On efficient design of protograph LDPC codes

Huong-Giang Nguyen, Nghia Xuan Pham, Thu Phuong Nguyen and Chi Dinh Nguyen*

Abstract—This paper designs two protograph low-density parity-check (LDPC) codes with code-rate $R > 1/2$. A simple method using the protograph extrinsic information transfer (PEXIT) to design the codes with a low decoding threshold and the asymptotic weight enumerator (AWE) to evaluate the error floor of the codes is deployed. Simulation results show that the proposed codes have a better error floor than prior art protograph codes and offer higher rate protographs.

Index Terms—LPDC codes, protograph codes, weight enumeration, iterative decoding threshold.

1. Introduction

ONE of the most critical targets of communication channels is reliability. In order to ensure the reliability of the data transmission, robust channel codes are usually deployed. There are two common-used channel coding schemes, namely error-correction coding (ECC) and modulation (constrained) coding. The modulation codes shape the input sequences to match the characteristic of the channel. The ECC schemes attempt to correct already-occurred errors.

Low-density parity-check (LDPC) codes that can achieve performances very close to the Shannon limit over an additive white Gaussian noise (AWGN) channel are currently regarded as one of the most potent codes for the error correction. The LDPC codes were proposed by Gallager [1] in 1962. Since 1993, there have been many contributions in revisiting and extending the design and analysis of LDPC codes. Together with polar codes (for the control channel), the LDPC codes (for the user-data channel) have been adopted for the fifth generation mobile communications system (5G) [2]. One of the structured LDPC code designs having been received significant attention is based on protographs [3]. A protograph is a Tanner graph containing a few check and variable nodes. Larger derived graphs can be generated by an operation of "copy-and-permute" on the protograph [4]. Moreover, it is also important to note that the protograph-structured LDPC codes are a subclass of multi-edge-type LDPC codes [5].

Designing protograph LDPC is often based on the protograph design criteria of iterative decoding threshold and linear minimum distance growth. The good LDPC codes obtain a low decoding threshold and guarantee the property of linear minimum distance growth. Furthermore, the complexity of encoding and decoding is also an important issue needed to address.

The protograph's mentioned-above decoding threshold refers to the minimum channel SNR supporting reliable decoding of asymptotically large LDPC codes built from the protograph. This threshold is calculated by the protograph extrinsic information transfer (PEXIT) method. The property of linear minimum distance growth can be verified by the asymptotic weight distributions (AWD) analysis. The protograph design criteria and related schemes are discussed in more detail in the next Section.

Protograph LDPC codes have been recently applied in many fields such as the next-generation magnetic recording systems [6], [7], flash memory [8], underwater acoustic channels [9], spin-torque transform magnetic random access memory (STT-MRAM) [10], MIMO system [11]. Recent works related to our results are the works of Uchikawa [12] and Nguyen and Nguyen [13]. In [12], the author proposed non-punctured protograph codes having a good performance with the small number of decoding iteration regimes. In [13], the authors designed two protograph codes with the predefined number of decoding iterations. To the best of our knowledge, the authors in [12]–[16] have shown the best-structured 1/2-rate and 2/3-rate LDPC codes so far. In fact, it is too complex to find out the better ones. Therefore, we concentrate on the LDPC codes having a base matrix of code-rate $1/2 < R < 2/3$ in this study. In detail, our main contribution is to design two protograph LDPC codes, namely 5/9-rate and 3/5-rate codes, by using the PEXIT method and AWD analysis. Higher rate protograph codes can be achieved by lengthening or puncturing techniques [14]–[16].

The paper is organized as follows. Section II introduces how to construct a good protograph with error correction based on the design criteria. A review of the PEXIT method and AWD analysis is also presented in this Section. In Section III, the proposed codes are designed based on the analyses. The simulation results and discussion are presented in Section IV. Finally, Section V concludes the paper.

2. Designing good protograph LDPC codes

2.1. How a good protograph with error correction

In this section, we present the properties of a good protograph. Designing protographs concern the search for a

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base matrix with the lowest possible decoding threshold while maintaining linear minimum distance growth property. In general, an excellent structured protograph should contain one or more degree-1 (D-1) variable nodes, several D-2 variable nodes, and at least one very high degree variable node. Such constructions lower the iterative decoding threshold and improve the system performance.

For the property of linear minimum distance growth, it is well-known that a graph having a whole of variable node degrees larger than or equal to three has this property automatically [14]. Therefore, a splitting technique, for instance, proposed in [14], can be applied to construct a graph with variable nodes of D-2 from a graph having variable nodes of at least D-3 while still preserving its linear minimum distance growth property. This technique requires the maximum number of D-2 variable nodes in the protograph to be limited by the total number of check nodes – 1.

Another factor affecting the performance of the code design is puncturing. One of the first famous conventional protograph designs proposed [14] was with some punctured node. However, recent research shows that puncturing increases complexity for both the encoder and decoder and results in worse performance in some cases [13], [17], [18].

2.2. Protograph EXIT Analysis

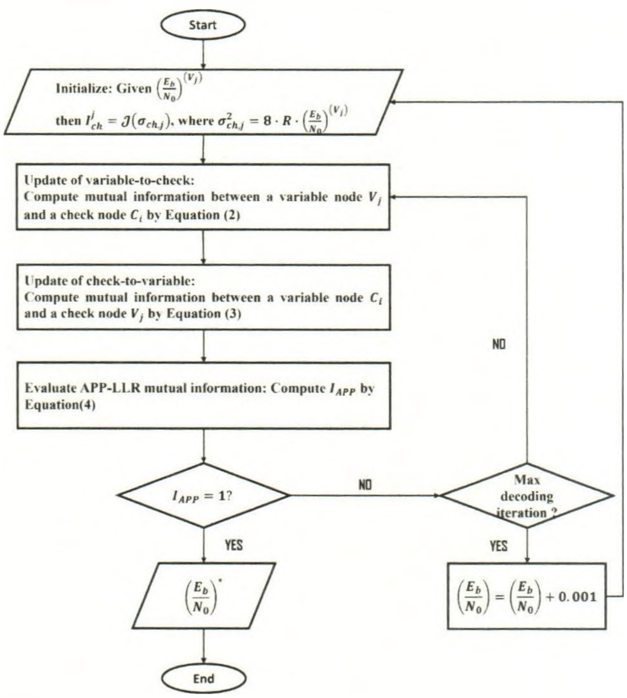

Fig. 1: Algorithm flowchart for finding out the iterative decoding threshold.

An iterative decoding threshold of a protograph is the minimum channel quality that ensures successful decoding for infinite-length LDPC codes built from the protograph. Extrinsic information transfer (EXIT) charts [19] are a great tool to design LDPC codes thanks to because of their accuracy in performance prediction. Yet, the EXIT charts generally cannot be applied to the study of protograph-based LDPC codes. To match the property of these codes, Liva and Chiani [20] proposed the PEXIT method. By using this technique, the iterative threshold of a protograph is calculated based on its edge degree distribution. The PEXIT technique provides a simple tool to analyze protograph-based codes with a remarkable reduction in computational complexity. We briefly review this technique here.

First, we assume that a protograph has P variable nodes, named $V_1, \ldots, V_P$, and Q check nodes, named $C_1, \ldots, C_Q$. We denote also $b^{i,j}$ is the number of edges connecting V_j to C_i, where $j = 1, \ldots, P$ and $i = 1, \ldots, Q$. We define four types of mutual information as follow,

- $I_{ch}^{(j)}$: a priori knowledge of a variable node V_j in the LDPC decoder.
- $I_{EV}^{(i,j)}$ and $I_{EC}^{(i,j)}$: extrinsic mutual information between a variable node V_j and a check node C_i, and between a check node C_i and a variable node V_j, respectively.
- $I_{AV}^{(i,j)}$ and $I_{AC}^{(i,j)}$: incoming a priori knowledge from C_i to V_j, and from V_j to C_i, respectively.
- $I_{AP}(j)$: a posteriori mutual information calculated by the corresponding coded symbol V_j.

The algorithm to find out the iterative decoding threshold is summarized as follows,

- **Initialization**
  For the given $\left(\frac{E_b}{N_0}\right)^{(V_j)}$ at the j-th variable node, initialize $I_{ch}^{j} = \mathcal{J}(\sigma_{ch,j}), j = 1, \ldots, P$. Where, the value of $\sigma_{ch,j}^2 = 8 \cdot R \cdot \left(\frac{E_b}{N_0}\right)^{(V_j)}$, where R is the code-rate of the protograph. The $\mathcal{J}(.)$, given by [1], represents the capacity of Gaussian channel with the binary input, and can be expressed by,
  $$\mathcal{J}(\sigma) = 1 - \int_{-\infty}^{-\infty} \frac{1}{(2\pi\sigma^2)^{1/2}} e^{-\frac{(\xi-\sigma^2/2)^2}{2\sigma^2}} \cdot \log_2(1+e^{-\xi})\, d\xi. \tag{1}$$
- **Update of variable-to-check**
  For $j = 1, \ldots, P$ and $i = 1, \ldots, Q$, if $b^{i,j} \neq 0$,
  $$I_{EV}^{(i,j)} = \mathcal{J}\Bigg(\Big(\sum_{s \neq i} b^{s,j}[\mathcal{J}^{-1}(I_{AV}^{(s,j)})]^2 + (b^{i,j}-1)[\mathcal{J}^{-1}(I_{AV}^{(i,j)})]^2 + [\mathcal{J}^{-1}(I_{ch}^{j})]^2\Big)^{1/2}\Bigg). \tag{2}$$
  If $b^{i,j} = 0$, then $I_{EV}^{(i,j)} = 0$.
  For $j = 1, \ldots, P$ and $i = 1, \ldots, Q$, set $I_{AC}^{(i,j)} = I_{EV}^{(i,j)}$.
- **Update of check-to-variable**
  For $j = 1, \ldots, P$ and $i = 1, \ldots, Q$, if $b^{i,j} \neq 0$,
  $$I_{EC}^{(i,j)} = 1 - \mathcal{J}\Bigg(\Big(\sum_{s \neq j} b^{i,s}[\mathcal{J}^{-1}(1 - I_{AC}^{(i,s)})]^2 + (b^{i,j}-1)[\mathcal{J}^{-1}(1 - I_{AC}^{(i,j)})]^2\Big)^{1/2}\Bigg). \tag{3}$$
  If $b^{i,j} = 0$, then $I_{EC}^{(i,j)} = 0$.
  For $j = 1, \ldots, P$ and $i = 1, \ldots, Q$, set $I_{AV}^{(i,j)} = I_{EC}^{(i,j)}$.

- **APP-LLR mutual information evaluation**
  For $j = 1, \ldots, P$

$$I_{APP}(j) = \mathcal{J}\left(\left(\sum_s b^{s,j}[\mathcal{J}^{-1}(I_{AV}^{(s,j)})]^2 + [\mathcal{J}^{-1}(I_{ch}^{(j)})]^2\right)^{1/2}\right). \quad (4)$$

- **Iteration**
  Evaluation process stops if either $I_{APP}(j) = 1, \forall j$, or the algorithm reaches the predetermined maximum number of iteration.

The lowest value of $\left(\frac{E_b}{N_0}\right)$, denoted as $\left(\frac{E_b}{N_0}\right)^*$, where the mutual information between the APP-LLR messages and corresponding symbol converges to 1, is the desired value of iterative decoding threshold. The summary flowchart of the algorithm is illustrated in Figure 1.

2.3. Asymptotic Weight Distribution Analysis

In this section, we evaluate the minimum distance and error floor for the protograph codes by using the AWD analysis. We still keep the above mentioned assumption that the protograph has P variable nodes and Q check nodes. Let δ denote the scalar normalized total codeword weight, and $r(\delta)$ denote a corresponding normalized logarithmic AWD for each vector δ of partial weights. The $r(\delta)$ can be expressed as follows,

$$r(\delta) = \sum_{i=1}^{Q} a^C(\delta_i) - \sum_{j=1}^{P}(q_j^V - 1)H(\delta_j). \quad (5)$$

where $a^C(\delta_i)$ denotes the normalized logarithmic AWD for the check node C_i with the normalized partial weight vector δ_i, q_j^V denotes the degree of variable node V_j, and $H(\delta_j)$ is the binary entropy function with the argument of δ_j. The evaluation of the $r(\delta)$ can be determined as,

$$Pr(\delta) = \max_{\delta:|\delta_t|=P\delta} r(\delta) = \max_{\delta:|\delta_t|=P\delta} r_t(\delta_t). \quad (6)$$

where $r(\delta)$ for any sub-vector δ_t of the normalized partial weight of the variable nodes is obtained by maximizing $r(\delta)$.

The normalized weight distribution $r(\delta)$ is used to decide whether or not the minimum distance of codes increase linearly with the length of the codes. One of the primary signs is that if $r(\delta)$ initially goes negative before returning and crossing zero, the first zero-cut point, denoted by δ_{min} is called the typical minimum distance ratio. The $\delta_{min} > 0$ means that with high probability the minimum distance d of most codes in the ensemble increases linearly with the code length L with proportionality constant δ_{min}, i.e., $d \approx \delta_{min} \times L$.

3. Proposed code designs

Based on the guidelines presented in Section II, we design the codes with the code-rate $R > 1/2$ by concentrating on the search of good protographs which meet design criteria of the iterative decoding threshold and linear minimum distance growth. In fact, a rate-5/9 protograph and a rate-3/5 protograph are proposed herein. We first design the rate-5/9 protograph code corresponding to a 4×9 base matrix. Note that the proposed codes are non-punctured codes in this work. We can run the search space with reasonable complexity by initializing the base matrix with some constrains. For the first constraint, these elements in the base matrix have been limited to no larger than 3. For the second one, the form of base matrix is initialized with one D-12, two D-2, and three D-3 variable nodes. Therefore, the base matrix of the rate-5/9 protograph code can be initialized in the following form,

$$H_{5/9}^{ser} = \begin{pmatrix} 3 & x_{1,1} & x_{1,2} & x_{1,3} & 1 & 0 & 0 & 0 & 1 \\ 3 & x_{2,1} & x_{2,2} & x_{2,3} & 0 & 1 & 0 & 0 & 0 \\ 3 & x_{3,1} & x_{3,2} & x_{3,3} & 0 & 0 & 1 & 1 & 0 \\ 3 & x_{4,1} & x_{4,2} & x_{4,3} & 2 & 2 & 2 & 1 & 1 \end{pmatrix} \quad (7)$$

where the value of $x_{i,j}$are the number of edges connecting their associated variable nodes (column) and check nodes (row). To further simplify the complexity, we impose another constraint of the edge summation over three columns (from the 2^{nd} column to 4^{th} column) such that the summation must be larger than 3. After the brute-force search, the base matrix, denoted by $H_{5/9}^{c1}$ is in the form of

$$H_{5/9}^{c1} = \begin{pmatrix} 3 & 2 & 0 & 2 & 1 & 0 & 0 & 0 & 1 \\ 3 & 2 & 2 & 2 & 0 & 1 & 0 & 0 & 0 \\ 3 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 \\ 3 & 0 & 2 & 1 & 2 & 2 & 2 & 1 & 1 \end{pmatrix} \quad (8)$$

The protograph of the rate-5/9 protograph code is plotted in Figure 2.

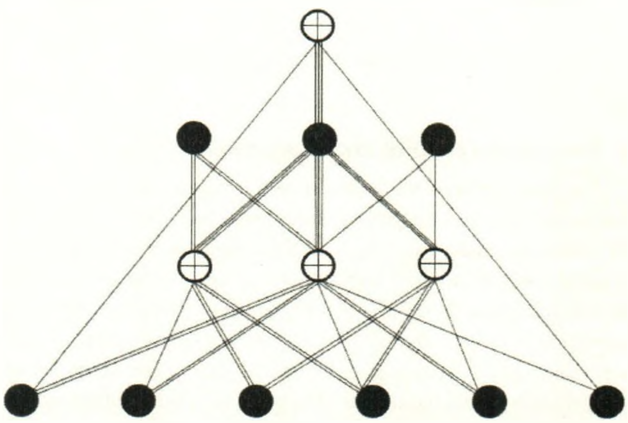

Fig. 2: Proposed 5/9-rate protograph.

The second proposed code of rate-3/5 corresponding to a 4×10 base matrix is built by increasing the proportion of D-2 variable nodes to reduce decoding threshold. The base matrix of the second proposed code can be initialized in the following form,

$$H_{3/5}^{ser} = \begin{pmatrix} 3 & x_{1,1} & x_{1,2} & x_{1,3} & 1 & 0 & 0 & 0 & 1 & 1 \\ 3 & x_{2,1} & x_{2,2} & x_{2,3} & 0 & 1 & 0 & 0 & 0 & 1 \\ 3 & x_{3,1} & x_{3,2} & x_{3,3} & 0 & 0 & 1 & 1 & 0 & 0 \\ 3 & x_{4,1} & x_{4,2} & x_{4,3} & 2 & 2 & 2 & 1 & 1 & 0 \end{pmatrix} \quad (9)$$

After a simple search, the base matrix of the rate-3/5 protograph code, denoted by $H_{3/5}^{c2}$ is in the form of

$$H_{3/5}^{c2} = \begin{pmatrix} 3 & 2 & 2 & 2 & 1 & 0 & 0 & 0 & 1 & 1 \\ 3 & 2 & 2 & 2 & 0 & 1 & 0 & 0 & 0 & 1 \\ 3 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 \\ 3 & 0 & 0 & 0 & 2 & 2 & 2 & 1 & 1 & 0 \end{pmatrix} \quad (10)$$

The protograph of the rate-3/5 protograph code is plotted in Figure 3.

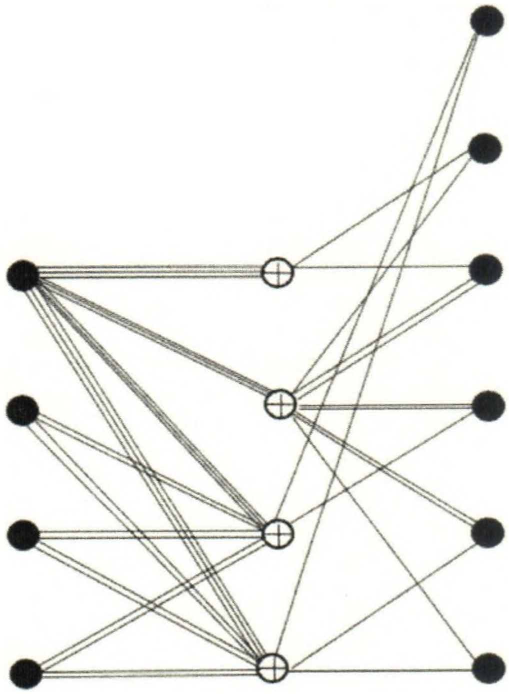

Fig. 3: Proposed 3/5-rate protograph.

4. Simulation results and discussion

In this section, we present some simulation results of the priori arts and proposed codes over the AWGN channel. In particular, the protograph LDPC codes are decoded by a belief propagation (BP) algorithm and the maximum number of BP iterations is equal to 100. The copy-and-permutation operation is carried out by the progressive edge growth (PEG) algorithm [21]. This algorithm is to determine a circulant permutation of each edge, aiming to avoid short-length cycles occurred with the desired code block length. The operation is with the factor of 256. We used the binary phase shift keying (BPSK) herein. The proposed rate-5/9 protograph code has the decoding threshold of 0.902 dB, for the maximum number of decoding iterations of 20, whereas the rate-3/5 protograph code has the decoding threshold of 1.070 dB. By observation, we see that the proposed 5/9-rate code has the code-rate loss of 7.4 %, compared to the the proposed 3/5-rate code. However, the former proposed code provides a gain of approximate 0.168 dB lower than that of the proposed latter for the iterative decoding threshold.

This section studies the AWD of the two proposed codes. Fig. 3 shows that the typical minimum distance ratios of the 5/9-rate code and the 3/5-rate code are 0.0088 and 0.0027, respectively. As can be seen in Fig. 3, both the δ_{min} values are greater than zero. Thus, the proposed LDPC codes with corresponding protographs are guaranteed to have linear minimum distance growth. Moreover, the 5/9-rate code having a larger growth rate δ_{min} offers a larger minimum distance and a lower error floor in the high SNR region.

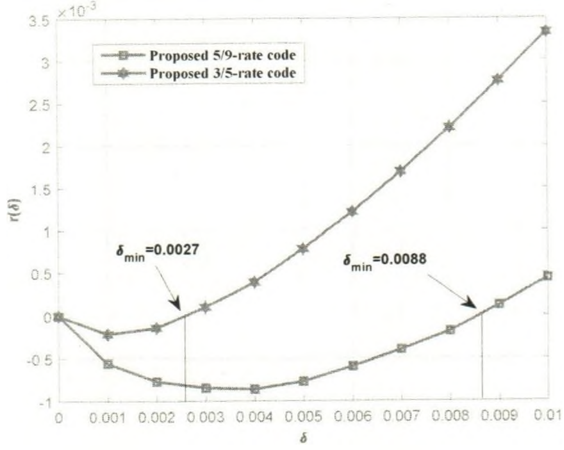

Fig. 4: Asymptotic weight distributions and zero crossings for the proposed protographs.

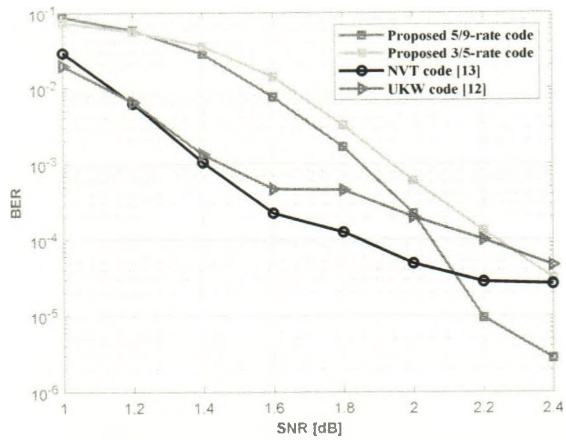

Fig. 5: BER performance comparison of the proposed codes and prior art codes.

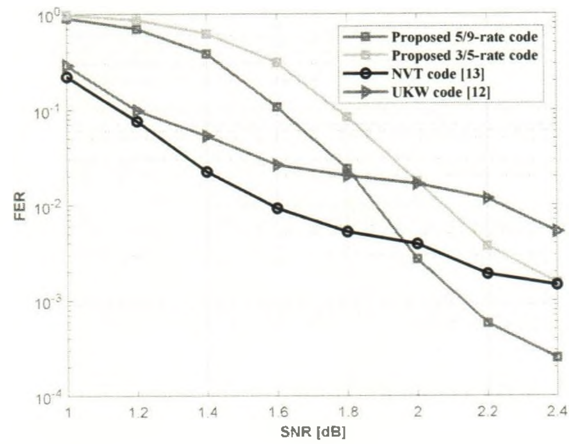

Fig. 6: FER performance comparison of the proposed codes and prior art codes.

Bit-error-rate (BER) and frame-error-rate (FER) performances of our two new codes compared to two prior art 1/2-rate codes, named UKW code [12] and NVT code [13], respectively, are shown in Figs. 4 and 5. We can see that the performance of proposed codes are worse the prior art codes in the waterfall region. Moreover, the performace of the 3/5-rate code is slightly better than that of the 5/9-rate code. The result can be explained by the ratio of D-2 variable nodes of the 3/5-rate code is larger than that of the 5/9-rate one. In the error floor regime, the proposed 5/9-rate has the best error performance, followed by the NVT code, the proposed 3/5-rate code, and the UKW code, respectively. For instance, at SNR of 2.2 dB, the BER performances of the proposed 5/9-rate, the NVT code, the proposed 3/5-rate code, and the UKW code are approximately 9.4×10^{-6}, 2.8×10^{-5}, 1.3×10^{-4}, 1×10^{-4}, respectively. Moreover, there is no error floor observed down to BER 10^{-6} and FER 10^{-4}.

5. Conclusion

In this work, we have designed LDPC codes with code rate $R > 1/2$. The performance of the proposed codes is evaluated by the iterative decoding threshold and the AWD analysis. The simulation results show that the proposed 5/9-rate code outperforms the other conventional codes in the error floor regime. Thus, the proposed codes are good alternatives compared with other error-correction codes for practical applications with reasonable complexity. Finally, higher rate protograph codes can be obtained by lengthening or puncturing techniques on these proposed codes. Some slight modification is needed when implementing the proposed code on other channel models.

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