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基于滑动窗译码的不规则原模图LDPC卷积码的构造

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Construction of irregular protograph-based LDPC convolutional codes with windowed decoding

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Abstract: Latency is an important indicator for modern communication systems. The windowed decoding scheme exhibits good performance with reduced latency. In this paper, a construction scheme for irregular protograph-based low-density parity-check (LDPC) convolutional codes with windowed decoding is proposed. The protograph-EXIT (P-EXIT) analysis for the accumulate-repeat-by-4-jagged-accumulate (AR4JA)-based LDPC convolutional codes over the additive white Gaussian noise (AWGN) channel shows that this flexible construction technique can give rise to the LDPC convolutional codes with different code rates and thresholds close to capacity, for both BP decoding and windowed decoding. The computer simulations identify the AR4JA-based LDPC convolutional codes outperform the regular LDPC convolutional codes and the AR4JA-based LDPC convolutional codes exhibit good performance with at least 56.7% reduced latency. Combining the proposed construction scheme for irregular protograph-based LDPC convolutional codes and the windowed decoding scheme can provide an efficient way to trade-off the decoding latency and the code performance.

Key words: low-density parity-check(LDPC); convolutional codes, protograph; windowed decoding; belief propagation; thresholds; additive white Gaussian noise(AWGN) channel

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基于滑动窗译码的不规则原模图 LDPC 卷积码的构造

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摘 要:时延是现代通信系统的一个重要指标。滑动窗译码能够在保证性能的基础上降低时延。基于滑动窗译码提出了一种不规则原模图低密度奇偶校验(low density parity check, LDPC)卷积码的构造方法。通过对基于 AR4JA (accumulate-repeat-by-4-jagged-accumulate) 的 LDPC 卷积码在 AWGN(additive white Gaussian noise)信道下的 P-EXIT 性能分析发现,利用这种构造方式能够设计出多码率并且在 BP 译码和滑动窗译码方式下都能逼近容量限的 LDPC 卷积码。计算机仿真证明了基于 AR4JA 的 LDPC 卷积码性能优于规则的 LDPC 卷积码,而且在滑动窗译码方式下在降低至少 56.7% 时延的同时表现出了很好的性能。结合提出的不规则原模图 LDPC 卷积码的构造方法和滑动窗译码得到了一种能够实现译码时延与码字性能良好折中的码字构造有效方式。

关键词:低密度奇偶校验码(LDPC);卷积码;原模图;滑动窗译码;置信传播译码;门限;加性高斯白噪声(AWGN)信道

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1 Introduction

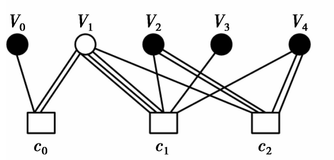
Low-density parity-check convolutional (LDPCC) codes were first introduced in[1], which can be considered as the convolutional counterpart of LDPC block codes. Ensembles of LDPCC code have several attractive characteristics, such as thresholds approaching capacity with belief-propagation (BP) decoding[2], and BP thresholds close to the maximum a-posteriori (MPA) thresholds of random ensembles with the same degree distribution [3]. But it requires large block length, thereby significantly increasing the latency. In order to get around this problem, the windowed decoding scheme was proposed to provide an efficient way to trade-off the code performance and the decoding latency when used to decode terminated (block) LDPCC codes[4-5]. Moreover, this scheme can provide the flexibility to set and change the decoding latency on the fly. This proves to be an extremely useful feature when used to decode codes over upper layers of the internet protocol.

In recent years, the studies of LDPCC codes based on a protograph[6] have shown that the protograph-based LDPCC codes have several attractive characteristics, such as linear distance growth and thresholds close to capacity[7-8]. In this paper, a construction of irregular LDPCC codes based on protograph with windowed decoding scheme over the additive white Gaussian noise (AWGN) channel is investigated. Taking the accumulate-repeat-by-4-jagged-accumulate (AR4JA) protograph [9] for example, AR4JA-based LDPCC code ensemble can be obtained by means of the proposed construction method. The LDPCC code ensemble has the same degree distribution as the AR4JA-based LDPC block code ensemble. Adding variable nodes can give rise to a family of LDPCC code ensembles with different code rates. Moreover, using protograph-based EXIT(P-EXIT) analysis for these ensembles over AWGN channel, the thresholds of these ensembles are shown to be close to capacity for both BP decoding and windowed decoding. Furthermore, it can be found from the computer simulation results that the LDPCC code ensembles obtained using the proposed construction scheme with windowed decoding scheme can achieve a good trade-off between performance and latency in comparison with BP decoding scheme over AWGN channel.

2 Preliminaries

2.1 Protograph-based LDPC block codes

A protograph [6] is a relatively small bipartite graph $\boldsymbol{B} = (V, C, E)$ that connects a set of n_v variable nodes $V = \{v_0, v_1, \cdots, v_{n_v - 1}\}$ to a set of n_c check nodes $C = \{c_0, c_1, \cdots, c_{n_c - 1}\}$ by a set of edges E. Multiple parallel edges are permitted. The protograph can be represented by a $n_c \times n_v$ bi-adjacency matrix $\boldsymbol{B}$, called base matrix. The entries of the base matrix are taken to be the number of edges connecting the variable nodes to its corresponding check nodes. For example, the AR4JA protograph and its associate base matrix are shown in Fig. 1. The AR4JA protograph has multiple repeated edges between V and C. In addition, as illustrated by the undarkened circle, variable node V_1 is punctured.



$$\boldsymbol{B} = \begin{bmatrix} 1 & 2 & 0 & 0 & 0 \\ 0 & 3 & 1 & 1 & 1 \\ 0 & 1 & 2 & 1 & 2 \end{bmatrix}$$

Fig. 1 AR4JA protograph and associated base matrix $\boldsymbol{B}$.

An ensemble of protograph-based LDPC block codes can be created from a base matrix $\boldsymbol{B}$ by the use the copy-and-permute operation [6]. Then a parity-check matrix $\boldsymbol{H}$ from the ensemble of protograph-based LDPC block codes can be obtained by replacing each 1 in $\boldsymbol{B}$ with a $M \times M$ permutation matrix and each 0 with a $M \times M$ zero matrix. If the entry in $\boldsymbol{B}$ is r, that is, the corresponding variable node and check node are connected by r repeated edges, the corresponding block in $\boldsymbol{H}$ consists of a summation of $rM \times M$ permutation matrices. Obviously, the parity-check matrix $\boldsymbol{H}$ consists of Mn_c check nodes and Mn_v variable nodes. The permutation matrices can be generated using progressive edge growth (PEG) algorithm [10] such that short cycles are avoided.

2.2 Protograph-based LDPCC codes

Analogous to block codes, an ensemble of LDPCC codes can also be described by means of a convolutional protograph with base matrix

$$B_{[-\infty,+\infty]} = \begin{bmatrix} \cdots & & \cdots & & \\ B_{m_s} & \cdots & B_0 & & \\ \vdots & & \vdots & & \\ & & B_{m_s} & \cdots & B_0 \\ & & \vdots & & \vdots \end{bmatrix}, \quad (1)$$

where m_s denotes the syndrome former memory of the convolutional codes and the $b_c \times b_v$ component base matrices $B_i, i = 0, \cdots, m_s$, describe the edges from the b_v variable nodes at time t to the b_c check nodes at time $t+i$. Utilizing the copy-and-permute operation, the LDPCC code ensemble with decoding constraint length $\nu_s = (m_s + 1)Mb_v$ can be obtained.

Suppose that we start the convolutional code with parity-check matrix defined in (1) at time $t = 0$ and terminate it after L time instants. As a result, we obtain a protograph representation with finite-length base matrix

$$B_{[0,L-1]} = \begin{bmatrix} B_0 & \cdots & \\ \vdots & & \\ B_{m_s} & \cdots & B_0 \\ & & \vdots \\ & \cdots & B_{m_s} \end{bmatrix}_{(L+m_s)b_c \times Lb_v} \quad (2)$$

The matrix $B_{[0,L-1]}$ can be considered as the base matrix of a terminated protograph-based LDPCC code. Without puncturing, the design rate of the terminated ensemble is given by

$$R_L = 1 - \frac{(L + m_s)b_c}{Lb_v} = 1 - \left(\frac{L + m_s}{L}\right)(1 - R), \quad (3)$$

where $R = 1 - Nb_c/Nb_v = 1 - b_c/b_v$ is the rate of the non-terminated convolutional code. Note that the rate of the terminated ensemble increases and approaches the rate of the non-terminated convolutional ensemble as the termination factor L increases.

2.3 Obtaining LDPCC ensembles from block protographs

From the definition of LDPCC code protograph given in (1), the case $m_s = 0$ results in disconnected protographs corresponding to a block code ensemble with base matrix $B = B_0$. Conversely, starting from the base matrix B of a block code ensemble, one can construct LDPCC ensembles that maintain the degree distribution and structure of the original ensemble. This can be achieved by the edge-spreading procedure that divides the edges from the variable nodes at time t among equivalent check nodes at time $t + i, i = 0, 1, \cdots, m_s$. The edge-spreading has to satisfy the equation given by

$$B = \sum_{i=0}^{m_s} B_i, \quad (4)$$

where the component base matrices B_i have the same size of the original block protograph. Since the entries of the base matrix B are divided among the component base matrices B_i in such a way that the sums over the columns and rows of $B_{[-\infty,+\infty]}$ are equal to those of B.

3 Design and analysis of protograph-based LDPCC codes with windowed decoding

3.1 Windowed decoding (WD)

The WD scheme was proposed in [4]. This decoding scheme mainly exploits the convolutional structure of the code which imposes a maximum distance constraint on the variable nodes connected to the same parity check equations-two variable nodes that are at least $(m_s + 1)$ time units apart cannot be involved in the same equation. In what follows, we will review the decoding scheme which can be utilized to decode the terminated codes consecutively with reduced latency and propose a modified stopping rule for WD to improve the performance.

Consider a terminated parity-check matrix H built from a base protograph B and a sliding window consisting of WMb_c rows and $(W + m_s)Mb_v$ columns, $m_s + 1 \leqslant W \leqslant L + m_s$, i.e., the sliding window covers Wb_c rows and $W(b_v + m_s)$ columns of the protograph B. At the first time instant, $t = 1$, the decoder performs belief propagation to decode all of the first b_vM symbols in the window, called the targeted symbols. Then the window shifts down Mb_c rows and right Mb_v columns in

$\boldsymbol{H}$ when all the targeted symbols in the first window have been recovered, and continues decoding at the new position at the second time instant, i. e., $t=2$.

Fig. 2 shows a schematic representation of WD with window size $W=5$ for the terminated LDPCC code ensemble with $m_s=3$ and $L=12$ at the fifth decoding instant. This window consists of WMb_c rows of the parity-check matrix and all the $(W+m_s)Mb_v$ columns involved in these equations: this comprises the white (vertically hatched) and the black edges shown within the matrix. Note that the symbols shown in gray above the parity-check matrix have all been processed. The targeted symbols are shown in black above the parity-check matrix and the symbols that are yet to be decoded are shown in white above the parity-check matrix.

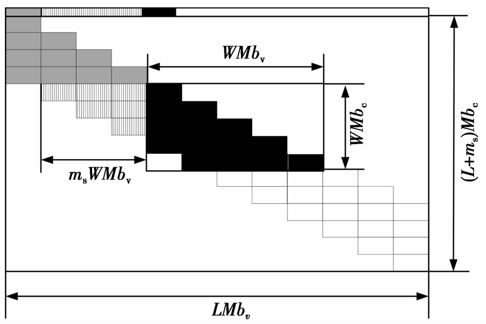


Fig. 2　Windowed decoder with window size $W=5$ for the terminated LDPCC code with the termination factor $L=12$ at time instant $t=5$.

Modified stopping rule: in order to decrease the influence of the lack of extrinsic information from the check nodes within a window, the modified stopping rule of windowed decoding is proposed. In the BP decoding, the decoder will stop after a maximum number of belief propagation iterations have been performed or the codeword satisfies the check equations. While for the windowed decoder, the window decoder at position t will stop and slide to the next position $t+1$ after a maximum number of belief propagation iterations have been performed or the current targeted symbols satisfy the parity constraint after performing a fixed number (the minimum number) of belief propagation iterations. Using this modified stopping rule, a good BER performance with windowed decoding can be achieved.

The relation between the decoding latencies of windowed decoding and BP decoding is given by

$$T_{\mathrm{WD}} \leqslant \frac{(W+m_s)}{L} T_{\mathrm{BP}} \tag{5}$$

It observes from (5) that the windowed decoding latency reduction decreases as W increases in the case of a fixed termination factor.

3.2　Design and analysis of AR4JA-based LDPCC codes

The AR4JA protograph and associated base matrix are displayed in Fig. 1. The ensemble defined by this protograph is of practical interest, since it has a minimum distance growth rate $\delta_{\min}=0.015$ and AWGN iterative decoding threshold $\varepsilon=0.628$ dB. Consider splitting $\boldsymbol{B}$ into component sub-matrices $\boldsymbol{B}_0$ and $\boldsymbol{B}_1$ of size $b_c \times b_v = 3\times 5$ as follows:

$$\boldsymbol{B}_0=\begin{bmatrix}1&1&0&0&0\\0&1&1&0&0\\0&0&0&1&1\end{bmatrix},\boldsymbol{B}_1=\begin{bmatrix}0&1&0&0&0\\0&2&0&1&1\\0&1&2&0&1\end{bmatrix},$$

where $\boldsymbol{B}_0+\boldsymbol{B}_1=\boldsymbol{B}$. Then we can form a convolutional base matrix as in (1). Note that the variable nodes associated with the second column of the component sub-matrices are punctured in accordance with the AR4JA protograph. The design criteria based on the edge spreading procedure are presented as follows:

1) Make sure the checks at time $t=1$ have low degree (but at least degree two).

2) Puncture the variable nodes with the largest degree, which is the same as the original AR4JA protograph.

3) Ensure that the edges from variable nodes at time t are divided among check nodes at times $t, t+1, \cdots, t+m_s$.

The convolutional base matrix may then be terminated as shown in (2), for terminated factors $L\geqslant 2$. Then a block protograph $\boldsymbol{B}_{[0,L-1]}$ with Lb_v variable nodes and $(L+m_s)b_c$ check nodes can be obtained by terminating the convolutional protograph after an arbitrary L. The design rate of the terminated ensemble is given by

$$R_L=\frac{n_v-n_c}{u_{\mathrm{trans}}}=\frac{5L-3(L+1)}{4L}=\frac{2L-3}{4L} \tag{6}$$

The AR4JA protograph can be extended by adding $2e$ variable nodes of degree 4 as shown in Fig. 3. Extending the AR4JA protograph in this way can preserve linear minimum distance growth and the corresponding LDPC code ensembles have shown to have good iterative decoding thresholds [9]. Note that the AR4JA protograph with extension factor $e=0$ is the original AR4JA protograph.

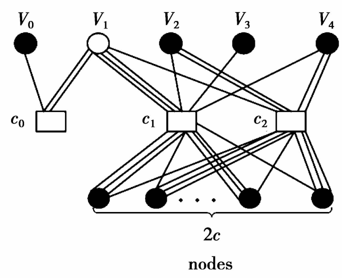


Fig. 3 AR4JA protographs with extension factor e

Using the edge spreading method proposed above, we can construct a family of AR4JA-based LDPCC code ensemble using the component protographs $\boldsymbol{B}_0$ and $\boldsymbol{B}_1$ as shown in Fig. 4 (undarkened circles represent the punctured node). Terminated AR4JA base matrix $\boldsymbol{B}_{[0,L-1]}$ with extension factor e can be formed as in (2). Note that there are L punctured nodes. After puncturing, the design rate of the terminated ensemble with extension factor e is given by

$$R_L=\frac{n_{\mathrm{v}}-n_{\mathrm{c}}}{u_{\mathrm{trans}}}=\frac{(5L+2e)-3(L+1)}{4L+2e}=\frac{2(L+e)-3}{4L+2e}. \tag{7}$$

Similar to LDPC block code, the AR4JA-based LDPCC code with extension factor $e=0$ is the code proposed in this section.

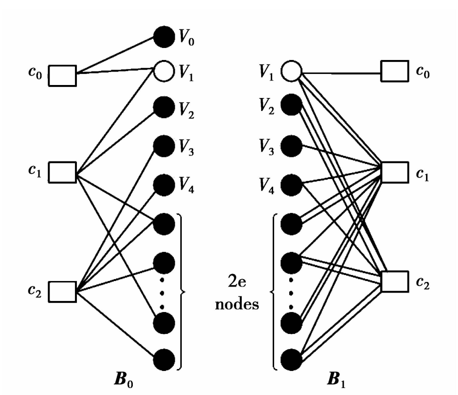


Fig. 4 Component protographs for the AR4JA-based LDPCC code ensembles with extension factor e

The P-EXIT analysis of protograph-based LDPC codes with the BP decoding over the AWGN channel was studied in [11]. In order to analyze the windowed decoding thresholds of protograph-based LDPCC codes, the modified P-EXIT algorithm based on the original P-EXIT algorithm is proposed.

The modified P-EXIT algorithm is similar to that of the BP decoder owing to the fact that the part of the code within a window is itself a protograph-based code. However, the main distinction between them is the updating of the mutual information. In BP decoding, we update the mutual information on the d^{th} edge at a node of degree d with all the mutual information along the edge, while the updating of mutual information for the windowed decoding on the d^{th} edge only includes a fraction of the mutual information owing to the termination. Using the original and modified P-EXIT analysis, the calculated AWGN thresholds of the AR4JA-based LDPCC code ensembles with BP decoding and windowed decoding are given in Tab. 1.

Tab. 1 P-EXIT thresholds of the AR4JA-based LDPCC codes

AR4JA	Capacity/dB	BP/dB	WD($W=12$)/dB
$e=0$	0.187	0.419	0.439
$e=1$	1.059	1.190	1.205
$e=2$	1.626	1.721	1.735

From Tab. 1, we can see that the WD thresholds of AR4JA-based LDPCC codes with window size $W=12$ are very close to that of BP decoding. Moreover, by adding different number of variable nodes, the thresholds of the LDPCC codes with both BP decoding and windowed decoding are close to capacity. Further, we observe that the gap to capacity decreases as the extension factor increases.

We also analyze the WD thresholds of the AR4JA-based LDPCC codes discussed in [8], which outperform the codes we proposed above. Nevertheless, the computer simulations indicate that the error floor is achieved at a BER of 10-4 which is not suitable for many communication scenarios.

4 Simulation results

In this section, we evaluate the performance of the irregular protograph-based LDPCC codes which are constructed using the proposed construction method through the computer simulations. Taking the AR4JA-based LDPCC code ensemble for example, the AR4JA-based LDPCC codes with rate $R = 0.475$ and rate $R = 0.65$ are obtained by setting $e = 0$ and $e = 1$. For comparison, the regular ensemble defined by edge spreading $\boldsymbol{B}_0 = [2, 2]$ and $\boldsymbol{B}_1 = [1, 1]$ of $\boldsymbol{B} = [3, 3]$ is also simulated.

The maximum number of iterations is set to $I_{\max} = 100$ for both BP decoding and WD scheme. In WD, the minimum number of iterations is $I_{\min} = 5$. The decoding constraint lengths for the (3, 6)-regular and AR4JA-based LDPCC codes are $\nu_s = 640$. Meanwhile, the AR4JA-based LDPC block code length is set to $N = 640$, which is the same as the LDPCC code constraint length. And to ensure the codes have the same code rate ($R = 0.475$), the termination factor of (3, 6)-regular LDPCC code is set to $L = 20$, while the AR4JA-based LDPCC codes are set to $L = 30$.

Fig. 5 shows the simulation results of (3, 6)-regular and AR4JA-based LDPCC code ($e = 0$) with BP decoding and windowed decoding. It can be found that the AR4JA-based LDPCC code outperforms the regular one with both BP decoding and WD.

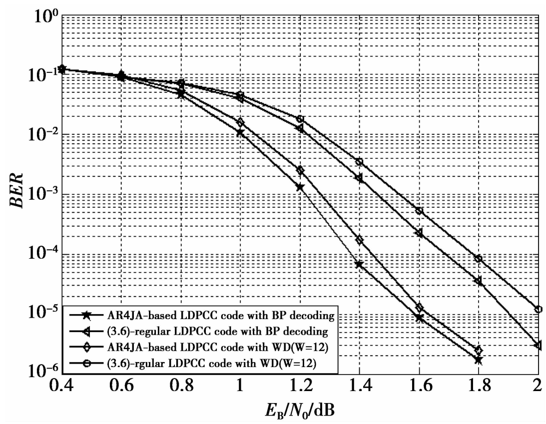


Fig. 5　AWGN channel performance of terminated AR4JA-based LDPCC code and (3,6)-regular LDPCC code with the same constraint length $\nu_s = 640$ and rate $R = 0.475$.

Fig. 6 and Fig. 7 show the simulation results with the same decoding constraint length $\nu_s = 640$ for rate $R = 0.475$ and $R = 0.65$ AR4JA-based LDPCC codes, respectively. In the simulation, both BP decoding and WD are utilized for the AR4JA-based LDPCC codes. In order to gauge the performance, the corresponding AR4JA-based LDPC block codes with equivalent code length $N = 640$ are also shown. One observes from the Fig. 6 and Fig. 7 that compared with the BP decoding, the irregular protograph-based LDPCC codes with windowed decoding shows a little worse performance. Nevertheless, a latency reduction of at least $\frac{W + m_s}{L} T_{BP}$ can be obtained. For example, the latency reduction can achieve 56.7% with window size $W = 12$ and 76.7% with window size $W = 6$, respectively. It can also be seen that the LDPCC codes outperform the corresponding LDPC block codes, which is referred to as "convolutional gain". In [12-13], Costello et al. conjecture that the "convolutional gain" is due to the concatenation of many constraint lengths worth of received symbols in the decoding process.

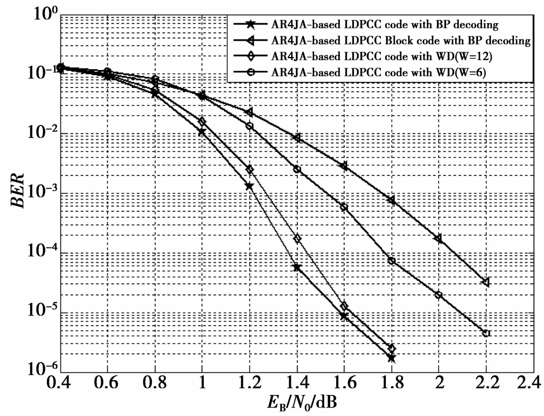


Fig. 6　AWGN channel performance of terminated AR4JA-based LDPCC code with constraint length $\nu_s = 640$ and rate $R = 0.475$. For comparison, AR4JA-based LDPC block code with code length $N = 640$ and rate $R = 0.5$ is also shown.

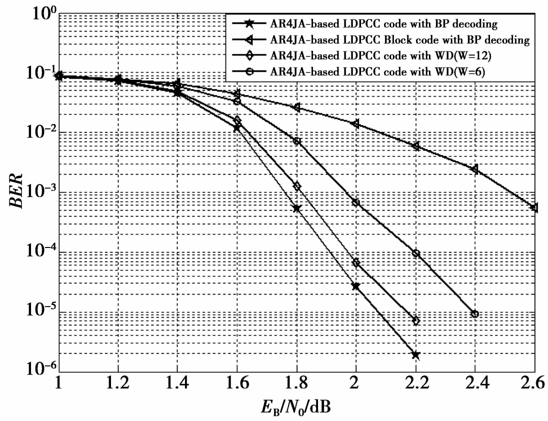


Fig. 7　AWGN channel performance of terminated AR4JA-based LDPCC code with constraint length $\nu_s = 640$ and rate $R = 0.65$. For comparison, AR4JA-based LDPC block code with code length $N = 640$ and rate $R = 0.67$ is also shown.

From the simulation results and the discussions above, it observes that the irregular protograph-based LDPCC codes obtained by using the proposed construction scheme can exhibit good performance with reduced decoding latency with windowed decoding.

5 Conclusions

In this paper, a construction scheme for the irregular protograph-based LDPCC codes with windowed decoding was proposed. The P-EXIT analysis and simulation results based on the AR4JA-based LDPCC codes indicate that the irregular protograph-based LDPCC codes obtained using the construction scheme outperform the regular LDPCC code and have thresholds close to capacity for both BP decoding and windowed decoding. Moreover, combining the proposed construction scheme for irregular protograph-based LDPCC codes and the windowed decoding scheme can provide an efficient way to trade-off the decoding latency and the code performance.

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