Spatially-Coupled Protograph LDPC-Coded Hierarchical Modulated BICM-ID Systems: A Promising Transmission Technique for 6G-Enabled Internet of Things

Zhaojie Yang, Yi Fang, *Member, IEEE*, Guojun Han, *Senior Member, IEEE*,
and Kazi Mohammed Saidul Huq, *Senior Member, IEEE*

Abstract—As a spectral-efficiency technique for unequal error protection (UEP), hierarchical modulated (HM) bit-interleaved coded modulation (BICM) with iterative decoding (ID) has attracted interests in wireless communication community. In this paper, we conduct an investigation on spatially coupled (SC) protograph low-density parity-check (P-LDPC)-coded M -ary quadrature amplitude modulation (QAM) HM-BICM-ID systems. We first develop an information-theoretic methodology to calculate $(\log_2 M)/2$ types of constellation-constrained average mutual information (AMI), which can be used to characterize the performance limits of different layers in the HM-BICM systems. We further propose a two-stage design approach to construct a novel type of constellations, called as *structural quadrant (SQ) constellations*, and develop a quadrant-based harmonic mean analysis to evaluate the non-feedback and iterative-feedback asymptotic performance of the proposed constellations. In addition, we conceive a performance-analysis tool, referred to as *multi-stream-based extrinsic information transfer (MS-EXIT) algorithm*, for predicting the decoding thresholds of all individual coded-bit streams in the proposed SC P-LDPC-coded HM-BICM-ID systems. Simulation results not only agree well with the theoretical analyses, but also indicate that the proposed SC P-LDPC-coded HM-BICM-ID systems are remarkably superior to the state-of-the-art counterparts. Thereby, the proposed SC P-LDPC-coded HM-BICM-ID systems are competent to provide diverse quality-of-service (QoS) for future wireless applications, such as 6G-enabled Internet of Things (IoT).

Index Terms—Hierarchical modulation (HM), spatially coupled (SC) protograph low-density parity-check (P-LDPC), constellation, harmonic mean, extrinsic information transfer (EXIT), 6G-enabled Internet of Things (IoT).

Copyright (c) 20xx IEEE. Personal use of this material is permitted. However, permission to use this material for any other purposes must be obtained from the IEEE by sending a request to pubs-permissions@ieee.org.

Manuscript received June 29, 2020; revised September 2, 2020; accepted September 23, 2020. Date of publication Month XX, 2020; date of current version Month XX, 2020. The work of Z. Yang, Y. Fang, and G. Han was supported in part by the NSF of China under Grants 62071131, 61771149 and 61871136, in part by the Open Research Fund of the State Key Laboratory of Integrated Services Networks under Grant ISN19-04, in part by the NSF of Guangdong Province under Grant 2019A151011465, in part by the Science and Technology Program of Guangzhou under Grant 201904010124, in part by the Guangdong Province Universities and Colleges Pearl River Scholar Funded Scheme under Grant 2017-ZJ022, in part by the Research Project of the Education Department of Guangdong Province under Grants 2017KTSX060 and 2017KZDXM028, in part by the Graduate Education & Innovation Project of Guangdong Province under Grant 2020SQXX12, and in part by the Guangdong Innovative Research Team Program under Grant 2014ZT05G157. The work of K. M. S. Huq was supported in part by the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie Grant Agreement No. 839573. (Corresponding author: Yi Fang.)

Z. Yang, Y. Fang, and G. Han are with the School of Information Engineering, Guangdong University of Technology, Guangzhou 510006, China (email: zjyang0131@163.com; fangyi@gdut.edu.cn; gjhan@gdut.edu.cn).

K. M. S. Huq is with the Faculty of Computing, Engineering and Science, University of South Wales, Pontypridd, CF37 1DL, UK (email: kazi.huq@southwales.ac.uk).

I. INTRODUCTION

With the rapid development of modern communication technology, large coverage and multiple users have become the most fundamental features of digital transmission scenarios, such as multi-media transmissions [1], broadcasting systems [2], and cellular networks [3]. Hence, there is a surge of demand to develop advanced technologies to realize high-throughput and high-reliability wireless communications, especially for the 6G-enabled massively data-intensive Internet of Things (IoT) applications [4]. To achieve the above goal, many researchers have focused their attention on the hierarchical modulation (HM), which is a powerful solution to meet the requirements for diverse communication services simultaneously [5]. In particular, the HM scheme not only can carry multiple transmitted data streams at the same time, but also possesses strong flexibility and compatibility; because the layered structure of HM can provide unequal error protection (UEP) for these transmitted data streams based on their different importance and priorities [6]. For this reason, HM has been widely used in various communication scenarios, such as multiclass data transmissions [7], relay systems [8], [9], digital broadcast systems [10], and cooperative communication systems [11]. Thanks to the intrinsic UEP characteristics, it is advisable to deploy the HM-aided techniques to optimize the resource allocation in 6G-enabled IoT.

In order to achieve higher transmission throughput, bit-interleaved coded modulation (BICM) [12] can be incorporated into HM to formulate a spectral-efficiency framework, referred to as *HM-BICM*. Owing to the advantages of intrinsic UEP and spectral efficiency, extensive research works for analyzing and optimizing the HM-BICM systems have been carried out. For instance, some attempts have concentrated on deriving excellent mapping rules, which are one of the critical parameters that determine the achievable rates of HM-BICM systems [13]–[16]. In [13], a type of non-uniform constellations has been designed for HM-BICM systems based on the minimum-Euclidean-distance (MED) property of adjacent labels. Moreover, by adjusting the MED ratio between different labels, a type of dynamic constellations has been presented to improve the performance of HM-BICM systems under varying channel conditions [14]. Furthermore, a protection-level-exchanging scheme has been introduced in HM-BICM systems [15], which can be used to enhance the performance of cooperative networks by adopting two different constellations to process the information at the source node and relay node, respectively. In [16], the authors have applied the HM-BICM to ultra-broadband Terahertz (THz)

communications and generated a novel constellation, which is referred to as the *hierarchical bandwidth modulation (HBM)*. Besides, the design and implementation of hierarchical amplitude and phase-shift keying (HAPSK) constellations and hierarchical quadrature amplitude modulation (HQAM) constellations have been discussed in [17] and [18], respectively.

However, BICM is not an optimal transmission technique due to its independent demapping framework. The performance of such a technique can be further boosted by including iterative decoding (ID) between the demodulator and decoder to process the soft information iteratively [19]. Therefore, an enhanced version of HM-BICM systems, called *HM-BICM-ID systems*, has been formulated [20]. The HM-BICM-ID not only can maintain the spectral-efficiency superiority of HM-BICM, but also can exhibit a higher achievable rate and better error performance. Recently, the constellation design for HM-BICM-ID systems has been intensely investigated [20], [21].¹

Error-correction codes (ECCs) are another important issue to determine the overall performance of HM-BICM systems. During the past decade, a significant amount of research effort has been devoted to spurring the theoretical investigation and practical application of ECCs for the HM-BICM systems. In particular, a type of capacity-approaching ECCs, called *low-density parity-check (LDPC) codes*, has been widely investigated in the HM scenarios [17], [21]. For instance, a degree-distribution design strategy, which can be used to construct the UEP LDPC codes, has been presented for HM-BICM systems [22]. Moreover, two different complexity-reduced decoding algorithms have been proposed for the LDPC-coded HM-BICM systems [23] and their HM-BICM-ID counterparts [24], respectively. Although conventional LDPC codes exhibit desirable error performance in the ID context, the irregular structure leads to relatively high encoding and decoding complexities [25]. To overcome such weakness, a class of structured LDPC codes, referred to as *protograph LDPC (P-LDPC) codes*, has been conceived [26]. To facilitate the analysis and design of P-LDPC-coded BICM systems, a variety of protograph-based extrinsic information transfer (P-EXIT) algorithms have been proposed [27]–[29]. Following the information-theoretic advancements, the optimization of P-LDPC-coded BICM-ID counterparts has been investigated in Poisson pulse-position modulation (PPM) scenarios [30], [31]. Motivated by the superiorities of protograph, a type of convolutional-based P-LDPC codes, referred to as *spatially coupled (SC) P-LDPC codes*, has also been studied. Such codes not only inherit the appealing advantages of P-LDPC codes, but also have the convolutional feature to improve the error performance [32], [33]. In the past few years, a variety of research works related to the SC P-LDPC codes have been invoked over different channels, such as binary erasure channels (BECs) [34] and additive white Gaussian noise (AWGN) channels [35]. Due to their own superiorities (e.g., outstanding performance and simple implementation), the SC P-LDPC codes have great potential to be a desirable error-correction coding scheme for HM scenarios. Nevertheless, as far as we know, there have been few previous works on SC P-LDPC codes for the bandwidth-limited systems,

especially HM-BICM-ID systems, to date.

Inspired by the aforementioned discussion, a comprehensive investigation on SC P-LDPC-coded M -ary QAM HM-BICM-ID systems is conducted in this paper, whose main contributions can be summarized as four-fold. Specifically, an information-theoretic method is proposed to calculate $(\log_2 M)/2$ types of constellation-constrained average mutual information (AMI), which can be utilized to exactly evaluate the achievable capacity limits of different layers in HM-BICM systems.² Furthermore, a novel type of constellations, referred to as *structural quadrant (SQ) constellations*, is designed based on a two-stage design approach, while a quadrant-based harmonic mean analysis is presented to measure the non-feedback and iterative-feedback performance of different constellations in HM-BICM-ID systems. The SQ constellations not only exhibit higher capacities and larger harmonic mean than the state-of-the-art counterparts in HM-BICM scenarios, but also attain desirable performance gain in HM-BICM-ID scenarios. In addition, we develop an asymptotic-performance analytical tool, called as *multi-stream-based EXIT (MS-EXIT) algorithm*, to predict the asymptotic convergence performance of all individual coded-bit streams in HM-BICM-ID systems. Analytical and experimental results reveal that our proposed SC P-LDPC-coded HM-BICM-ID systems significantly outperform the existing counterparts. As a consequence, the proposed SC P-LDPC-coded HM-BICM-ID systems can be considered as a promising technique for the wireless communication applications with UEP requirement, such as massive IoT.

The rest of this work consists of five parts. In Sect. II, we present the SC P-LDPC-coded HM-BICM-ID system model and develop an information-theoretic methodology to calculate its AMIs. In Sect. III, we propose a two-stage design approach to construct the SQ constellations and illustrate their advantages from the perspective of both capacity and quadrant-based harmonic mean analyses. In Sect. IV, we put forward an MS-EXIT algorithm and estimate the convergence performance for HM-BICM-ID systems with different constellations. We perform simulations to demonstrate the superiority of the proposed SC P-LDPC-coded HM-BICM-ID systems in Sect. V and give conclusions in Sect. VI.

II. SC P-LDPC-CODED HM-BICM-ID SYSTEM AND AMI CALCULATION

We first briefly describe the SC P-LDPC-coded HM-BICM-ID system model. Subsequently, we propose an information-theoretic methodology to calculate the constellation-constrained AMI of such a system.

A. SC P-LDPC-Coded HM-BICM-ID Systems

The system model of an SC P-LDPC-coded HM-BICM-ID scheme is depicted in Fig. 1. As can be seen, $(\log_2 M)/2$ different information-bit streams are first encoded by $(\log_2 M)/2$ individual SC P-LDPC encoders to yield their corresponding coded-bit streams, respectively. Moreover, these $(\log_2 M)/2$

¹It is worth noting that the constellations that exhibit outstanding performance in BICM may not work well in BICM-ID because the former does not take the impact of ID into consideration.

²In this paper, “BICM” is used to represent “BICM with non-iterative decoding” unless otherwise stated.

Fig. 1. Block diagram of an SC P-LDPC-coded HM-BICM-ID system.

types of coded-bit streams are permuted by their individual bit-level interleavers. Then, every $m = \log_2 M$ consecutive coded bits output from these $(\log_2 M)/2$ individual interleavers are grouped together and modulated into an M -ary transmitted signal by a given hierarchical modulator, e.g., an M -QAM hierarchical modulator. It should be noted that the coded bits output from the layer-1 interleaver, layer-2 interleaver, $\dots$, layer- $(\log_2 M)/2$ interleaver are assumed to be the highest-priority data stream, second highest-priority data stream, $\dots$, lowest-priority data stream, respectively. These data streams are successively assigned into the most significant bit (MSB) positions, second MSB positions, $\dots$, least significant bit (LSB) positions in the mapping process.³ To ease the understanding of HM process, a specific example is given in Fig. 2. As illustrated in this figure, the parameters m , $(\log_2 M)/2$, and m' in the Gray constellation for a 16-QAM HM-BICM-ID system are 4, 2, and 2, respectively. Besides, the minimum distance between the labels in adjacent quadrants is denoted as d_1 , while the minimum distance between the labels in a given quadrant is denoted as d_2 . By adjusting the distance rate $r_d = d_1/d_2$, UEP can be changed for the layer-1 and layer-2 coded-bit streams. Through the above procedure, two length- n coded-bit streams are transformed into a length- $(2n)/m$ M -ary modulated symbol sequence. Then, the j -th modulated symbol x_j is transmitted over an AWGN channel, and the corresponding

Fig. 2. Gray constellation for the 16-QAM HM-BICM-ID system. The parameters m , $(\log_2 M)/2$, and m' are 4, 2, and 2, respectively.

output y_j is given by

$$y_j = x_j + n_j, \quad (1)$$

where $j = 1, 2, \dots, 2n/m$; x_j stands for a modulated symbol taken from an M -ary constellation set χ ; n_j represents the complex Gaussian noise with zero mean and variance $\sigma^2 = N_0/2$ in each dimension. Furthermore, the transmitted energy per symbol is assumed to be normalized to unit, i.e., $E_s = \mathbb{E}[|x_j|^2] = 1$, where $\mathbb{E}[\cdot]$ denotes the expectation function.

On the receiver side, the signal is processed by a hierarchical serial-parallel concatenated structure, which is formulated by a multiple-input multiple-output (MIMO) hierarchical demodulator and $(\log_2 M)/2$ single-input single-output (SISO) decoders. To be specific, given the received signal y_j and the a-priori log-likelihood ratios (LLRs) of hierarchical demodulator, i.e., $L_{A, Dem}^k$, the extrinsic LLRs output from the hierarchical demodulator can be computed (i.e., $L_{E, Dem}^k = L_{P, Dem}^k - L_{A, Dem}^k$) and passed to their corresponding layer- k deinterleavers through

³In this paper, $x_l \triangleq \{x_l^{b_1}, x_l^{b_2}, \dots, x_l^{b_i}, \dots, x_l^{b_m}\}$ is defined as the l -th label in a given 2^m -ary constellation, where $l = 1, 2, \dots, 2^m$; $x_l^{b_i}$ denotes the i -th labeling bit of x_l , and $i = 1, 2, \dots, m$. The labeling bit sequence is divided into $(\log_2 M)/2$ groups in a sequential order and the k -th group contains m_k labeling bits, where $k = 1, 2, \dots, (\log_2 M)/2$ and $m = \sum_{k=1}^{(\log_2 M)/2} m_k$. The labeling bits within the 1-st group, 2-nd group, $\dots$, $(\log_2 M)/2$ -th group correspond to the MSB positions, second MSB positions, $\dots$, LSB positions, respectively. For simplicity, this work focuses on the case of even $\log_2 M$, e.g., 16-ary HM-BICM-ID systems [15], [16], [20] and 64-ary HM-BICM-ID systems [18]. Moreover, the numbers of labeling bits in each group are assumed to be identical and equal to m' (i.e., $m_1 = m_2 = \dots = m_{(\log_2 M)/2} = m' = 2$) [15], [16], [18], [20].

a serial-to-parallel operation, where $k = 1, 2, \dots, (\log_2 M)/2$. Through a designated deinterleaving procedure, the extrinsic LLRs $L_{E, \text{Dem}}^k$ are assumed to be the a-priori LLRs $L_{A, \text{Dec}}^k$ for the corresponding layer- k decoders. Subsequently, the extrinsic LLRs output from the $(\log_2 M)/2$ individual decoders can be calculated (i.e., $L_{E, \text{Dec}}^k = L_{P, \text{Dec}}^k - L_{A, \text{Dec}}^k$) and sent to the corresponding layer- k interleavers. After being permuted, these extrinsic LLRs are processed by a parallel-to-serial operation and fed back to the hierarchical demodulator so as to serve as a sequence of latest input parameters for the next iterative decoding process. By using the above decoding framework, the extrinsic LLRs can be updated iteratively, which will help to promote the information convergence and improve the overall performance of HM-BICM-ID systems. Note that the max-sum approximation of the log-domain maximum a-posteriori probability (Max-Log-Map) algorithm [36] and belief-propagation (BP) algorithm [33] are exploited in the hierarchical demodulator and $(\log_2 M)/2$ types of decoders, respectively.

Remark 1: As proved in [25] and [37], LDPC-based codes (including the P-LDPC codes and SC P-LDPC codes), which possess excellent performance over AWGN channels, can also perform well over other memoryless channels. For this reason, although an AWGN channel is assumed in this paper, our proposed design can be applicable to other types of ergodic channels, such as fast fading channels.

B. AMI Calculation

1) *CM Capacity:* As is well known, AMI between the channel input and corresponding output specifies the maximum achievable rate in the case of error-free transmissions [38], [39]. Thus, the AMI can be considered as the performance limit for the HM system over a given channel. Given an M -ary constellation, when the modulated symbol is chosen from the corresponding set χ with equal probability, the constellation-constrained AMI for coded modulation (CM), i.e., CM capacity C_{CM} , over an AWGN channel is evaluated as

$$C_{\text{CM}} = m - \mathbb{E}_{x,y} \left[\log_2 \frac{\sum_{z \in \chi} p(y|z)}{p(y|x)} \right], \quad (2)$$

where $p(y|z)$ and $p(y|x)$ denote the conditional probability density functions (PDFs) of the received signal y with the complex symbol z taken from χ and the modulated symbol x , respectively. It is noteworthy that CM is considered as an optimal transmission technique, which can obtain the maximum achievable rate [40]. In the BICM-ID scenario, an iterative procedure is executed at the receiver to exchange the soft information between the demodulator and decoder. Based on the above procedure, each labeling bit of a modulated symbol can be estimated with the aid of the a-priori information of the remaining $m - 1$ labeling bits, which can enhance the system reliability. Actually, BICM-ID is capable of achieving the maximum information rate by performing substantially iterative operations [41], [42]. In consequence, BICM-ID is viewed as an optimal transmission technique, and thus can achieve the same constellation-constrained AMI as CM [40], [43], i.e., $C_{\text{BICM-ID}} \triangleq C_{\text{CM}}$.

2) *BICM Capacity:* It is worth noting that BICM is a sub-optimal alternative technique due to its independent demapping

structure [41]. The constellation-constrained AMI, i.e., BICM capacity C_{BICM} , can be measured by

$$C_{\text{BICM}} = m - \sum_{i=1}^m \mathbb{E}_{b,y} \left[\log_2 \frac{\sum_{z \in \chi} p(y|z)}{\sum_{z \in \chi_i^{(b)}} p(y|z)} \right], \quad (3)$$

where $\chi_i^{(b)}$ stands for a constellation subset with the i -th labeling bit being b ($b \in \{0, 1\}$).

3) *HM-BICM Capacity:* Based on the relationship between the labeling bits and the parallel channels, an M -ary constellation is equivalent to m parallel independent and binary input memoryless sub-channels [12]. Moreover, these m sub-channels correspond to the m labeling bits within modulated symbols. Thereby, the C_{BICM} defined in (3) can be re-formulated as

$$C_{\text{BICM}} = \sum_{i=1}^m I(b; y|S = i), \quad (4a)$$

$$I(b; y|S = i) = 1 - \mathbb{E}_{b,y} \left[\log_2 \frac{\sum_{z \in \chi} p(y|z)}{\sum_{z \in \chi_i^{(b)}} p(y|z)} \right], \quad (4b)$$

where $I(b; y|S = i)$ denotes the conditional MI and S denotes the index of a labeling bit (i.e., $1 \leq S \leq m$). In an HM-BICM system, aiming to simultaneously process the $(\log_2 M)/2$ individual coded-bit streams with different priorities, the constellation should be divided into $(\log_2 M)/2$ layers, and each layer is composed of m' fixed positions within corresponding labeling bit sequence. Due to the above feature of HM-BICM system, its AMI analysis must be divided into $(\log_2 M)/2$ parts, and each part corresponds to only one of these $(\log_2 M)/2$ layers. Let $C_{\text{HM-BICM}}^k$ denotes the constellation-constrained AMI of the k -th layer, where $k = 1, 2, \dots, (\log_2 M)/2$; Then, $C_{\text{HM-BICM}}^k$ is equal to the summation of conditional MIs corresponding to the k -th group of labeling bits within a labeling bit sequence. In consequence, $C_{\text{HM-BICM}}^k$, referred to as *layer- k capacity*, can be measured by

$$C_{\text{HM-BICM}}^k = m' - \sum_{i=(k-1)m'+1}^{km'} \mathbb{E}_{b,y} \left[\log_2 \frac{\sum_{z \in \chi} p(y|z)}{\sum_{z \in \chi_i^{(b)}} p(y|z)} \right], \quad (5)$$

Remark 2: $C_{\text{HM-BICM}}^k$ is used to evaluate the maximum achievable rate of the k -th layer (resp. the k -th coded-bit stream) in a BICM scenario. However, in actual implementation, a constellation possessing larger $C_{\text{HM-BICM}}^k$ may help an SC P-LDPC code achieving more desirable error performance in a BICM-ID scenario than the counterparts possessing small $C_{\text{HM-BICM}}^k$.

III. DESIGN AND ANALYSIS OF PROPOSED SQ CONSTELLATIONS FOR HM-BICM-ID SYSTEMS

A. Proposed SQ Constellations

In wireless communication systems, constellation is a critical parameter to determine the transmission rate and error performance. Therefore, the constellations should be carefully designed and optimized so as to meet the practical requirements for different transmission environments. For example, the Gray constellation, which is considered as an optimal mapping scheme in the BICM systems, is not applicable in ID systems since there is nearly no performance gain in the iterative process

Fig. 3. Constellations for the MSSED [20], MSSED-B [20], M3 [15], and HBM [16]. A 16-QAM modulation is considered.

[20], [44]. In order to address this weakness, a variety of new constellations have been proposed for the BICM-ID systems [45]. Different from conventional BICM-ID systems, HM-BICM-ID systems can be viewed as layered systems, whose constellations are decomposed into several different layers so as to facilitate the processing of different data streams. Thus, the investigation on the constellation design for HM-BICM-ID systems deserves further exploration. Fig. 3 shows four well-performing constellations, i.e., maximum squared Euclidean distance (MSSED) constellation [20], MSSED-B constellation [20], M3 constellation [15], and HBM constellation [16], proposed in recent years.

For an M -QAM HM-BICM-ID system, its constellation can be divided into $(\log_2 M)/2$ different layers so as to carry $(\log_2 M)/2$ types of data streams. According to the importance and priorities of such $(\log_2 M)/2$ individual data streams, the layers constructed from the relatively significant labeling bit positions must be first processed in the constellation-design procedure. The remaining layers should be optimized to enhance the overall system performance. Based on the above discussion, we propose a two-stage design approach to generate a novel type of constellations, called *SQ constellations*, for the sake of improving the HM-BICM-ID performance. The detailed design process is described as follows.

1) **Gray-mapped base layer:** Given an M -ary modulated scheme, the labeling bit sequence can be decomposed into $(\log_2 M)/2$ groups sequentially, and every group consists of m' labeling bits. The labeling bits within the first group correspond to the MSB positions, which are used to construct the first layer to carry the highest-priority data stream. The remaining labeling bits within the second group, third group, ..., last group correspond to the second MSB positions (i.e., second layer), third MSB positions (i.e., third layer), ..., LSB positions (i.e., last layer), respectively, which are used to carry the second highest-priority data stream, third highest-priority data stream, ..., lowest-priority data stream. Therefore, one should first process the 1-st layer so as to ensure the performance of the highest-priority data stream. To be specific, the constellation is first divided into four quadrants equally, called as *layer-1 quadrants*; For the first group, the $4m'$ component labeling bits within all the $M/4$ labels in a given layer-1 quadrant are set to be the same value, while there is only one different labeling bit between two adjacent layer-1 quadrants. From the layer-1 perspective, the above operation makes the first-group labeling bits of all labels

Fig. 4. SQ constellation for the 16-QAM HM-BICM-ID system.

formulating a Gray mapping, which is able to achieve the maximum AMIs.

2) **Structural enhanced layers:** The labeling bits within the other $(\log_2 M)/2 - 1$ groups, which correspond to the remaining $(\log_2 M)/2 - 1$ layers, can be processed through a structural scheme in a sequence order. Specifically, a layer-1 quadrant can be further equally divided into four sub-quadrants, called as *layer-2 quadrants*; The $4m'$ second-group labeling bits within these four layer-2 quadrants, which are generated from a given layer-1 quadrant, can formulate a fixed structure (e.g., the Gray structure or anti-Gray structure). From the perspective of the layer-1 quadrant, the second-group labeling bits constitute two Gray mappings and two anti-Gray mappings. In particular, every two adjacent layer-1 quadrants have different second-group constellation structures, each of which includes 4 virtual labels (i.e., $4m'$ labeling bits). Furthermore, the layer-3 quadrants, layer-4 quadrants, ..., layer- $(\log_2 M)/2$ quadrants can be generated by processing the labeling bits of remaining $(\log_2 M)/2 - 2$ groups in a similar method. For example, the $4m'$ k -th-group labeling bits within the four layer- k quadrants, which are formulated by equally dividing a given layer- $(k-1)$ quadrant, can also constitute two Gray mappings and two anti-Gray mappings.

Based on the above two steps, one can generate the SQ constellations, which not only can ensure excellent HM-BICM performance, but also can realize desirable HM-BICM-ID performance. It should be noted that the number of labeling bits within each group is set to be $m' = 2$. Then, the k -th-group labeling bits

Fig. 5. C_{CM} , C_{BICM} , and $C_{HM-BICM}^k$ ($k = 1, 2$) for the proposed SQ constellation and four existing constellations, i.e., MSED, MSED-B, M3, and HBM constellations. A 16-QAM modulation is considered.

has four different settings (i.e., 00, 01, 10, 11) in its corresponding layer- k quadrants. Hence, there are different realizations for the resultant SQ constellation. Nevertheless, all possible realizations have the same constellation structure (i.e., Gray structure or anti-Gray structure) from the quadrant perspective. As an example, the SQ constellation for 16-QAM modulation is given in Fig. 4. To verify the superiority of the proposed SQ constellation, three different types of capacities, i.e., C_{CM} , C_{BICM} , and $C_{HM-BICM}^k$ for $k = 1, 2$ will be investigated in the forthcoming capacity analysis.

B. Capacity Analysis

According to Sect. II-B, the constellation-constrained AMI (i.e., capacity) for a given constellation can be calculated. Let E_s/N_0 be the signal-to-noise ratio (SNR) per symbol, the capacities C_{CM} , C_{BICM} , and $C_{HM-BICM}^k$ ($k = 1, 2$) for a 16-QAM modulation with the proposed SQ constellation and four state-of-the-art constellations, i.e., MSED [20], MSED-B [20], M3 [15], and HBM [16] constellations, are presented in Fig. 5. As observed, the SQ constellation exhibits a larger C_{BICM} with respect to the other four constellations. This phenomenon illustrates that the HM-BICM system with an SQ constellation performs better than the counterparts using MSED, MSED-B, M3, and HBM constellations. More specifically, one can observe that the layer-1 capacities (i.e., $C_{HM-BICM}^1$) of the M3, HBM, and SQ constellations are the same, which are larger than those of the MSED and MSED-B constellations. In addition, the layer-2 capacity (i.e., $C_{HM-BICM}^2$) of the SQ constellation is the largest one among all the five constellations, which indicates that the HM-BICM system with an SQ constellation exhibits better layer-2 performance than the counterparts with other four constellations.

Remark 3: The capacity analysis verifies the superiority of the proposed SQ constellation in HM-BICM system, its advantage in HM-BICM-ID systems will be further demonstrated in the next subsection and Sect. IV.

C. Quadrant-Based Harmonic Mean Analysis

Different from the BICM-ID system, an M -ary HM-BICM-ID system is used to carry $(\log_2 M)/2$ coded-bit streams, and thus each label within a given M -ary HM constellation is divided into $(\log_2 M)/2$ different groups, which correspond to $(\log_2 M)/2$ different layers and are used for mapping $(\log_2 M)/2$ different coded-bit streams in the bit-to-symbol process. Therefore, the selection scheme for the labels and labeling bits in the conventional harmonic mean analysis [46], which is tailored for the BICM-ID systems, is no longer suitable for the HM-BICM-ID systems. Then, we modify the conventional harmonic mean analysis [46] and conceive a novel counterpart, referred to as *quadrant-based harmonic mean analysis*, so as to verify the superiority of the SQ constellations in HM-BICM-ID system. Based on a given M -ary HM constellation, the quadrant-based harmonic mean analysis can be used to calculate $(\log_2 M)/2$ different harmonic means of the minimum squared Euclidean distance (HMMSED), which is of great importance to evaluate the asymptotic performance of a constellation in both non-feedback and iterative-feedback scenarios. In the following, we elaborate on the analysis process.

1) *Non-Feedback HMMSED:* Given an M -ary HM constellation, there exists $(\log_2 M)/2$ layers. In particular, each layer contains m' labeling bits. We define $\chi_i^{(\bar{b})}$ as the complementary subset of $\chi_i^{(b)}$, where $i = 1, 2, \dots, m$ and $b \in \{0, 1\}$. Then, one can calculate the non-feedback HMMSED corresponding to the first layer, as

$$D^1 = \left(\frac{1}{m'2^{m'}} \sum_{i=1}^{m'} \sum_{b=0}^1 \sum_{x \in \chi_i^{(\bar{b})}} \frac{1}{\|x - z\|^2} \right)^{-1}, \quad (6)$$

where $z \in \chi_i^{(\bar{b})}$ denotes the label closest to x , and $\|x - z\|$ denotes the Euclidean distance between the label x and z . For the remaining $(\log_2 M)/2 - 1$ layers, we define $\chi_{i,j}^{(\bar{b})}$ as the subset of $\chi_i^{(\bar{b})}$ whose labels are located at the j -th layer- $(k-1)$ quadrant for $j \in \{1, 2, \dots, 4^{(k-1)}\}$, while $\chi_{i,j'}^{(\bar{b})}$ as the subset of $\chi_i^{(\bar{b})}$ whose labels are located at the j' -th layer- $(k-1)$ quadrant for $j' \in \{1, 2, \dots, 4^{(k-1)}\}$ and $j' \neq j$. Accordingly, the non-feedback HMMSED corresponding to the k -th layer for $k = 2, 3, \dots, (\log_2 M)/2$ can be calculated as

$$D^k = \left(\frac{1}{m'2^{m'}} \sum_{i=(k-1)m'+1}^{km'} \sum_{b=0}^1 \sum_{x \in \chi_{i,j}^{(\bar{b})}} \frac{1}{\|x - z_{j'}\|^2} \right)^{-1}, \quad (7)$$

where $z_{j'} \in \chi_{i,j'}^{(\bar{b})}$ denotes the label closest to x .

2) *Iterative-Feedback HMMSED:* In the ID scenario, the iterative-feedback HMMSED corresponding to a given M -ary HM constellation can be calculated as [46]

$$\tilde{D} = \left(\frac{1}{m2^m} \sum_{i=1}^m \sum_{b=0}^1 \sum_{x \in \chi_i^{(b)}} \frac{1}{\|x - \tilde{z}\|^2} \right)^{-1}, \quad (8)$$

where $\tilde{z} \in \chi_i^{(\bar{b})}$ denotes the label whose m labeling bit positions are the same as those of x except the i -th position.

TABLE I
TWO NON-FEEDBACK HMMSEDs (I.E., D^1 AND D^2) AND ONE ITERATIVE-FEEDBACK HMMSED (I.E., $\tilde{D}$) FOR THE PROPOSED SQ CONSTELLATION AND EXISTING MSED, MSED-B, M3, AND HBM CONSTELLATIONS. A 16-QAM MODULATION IS CONSIDERED.

HMMSED \ Constellation	MSED	MSED-B	M3	HBM	SQ
D^1	0.1391	0.1391	0.1600	0.1600	0.1600
D^2	0.1356	0.1600	0.1231	0.1481	0.2148
$\tilde{D}$	0.8533	0.8828	0.6667	0.6400	0.5920

Remark 4: It should be noted that Eq. (8), which is used to evaluate the iterative gain of constellations, is obtained from [46], while Eqs. (6)-(7), which are used to evaluate the non-feedback performance of constellations, are derived from the conventional harmonic mean based on the HM characteristics.

3) *HMMSED Analysis:* From the information-theoretic perspective, the non-feedback HMMSED is tailored for the non-iterative decoding scenario, and thus it can be utilized to estimate the intrinsic performance of constellations separately from the decoding algorithm. Besides, it should be noted that a constellation possessing larger non-feedback HMMSED can ensure high reliability for the initial soft information output from the decoder, which may help the system achieving more desirable error performance in the ID context. Therefore, the non-feedback HMMSED not only can perfectly measure the performance of HM-BICM systems, but also plays an important role on the performance of HM-BICM-ID systems. Different from the non-feedback HMMSED, the iterative-feedback HMMSED is derived under an assumption of error-free feedback [46], i.e., the soft information fed back from the decoder to the demodulator is totally correct. However, since the BP algorithm is a sub-optimal decoding scheme [25], error-free feedback can not be realized in the practical communication scenarios. For this reason, the iterative-feedback HMMSED can not perfectly reflect the constellation performance in HM-BICM-ID systems, and thus is mainly used as a sub-optimal criterion to analyze the performance gain of constellations in the iterative process. Based on the above discussion, one can easily find that devising a constellation enabling the maximum non-feedback HMMSEDs for each layer and a relatively large iterative-feedback HMMSED is preferable in practical applications. It is because that a constellation having the above two features allows the system to reach desirable performance after a few outer iterations. To further elaborate on the advantages of the proposed SQ constellation, its non-feedback HMMSED and iterative-feedback HMMSED are calculated, and four state-of-the-art counterparts, i.e., MSED [20], MSED-B [20], M3 [15], and HBM [16] constellations are used for comparison.

In Table I, the two non-feedback HMMSEDs (i.e., D^1 and D^2) and one iterative-feedback HMMSED (i.e., $\tilde{D}$) are presented for a 16-QAM HM-BICM-ID system. One can easily find that the MSED and MSED-B constellations have the same D^1 , which implies that they exhibit the same layer-1 performance in non-feedback scenario. Similar conclusions can be drawn from the M3, HBM, and SQ constellations, which achieve better layer-1 performance than the MSED and MSED-B constellations due to a larger D^1 . Furthermore, in the case of the same D^1 , the SQ constellation achieves better layer-2 performance than the M3 and HBM constellations, while the MSED-B constellation exhibits better layer-2 performance than the MSED constellation. Con-

sequently, the SQ constellation possesses the best performance among all the five constellations for both two layers in non-feedback scenario, which is consistent with the capacity analysis. Although the SQ constellation has a relatively smaller iterative-feedback HMMSED (i.e., $\tilde{D}$) with respect to those of the MSED, MSED-B, M3, and HBM constellations, the former still obtains a significant iterative gain over its non-feedback counterparts. This phenomenon illustrates that the SQ constellation not only can exhibit outstanding non-feedback performance for each layer, but also can guarantee ideal iterative performance. To further illustrate the iterative gain of the SQ constellation in the HM-BICM-ID scenarios, we will resort to a novel EXIT algorithm to achieve this goal.

IV. MS-EXIT ALGORITHM AND CONVERGENCE ANALYSIS FOR SC P-LDPC-CODED HM-BICM-ID SYSTEMS

A. SC P-LDPC Codes

A protograph $\mathcal{G} = (\mathcal{V}, \mathcal{C}, \mathcal{E})$ proposed in [47] can be viewed as a small Tanner graph composed of three different types of sets, i.e., a variable node (VN) set $\mathcal{V} = \{v_1, v_2, \dots, v_{n_p}\}$, a check node (CN) set $\mathcal{C} = \{c_1, c_2, \dots, c_{m_p}\}$, as well as an edge set $\mathcal{E} = \{e_{i,j}\}$ for $i = 1, 2, \dots, m_p$ and $j = 1, 2, \dots, n_p$. In particular, each edge $e_{i,j} \in \mathcal{E}$ connects a CN $c_i \in \mathcal{C}$ with a VN $v_j \in \mathcal{V}$, and the presence of parallel edges are allowed. Alternatively, a protograph of a code rate $R = (n_p - m_p)/n_p$ can be represented by an $m_p \times n_p$ base matrix $\mathbf{B} = (b_{i,j})$, where $b_{i,j}$ is the number of edges connecting c_i with v_j . Furthermore, a large protograph corresponding to a P-LDPC code, referred to as *derived graph*, can be generated by exploiting a “lifting” operation on a given protograph [25], [48].

By implementing L ($L \geq 2$) times replication on a given protograph, a tail-biting SC (TB-SC) protograph can be constructed by coupling these identical replicas into a single coupled chain, where L represents the coupling length. From the matrix viewpoint, the base matrix $\mathbf{B}$, which corresponds to a protograph of size $m_p \times n_p$, is decomposed into $w + 1$ sub-matrices (resp. $\mathbf{B}_0, \mathbf{B}_1, \dots, \mathbf{B}_w$) by exploiting an edge-spreading scheme. Particularly, all matrices (i.e., the base matrix and sub-matrices) have the same size and their relationship satisfies the condition of $\sum_{k=0}^w \mathbf{B}_k = \mathbf{B}$. In the sequel, a TB-SC protograph can be generated and its base matrix of size $m_p L \times n_p L$ is expressed

as

$$\mathbf{B}_L^{\text{TB-SC}} = \begin{bmatrix} \overbrace{\mathbf{B}_0 \quad \mathbf{B}_w \quad \cdots \quad \mathbf{B}_1}^L \\ \vdots \\ \mathbf{B}_{w-1} & & & \mathbf{B}_w \\ \mathbf{B}_w & \ddots & & \\ & & \mathbf{B}_0 & \\ & \ddots & \vdots & \mathbf{B}_0 \\ & & \ddots & \mathbf{B}_{w-1} \\ & & \mathbf{B}_w & \mathbf{B}_{w-1} \quad \cdots \quad \mathbf{B}_0 \end{bmatrix}. \quad (9)$$

B. MS-EXIT Algorithm

In order to investigate the convergence performance of SC P-LDPC-coded HM-BICM-ID systems, an asymptotic-performance analysis tool, called *MS-EXIT algorithm*, is conceived in this subsection. One can use this algorithm to analyze the convergence procedure of MI between the hierarchical demodulator and the SC P-LDPC decoder. To be specific, the MS-EXIT algorithm can be used to calculate the decoding threshold of an SC P-LDPC code, which is regarded as the minimum SNR per information bit (i.e., the minimum E_b/N_0) that allows the code to realize error-free transmission in an HM-BICM-ID system. For the sake of illustrating the MS-EXIT algorithm in detail, the principle of such an algorithm is shown in Fig. 6, and several concepts are needed to be introduced first.

In an AWGN scenario, assuming that the LLRs of coded bits follows a Gaussian distribution, i.e., $l \sim \mathcal{N}(\frac{\sigma_{\text{ch}}^2}{2}, \sigma_{\text{ch}}^2)$, where $\frac{\sigma_{\text{ch}}^2}{2}$ and σ_{ch}^2 represent the mean and variance, respectively. Then, the MI between the coded bits and their corresponding LLRs is measured by

$$J(\sigma_{\text{ch}}) = 1 - \int_{-\infty}^{+\infty} \frac{\exp\left(-\frac{(\mu - \sigma_{\text{ch}}^2/2)^2}{2\sigma_{\text{ch}}^2}\right)}{\sqrt{2\pi\sigma_{\text{ch}}^2}} \log_2[1 + \exp(-\mu)] d\mu, \quad (10)$$

where the inverse function of $J(\cdot)$ (i.e., $J^{-1}(\cdot)$) and its corresponding closed-form approximation are provided in [49]. Besides, several types of MIs used in the MS-EXIT algorithm are defined as follows.

- I_{Ad}^k and I_{Ed}^k represent the *a-priori* MI and *extrinsic* MI of the hierarchical demodulator, respectively;
- $I_{\text{Av}}^k(i, j)$ and $I_{\text{Ac}}^k(i, j)$ represent the *a-priori* MI passed from c_i to v_j and v_j to c_i , respectively;
- $I_{\text{Ev}}^k(i, j)$ and $I_{\text{Ec}}^k(i, j)$ represent the *extrinsic* MI passed from v_j to c_i and c_i to v_j , respectively;
- $I_{\text{AP}}^k(j)$ represents the *a-posteriori* MI of v_j ;

where $k \in \{1, 2, \dots, (\log_2 M)/2\}$ is used to represent the index of the coded-bit stream located at the k -th layer.

The maximum number, which corresponds to the outer iterations between the hierarchical demodulator and the decoder, is assumed to be T_1 , while that corresponding to the inner iterations for the decoder is assumed to be T_2 . Moreover, there is an exchange of MI from VN to CN and vice versa in each inner iteration. Based on the aforementioned foundations, the MS-EXIT algorithm can be illustrated as follows.

- 1) **Initialization:** Before the implementation of this algorithm, there exist an initial E_b/N_0 and $(\log_2 M)/2$ types of initial *a-priori* MIs (i.e., I_{Ad}^k for $k = 1, 2, \dots, (\log_2 M)/2$), which are assumed to be the input parameters in the hierarchical demodulator.
- 2) **Calculating $(\log_2 M)/2$ types of *extrinsic* MIs for hierarchical demodulator:** After a Monte-Carlo simulation, the hierarchical demodulator can output a sequence of coded bits and their corresponding *extrinsic* LLRs. Then, the *extrinsic* MI I_{Ed}^k for $k = 1, 2, \dots, (\log_2 M)/2$, which is assumed to be output from the hierarchical demodulator, is calculated as

$$I_{\text{Ed}}^k = 1 - \mathbb{E} \left[\log_2(1 + e^{-\tilde{u}_j^k l_j^k}) \right], \quad (11)$$

where $\tilde{u}_j^k = (-1)^{v_j^k} \in \{+1, -1\}$ and l_j^k denote the j -th converted binary symbol and its corresponding *extrinsic* LLR, respectively; $v_j^k \in \{0, 1\}$ denotes the j -th coded bit within the k -th coded-bit stream, for $j = 1, 2, \dots, n$.

- 3) **Passing $(\log_2 M)/2$ types of *extrinsic* MIs from hierarchical demodulator to layer- k decoder:** The channel MIs for these $(\log_2 M)/2$ types of decoders are set to be $I_{\text{ch}}^k(j) = I_{\text{Ed}}^k$, where $k = 1, 2, \dots, (\log_2 M)/2$ and $j = 1, 2, \dots, n_p$. As a special case, $I_{\text{ch}}^k(j)$ equals zero if v_j is a punctured VN in the protograph.
- 4) **Updating $(\log_2 M)/2$ types of *extrinsic* MIs for VNs:** Based on the channel MI $I_{\text{ch}}^k(j)$ and the *a-priori* MI $I_{\text{Av}}^k(i, j)$, the corresponding *extrinsic* MI $I_{\text{Ev}}^k(i, j)$ can be calculated for $k = 1, 2, \dots, (\log_2 M)/2$, $i = 1, 2, \dots, m_p$, and $j = 1, 2, \dots, n_p$ (if $b_{i,j} \neq 0$ in the corresponding protograph), as

$$I_{\text{Ev}}^k(i, j) = J \left(\left(\sum_{s \neq i} b_{s,j} \left[J^{-1} \left(I_{\text{Av}}^k(s, j) \right) \right]^2 + (b_{i,j} - 1) \left[J^{-1} \left(I_{\text{Av}}^k(i, j) \right) \right]^2 + \left[J^{-1} \left(I_{\text{ch}}^k(j) \right) \right]^2 \right)^{1/2} \right), \quad (12)$$

otherwise, $I_{\text{Ev}}^k(i, j) = 0$ if $b_{i,j} = 0$.

- 5) **Updating $(\log_2 M)/2$ types of *extrinsic* MIs for CNs:** Utilizing the *a-priori* MI $I_{\text{Ac}}^k(i, j)$, the corresponding *extrinsic* MI $I_{\text{Ec}}^k(i, j)$ can be calculated for $k = 1, 2, \dots, (\log_2 M)/2$, $i = 1, 2, \dots, m_p$, and $j = 1, 2, \dots, n_p$ (if $b_{i,j} \neq 0$ in the corresponding protograph), as

$$I_{\text{Ec}}^k(i, j) = 1 - J \left(\left(\sum_{s \neq j} b_{i,s} \left[J^{-1} \left(1 - I_{\text{Ac}}^k(i, s) \right) \right]^2 + (b_{i,j} - 1) \left[J^{-1} \left(1 - I_{\text{Ac}}^k(i, j) \right) \right]^2 \right)^{1/2} \right), \quad (13)$$

otherwise, $I_{\text{Ec}}^k(i, j) = 0$ if $b_{i,j} = 0$.

- 6) **Updating $(\log_2 M)/2$ types of *a-priori* MIs for hierarchical demodulator:** Using the *a-priori* MI $I_{\text{Av}}^k(i, j)$, the average *extrinsic* MI passing from layer- k decoder to hierarchical demodulator can be calculated as

$$I_{\text{Ad}}^k = \frac{1}{n_p} \sum_{j=1}^{n_p} J \left(\left(\sum_{i=1}^{m_p} b_{i,j} \left[J^{-1} \left(I_{\text{Av}}^k(i, j) \right) \right]^2 \right)^{1/2} \right), \quad (14)$$

Fig. 6. Flow chart of the MS-EXIT algorithm for an SC P-LDPC-coded HM-BICM-ID system.

where $k = 1, 2, \dots, (\log_2 M)/2$. I_{Ad}^k can be regarded as an updated *a-priori* MI for the demodulator in the next outer iteration. It should be noted that there exists a parallel-to-serial operation to process these $(\log_2 M)/2$ different types of MIs for a coded-bit stream of length $((\log_2 M)/2)n$ in the hierarchical demodulator. Because the entire coded-bit stream in the hierarchical demodulator is formulated by combining $(\log_2 M)/2$ different coded-bit streams of length n .

- 7) **Calculating $(\log_2 M)/2$ types of *a-posteriori* MIs for VNs:** Exploiting $I_{Av}^k(i, j)$ and $I_{ch}^k(j)$, the *a-posteriori* MI $I_{APP}^k(j)$ can be computed as

$$I_{APP}^k(j) = J \left(\left(\sum_{i=1}^{m_p} b_{i,j} \left[J^{-1} \left(I_{Av}^k(i, j) \right) \right]^2 + \left[J^{-1} \left(I_{ch}^k(j) \right) \right]^2 \right)^{1/2} \right), \quad (15)$$

where $k = 1, 2, \dots, (\log_2 M)/2$ and $j = 1, 2, \dots, n_p$. Due to the convergence-performance difference among these $(\log_2 M)/2$ types of coded-bit streams, the *a-posteriori* MIs should be calculated in ascending order of the layer index. Specially, for $j = 1, 2, \dots, n_p$ and $z = 1, 2, \dots, (\log_2 M)/2 - 1$, the MI for the z -th coded-bit stream $I_{APP}^z(j)$ should be computed prior to the MI for the $(z+1)$ -th coded-bit stream $I_{APP}^{z+1}(j)$.

- 8) **Finalization:** The execution process of such an algorithm is stopped if $I_{APP}^{(\log_2 M)/2}(j) = 1$ for $j = 1, 2, \dots, n_p$; or the value of T_1 is arrived; Otherwise, return to Step 2) and start a new outer iteration.

Based on the MS-EXIT algorithm, $(\log_2 M)/2$ different decoding thresholds (i.e., $\tau^1, \tau^2, \dots, \tau^{(\log_2 M)/2}$), which correspond to $(\log_2 M)/2$ individual coded-bit streams in the HM-BICM-ID systems, can be obtained.

Note also that:

Fig. 7. Protograph structure of the (3, 6) TB-SC P-LDPC code.

- The MS-EXIT algorithm is designed to investigate the convergence performance for SC P-LDPC-coded M -ary QAM HM-BICM-ID systems, and thus contains an iterative procedure between the hierarchical demodulator and $(\log_2 M)/2$ SC P-LDPC decoders. Importantly, this algorithm can also be used for the HM-BICM counterparts by setting the number of outer iterations to be zero.
- Different from the standard EXIT algorithm, which only can process one data stream and calculate one decoding threshold, the proposed MS-EXIT algorithm can process $(\log_2 M)/2$ individual data streams at the same time. Therefore, $(\log_2 M)/2$ different decoding thresholds can be obtained in this algorithm.
- From the viewpoint of information-theoretic derivation, only one group of (i.e., n_p) *a-priori* MIs, *extrinsic* MIs, and *a-posteriori* MIs can be obtained in each step of the standard EXIT algorithm. Nonetheless, in the proposed MS-EXIT algorithm, $(\log_2 M)/2$ groups of (i.e., $(\log_2 M)/2 \times n_p$) *a-priori* MIs, *extrinsic* MIs, and *a-posteriori* MIs are calculated due to the introduction of HM mechanism. Consequently, all steps, i.e., Steps 1)-8), in the proposed MS-EXIT algorithm are different from those in the existing counterparts.

TABLE II

DECODING THRESHOLDS OF BOTH THE LAYER-1 AND LAYER-2 DATA STREAMS, WHICH ARE GENERATED BY THE (3, 6) TB-SC P-LDPC CODE, FOR THE 16-QAM HM-BICM-ID SYSTEMS WITH FIVE TYPES OF CONSTELLATIONS. THE MAXIMAL OUTER ITERATIONS T_1 AND INNER ITERATIONS T_2 ARE SET TO BE 8 AND 25, RESPECTIVELY.

$T_1 = 0$ Constellation		MSED	MSED-B	M3	HBM	SQ
τ^1		3.13	3.13	1.14	1.14	1.14
τ^2		7.87	7.44	7.66	6.86	6.35
$T_1 = 8$ Constellation		MSED	MSED-B	M3	HBM	SQ
τ^1		1.52	1.51	1.14	1.14	1.14
τ^2		5.56	5.57	5.35	5.34	5.25

C. Convergence-Performance Analysis

1) *Decoding Thresholds:* In order to further verify the superiority of the proposed SQ constellations, we analyze the convergence-performance for HM-BICM-ID systems with different constellations by using the proposed MS-EXIT algorithm. More specifically, it is assumed that all the data streams used in such systems are generated by the (3, 6) TB-SC P-LDPC code. Unless otherwise stated, the coupling length adopted for the (3, 6) TB-SC P-LDPC code is set to be $L = 12$ in this paper. The protograph structure of such a code is given in Fig. 7, where the VNs and CNs are denoted by the filled circles and circles with a plus sign, respectively. Furthermore, the MSED [20], MSED-B [20], M3 [15], and HBM [16] constellations are considered as benchmarks. Referring to Table II, two types of decoding thresholds, i.e., τ^1 and τ^2 , which correspond to the layer-1 and layer-2 data streams, respectively, are presented for the 16-QAM HM-BICM-ID systems with five different constellations.

Based on the condition of $T_1 = 0$, the SC P-LDPC-coded HM-BICM-ID system exhibits the same layer-1 decoding threshold τ^1 when the MSED and MSED-B constellations are adopted. This phenomenon is reasonably consistent with the capacity analysis in Sect. III-B and HMMSED analysis in Sect. III-C, i.e., the MSED and MSED-B constellations have the same $C_{\text{HM-BICM}}^1$ and D^1 . Similar conclusions can be drawn from the M3, HBM, and SQ constellations. From the perspective of the layer-2 data stream, the five constellations have five different layer-2 decoding thresholds τ^2 , which are also consistent with the capacity analysis and HMMSED analysis (i.e., $C_{\text{HM-BICM}}^2$ and D^2). Especially, the SC P-LDPC-coded HM-BICM-ID system with the SQ constellation exhibits the smallest layer-2 decoding threshold (i.e., $\tau^2 = 6.35$ dB) compared with the other four constellations, and thus can achieve the best layer-2 performance.

By setting the maximum number of outer iterations to be $T_1 = 8$, the SC P-LDPC-coded HM-BICM-ID systems with the MSED and MSED-B constellations exhibit nearly the same decoding thresholds for both two layers. On the other hand, the layer-1 decoding thresholds τ^1 of the M3, HBM, and SQ constellations in the case of $T_1 = 8$ are the same as those in the case of $T_1 = 0$. This is because the 1-st layer of the above three constellations is generated by the Gray-mapped base structure, and thus no iterative gain can be obtained by exploiting ID. For the 2-nd layer, the SC P-LDPC-coded HM-BICM-ID system with the SQ constellation can obtain additional threshold gain over the counterparts with other four existing constellations. Hence, the SQ constellation can make such systems achieving the best layer-2 performance in ID scenarios.

Fig. 8. Extrinsic MIs of four different labeling bits, which are output from the demodulator of the proposed SQ-constellation-aided SC P-LDPC-coded HM-BICM-ID system, while the (3, 6) TB-SC P-LDPC code is adopted: (a) the first labeling bit, (b) the second labeling bit, (c) the third labeling bit, and (d) the fourth labeling bit. A 16-QAM modulation is considered.

2) *Extrinsic MIs of Demodulator:* To get further insight, we investigate the extrinsic MIs of four different labeling bits, which are output from the demodulator of the SQ-constellation-aided 16-QAM HM-BICM-ID system. One can easily find from Fig. 8 that the extrinsic MIs of the first and second labeling bits, which constitute the 1-st layer, keep the same value for both two different cases (i.e., the case of $T_1 = 0$ and the case of $T_1 = 8$). This implies that introducing outer iterations cannot improve the layer-1 performance of such an HM-BICM-ID system. Different from the 1-st layer, the 2-nd layer is constructed by the third and fourth labeling bits, whose extrinsic MIs can be improved by increasing the number of outer iterations T_1 . Accordingly, the 2-nd layer can attain desirable performance gain by exploiting ID, and thus the overall performance of such an HM-BICM-ID system is further improved.

V. SIMULATION RESULTS

To demonstrate the merit of the proposed design, we provide various bit-error-rate (BER) simulation results on the SC P-LDPC-coded M -ary QAM HM-BICM-ID systems over AWGN

Fig. 9. BER curves of the layer-1 and layer-2 data streams in the SC P-LDPC-coded HM-BICM-ID systems with the MSED, MSED-B, M3, HBM, and proposed SQ constellations: (a) layer-1 data streams in the case of $T_1 = 0$, (b) layer-2 data streams in the case of $T_1 = 0$, (c) layer-1 data streams in the case of $T_1 = 8$, and (d) layer-2 data streams in the case of $T_1 = 8$.

channels. In particular, all the data streams used in such systems are generated by the (3,6) TB-SC P-LDPC code, which has a code rate of $1/2$ and a codeword length of 2400. In addition, the maximum numbers of the outer iterations T_1 and the inner iterations T_2 are set to be 8 and 25, respectively. Unless otherwise mentioned, we assume a 16-QAM modulation and a standard distance rate $r_d = 1$ for all the constellations in simulations (i.e., A constellation with $r_d = 1$ is referred to as *standard constellation*).

A. BER Performance for the 16-QAM HM-BICM-ID Systems

1) *BER Performance for Standard Constellations:* For the 16-QAM standard constellations, Fig. 9 depicts the BER curves of both the layer-1 and layer-2 data streams in the SC P-LDPC-coded HM-BICM-ID systems with five different types of constellations, i.e., the MSED, MSED-B, M3, HBM, and proposed SQ constellations. It is observed in Fig. 9(a)-(b) that the SQ constellation not only can possess excellent layer-1 performance as the M3 and HBM constellations, which exhibit a remarkable gain of about 2.2 dB over the MSED and MSED-B constellations at a BER of 2×10^{-6} , but also can achieve better

layer-2 performance with respect to the other four constellations. Specifically, the SQ constellation achieves gains of about 0.4 dB, 0.9 dB, 1.1 dB, and 1.4 dB over the HBM, MSED-B, M3, and MSED constellations, respectively, at a BER of 4×10^{-6} . Referring to Fig. 9(c)-(d), the relative performance among the MSED, MSED-B, M3, HBM, and proposed SQ constellations in the case of $T_1 = 8$ is similar to that in the case of $T_1 = 0$. As a result, the proposed SQ constellation appears to be the best mapping scheme compared with the other four counterparts when ID is considered. It can be easily observed that the simulated BER curves of the five different constellations agree well with their corresponding analytical results in Sect. IV-C.

As a further advancement, Fig. 10 compares the BER performance between the Gray constellation and the SQ constellation.⁴ As observed, although the SQ-constellation-aided (3,6) TB-SC P-LDPC code achieves the same layer-1 performance as the Gray-constellation-aided counterpart (see Fig. 10(a)), the former can accomplish better layer-2 performance than the latter (see Fig. 10(b)). Particularly, at a BER of 6×10^{-6} , the former only

⁴It is well known that Gray constellation is one of the best-performing mappers in BICM systems over AWGN channels [20], [50].

(a)

(b)

Fig. 10. BER curves of the layer-1 and layer-2 data streams in the SC P-LDPC-coded HM-BICM-ID systems with the Gray and proposed SQ constellations: (a) layer-1 data streams and (b) layer-2 data streams.

requires about an SNR of 6 dB to achieve this BER value, while the latter needs about an SNR of 6.2 dB to do so.

2) *BER Performance for Non-Standard Constellations:* Aiming to further demonstrate the superiority of the SQ constellation, some BER simulation results in the case of non-standard constellations (i.e., the distance rate $r_d = 1/2$) are provided in Fig. 11, where the maximum number of outer iterations is set to be $T_1 = 8$. Referring to Fig. 11(a) for the layer-1 performance, at $E_b/N_0 = 4.2$ dB, the SQ-constellation-aided (3, 6) TB-SC P-LDPC code can achieve a BER of 1×10^{-6} , while the HBM, M3, MSSED-B, and MSSED constellations accomplish BERs of 1×10^{-5} , 6×10^{-4} , 3×10^{-2} , and 5×10^{-2} , respectively. Moreover, at a BER of 2×10^{-5} , the SQ constellation can obtain gains of about 0.2 dB, 0.7 dB, 1.8 dB, and 2.4 dB over the HBM, M3, MSSED-B, and MSSED constellations, respectively. Similar phenomenon can be observed from Fig. 11(b), which shows the layer-2 performance. The above observations verify the effectiveness of our proposed SQ constellation in the case of non-standard constellations.

Fig. 12 presents the BER curves of the Gray constellation and proposed SQ constellation in 16-QAM HM-BICM-ID systems with $T_1 = 8$. It is apparent that our proposed SQ constellation is better than the Gray constellation in terms of both layer-1 and

(a)

(b)

Fig. 11. BER curves of the layer-1 and layer-2 data streams in the SC P-LDPC-coded HM-BICM-ID systems with the MSSED, MSSED-B, M3, HBM, and proposed SQ constellations: (a) layer-1 data streams and (b) layer-2 data streams. The distance rate $r_d = 1/2$.

Fig. 12. BER curves of the layer-1 and layer-2 data streams in the SC P-LDPC-coded HM-BICM-ID systems with the Gray and proposed SQ constellation. The distance rate $r_d = 1/2$.

layer-2 data streams. Specifically, at a BER of 1×10^{-6} , the layer-1 performance and layer-2 performance of the former can attain gains of about 1.1 dB and 0.3 dB over that of the latter. As a consequence, our proposed SQ constellation can keep a desirable balance between the layer-1 performance and layer-2 performance, while the Gray constellation cannot to do so.

Fig. 13. SQ constellation for the 64-QAM HM-BICM-ID system.

Fig. 14. BER curves of the layer-1, layer-2, and layer-3 data streams in the SC P-LDPC-coded HM-BICM-ID systems with the Gray, VM, and proposed SQ constellations: (a) layer-1 data streams, (b) layer-2 data streams, and (c) layer-3 data streams. A 64-QAM modulation is considered.

Remark 5: We have also performed simulations with other values of r_d (i.e., $r_d = 1/3$) and have found that the proposed SQ constellation also outperforms the HBM, M3, MSSED-B, MSSED, and Gray constellations in the HM-BICM-ID systems.

B. BER Performance for the 64-QAM HM-BICM-ID Systems

To illustrate the feasibility of our proposed two-stage design approach, we construct a 64-ary SQ constellation, whose structure is given in Fig. 13, to process three data streams with different priorities. In Fig. 14(a)-(c), we measure the performance of the proposed 64-ary SQ constellation and two state-of-the-art counterparts (i.e., called as 64-ary *Gray constellation* [14] and 64-ary *vectored modulated (VM) constellation* [18]). As observed, the 64-ary SQ constellation not only possesses excellent layer-1 performance as the 64-ary Gray constellation and 64-ary VM constellation, but also can achieve better layer-2 performance and layer-3 performance. Specifically, at a BER of 1×10^{-5} , the (3,6) TB-SC P-LDPC code with the 64-ary SQ constellation

can achieve gains of about 0.1 dB and 0.2 dB for the layer-2 data stream and layer-3 data stream, respectively, over the other two constellations. This implies that the SQ constellations are very suitable for HM-BICM-ID systems, especially multi-layer scenarios (i.e., $k > 2$).

VI. CONCLUSIONS

In this paper, we have presented a comprehensive study on the design and analysis of the SC P-LDPC-coded HM-BICM-ID systems. We have first proposed an information-theoretic methodology to calculate $(\log_2 M)/2$ types of AMIs for the HM-BICM scenarios. Based on the AMI analysis, we have accurately evaluated the capacity limits (resp. maximum achievable rates) for all the individual coded-bit streams in the HM-BICM scenarios. We have also conceived a two-stage design approach to generate a novel type of constellations, called *SQ constellations*, for the HM-BICM-ID scenarios. Additionally, we have put forward the quadrant-based harmonic mean analysis to demonstrate that the

SQ constellations not only can guarantee the largest HMMSEDs for all layers, but also can realize desirable iterative performance. As a further insight, we have developed an MS-EXIT algorithm and analyzed the convergence performance for the HM-BICM-ID scenarios. Simulative results have indicated that the proposed SC P-LDPC-coded HM-BICM-ID systems are superior to the state-of-the-art counterparts in the cases of both standard and non-standard distance rates. Owing to the aforementioned benefits, our proposed SC P-LDPC-coded HM-BICM-ID systems can be viewed as a promising alternative for use in future wireless-communication scenarios with different quality-of-service (QoS) requirements, e.g., the 6G-enabled IoT. As a future line, we will extend this work to more general and practical IoT scenarios (e.g., different coded-bit streams have different codeword lengths and code rates, and the numbers of labeling bits assigned into different layers are assumed to be different). Besides, we plan to exploit the intrinsic UEP characteristics to trigger the wave-like convergence of SC P-LDPC codes, so as to further enhance the performance of SC P-LDPC-coded HM-BICM-ID systems.

REFERENCES

- [1] S. J. Lee, K. Kim, J. S. Jung, and S. Lee, "Analytical performance evaluation of hierarchical 16 QAM for multicast/broadcast transmission," *IEEE Commun. Lett.*, vol. 16, no. 10, pp. 1536–1539, Oct. 2012.
- [2] H. Jiang, P. A. Wilford, and S. A. Wilkus, "Providing local content in a hybrid single frequency network using hierarchical modulation," *IEEE Trans. Broadcast.*, vol. 56, no. 4, pp. 532–540, Dec. 2010.
- [3] M. J. Hossain, M. Alouini, and V. Bhargava, "Two-user opportunistic scheduling using hierarchical modulations in wireless networks with heterogeneous average link gains," *IEEE Trans. Commun.*, vol. 58, no. 3, pp. 880–889, Mar. 2010.
- [4] H. Wu, A. Ashikhmin, X. Wang, C. Li, S. Yang, and L. Zhang, "Distributed error correction coding scheme for low storage blockchain systems," *IEEE Int. Things J.*, vol. PP, no. 99, pp. 1–17, 2020, doi: 10.1109/IJOT.2020.2982067.
- [5] P. K. Vitthaladevuni and M.-S. Alouini, "A recursive algorithm for the exact BER computation of generalized hierarchical QAM constellations," *IEEE Trans. Inf. Theory*, vol. 49, no. 1, pp. 297–307, Jan. 2003.
- [6] H. Sun, C. Dong, S. X. Ng, and L. Hanzo, "Five decades of hierarchical modulation and its benefits in relay-aided networking," *IEEE Access*, vol. 3, pp. 2891–2921, Dec. 2015.
- [7] M. J. Hossain, P. K. Vitthaladevuni, M. S. Alouini, V. K. Bhargava, and A. J. Goldsmith, "Adaptive hierarchical modulation for simultaneous voice and multiclass data transmission over fading channels," *IEEE Trans. Veh. Technol.*, vol. 55, no. 4, pp. 1181–1194, Jul. 2006.
- [8] C. Hausl and J. Hagenauer, "Relay communication with hierarchical modulation," *IEEE Commun. Lett.*, vol. 11, no. 1, pp. 64–66, Jan. 2007.
- [9] J. M. Park, S. Kim, and J. Choi, "Hierarchically modulated network coding for asymmetric two-way relay systems," *IEEE Trans. Veh. Technol.*, vol. 59, no. 5, pp. 2179–2184, Jun. 2010.
- [10] H. Jiang and P. A. Wilford, "A hierarchical modulation for upgrading digital broadcast systems," *IEEE Trans. Broadcast.*, vol. 51, no. 2, pp. 223–229, Jun. 2005.
- [11] M. Chang and S. Lee, "Performance analysis of cooperative communication system with hierarchical modulation over Rayleigh fading channel," *IEEE Trans. Wireless Commun.*, vol. 8, no. 6, pp. 2848–2852, Jun. 2009.
- [12] G. Caire, G. Taricco, and E. Biglieri, "Bit-interleaved coded modulation," *IEEE Trans. Inf. Theory*, vol. 44, no. 3, pp. 927–946, May 1998.
- [13] J. Wu, "Non-uniform and large distance constellation design for hierarchical modulation," in *Proc. IEEE Int. Conf. Commun. (ICC)*, May 2010, pp. 1–5.
- [14] M. Gangadharappa, R. Kapoor, and H. Dixit, "An efficient hierarchical 16-QAM dynamic constellation to obtain high PSNR reconstructed images under varying channel conditions," *IET Commun.*, vol. 10, no. 2, pp. 139–147, Jan. 2016.
- [15] H. Huang and Y. Tsai, "Protection-level-exchanging hierarchical modulation for multiresolution services under decode-and-forward cooperative networks," *IEEE Trans. Veh. Technol.*, vol. 66, no. 8, pp. 6742–6753, Aug. 2017.
- [16] Z. Hossain and J. M. Jornet, "Hierarchical bandwidth modulation for ultra-broadband Terahertz communications," in *Proc. IEEE Int. Conf. Commun. (ICC)*, May 2019, pp. 1–7.
- [17] H. Méric, J. Lacan, F. Arnal, G. Lesthievant, and M. Boucheret, "Combining adaptive coding and modulation with hierarchical modulation in Satcom systems," *IEEE Trans. Broadcast.*, vol. 59, no. 4, pp. 627–637, Dec. 2013.
- [18] H. Alasti and S. Gazor, "Vectorized implementation of hierarchical 2^{2n} QAM," *IEEE Trans. Circuits Syst. II: Exp. Briefs*, vol. 62, no. 11, pp. 1103–1107, Nov. 2015.
- [19] X. Li, A. Chindapol, and J. A. Ritcey, "Bit-interleaved coded modulation with iterative decoding and 8PSK signaling," *IEEE Trans. Commun.*, vol. 50, no. 8, pp. 1250–1257, Aug. 2002.
- [20] Q. Li, J. Zhang, L. Bai, and J. Choi, "Performance analysis and system design for hierarchical modulated BICM-ID," *IEEE Trans. Wireless Commun.*, vol. 13, no. 6, pp. 3056–3069, Jun. 2014.
- [21] B. Xiao, K. Xiao, Z. Chen, B. Xia, and H. Liu, "Joint design for modulation and constellation labels in multiuser superposition transmission," *IEEE Trans. Broadcast.*, vol. 65, no. 2, pp. 245–259, Jun. 2019.
- [22] S. Sandberg and N. V. Deetzen, "Design of bandwidth-efficient unequal error protection LDPC codes," *IEEE Trans. Commun.*, vol. 58, no. 3, pp. 802–811, Mar. 2010.
- [23] Z. Hu and H. Liu, "A low-complexity LDPC decoding algorithm for hierarchical broadcasting: Design and implementation," *IEEE Trans. Veh. Technol.*, vol. 62, no. 4, pp. 1843–1849, May 2013.
- [24] Z. Hu, H. Jiang, H. Li, Z. Chen, and H. Liu, "A low-complexity decoding algorithm for coded hierarchical modulation in single frequency networks," *IEEE Trans. Broadcast.*, vol. 60, no. 2, pp. 302–312, Jun. 2014.
- [25] Y. Fang, G. Bi, Y. L. Guan, and F. C. M. Lau, "A survey on protograph LDPC codes and their applications," *IEEE Commun. Surveys & Tutorials*, vol. 17, no. 4, pp. 1989–2016, 4th Quarter 2015.
- [26] G. Liva and M. Chiani, "Protograph LDPC codes design based on EXIT analysis," in *Proc. IEEE Glob. Commun. Conf. (GLOBECOM)*, Nov. 2007, pp. 3250–3254.
- [27] Y. Jin, M. Jiang, and C. Zhao, "Optimized variable degree matched mapping for protograph LDPC coded modulation with 16QAM," in *Proc. Int. Symp. Turbo Codes & Iterative Inf. Process. (ISTC)*, Sep. 2010, pp. 161–165.
- [28] T. V. Nguyen, A. Nosratinia, and D. Divsalar, "Threshold of protograph-based LDPC coded BICM for Rayleigh fading," in *Proc. IEEE Glob. Telecommun. Conf. (GLOBECOM)*, Dec. 2011, pp. 1–5.
- [29] C. Tang, H. Shen, M. Jiang, and C. Zhao, "Optimization of generalized VDM for protograph-based LDPC coded BICM," *IEEE Commun. Lett.*, vol. 18, no. 5, pp. 853–856, May 2014.
- [30] H. Zhou, M. Jiang, C. Zhao, and J. Wang, "Optimization of protograph-based LDPC coded BICM-ID for the Poisson PPM channel," *IEEE Commun. Lett.*, vol. 17, no. 12, pp. 2344–2347, Dec. 2013.
- [31] F. Zabini, B. Matuz, G. Liva, E. Paolini, and M. Chiani, "The PPM Poisson channel: Finite-length bounds and code design," in *Proc. Int. Symp. Turbo Codes & Iterative Inf. Process. (ISTC)*, Aug. 2014, pp. 193–197.
- [32] D. G. M. Mitchell, A. E. Pusane, and D. J. Costello, "Minimum distance and trapping set analysis of protograph-based LDPC convolutional codes," *IEEE Trans. Inf. Theory*, vol. 59, no. 1, pp. 254–281, Jan. 2013.
- [33] D. G. M. Mitchell, M. Lentmaier, and D. J. Costello, "Spatially coupled LDPC codes constructed from protographs," *IEEE Trans. Inf. Theory*, vol. 61, no. 9, pp. 4866–4889, Sep. 2015.
- [34] M. Stinner and P. M. Olmos, "On the waterfall performance of finite-length sc-ldpc codes constructed from protographs," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 2, pp. 345–361, Feb. 2016.
- [35] D. G. M. Mitchell, M. Lentmaier, A. E. Pusane, and D. J. Costello, "Randomly punctured LDPC codes," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 2, pp. 408–421, Feb. 2016.
- [36] J. Tan, Q. Wang, C. Qian, Z. Wang, S. Chen, and L. Hanzo, "A reduced-complexity demapping algorithm for BICM-ID systems," *IEEE Trans. Veh. Technol.*, vol. 64, no. 9, pp. 4350–4356, Sep. 2015.
- [37] M. Franceschini, G. Ferrari, and R. Raheli, "Does the performance of LDPC codes depend on the channel?" *IEEE Trans. Commun.*, vol. 54, no. 12, pp. 2129–2132, Dec. 2006.
- [38] J. Bao, Z. Ma, M. Xiao, T. A. Tsiftsis, and Z. Zhu, "Bit-interleaved coded SCMA with iterative multiuser detection: Multidimensional constellations design," *IEEE Trans. Commun.*, vol. 66, no. 11, pp. 5292–5304, Nov. 2018.
- [39] Z. Wu, X. Gao, and C. Jiang, "Nonbinary LDPC-coded spatial multiplexing for rate-2 MIMO of DVB-NGH system," *IEEE Trans. Broadcast.*, vol. 64, no. 2, pp. 201–210, Jun. 2018.
- [40] Q. Xie, K. Peng, J. Song, and Z. Yang, "Bit-interleaved LDPC-coded modulation with iterative demapping and decoding," in *Proc. IEEE Veh. Technol. Conf. (VTC)*, Apr. 2009, pp. 1–5.

- [41] T. Cheng, K. Peng, Z. Liu, and Z. Yang, "Efficient receiver architecture for LDPC coded BICM-ID system," *IEEE Commun. Lett.*, vol. 19, no. 7, pp. 1089–1092, Jul. 2015.
- [42] M. C. Valenti and X. Xiang, "Constellation shaping for bit-interleaved LDPC coded APSK," *IEEE Trans. Commun.*, vol. 60, no. 10, pp. 2960–2970, Oct. 2012.
- [43] Q. Xie, J. Song, K. Peng, F. Yang, and Z. Wang, "Coded modulation with signal space diversity," *IEEE Trans. Wireless Commun.*, vol. 10, no. 2, pp. 660–669, Feb. 2011.
- [44] P. Chen, Z. Xie, Y. Fang, Z. Chen, S. Mumtaz, and J. J. P. C. Rodrigues, "Physical-layer network coding: An efficient technique for wireless communications," *IEEE Netw.*, vol. 34, no. 2, pp. 270–276, Mar. 2020.
- [45] H. M. Navazi and M. J. Hossain, "A novel symbol mapping method for BICM-ID systems for higher order signal constellations," *IEEE Commun. Lett.*, vol. 18, no. 8, pp. 1323–1326, Aug. 2014.
- [46] A. Chindapol and J. A. Ritcey, "Design, analysis, and performance evaluation for BICM-ID with square QAM constellations in Rayleigh fading channels," *IEEE J. Sel. Areas Commun.*, vol. 19, no. 5, pp. 944–957, May 2001.
- [47] J. Thorpe, "Low-density parity-check (LDPC) codes constructed from protographs," in *Proc. IPN Progr. Rep.*, vol. 154, Aug. 2003, pp. 1–7.
- [48] Y. Fang, P. Chen, G. Cai, F. C. M. Lau, S. C. Liew, and G. Han, "Outage-limit-approaching channel coding for future wireless communications: Root-protograph low-density parity-check codes," *IEEE Veh. Technol. Mag.*, vol. 14, no. 2, pp. 85–93, Jun. 2019.
- [49] S. ten Brink, G. Kramer, and A. Ashikhmin, "Design of low-density parity-check codes for modulation and detection," *IEEE Trans. Commun.*, vol. 52, no. 4, pp. 670–678, Apr. 2004.
- [50] S. Chaabouni, N. Sellami, and M. Siala, "Mapping optimization for a MAP turbo detector over a frequency-selective channel," *IEEE Trans. Veh. Technol.*, vol. 63, no. 2, pp. 617–627, Feb. 2014.

Guojun Han (M'12-SM'14) obtained his Ph.D. from Sun Yat-sen University, Guangzhou, China, and the M.E. degree in electronic engineering from South China University of Technology, Guangzhou, China. From March 2011 to August 2013, he was a Research Fellow at the School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore. From October 2013 to April 2014, he was a Research Associate at the Department of Electrical and Electronic Engineering, Hong Kong University of Science and Technology. He is now a Full Professor and Executive Dean at the School of Information Engineering, Guangdong University of Technology, Guangzhou, China. His research interests include wireless communications, coding and signal processing for data storage.

Zhaojie Yang (S'17) received the B.Sc. degree in applied electronic technology from Lingnan Normal University, China, in 2016. He is currently pursuing the Ph.D. degree in the Department of Communication Engineering, Guangdong University of Technology, China. His primary research interest is channel coding.

Yi Fang (M'15) received the B.Sc. degree in electronic engineering from East China Jiaotong University, China, in 2008, and the Ph.D. degree in communication engineering, Xiamen University, China, in 2013. From May 2012 to July 2012, He was a Research Assistant in electronic and information engineering, Hong Kong Polytechnic University, Hong Kong. From September 2012 to September 2013, he was a Visiting Scholar in electronic and electrical engineering, University College London, UK. From February 2014 to February 2015, he was a Research Fellow at the School of Electrical

Kazi Mohammed Saidul Huq (SM'17) is currently a Senior Research Fellow with the Faculty of Computing, Engineering, and Science, University of South Wales, Pontypridd, U.K. He has served as a Project Coordinator for major international research projects. He is a founding member of the IEEE 1932.1 Standard for Licensed/Unlicensed Spectrum Interoperability in Wireless Mobile Networks. He is the Associate Editor of the IET Quantum Communication Journal. He was also the lead Guest Editor of the IEEE Communications Magazine Feature Topic on THz Communications in the June 2018 issue. He has vast experiences in 5G networks. He has authored several publications, including papers in high-impact international conferences and journals, books, and book chapters. His research activities include 5G, 6G paradigm, communication haul, D2D, Green radio, Higher frequency communication (mmWave, THz), IoT, MAC-PHY, RRM, and URLLC.

and Electronic Engineering, Nanyang Technological University, Singapore. He is currently a Full Professor at the School of Information Engineering, Guangdong University of Technology, China. He has been an Associate Editor for the IEEE Access since 2018 and a core member of the Guangdong Innovative Research Team since 2016. He served as the Publicity Co-Chair of the International Symposium on Turbo Codes and Iterative Information Processing 2018. His current research interests include information and coding theory (especially LDPC codes), spread-spectrum modulation, and cooperative communications. He is the corresponding author of this article.