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Usage of polar codes for fixed and random length error bursts correction

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Abstract

Error correction during data storage, processing, and transmission allows for ensuring data integrity. Channel coding techniques are used to counteract these errors. Noise in real systems is often correlated, whereas traditional coding and decoding approaches are based on decorrelation which in turn reduces the performance limits of channel coding. Polar codes, adopted as a coding scheme in the modern fifth-generation communication standard, demonstrate low error probabilities during decoding in memoryless channels. The current task is to investigate the suitability of polar codes for channels with memory, analyze their burst error-correcting capabilities, and compare them with known error-correcting coding methods. To evaluate burst error-correcting capability, the method of calculating the ranks of each submatrix of the parity-check matrix of a fixed-size polar code is used. The burst error-correcting capability of polar codes can be improved through a proposed interleaving procedure. The analysis of the burst error-correcting capability is carried out for short-length polar codes. An analysis of the burst error-correcting capability of polar codes has been performed. A comparison of burst error-correcting capabilities of polar codes with codes defined by random generator matrix, Gilbert codes and low-density parity-check codes was conducted. An analysis of the decoding error probability shows that standard polar code decoding algorithms do not achieve low error probabilities. The same decoding error probability 0.01 as for Gilbert channel is achieved by polar code in binary symmetric channel with an unconditional error probability two times as high. From the analysis, it can be concluded that the burst error-correcting capability of standard polar codes is low. The proposed interleaving approach improves the burst error-correcting capability and allows achieving values close to the Reiger bound. Further research directions may include developing decoding algorithms for polar codes adapted for channels with variable packet lengths

Keywords

polar codes, channels with memory, Gilbert channel, interleaving

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Использование полярных кодов для исправления пакетов ошибок случайной и детерминированной длины

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Аннотация

Введение. Исправление ошибок, возникающих при хранении, обработке и передаче данных позволяет обеспечивать их целостность. Для противодействия этим ошибкам используются методы канального кодирования. Возникающий в реальных системах шум часто имеет коррелированный характер, в то время как традиционные подходы к кодированию и декодированию основаны на декорреляции, что приводит к снижению предельных характеристик канального кодирования. Полярные коды, принятые в качестве схемы кодирования в современном стандарте связи пятого поколения, показывают низкие вероятности ошибки при декодировании в каналах без памяти. Актуальной является задача исследования пригодности полярных кодов для каналов с памятью, анализа их пакетной корректирующей способности, а также сравнение с известными методами помехоустойчивого кодирования. **Метод.** Для оценки пакетной корректирующей способности использован метод вычисления рангов каждой из подматриц проверочной матрицы полярного кода фиксированного размера. Увеличение пакетной корректирующей способности полярного кода возможно с помощью предложенной процедуры перемежения. Анализ пакетной корректирующей способности полярных кодов проводится для кодов небольшой длины. **Основные результаты.** Выполнен анализ и сравнение пакетной корректирующей способности полярных кодов с кодами, определяемыми случайной порождающей матрицей, кодами Гилберта и низкоплотностными кодами. Анализ вероятности ошибки декодирования показал, что стандартные алгоритмы декодирования полярных кодов не позволяют достигать малых вероятностей ошибок. Такая же вероятность ошибки декодирования 0,01, как и для канала Гилберта, достигается полярным кодом в двоичном симметричном канале с большей, чем в два раза безусловной вероятностью ошибки. **Обсуждение.** Результаты исследования показывают, что пакетная корректирующая способность стандартных полярных кодов мала. Предложенный подход с перемежением улучшает пакетную корректирующую способность и позволяет достичь значений, близких к границе Рейгера. Направлением дальнейших исследований может быть разработка алгоритмов декодирования полярных кодов, адаптированных для каналов с длиной пакетов, имеющих случайную длину.

Ключевые слова
канал с памятью, канал Гилберта, полярные коды, перемежение

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Introduction

Information in the modern world is one of the key resources. The procedures of processing, transmitting, and storing information are often accompanied by the occurrence of errors. These processes are modeled mathematically, and errors are often dependent, leading to the formation of error bursts or memory in the channel. In the absence of error dependence, it is assumed that the channel has no memory. The memory effect in data transmission channels can be caused by various physical characteristics, such as multipath propagation, signal scattering, or the peculiarities of data storage equipment [1]. Among the widely used mathematical models for describing channels with memory are the Gilbert channel, the Gilbert-Elliott channel, and the Rayleigh fading channel with dependent fading, inter-symbol interference channel models, and others. To correct errors, coding theory offers the use of error-correcting codes, which introduce redundancy into the data to enable error detection and correction. Reliability issues, including the introduction of information redundancy, are a crucial task in the development of info communication systems [2, 3].

Polar codes, proposed by Erdal Arikan in 2009 [4], became the first codes with a clear construction capable of asymptotically achieving the capacity of a symmetric channel with simple encoding and decoding procedures. Recently, interest in polar codes has significantly increased due to their inclusion in the fifth-generation wireless communication standard, where they are particularly used for control channel coding. The theoretical analysis of polarization properties for channels with memory has been examined in [5, 6].

This paper will investigate the burst error-correcting capabilities of polar codes, with a focus on their application in channels with bursts. A comparison of the burst error-correcting capabilities of polar codes with other error-correcting methods will be presented, along with an analysis of the decoding error probability of polar codes in channels with memory. The results will also be compared with those obtained using other error-correcting methods.

Channels with memory

Let X and Y be the alphabets of the input and output symbols of the channel, respectively. This work considers discrete-time channels, i.e., channels where the transmission and reception of messages occur at discrete moments in time. A communication channel is defined by a set of transition probabilities $p(\mathbf{y}|\mathbf{x})$ for any $\mathbf{x} \in X$, $\mathbf{y} \in Y$. Let $\mathbf{x} = [x_0, \ldots, x_{N-1}]$ and $\mathbf{y} = [y_0, \ldots, y_{N-1}]$ be sequences of length N at the input and output of the channel, respectively. The effect of noise in the channel on the transmitted information is described by an error vector $\mathbf{e}$ such that $\mathbf{y} = \mathbf{x} + \mathbf{e}$. Formally, a memoryless channel is defined as a channel for which the following holds [7]:

$$p(\mathbf{y}|\mathbf{x}) = \prod_{i=0}^{N-1} p(y_i|x_i).$$

One common type of memoryless channel is the Binary Symmetric Channel (BSC), described by the transition error probability p_e with the input and output alphabets $X = Y = \{0, 1\}$.

One of the key characteristics of a communication channel is its transmission rate. The channel capacity refers to the maximum data transmission rate at which communication can be reliable, meaning with an arbitrarily low error probability. C. Shannon proved that there exist coding methods that can ensure reliable communication at rates approaching the channel capacity. It was also shown that the capacity of a channel with memory exceeds the capacity of a channel where memory is not accounted for (e.g., when channel decorrelation is applied using interleaving).

As mentioned earlier, in real communication channels, transmission errors are not independent. The causes of dependency between symbols can include the physical properties of the channel, such as signal multipath propagation in fading and scattering channels, the physical principles of information storage, or the organizational structure in data storage systems. The simplest model describing a channel with memory is a two-state channel model. Within the two-state model, one can consider a Markov model, the Gilbert model [8], and the Gilbert-Elliott (GE) model [9].

The GE model was proposed by E. Elliott in 1963 and is a generalization of the Gilbert channel model introduced in 1960. The GE model describes a discrete channel with memory, where the transition to the next state is determined by the previous state. We will use traditional notations for this model, where the GE channel is described by two states: "good" (G) and "bad" (B). In the "good" state, the probability of a bit error in the channel is p_G, and in the "bad" state, it is p_B. In the Gilbert model, it is assumed that p_G is always equal to zero. Let the probability of transitioning from the "good" state to the "bad" state be denoted as P_{GB}, and the probability of transitioning from the "bad" state to the "good" state as P_{BG}. The unconditional probabilities of being in states B and G are

$$P_B = \frac{P_{GB}}{P_{GB} + P_{BG}},\ P_G = \frac{P_{BG}}{P_{GB} + P_{BG}}.$$

Using the transition probabilities of the GE channel, the unconditional bit error probability can be calculated as:

$$p_e = p_B P_B + p_G P_G = \frac{p_B P_{GB} + p_G P_{BG}}{P_{GB} + P_{BG}}. \quad (1)$$

If an infinite-length interleaving procedure is applied to the output of the channel described by the two-state model, a memoryless channel is obtained, which is described by the BSC model with the transition probability (1). Such a channel will hereafter be referred to as equivalent (to the original two-state channel), and the value p_e will be referred to as the equivalent error probability.

Burst error-correcting capability of linear codes

In channels with memory, the error vector represents a burst, meaning an error vector in which non-zero elements tend to group together. The article examines bursts of length l, defined as vectors in which all non-zero components are located in l consecutive positions, with the first and last positions being non-zero. For example, the error vector $\mathbf{e} = (0, 0, 0, 0, 1, 0, 1, 1, 0, 1, 0, 0, 0, 0, 0)$ represents a burst of length 6. A linear code capable of correcting all error bursts of length l or less, but not all bursts of length $l + 1$, is called a code correcting error bursts of length l, or a code with a burst error-correcting capability of l. When correcting bursts at a given code length n, number of information symbols k, and burst error-correcting capability l, the goal is to construct a code (n, k) with the smallest possible redundancy (the number of check symbols) $r = n - k$. Next, we will establish certain limits on $n - k$ for a given l or on l for a given $n - k$ [10].

A necessary condition for a linear code (n, k) to correct all error bursts of length l or less is that no burst of length $2l$ or less can be a codeword. The number of check symbols in a linear code (n, k) which contains no bursts of length b or less as codewords, must be at least b (i.e. $n - k \geq b$). The number of check symbols in a code correcting error bursts of length l must be at least $2l$, i.e., $n - k \geq 2l$. For given n and k, this implies that the burst error-correcting capability of the (n, k) code is no more than $\lfloor (n - k)/2 \rfloor$, or $l \leq \lfloor (n - k)/2 \rfloor$. This is the upper bound on the burst error-correcting capability of a linear code (n, k), known as the Reiger bound. Codes that meet the Reiger bound are considered optimal. The ratio $z = 2l/(n - k)$ is used as a measure of the burst error-correcting efficiency of the code. An optimal code has a burst error-correcting efficiency of one.

The following approach can be used to assess the burst error-correcting capability of a linear code [11]. The burst error-correcting capability of a code with a parity-check matrix $\mathbf{H}$ is the maximum l for which any matrix formed by two submatrices of l consecutive columns of $\mathbf{H}$ has a rank equal to $2l$. By successively reducing the value of l from $\lfloor (n - k)/2 \rfloor$ and considering all possible pairs of submatrices, the maximum correctable burst length $l_{\max}$ can be found with polynomial complexity. From the described procedure, it follows that for a code to correct error bursts of length l, the code must not only lack codewords forming bursts of length $2l$, but also codewords forming two bursts of l symbols.

Modern communication standards employ various error-correcting code constructions that help ensure reliable data transmission in the presence of noise and distortions. Among the most common are Low-Density Parity-Check (LDPC) codes and polar codes. The error-correcting performance of these constructions has been widely studied for memoryless channels, but the study of the properties of codes and their error-correcting performance in channels with memory is a less developed topic.

The burst error-correcting capability of LDPC codes based on block-permutation construction has been studied in the literature. It is known that for a block-permutation LDPC code with zero blocks, the correctable burst length cannot exceed the block size. The burst error-correcting capability of LDPC codes constructed using the Progressive Edge Growth (PEG) algorithm was evaluated in [12]. The burst error identification problem for LDPC codes was investigated in [13]. Decoding of polar codes without channel state information knowledge is considered in [14].

Polar code and its burst error-correcting capability

Polar codes belong to the class of binary linear block codes. The encoding procedure of polar codes is based on channel polarization, which is described by a linear transformation defined by the matrix $\mathbf{G} = \mathbf{F}^{\otimes m}$, where

$\mathbf{F} = \begin{bmatrix} 1 & 0 \\ 1 & 1 \end{bmatrix}$ is the polarization kernel, and $\otimes m$ denotes the m-fold Kronecker product of matrix $\mathbf{F}$ with itself, where $m = \log_2 n$, and n is the length of the codeword of the constructed code. A polar code is defined by a set of parameters (n, k, A_c), where n is the codeword length, k is the number of information symbols, and A_c is the set of "frozen" symbols whose values are predetermined, usually equal to zero, with $|A_c| = n - k$, $A_c \subset \{0, \ldots, n - 1\}$. Methods for constructing polar codes are detailed in [15]. One of the most common approaches to constructing the set of frozen symbols is the Polarization Weight (PW) method. It should be noted that the well-known Reed-Muller (RM) codes from coding theory can also be described as polar codes.

The non-systematic encoding of polar codes is described by the expression $\mathbf{x} = \mathbf{uG}$, where $\mathbf{x}$ is a codeword, $\mathbf{u}$ is a vector including the information symbols ($u_i \notin A_c$, $1 \le i \le n$) and "frozen" positions ($u_i \in A_c$, $1 \le i \le n$).

The classic method for decoding polar codes is the successive cancellation algorithm which does not provide maximum likelihood decoding and has a relatively high error probability. To reduce the error probability of decoding polar codes, I. Tal and A. Vardy [15] proposed the list decoding algorithm, which involves considering multiple paths at each level of the tree, with the maximum number of paths limited by the algorithm parameter L. List decoding with a sufficiently large L approaches near-maximum likelihood decoding.

We will now analyze the burst error-correcting capability of polar codes defined by the matrix $\mathbf{G}_N = \mathbf{F}^{\otimes n}$. Fig. 1 shows an example of the generator matrix of a (64, 42) RM code. As can be seen from the figure, the rows of the generator matrix form short-length bursts. Thus, the very procedure for constructing the generator matrix of a polar code results in a structure with low correcting capability for burst errors.

Next, let's consider the possibility of constructing codes with improved burst error-correcting capability based on the polar code structure. We apply a random interleaving procedure, defined by the random permutation of the columns of the polar code generator matrix, resulting in a code referred to as equivalent to the polar code. It is known that switching to an equivalent code via interleaving preserves the code minimum distance (i.e., does not alter its ability to correct independent errors), but it can significantly impact the value of l_{max}. Fig. 2 presents the results of calculating the burst error-correcting capability of the RM code, which is a special case of a polar code, with length $n = 64$ and various values of $r = \{22, 42, 57\}$.

The figure also shows a line corresponding to the Reiger bound. The burst error-correcting capability for the original code without interleaving is depicted in the figure with the symbol "○", and for the interleaved codes with the symbol "*". As can be seen from the figure, interleaving increases the burst error-correcting capability and yields codes with l_{max} values close to the Reiger bound and with greater efficiency z.

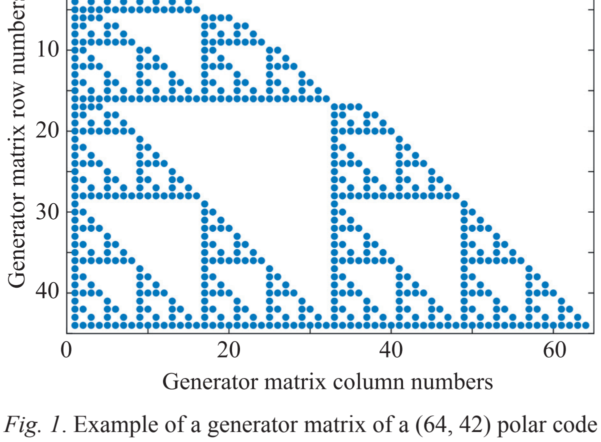

Fig. 1. Example of a generator matrix of a (64, 42) polar code

Comparative analysis of burst error-correcting capability of code constructions

In this section, we compare the burst error-correcting capability of polar codes (RM and PW constructions), their equivalent codes, and several other code constructions: codes defined by a random generator matrix, Gilbert codes specified by a (2 × 3) block-permutation parity-check matrix, and LDPC codes constructed using PEG algorithm. Similar to polar codes, we also consider equivalent codes for these constructions. To build equivalent codes, samples of 100 random permutations was generated.

Fig. 3 shows the burst error-correcting capability for random codes and Gilbert codes. For clarity, only some of the results for equivalent codes are displayed in the figures. Since a code equivalent to a random code is still a random code, we observe a small scatter of l_{max} values in Fig. 3, *a*. It is worth noting that random linear codes are located near the Reiger bound. Fig. 3, *b* shows the results for Gilbert codes. The considered Gilbert codes lie on the Reiger bound, as confirmed by the experiments. Their equivalent codes disrupt the block-permutation structure, leading to a sharp decrease in burst error-correcting capability.

Fig. 4 shows the results for the PEG construction and Reed-Muller codes. The burst error-correcting capability of PEG codes is quite close to the Reiger bound. In rare

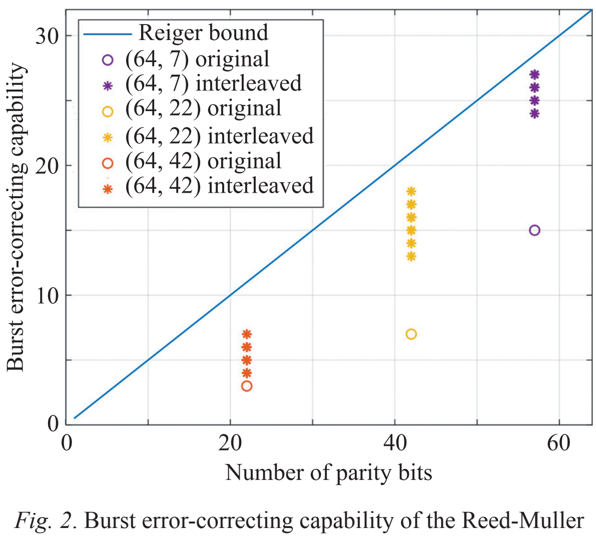

Fig. 2. Burst error-correcting capability of the Reed-Muller code and equivalent codes

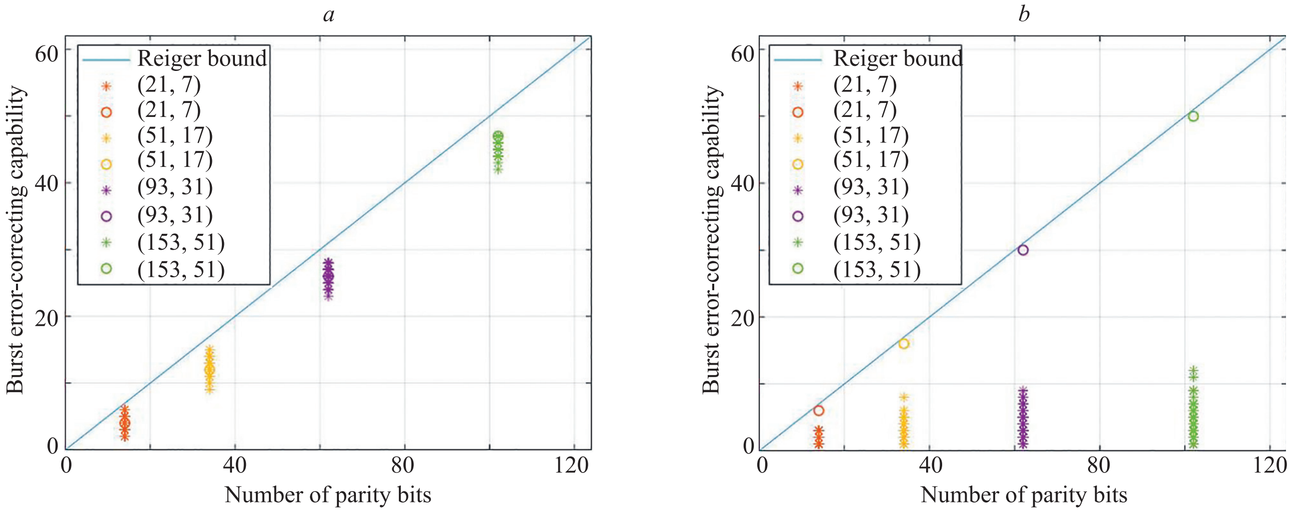

Fig. 3. Estimates of burst error-correcting capability for (*a*) codes defined by a random generator matrix and (*b*) Gilbert codes

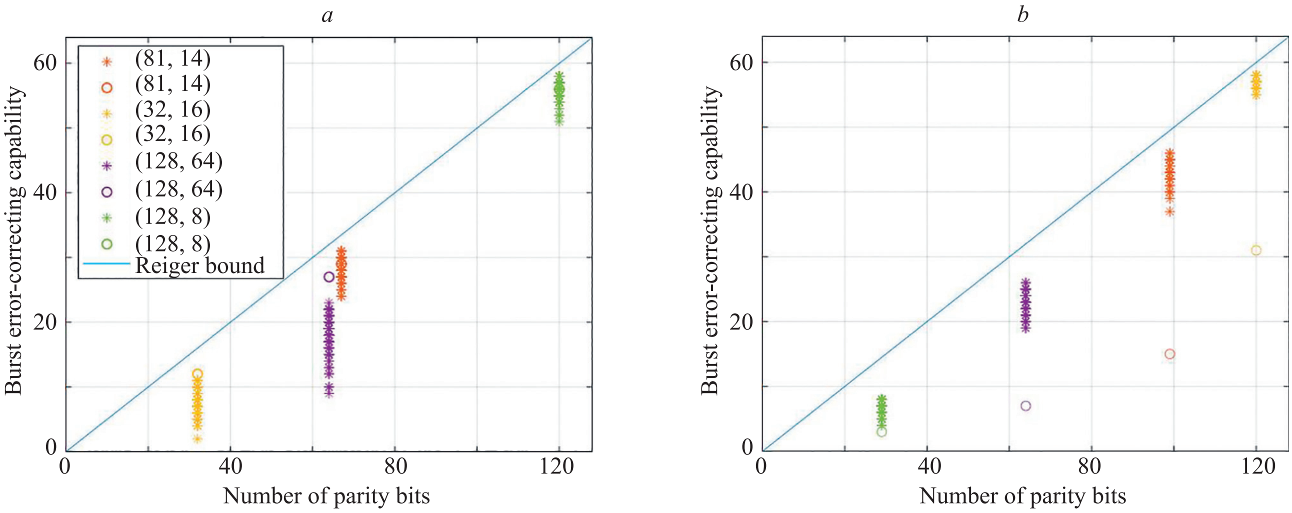

Fig. 4. Estimates of burst error-correcting capability for (*a*) low-density codes based on the PEG construction and (*b*) Reed-Muller codes with $n = 128$

cases, equivalent codes slightly increase the length of the correctable burst, but more often, interleaving degrades the burst error-correcting capability. Reed-Muller codes, as noted earlier, exhibit extremely low l_{max} values, but these can be significantly increased through interleaving.

Fig. 5, *a* presents the results for the PW polar code construction. The results are similar to those of RM codes in Fig. 4, *b*.

Fig. 5, *b* provides comparative results for all the considered constructions with parameters $n = 128$, $k = 64$ (results for codes with other parameters are similar). As can be seen from the figure, while polar codes initially have an extremely low correctable burst length, they can be improved with interleaving. The resulting equivalent polar codes have a burst error-correcting capability comparable to other constructions and are close to the Reiger bound.

It should be noted that existing decoding methods for polar codes are tailored to their structure and cannot be applied to equivalent codes. Thus, the obtained results enable the construction of error-correcting codes based on polar codes that can be effectively used for correcting single burst errors. However, decoding such codes remains an open challenge, or general burst error-correcting algorithms may need to be applied [16].

Experimental results of polar codes error correction capability in channels with memory

In the previous section, we compared various code constructions based on their burst error-correcting capability. Maximizing burst error-correcting capability is useful when the channel does not produce bursts longer or more severe than the code can correct. However, in many channel models with memory, including the GE channel model with two states, burst length and burst severity are random variables. For this reason, burst error-correcting capability is an indirect characteristic describing the code error-correcting properties. Therefore, we will analyze the decoding error probability of polar codes with various decoding parameters in the Gilbert channel. Using simulation, we will compare the obtained error probability estimates with the error probability in a BSC with a

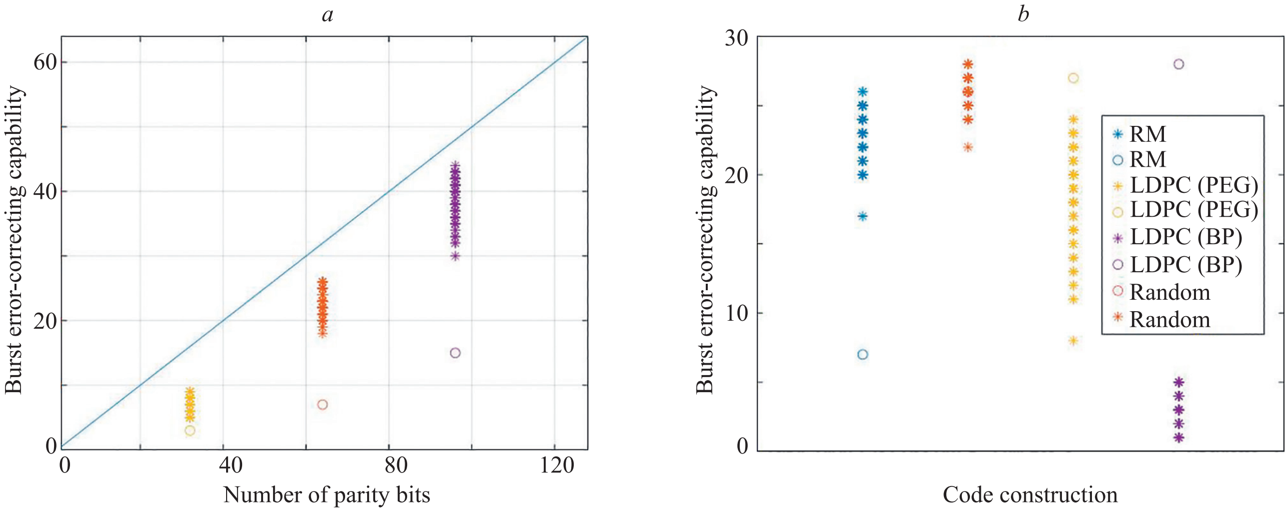

Fig. 5. Estimates of burst error-correcting capability for n = 128 (*a*) Polarization Weight polar codes and (*b*) comparing different constructions

transition probability equivalent to the error probability p_e (1). The decoding of polar codes is performed using the CRC-Aided Successive Cancellation List (CA-SCL) algorithm with a list size L and a CRC polynomial $\mathbf{g}_{crc} = x^8 + x^7 + x^6 + x^4 + x^2 + 1$. The PW procedure is used to construct the polar code.

We will examine the decoding error probability as a function of the equivalent bit error probability p_e in the channel. The values of p_e will be obtained by fixing the parameters $P_{GB} = 0.01$, $p_G = 0$, and $p_B = 0.5$ in equation (1), and varying P_{BG}. These simulation parameters correspond to the use of a Gilbert channel. Fig. 6 shows the decoding error probability with list size L = 8 for a polar code with parameters n = 256, k = 128 in the Gilbert channel (G) and the BSC with corresponding values of p_e. Dotted curves are also presented, showing the probability that the burst length b generated by the channel will exceed the burst error-correcting capability. Let us denote the burst error-correcting capability of the code, according

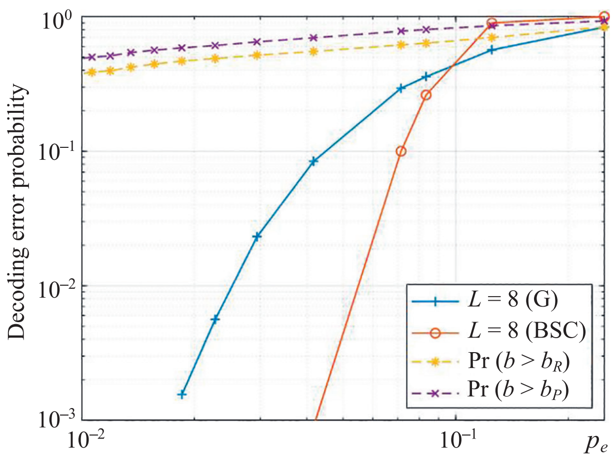

Fig. 6. Comparison of decoding error probability for a polar code with n = 256, k = 128 and different list sizes L in the Gilbert channel and BSC

to the Reiger bound, as b_R. Let the burst error-correcting capability calculated using the algorithm described in [11] be denoted as b_P. Then, the probabilities that the burst length generated by the channel will exceed the respective burst error-correcting capabilities b_R and b_P are denoted as $\Pr(b > b_R)$ and $\Pr(b > b_P)$.

Although at high error probability intervals, decoding in the BSC lags behind in terms of error probability compared to the Gilbert channel, the error probabilities in this range are quite high (close to one). As the equivalent error probability decreases, the BSC results significantly outperform those for the Gilbert channel. It is important to consider that the BSC simulation with transition probability (1) assumes infinite-length interleaving, and with a limited buffer size, error probabilities would be higher. Overall, it can be concluded that polar codes traditionally used with the classic decoder perform poorly in the presence of error bursts. This conclusion is consistent with the analysis of the burst error-correcting capability of polar codes. Moreover, as indicated by the results of the dotted curves, i.e., the probability that the burst length in the channel exceeds the burst error-correcting capability, even if the decoder were correcting bursts, in channels with random burst lengths, this would not ensure low decoding error probability due to the high probability of exceeding the burst-correcting limit. This means that in special channels with fixed burst lengths, burst error-correcting capability needs to be increased (for which interleaving was proposed). However, in channels with random burst lengths, this is insufficient, and a decoder is needed that not only corrects bursts but also corrects error patterns specific to Gilbert and GE channels.

Fig. 7 show the decoding error probability graphs for polar codes with lengths n = 64 and n = 256 and rates R = {1/4, 1/2, 3/4}. The list size used for decoding is L = 8. The results obtained at rates 1/4 and 3/4 generally correspond to those obtained earlier for rate 1/2, as shown in Fig. 6.

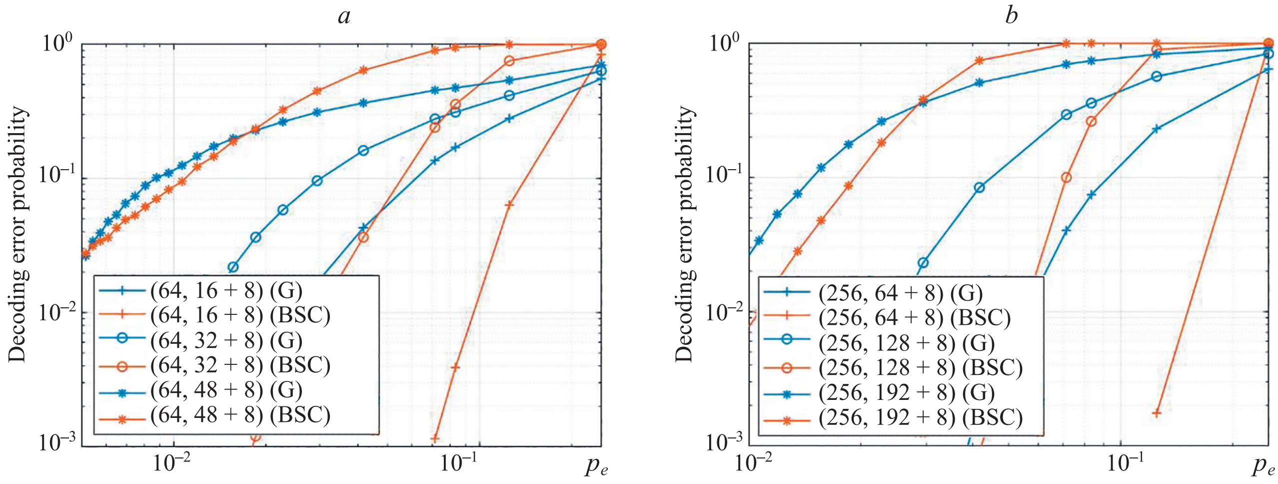

Fig. 7. Decoding error probability for: $n = 64$ (*a*); $n = 256$ (*b*)

Conclusion

In this study, we evaluated the burst error-correcting capabilities of polar codes in channels with memory and compared them to other error-correcting coding methods. Our analysis revealed that, while standard polar codes exhibit low burst error-correcting performance, this limitation can be significantly improved by applying an interleaving procedure. The proposed interleaving method enhances the error-correcting capability, bringing it closer to the Reiger bound. Additionally, we found that traditional polar code decoding algorithms do not perform well in channels with correlated noise. These results highlight the need for further research into decoding algorithms specifically adapted for channels with memory and variable packet lengths, aiming to optimize error correction in practical scenarios where noise is not memoryless.

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