10Gbps with error probability of approximately 10^{-15}. Given the bandwidth-limited nature of the backplane communication channel, the ever-increasing demands in computing and routing speeds place a large burden on high-speed links. Specifically, high data rates exacerbate the inter-symbol interference (ISI), while the power constraints and the resulting complexity constraints limit the ability to combat the ISI. As a result, the system is no longer able to provide the required quality of communication. In fact, this residual ISI limits the achievable link data rates to an order of scale below their projected capacity.

Although most modern communication systems employ some form of coding as a technique to improve the quality of communication, the residual ISI severely impairs the presentation of many such techniques. This is demonstrated in a thesis by, which consists of a series of experimental results that evaluate the potential of standard error-correction and error-detection schemes for high-speed link applications. Moreover, coding schemes are also generally considered impractical for high-speed links due to the required overhead and the resulting rate penalty. Specifically, Monte-Carlo-based simulation techniques are not suitable for performance estimation of a coded high-speed link due to the low error probabilities, while the closed-form expressions pertain to the limiting cases and may therefore not be sufficiently accurate.

The present work addresses the issue of coding for high-speed links from a theoretical perspective, by abstracting the high-speed link as a general system with noise and ISI. This abstraction allows for a classification of possible error mechanisms, which enables both a deeper characterization of the behavior of different codes in a high speed link and the development of new coding techniques adapted to these systems. The benefits of the regime classification also extend to system simulation, by allowing for more efficient simulation methods tailored for different regimes. In particular, this thesis develops the following results:

A more complete characterization of error mechanisms occurring in a high-speed link. This enables the classification of system's operating conditions based on the dominant error mechanism as one of three possible regimes, namely, the large-noise, the worst-case-dominant and the large-set-dominant regimes. A deeper classification of codes for high-speed links. A hypothetical framework for interpret previously-documented tentative behaviors. New reproduction methods for coded or encoded high-speed links. The regime classification provides a more accurate guideline for biasing the system parameters in simulation to capture error behaviors at low probabilities. Moreover, computational approaches that enable performance estimation without parameter biasing are identified for each of the regimes. An efficient arithmetical algorithm for computing marginal probability distributions in a coded system. The algorithm is of particular use under operating conditions that render the previous techniques impractical, either due to excessive computational complexity or insufficient accuracy. Note that, since the performance of pattern-eliminating codes is given by a closed-form expression for all regimes of interest, the algorithm focuses on systematic linear block codes whose behavior is the focus of previous experimental work.

Classification of Error Mechanisms in High speed Links:

Motivated by the model of a high-speed link introduced in the previous section, this section provides a more thorough characterization of the error mechanisms in systems limited by AWGN and ISI. Typically, the dominant error mechanism is loosely defined as the most likely source of detection errors. For instance, observes that the inter symbol interference, rather than noise alone or the timing jitter, is the dominant error mechanism in a high-speed link. In the present context, however, the term takes on a more precise meaning. Specifically, the dominant error mechanism refers to an attribute of a set of interference events which are found to be responsible for some large proportion of the detection errors. The concept of a dominant error mechanism is formalized in Section 2.2 of Chapter 2. In the meanwhile, to gain a qualitative understanding of the concept, different error mechanisms are examined through the a posteriori probability distribution of the random variable Zi, defined in the present context as the probability distribution of Zi conditioned on the occurrence of an error event. More precisely, letting P(Zi = z) denote the a priori probability of observing some signal component z of the total received signal, the corresponding unilateral a posteriori probabilities are given by P(Zi = z | Yi < 0,Xi = 1) and P(Zi = z | Yi > 0,Xi = −1). In a loose sense, the a posteriori distribution specifies the proportion of the errors that are due to each possible interference event. However, several factors jointly determine the a posteriori probability distributions and different combinations of these factors give rise to distinct scenarios or regimes. The large-set-dominant scenario encompasses the remaining conditions, but also allows for a general result regarding joint error behaviors. The corresponding classification framework is at the core of the results formulated in the later chapters, which develop both codes and simulation methodologies to suit particular regimes in a system with noise and ISI.

Prior to discussing individual scenarios, note that, from the theoretical perspective, the three different scenarios represent three different limiting behaviors. This view is further discussed in Chapter 2. On the other hand, from a practical standpoint, the three scenarios provide a classification framework where the boundaries are context-dependent. For instance, regarding the performance of codes optimized for a given limiting behavior3, the boundary of the corresponding regime is set to encompass the operating conditions under which such codes provide a benefit. Similarly, from the point of view of performance estimation, it is convenient to consider as large-set dominant all conditions under which the error events can be considered as statistically independent, with some sufficient accuracy.

The two sets of plots of Figures 1-2 and 1-3, depicting the a posteriori probability distributions for the random variable Zi as a function of σ and δ, are used in the sections that follow to exemplify and link the three scenarios. The probability distributions are computed based on the decision threshold of zero, for a channel with z = 1 and interference coefficients that take values from the set {-δ,δ}, for some positive real δ. Different scenarios are obtained by controlling the value of δ and σ. For the purpose of illustration, it is also assumed that the symbol patterns are unconstrained. Thus, the a priori probabilities for the normalized interference, appropriately shifted and scaled, follow a binomial distribution with p = 0.5. The changes in the behavior of the a posteriori probability distribution resulting from varying the channel and noise parameters are indicative of the shift in the error mechanism as the system transitions from one limiting case to another.

Large-noise Regime

The large-noise regime occurs when the noise variance σ^2 is sufficiently large relative to the variance of the ISI, σ^2_{ISI} . Then, conditioning on the signal variable Zi, in the Yi = Zi + Ni expression, provides little information about the received signal Yi and the a posteriori symbol interference probabilities are approximately equal to the a priori probabilities.

The relative magnitudes of noise variance and the ISI required for the system to operate in the large-noise regime also depend on the signal mean z. For a system operating "far" from the decision threshold, a tolerable amount of ISI for the large noise regime to apply is significantly lesser than that required for a system operating closer to the decision threshold. As an illustration, consider a system with noise of variance σ^2 and let δ be the channel coefficient of smallest magnitude. If the system indeed operates in the large-noise regime, then the ratio of the a posteriori probabilities for two different ISI values will be equal to the ratio of their a priori probabilities. Now, let z be sufficiently large, so that any detection error is due to a low-probability noise event. Since cumulative probabilities in the tails of the Gaussian distribution can be approximated as placing the decision threshold at zero. As z gets larger, keeping δ and σ constant, the ratio (z − 2δ)/z tends to unity, but the factor $e^{-z\delta/\sigma}$ tends to zero and the ratio of the a priori probabilities is thus not maintained.

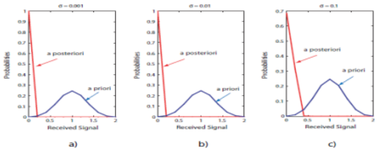

Figure: A priori and a posteriori probability

Worst-case-dominant Regime

The worst-case ISI occurs when a transmitted symbol pattern causes the received signal to deviate from its mean value z by the maximum possible amount _ in the direction of the decision threshold. For a channel of length L defined by coefficients h0, h1, . . . , hL−1, where h1, . . . , hL−1 cause interference, there are two possible worst-case patterns, depending on the value of the most-recently transmitted symbol Xi. The system effectively operates in the worst-case-dominant regime when both of the following two conditions are satisfied:

1. The signal value affected by the worst-case ISI is at some non-negative distance away from the decision threshold, i.e. the minimum decision distance is positive.
2. The noise standard deviation, σ, is small relative to the channel coefficient of least magnitude, δ.

The positive distance by which the signal mean z is separated from the decision threshold affects the allowed range for the δ/σ ratio. Applying the expression of Equation for the cumulative probability in the tails of the Gaussian distribution, it follows that the allowed range for the values of δ/σ can be relaxed as the mean signal value z moves away from the decision threshold. More precisely, the factor $e^{-z\delta/\sigma}$ now serves to suppress the a posteriori probability of symbol patterns which do not bring the signal the closest to the error region. For large z where this expression is valid, increasing z by a factor of α > 1 allows to reduce the δ/σ ratio roughly by a factor of 1/α.

Finally, it remains to justify the non-negativity requirement on the minimum decision distance. Placing once again the decision threshold at zero, assume that $z^1 = z - \Delta < 0$ where z^1 represents the value of the noiseless received signal Zi when affected by the worst-case ISI. Suppose in addition that there exists another possible value of Zi, denoted by z^{11},that is also at a negative distance from the decision threshold. More precisely, there exists some possible outcome z^{11} such that $z^1 < z^{11} < 0$. Then, for sufficiently large L, conditioning on an error event may assign a larger a posteriori probability to z^1 than to z^{11} simply on account of its multiplicity. An example of this occurring is depicted in Figures 1-4 a) - c) below. In particular, for the system depicted in the part a) of the figure and operating in the worst-case dominant regime, the signal mean z is reduced by 2.5δ and 4δ so that the worst-case interference crosses the decision threshold. The resulting a posteriori probability distributions, displayed in parts b) and c), are no longer worst-case-dominant, as the probability mass is centered on the interference values closer to the decision threshold.

Alternatively, a more precise argument justifying the non-negativity requirement is available when the noise variance is sufficiently small so that the probabilities $P(N < z^1)$ and $P(N < z^{11})$ are both from the tails of the Gaussian distribution. In those conditions, the ratio of the a posteriori probabilities becomes: Since $|z^1| > |z^{11}|$, the two ratios on the left-hand side are both less than unity. Thus, if z^{11} has an equal or greater a priori probability than z^1, the a posteriori probability will be biased in its favor. The regime will therefore not be worst-case-dominant. However, note that the non-negativity requirement on the minimum distance is in principle too strict. More precisely, it is possible to envision a case where z^1 is the only possible negative ISI value and the next-to-worst-case ISI is sufficiently removed for the above ratio to be large and for the error expression to remain dominated by the occurrence of the worst-case ISI. While this case may be of some practical importance, a simpler definition which encompasses a large number of cases is preferable for the purpose of the subsequent development.

Quasi-worst-case-dominant Scenarios

While the previous development concerns the regime where the worst-case interference is responsible for most of the error events, such a behavior is seldom observed in practice. Instead, a more common occurrence is that of a dichotomous channel. The term refers to any channel of length L whose l coefficients are more significant than the remaining ones. The notion of significance is context-dependent. For instance, it may pertain to the confidence of the channel response measurements, or, in dispersive channels, to the fact that the first l coefficients are typically of larger magnitude. In general, the corresponding l coefficients are referred to as the principal part of the channel, while the remaining coefficients belong to the secondary part of the channel. In all three plots, σ = 0.01, δ = 0.02,L = 50 which implies that Δ = 1. The decision threshold is placed at zero as indicated by the dashed line, and the corresponding minimum decision distance is given by z − Δ. The corresponding error probabilities perr are included for completeness. – a)z = 1, perr = 4.5×10^{-16}. b) z = 0.95, perr = 4.0×10^{-14}. c) z = 0.90, perr = 1.5×10^{-12}.

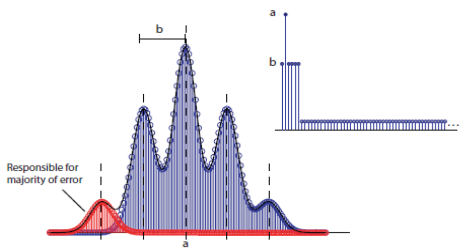

Figure: A Dichotomous Channel in the Quasi-worst-case-dominant Scenario

Note that, in general, the l coefficients need not occur consecutively, nor be restricted to a specific portion of the channel.

By considering an equivalent channel of length l, the previous characterization of the worst-case behaviors extends to worst-case interference caused by the principal part of the channel. The corresponding regime is referred to as the quasi-worst-case dominant regime and is illustrated in Figure 1-5 for a two-level channel. In this example, the principal part of the channel has length l = 5, signal mean z = a and interference coefficients of magnitude b, while the secondary part of the channel has coefficients of some lesser, unspecified magnitude. The plot illustrates only the a priori probability distribution of the random variable Zi and highlights the events that aggregately dominate the a posteriori probability. The latter correspond to all the events associated with the worst-case patterns ±(−1, 1,−1,−1) formed by the principal part of the channel and producing signal values centered at a − 4b.

Largest-dominant Regime

In the subsequent chapters, the large-set-dominant regime is principally considered as a default regime for all the cases that, in a given context, do not fit the two other regimes. For instance, it can be used to classify the behaviors illustrated in Figures 1-2 a - b) and, depending on the context, 1-2 c - d). It also applies to the conditions of Figure 1-4, where the system does not operate in either the worst-case or quasi-worst-case-dominant regime due to the negative decision distance. Since the large-set-dominant scenario encompasses a range of possible a posteriori probability distributions, more general results regarding the error affecting any given symbol are difficult to formulate. Instead, Chapter 3 develops a numerical algorithm for computing probability distributions when a system cannot be considered to operate in one of the limiting cases.

However, an important general result regarding the large-set-dominant scenario can be formulated with respect to the joint error behaviors. Specifically, in large-set dominant conditions that are sufficiently removed from the worst-case or quasi-worst case scenarios, the error events on the received signals can be considered effectively independent. Since the corresponding conditions pertain to joint error statistics, rather than the a posteriori error probabilities.

II. Related Work

Most modern communication systems employ some form of the coding as a technique to improve the quality of the communication. These often include redundancy-based error control codes that allow for error detection or correction, run-length-limiting codes that improve the receiver's clock recovery, or DC-balancing codes that protect the timing circuitry against capacitive coupling. While inter-symbol interference (ISI) has a limited effect on the timing properties of a code, the performance of error control codes is significantly impaired. A variety of higher complexity techniques discussed in Section 2.1.3 combat the ISI to some extent, but few are suitable for power or complexity-constrained systems.

The developments in this chapter build on the regime classification framework developed in Chapter 1 in order to further characterize the marginal and the joint error behaviors of systems with noise and inter-symbol interference. The corresponding results provide conditions under which standard error-control codes perform optimally and, otherwise, lead to a new approach to error-control coding for the worst-case dominant or quasi-worst-case-dominant regimes.

Preliminaries

This section overviews the basics of error-control coding and extends the previously described high-speed link model to include coded transmissions. Previous work regarding
coding for high-speed links is overviewed as well.

Error-control Coding

Error-control codes introduce controlled redundancy in order to improve the reliability of the transmission, either through forward error correction or error correction with retransmissions. Note that the corresponding stream of bits is therefore necessarily constrained. In an (n, k) binary linear block code, each n-bit codeword is obtained through some linear combination, over the binary field $F_2 = \{0, 1\}$, of the underlying k information bits. In a systematic linear block code, the k information bits appear explicitly, along with the n-k parity bits computed using a binary map. Linear block codes over finite fields of higher orders operate on the same principle. The most celebrated example are the Reed-Solomon codes, which are extensively used in data storage and telecommunications.

Linear block codes are intuitively simple and thus commonly provide a starting point for new applications, as further discussed in Section 2.1.3. However, the concept of error-control coding also extends to the more powerful convolution, LDPC and turbo codes. Regarding decoding, a system can implement hard-decision decoding or soft decision decoding. Hard-decision decoding operates over a finite field and is thus decoupled from the detection problem. In soft-decision decoding, the real-valued signals are used in order to make more informed decisions. Although hard-decision decoding allows for relatively simple hardware implementations—for binary linear block codes, the setup is a simple threshold device followed by delay and logic elements—the soft-decision decoding provides a performance benefit.

A notion of importance in linear block codes is that of Hamming distance. For any two codewords, the Hamming distance corresponds to the number of positions, out of n, where the code words differ. For some codebook C, defined as the set of allowed n-bit codewords, the minimum Hamming distance d_H is defined as the minimum distance between any two codewords in the codebook. Assuming hard-decision decoding and correcting to the nearest[2] codeword, a codeword will be decoded correctly if and only if there are less than bdH/2c detection errors in a codeword. The quantity $[d_H/2]$ is the error-correcting power of a code, denoted by the parameter t.

Note that in bandwidth-limited systems, an important factor of the code performance is the coding overhead. The coding overhead refers to the fact that only k bits out of the n codeword bits carry information. For a coded system operating at some signaling rate R, the equivalent information rate is thus Rk/n. When a system is severely bandwidth-limited, it can happen that an uncoded system operating at a rate of Rk/n can outperform a coded system operating at rate R. In the context of this thesis, this behavior is referred to as the rate penalty of a code.

System Model

The system model is that of the abstracted ISI-and-AWGN-limited system introduced in Chapter 1, with the addition of an encoder/decoder, as shown in Figure 2-1. Despite the fact that the depicted system implements hard-decision decoding, the developments of Chapters 2 and 3 are general, unless specified otherwise. The meaning of quantities X_i, Z_i, and Y_i is unchanged and the convolution equation, reproduced below for convenience, remains valid. Note that, for the ease of notation, the communication channel is assumed to be causal, that is hi = 0 for indices i < 0. This is also referred to as the channel causing no pre-cursor ISI. Through the remainder of the chapter, the cases where pre-cursor ISI changes the nature of the result will be discussed explicitly. Otherwise, it is to be assumed that the results hold unchanged or require trivial adjustments, such as adjustments to indexing. Simplified model of a high-speed link. Transmit/receive equalization is reflected on the symbol spaced pulse response. Although this chapter deals with a coded high-speed link, the development focuses on the abstracted physical layer, that is, on the behavior of the system between the encoder/modulator and decoder/ demodulator blocks.

Previous Work

Since coding schemes were previously considered impractical for high-speed links due to their rate penalty, most research efforts to bring more advanced communication techniques to high-speed links have focused on better signaling/modulation techniques and equalization. First, for the link channels tested, codeword with up two 10 errors occur with sufficiently high probability. Second, burst forward error correction codes, optimized to deal with a potentially large number of errors occurring within some separation, are impractical since the typical burst length is often too large to allow for a low-overhead code. Third, assuming accurate retransmissions, all the tested error detection schemes yielded an improvement in the bit error rate of five orders of magnitude or more, including the rate penalty. Since, relative to the corresponding error correction capability, error detection requires moderately low overhead, recommends the implementation of error detection codes with an automated repeat request (ARQ) scheme.

The principal reason why rely exclusively on new results is the previous lack of a suitable analytical framework as well as a lack of alternative performance evaluation techniques for coded high-speed links. The previous work in performance evaluation of high-speed links is discussed in Section 3.2 of the subsequent chapter. The general subject of communicating in ISI-dominated environments has been addressed in several different contexts. The standard approach consists of decoupling the equalization and coding. Although this has been known to combat the bandwidth limitations to a practical degree, the technique suffers from the rate penalty whose effects vary with the suavity of the ISI. Since for real-valued channels with noise and ISI, operating in the worst-case or quasi-worst-case-dominant regime reduces the communication channel to a binary signature, the results pertaining to binary-valued partial response channels are of interest for the present development. An example of such a channel is the Extended Partial Response 4 (E^2PR4) channel. A variety of communication techniques has been developed to improve the communication over partial response channels and other ISI-limited environments. However, the most relevant link to the pattern-eliminating codes introduced in this chapter is the work on distance-enhancing constraint codes for partial response channels. Shortly after, maximum-transition-run (MTR) codes were introduced and demonstrated to yield potentially large coding gains. Similarly, the last twelve years have witnessed a wealth of development in distance-enhancing constraint-codes for the partial response channels. Much like the pattern-eliminating codes, the distance-enhancing constraint codes yield a coding gain by preventing the occurrences of harmful symbol patterns. However, several fundamental differences distinguish the two types of codes. Structure wise, the pattern-eliminating codes are systematic, while the distance-enhancing constraint codes are not. Thus, both the proof techniques and the results differ between the two cases. More importantly, the pattern-eliminating codes are optimized to provide an improvement to the minimum decision distance, while this criterion is secondary in the distance-enhancing constraint codes. Note that the distance-enhancing benefit of constraint codes has only been reported for E2PR4 and E3PR4 channels, as the partial response channels of higher-orders are not binary. However, the codes may yield a benefit over a wider range of channel signatures5, a topic which remains unexplored since binary channels of arbitrary signatures are not encountered in magnetic recording. Since distance-enhancing constraint codes are primarily designed for timing purposes, it is unlikely that their distance-enhancing potential rivals that of pattern-eliminating codes. The DNC is characterized by a set of allowed transmitted symbol sequences, or alternatively by their complement, that is, the set of forbidden sequences. Thus, in a sense, error-free operation is achieved on the DNC by preventing the occurrence of symbol patterns from some given set. Shannon showed that the capacity C of the DNC is given by Specifically, Shannon's results apply directly to most forms of constraint coding over ISI-limited channels and have therefore found extensive application in magnetic recording channels, where constraint codes are commonly used.

III. RESULTS AND DISCUSSION

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. Although transmitted symbols in separate blocks need not be independent in a coded symbol stream, as the blocks from 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.

Error Lengths in High-Speed Links:

As discussed in SectionIII-C, the distribution of error lengths within a block of consecutive symbols provides spatial information on the error correlation in a given system. The measurements of observed error lengths for the high-speed link operating at 6.25 Gb/s. Taking into account statistical significance, the deviations from the independent-errors case in the measured distribution of error lengths predominantly occur at short lengths, further corroborating the insights of Section IV on the short-term nature of error correlation in high-speed links. The increase in the frequency of short error lengths is indicative of a high degree of nesting in the error prone sequences. In systems with strongly positive error correlation, burst-error correcting codes are frequently employed due to their ability to handle large error weights while requiring low overhead compared to standard error-correcting codes.

Comparison of Algebraic Error-Control Codes in a High-Speed Link:

The performance results for five different types of error-control codes, namely, Hamming codes em-n. Played for either forward error correction or error detection with automatic repeat request (ARQ), Single-error-correcting Double-error-detecting (SEC-DED) with ARQ, Bose-Chaudhuri-Hocquenghem (BCH), and Fire codes, are shown in at 6 Gb/s and 6.25 Gb/s.

IV. CONCLUSION & FUTURE SCOPE

Modeling a high-speed link as an ISI-limited system with additive white Gaussian noise allows for an abstracted framework suitable for a more theoretical approach to studying the benefit of coding for high-speed links. Possible error mechanisms are categorized according to three regimes, the large-noise, the large-set-dominant and the worst-case-dominant, which are entirely specified by the system's noise level and the channel's pulse response. While the worst-case-dominant regime occurs rarely in a high-speed link, the quasi-worst-case dominant regime is shown to occur on ATCA channels at realistic equalization levels and is also shown to be consistent with previous experimental observations. This thesis further examines the behavior of standard error-control codes in this regime and shows that for uncorrelated channels, where the notion of correlation is redefined through nesting of the worst-case symbol patterns, a single parity check code is optimal, as long as the codeword length is inferior to the correlation length. Conversely, for correlated channels, including channels with insufficiently equalized dispersion, a standard error-control code requires a potentially large overhead due to an increased probability of observing a relatively large number of errors in a codeword, conditioned on the occurrence of a worst-case symbol pattern.

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