Power-efficient Irregular Repeat-Accumulate Encoded BICM-ID for 16-ary Signal Constellations

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***Abstract*— The design of power-efficient forward error correction techniques over additive white Gaussian noise (AWGN) and frequency non-selective fading channels is considered in this work. The aim of this paper is to investigate the application of BICM with iterative demodulation and decoding (BICM-ID) system with irregular repeat-accumulate (IRA) codes to minimize the bit error rate (BER) and determine the most suitable constellation and mapping pairs for designing power-efficient BICM-ID systems over AWGN and Rayleigh fading channels using the concept of channel capacity limit. Simulation results have confirmed that a remarkable BER improvement can be achieved using the proposed design criterion. Based on the IRA-encoded BICM-ID technique considered, the BER improvement gained is exhibited either as an additional coding gain, error floor elimination, or both. The code components include the IRA codes, irregular low-density parity-check (ILDPC) codes and convolutional codes (CC). The modulation technique considered is the widely-used 16-ary constellations with various bit mappings.**

***Index Terms*— channel capacity, coded modulation, error correction codes, iterative decoding, OFDM, LTE**

I. Introduction

Trellis-coded modulation (TCM) [1] achieves good performance over additive white Gaussian noise (AWGN) channel by maximizing the free Euclidean distance using set partitioning (SP). For fading channels, the TCM code performance is dominated by the minimum Hamming distance between the coded symbol sequences rather than the minimum Euclidean distance. As a consequence, a new approach called bit-interleaved coded modulation (BICM) was developed by Zehavi [2] to increase the time diversity of the coded modulation at the expense of reducing the free squared Euclidean distance (FED), resulting in degradation over AWGN channels [2], [3]. BICM is a spectrally efficient coded modulation technique and it is well-suited for bandwidth efficient transmission over fading channels. The optimum receiver of the BICM is composed of a joint demapper and decoder. However, due to the high complexity of the optimum receiver, a low complexity receiver can be constructed when the demapping and decoding are decoupled. BICM with iterative demodulation and decoding (BICM-ID) achieves a turbo-like performance using 8-PSK and 16-QAM modulation over both AWGN and fading channels [4]-[6].

The optimised selection of the channel code and mapping leads to near capacity performance [7]. The selection process includes combinations of Gray mapping with powerful channel codes [7], [8] such as turbo codes [9], low-density parity-check (LDPC) codes or repeat-accumulate (RA) codes [10], and combinations of non-Gray mapping with less powerful channel codes [8] such as the simple convolutional codes (CC). For turbo codes, it is well-known that the 16-QAM combined with Gray mapping are very well-matched for BICM schemes [7], [11]. However, some constellations have been reported to outperform the 16-QAM over both AWGN and fading channels [12], [13]. Hence, these constellations can be used to design BICM-ID schemes. Motivated by the performance improvement gained by combining turbo codes with BICM schemes, this paper investigates the application of irregular RA (IRA) codes in BICM-ID systems to improve the error performance [14], [15]. The encoding efficiency of LDPC codes is quadratic in the block length since encoding requires multiplication by the generator matrix which is not sparse. On the other hand, the generator matrix for IRA codes is sparse. Similar to RA codes, IRA codes can be represented as a class of "turbo-like" codes and a class of LDPC codes. The aim of this paper is to investigate the application of BICM-ID system with IRA codes and determine the most suitable combinations of 16-ary constellations and mappings for designing power-efficient BICM-ID systems for AWGN and Rayleigh fading channels.

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The BICM and BICM-ID schemes can be designed by employing any two-dimensional constellation. In this paper, we consider the design criterion of finding the best signal constellation and mapping pairs to construct power-efficient BICM and BICM-ID schemes, over AWGN and fading channels, by using the concept of channel capacity limit. The capacity limit of BICM for various 16-ary signal constellations is then evaluated. It is worthwhile to note that the channel capacity of a BICM system is defined regardless the channel code used and the existence of iterative decoding [16]. The idea of evaluating capacity limits to find the best signal constellation and mapping pair comes from the fact that power-efficient BICM and BICM-ID schemes usually employ state-of-the-art codes, and are thus capable of achieving near-capacity performance. For illustrating the obtained results, the BER performance of BICM and BICM-ID systems using various signal constellation and mapping pairs with other selected error-correcting codes influencing the error performance of BICM and BICM-ID schemes is investigated via computer simulations.

The rest of the paper is organised as follows. Section II provides a background of the generic structure of BICM-ID and the IRA codes. Section III provides a design criterion for choosing the best parameters for BICM-ID schemes by evaluating capacity limits of various 16-ary constellation-mapping pairs to determine the optimum pair. Section IV is devoted for computer simulation results obtained for several BICM and BICM-ID schemes comprised of selected error-correcting codes with various signal constellations and mappings. Section V describes combination of BICM and OFDM in the context of 4G standards. Finally, Section VI concludes the paper.

II. Overview Of BICM-ID and IRA Codes

A. BICM-ID with soft-decision feedback

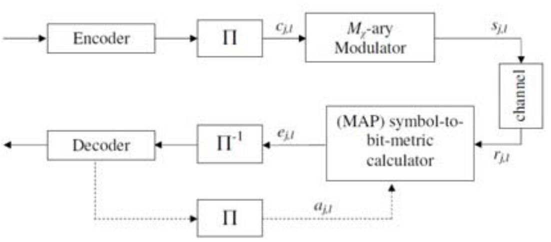

Figure 1. Structure of a BICM-ID transmission system. The dashed arrows represent iterations between RA decoder and the symbol-to-bit metric calculator.

A BICM-ID transmission system can be modelled as an interleaved concatenation of an encoder and a symbol mapper as shown in Fig. 1. Consider a 2^{m_b}-ary modulation represented by a two-dimensional signal constellation χ where $|\chi| = 2^{m_b} = M_\chi$. Let $\mathbf{c}_j = \{c_{j,1}, ..., c_{j,m_b}\} \in \{0,1\}^{m_b}$, $1 \leq j \leq N/m_b$, denote a set of m_b bits at the modulator input, N denotes the length of the codeword, $c_{j,1}$ is the most significant bit (MSB), and c_{j,m_b} is the least significant bit (LSB). A bit-reliability mapping [17] is employed where the systematic bits of a codeword are mapped to the more significant bits of the signal constellation and the parity-check bits are mapped to the less significant bits. In this paper, both AWGN and Rayleigh fading channel models are considered. The received complex symbol is $r_j = h_j s_j + n_j$, where n_j is a Gaussian noise sample with zero mean and variance $\sigma^2 = N_0/2$, N_0 being the one-sided power spectral density of white Gaussian noise and h_j is the complex time-invariant fading gain whose fading coefficients are normally distributed with zero mean and variance 1/2. It is worthy to note that h_j =1 for AWGN channels. In this paper, perfect channel state (CSI) is assumed. For Rayleigh fading channels, the fading coefficients are normally distributed with zero mean and variance 1/2. At the receiver side, the channel outputs and the *a priori* log-likelihood ratios (LLRs) $a_{j,l}$ obtained from the decoder feedback are processed by the demapper to obtain the extrinsic LLRs $e_{j,l}$ for $l = 1, ..., m_b$. The *a priori* and extrinsic LLRs are defined as,

$$a_{j,l} = \ln\left[\frac{P(c_{j,l}=1)}{P(c_{j,l}=0)}\right], \tag{1}$$

$$e_{j,l} = \ln\left[\frac{\sum_{s_j \in \chi^1} \exp\left\{-\frac{\left(r_j - h_j s_j\right)^2}{N_0} + \sum_{i=1,\neq l}^{m_b} s_{j,i} a_{j,i}\right\}}{\sum_{s_j \in \chi^0} \exp\left\{-\frac{\left(r_j - h_j s_j\right)^2}{N_0} + \sum_{i=1,\neq l}^{m_b} s_{j,i} a_{j,i}\right\}}\right], \tag{2}$$

where χ^t denotes the signals $s_j \in \chi$ whose labels have the value $t \in \{0, 1\}$. There is no feedback from the decoder to the demapper during the initial demapping, hence the *a priori* LLRs $a_{j,1}$ are set to zero. For subsequent iterations, the extrinsic information from the decoder is fed back as *a priori* information at the demapper.

B. Systematic IRA codes

The selection of the channel coding scheme can improve the BER performance of BICM and BICM-ID systems. Error floors can be reduced or eliminated by employing turbo-like codes (LDPC, RA) instead of CC. In this section, we consider the construction of IRA codes. The idea of jointly iterative detection and decoding has been proposed in [18]-[20]. The encoding of IRA codes is achieved by randomly generating its parity check matrix using the simple bit-filling algorithm [21] without any optimisation performed to the degree distributions of the IRA codes.

A systematic IRA code can be considered as an LDPC code which can be represented using a parity-check matrix **H**,

$$\mathbf{H} = [\mathbf{H}_1\ \mathbf{H}_2]. \tag{3}$$

As shown in Fig. 2, the matrix $\mathbf{H}_1$ is an $M \times K$ matrix with column weights $q_1, ..., q_K$ and row weights $p_1, ..., p_M$, the matrix $\mathbf{H}_2$ is an $M \times M$ matrix. The location of the nonzero entries is determined by the interleaver. An example illustrating an IRA code of length 15 with a parity-check matrix as described by (3) and Tanner graph is depicted in Fig. 2.

$$H = \left[\begin{matrix} \overbrace{\begin{matrix} 0&0&0&1&1&0\\ 0&1&1&0&0&1\\ 1&0&0&1&1&0\\ 0&1&0&0&1&1\\ 0&0&1&1&0&1\\ 1&1&0&0&1&0\\ 0&0&0&1&0&1\\ 1&0&1&0&0&0\\ 0&0&0&1&1&1 \end{matrix}}^{H_1} & \overbrace{\begin{matrix} 1&0&0&0&0&0&0&0&0\\ 1&1&0&0&0&0&0&0&0\\ 0&1&1&0&0&0&0&0&0\\ 0&0&1&1&0&0&0&0&0\\ 0&0&0&1&1&0&0&0&0\\ 0&0&0&0&1&1&0&0&0\\ 0&0&0&0&0&1&1&0&0\\ 0&0&0&0&0&0&1&1&0\\ 0&0&0&0&0&0&0&1&1 \end{matrix}}^{H_2} \end{matrix}\right]$$

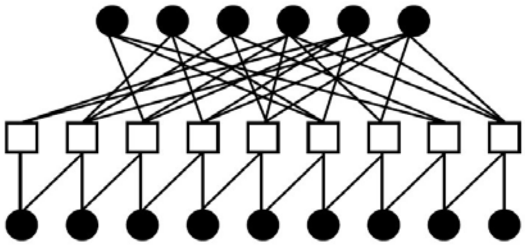

Figure 2. Parity-check matrix and Tanner graph representation of an IRA code of length 15 with q =[3,3,3,5,5,5], p =[2,3,3,3,3,3,2,2,3] and interleaver pattern Π =[10,15,4,7,20,1,11,16,5,17,21,8,12,22,2,6,18,13, 23,3,9,14,19,24].

For IRA codes, the variable node degree distribution in the code's Tanner graph is represented by $v(x) = \sum_i v_i x^{i-1}$ and the check node degree distribution is given by $\rho(x) = \sum_i \rho_i x^{i-1}$. The coefficient v_i is the fraction of the Tanner graph edges connected to variable nodes of degree i. The row degrees are similarly represented by $\rho(x)$. Hence, the number of variable nodes and check nodes of degree i are given by

$$N_\upsilon(i) = N\left[\frac{\upsilon_i / i}{\sum_k \upsilon_k / k}\right], \tag{4}$$

$$N_c(i) = N\left[\frac{\rho_i / i}{\sum_k \rho_k / k}\right]. \tag{5}$$

To construct systematic IRA codes, there must be at least M nodes of degree-2 required by the accumulator. Moreover, short cycles involving only degree-2 variable nodes are avoided by setting $N_v(i) = M - 1$ [22]. Similar to IRA codes, parity-check matrix of an irregular LDPC (ILDPC) code can be represented in the form of (3). The systematic generator matrix $\mathbf{G}$ for the parity-check matrix from (3) of a systematic IRA code is represented by (6) where $\mathbf{I}$ is the $K \times K$ identity matrix and $\mathbf{P}$ is of dimension $K \times M$.

$$\mathbf{G} = [\mathbf{I}\ \mathbf{P}] = [\mathbf{H}_1^T\ \mathbf{H}_2^T]. \tag{6}$$

The decoding of IRA codes employs the message passing algorithm which is an efficient iterative decoding algorithm used also for the decoding of LDPC codes [23], [24]. The message passing algorithm comprises two stages which are the initialisation and iteration. Let M_n be defined as the set of check nodes connected to variable node n and let N_m be expressed as the set of variable nodes connected to check node m. $M_{n,m}$ represents the set M_n, excluding check node m and $N_{m,n}$ describes the set N_m excluding variable node n. During the initialisation stage, each bit node computes its message defined in (7) and sends it to M_n.

$$\lambda_n^{[\tau=0]} = \ln\left[\frac{P(e_n \mid \upsilon_n = 1)}{P(e_n \mid \upsilon_n = 0)}\right] = L_c e_n, \qquad 1 \le n \le N. \tag{7}$$

The symbols τ, e_n and v_n correspond to the decoding iteration number, the extrinsic LLRs from the demapper defined in (2) and systematic codeword, respectively. The channel reliability $L_c = 2\sqrt{E_c}/\sigma^2$ where E_c and σ^2 denote the energy per coded bit and the variance of the channel noise respectively. Each iteration has two different phases known as the check node update and variable node update which are described in (8) and (9), respectively.

$$\eta_{m,n}^{[\tau]} = -2\tanh^{-1}\left[\prod_{j \in N_{m,n}} \tanh\left(-\frac{\lambda_j^{[\tau-1]} - \eta_{m,j}^{[\tau-1]}}{2}\right)\right], \tag{8}$$

$$\lambda_{n,m}^{[\tau]} = L_c e_n + \sum_{m \in M_{n,m}} \eta_{m,n}^{[\tau]}. \tag{9}$$

Equation (9) refers to the message that the bit node n sends to its check node m [25]. The intrinsic term $L_c e_n$ is determined by the measurement e_n influencing the bit c_n. The extrinsic term $\sum \eta_{m,n}^{[\tau]}$ is determined by the information given by all other observations and the code structure where $\eta_{m,n}$ is referred to as the message which is passed from the check node m to the bit node n during the τ-th iteration. These messages iterate among the variable nodes and check nodes to compute the *a posteriori* LLR for each variable node [4]. The LLR for each variable node is given by (10) where $\mathbf{E} = [e_1, e_2, ..., e_N]$ is the received extrinsic LLRs from the demapper.

$$\lambda_{n,m} = \ln\left[\frac{P(\upsilon_n = 1 \mid E)}{P(\upsilon_n = 0 \mid E)}\right] = L_c e_n + \sum_{m \in M_{n,m}} \eta_{m,n}. \tag{10}$$

III. Constellation-Mapping Pairs Design Criterion For BICM-ID Schemes

The selection of the best signal constellation and mapping pairs for BICM-ID schemes can be achieved based on the concept of channel capacity limit which is a computationally efficient technique. The 16-ary signal constellations are focused because they are widely used in many standards and practical systems such as WLAN, DVB, DAB, WiMAX, and coherent optical communication systems. The 16-ary constellations considered are the rectangular 16-QAM, optimum, (1, 5, 10) and (5, 11) which have been found to be the most power-efficient constellations for coded and uncoded systems over AWGN and fading channels [7], [11]-[13]. The exact locations of the signal points in (1, 5, 10) and (5, 11) are reported in [13]. Since the channel code and the mapping should be well-matched to achieve near capacity performance, various types of mappings are considered in this paper. This includes the Gray, Schreckenbach (Schrec), modified set partitioning (MSP) and maximum squared Euclidean weight (MSEW). The Schreckenbach mappings optimised for AWGN and Rayleigh fading channels are represented by $M16^a$ and $M16^r$, respectively and are obtained using the binary searching algorithm (BSA) [26]. However, for the 16-ary non-square constellations, some of these mappings are not applicable due to the structure of such constellations.

Mapping by set partitioning was originally proposed for TCM systems, hence it might not lead to optimum results for BICM-ID. It is shown in [6], [27] that the improvement of error performance for a BICM-ID scheme with SP mapping is not significant. As a result, quasi-Gray, quasi-MSP and quasi-MSEW mappings are used which are as close as possible to their respective mappings. The best combinations of rectangular and non-rectangular 16-ary signal constellations with mappings (Fig. 3) for error-correcting codes considered in this paper are selected based on the BICM capacity limit, which is discussed in the next paragraph.

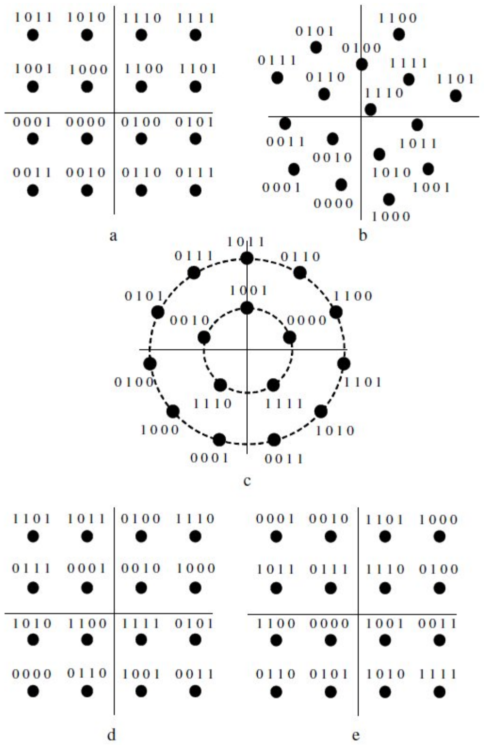

Figure 3. Optimal combinations of 16-ary signal constellations with mappings considered in this work. (a) 16-QAM signal constellation with Gray mapping, (b) optimum signal constellation with quasi-Gray mapping, (c) (5,11) signal constellation with quasi-MSEW mapping, (d) 16-QAM signal constellation with $M16^a$ mapping, (e) 16-QAM signal constellation with $M16^r$ mapping.

The expression of the BICM capacity limit over AWGN channels is evaluated to determine the most suitable constellation-mapping pairs. Consider a two-dimensional constellation χ of size $|\chi| = 2^{m_b}$. Based on the general results reported in [3], we can demonstrate that, under the constraint of uniform-input distribution and assuming ideal bit-by-bit interleaving, the capacity C of a BICM system using 2^{m_b}-ary constellation is expressed over AWGN channels as

$$C = m_b - \sum_{i=1}^{m_b} E_{c_j,r_j}\left[\log_2\left[\frac{\sum_{z_j\in\chi} P(r_j \mid z_j)}{\sum_{z_j\in\chi_{i,c_{j,i}}} P(r_j \mid z_j)}\right]\right], \tag{11}$$

where $P(r_j|z_j)$ denotes the transition probability density function of the AWGN channel, $E_{cj,rj}$ denotes the expectations with respect to c_j and r_j, and $\chi_{i,cj,i}$ designates the subset of all the signals $z_j \in \chi$ whose labels have the value $c_{j,i} \in \{0, 1\}$ in position i. The capacity is expressed in information bits per channel use (bit/channel use) here, where each channel use corresponds to the transmission of a complex signal $z_j \in \chi$. Assuming an AWGN channel and performing some minor modifications, we finally obtain

$$C = E_{c_j,r_j}\left[m_b - \log_2 \frac{\left(\sum_{z_j\in\chi}\exp\left(-\frac{d^2_{r_j,z_j}}{2\sigma^2}\right)\right)^{m_b}}{\prod_{i=1}^{m_b}\sum_{z_j\in\chi_{i,c_{j,i}}}\exp\left(-\frac{d^2_{r_j,z_j}}{2\sigma^2}\right)}\right]. \tag{12}$$

where $d_{rj,zj}$ is the Euclidean distance between the signals r_j and z_j. A general expression for representing the BICM capacity C for both AWGN and Rayleigh fading channel is given by

$$C = E_{c_j,r_j}\left[m_b - \log_2 \frac{\left(\sum_{z_j\in\chi}\exp\left(-\frac{(r_j - h_j\cdot z_j)^2}{2\sigma^2}\right)\right)^{m_b}}{\prod_{i=1}^{m_b}\sum_{z_j\in\chi_{i,c_{j,i}}}\exp\left(-\frac{(r_j - h_j\cdot z_j)^2}{2\sigma^2}\right)}\right]. \tag{13}$$

Moreover, (13) is used to evaluate the capacity when the mapping method is taken into consideration.

The capacity of a BICM is defined regardless of the channel code used as well as the presence of iterative demodulation and decoding [16]. Hence, the capacity for both BICM and BICM-ID can be defined using (13) for any mapping method. It is well known that for both turbo-like codes such as IRA codes and irregular LDPC (ILDPC), the sparse random parity check matrices were employed to establish promising distance properties. Both turbo-like codes have good minimum distance and possess a very small average number of nearest neighbour codewords (provided that the girth is greater than 4 [25]). The girth is known as the length of the smallest cycle in a Tanner graph. That is why the turbo-like codes achieve excellent BER performance at low SNR. Hence, in order to design a power-efficient BICM and BICM-ID schemes at moderate BERs, a modulation scheme optimised for operation at low SNR should be employed. The optimisation by Gray mapping, mainly consisting of minimizing the average number of nearest neighbours of the modulation, shows a profound impact on the error performance of BICM [7] and BICM-ID [28] schemes. Hence, for the case of powerful channel codes such as IRA codes, combined with Gray or quasi-Gray mapping is required to obtain high coding gain through iterative demodulation and decoding. To determine the optimal combination of 16-ary signal constellations with various Gray and quasi-Gray mappings for powerful channel codes, the BICM capacity C defined in (13) is evaluated for both AWGN and Rayleigh fading channels.

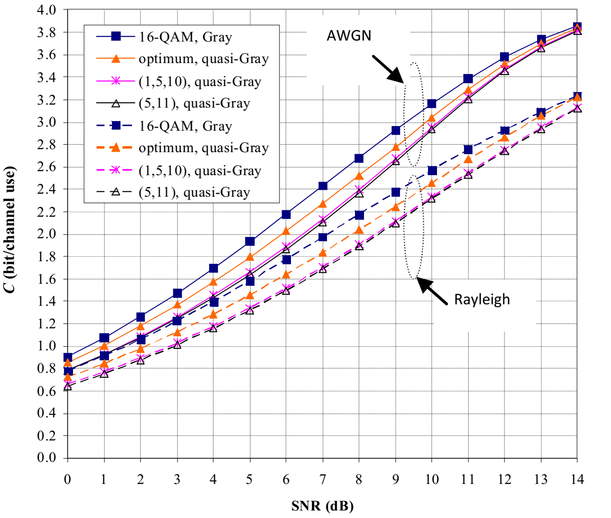

Figure 4. BICM capacity C versus SNR for different 16-ary signal constellations sets with Gray or quasi-Gray mappings over both the AWGN and Rayleigh fading channels for SNR ranging from 0 to 14 dB.

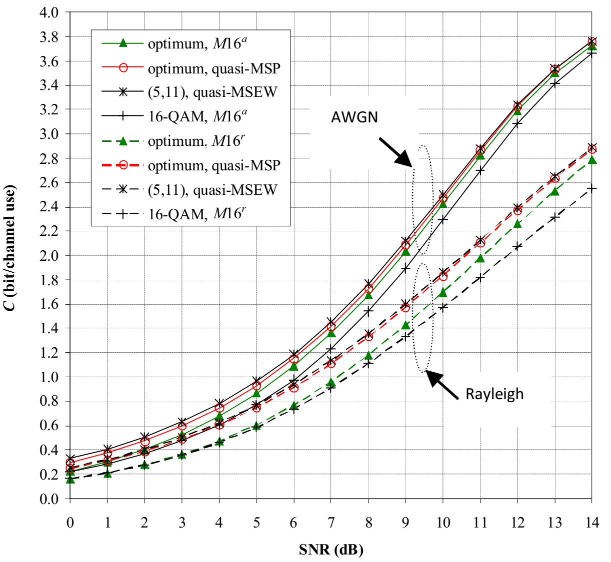

Figure 5. BICM capacity C versus SNR for different 16-ary signal constellations sets with non-Gray mappings over both the AWGN and Rayleigh fading channels for SNR ranging from 0 to 14 dB.

Fig. 4 shows the BICM capacity C versus SNR for various 16-ary signal constellations with Gray or quasi-Gray mappings over AWGN and Rayleigh fading channels. The SNR is defined as E_s/N_0, where E_s is the average energy per symbol. By utilising Fig. 4, the capacity limit of BICM scheme for a required spectral efficiency (S_{eff} = 2-bit/s/Hz) can be attained for both AWGN and Rayleigh fading channels. Table I shows the capacity limits or SNRs required to achieve error-free communications with a BICM scheme using various 16-ary signal constellations over AWGN and Rayleigh fading channels by employing Gray or quasi-Gray mappings. From Fig. 4, it can be noted that the best performance is achieved by the combination of rectangular 16-QAM signal constellation with Gray mapping over the entire SNR range considered for both AWGN and Rayleigh fading channels. For each of the non-Gray mappings, the best 16-ary signal constellation is selected and compared among the non- Gray mappings as shown in Fig. 5 for both AWGN and Rayleigh fading channels. From Table II, it is observed that for the case of non-Gray mappings, the combination of (5,11) signal constellation with quasi-MSEW mapping provides the best performance.

TABLE I.
CAPACITY LIMIT OF 2-BIT/S/HZ BICM FOR DIFFERENT 16-ARY SIGNAL CONSTELLATION SETS WITH GRAY OR QUASI-GRAY MAPPINGS.

Channel	Signal Constellations	Mapping Scheme	E_s/N_0 (dB)	E_b/N_0 (dB)
AWGN	16-QAM	Gray	5.26	2.25
AWGN	optimum	quasi-Gray	5.84	2.83
AWGN	(1,5,10)	quasi-Gray	6.45	3.44
AWGN	(5,11)	quasi-Gray	6.57	3.56
Rayleigh	16-QAM	Gray	7.06	4.05
Rayleigh	optimum	quasi-Gray	7.78	4.77
Rayleigh	(1,5,10)	quasi-Gray	8.41	5.40
Rayleigh	(5,11)	quasi-Gray	8.45	5.44

TABLE II.
CAPACITY LIMIT OF 2-BIT/S/HZ BICM FOR DIFFERENT 16-ARY SIGNAL CONSTELLATION SETS WITH NON-GRAY MAPPINGS.

Channel	Signal Constellations	Mapping Scheme	E_s/N_0 (dB)	E_b/N_0 (dB)
AWGN	optimum	$M16^a$	8.91	5.90
AWGN	optimum	quasi-MSP	8.77	5.76
AWGN	(5,11)	quasi-MSEW	8.67	5.66
AWGN	16-QAM	$M16^a$	9.28	6.27
Rayleigh	optimum	$M16^r$	11.08	8.07
Rayleigh	optimum	quasi-MSP	10.62	7.61
Rayleigh	(5,11)	quasi-MSEW	10.51	7.50
Rayleigh	16-QAM	$M16^r$	11.73	8.72

IV. SIMULATION RESULTS AND DISCUSSIONS

All the computer simulations consider the same codes having rate R = 1/2 and information block length K = 2000 bits. An interleaver block size of 4000 bits is used. The fading channels considered in this paper are frequency non-selective and frequency selective Rayleigh fading channels. The channel state information (CSI) is assumed to be known perfectly at the receiver side. A maximum of 10 iterations are performed between the decoder and demapper during iterative demodulation and decoding. For decoders using the message passing algorithm, a maximum of 100 decoding iterations are performed. The BER performance is investigated for several 2-bit/s/Hz coded modulation schemes using optimal combinations of 16-ary constellations with various mappings. Table III presents the types of channel codes, signal constellations and mappings used in the simulations. The parameters d_v and d_c in Table III correspond to the variable node and check node degrees, respectively. The channel codes considered in this work are IRA codes, ILDPC codes and CC. Both IRA and ILDPC codes are constructed free of 4-cycles using the bit-filling algorithm. It is worthwhile to note that in the context of this paper, we use RA codes to represent an extended class of ILDPC codes [22], thus the encoding complexity of both IRA and ILDPC codes are low. The irregular LDPC code for the simulations listed in Table III has weight-2 columns in its parity-check matrix, which is prone to error floors even for BPSK over AWGN channels. Hence, the error floors occurring in the simulations is due to the LDPC code itself. CC are constructed from a 4-state recursive systematic convolutional (RSC) codes with generator polynomials (7,5). Similar to turbo codes, BICM-ID can be added to RA/LDPC encoded BICM to achieve additional coding gain [6]. The effects of signal constellation and mapping combination from Fig. 3 on the BER performance for several BICMs and BICM-IDs are shown in Figs. 6 to 13. Each combination set of signal constellation and mapping is denoted by a different condition. A total of five conditions are provided in Table IV.

TABLE III.
PARAMETERS CONSIDERED FOR THE SIMULATIONS. THE CODEWORD AND INTERLEAVER BLOCK SIZES USED FOR ALL CHANNEL CODES ARE 4000 BITS FOR R = 1/2. NOTE THAT THE NOTATION 'N/A' IN THE TABLE INDICATES THAT THE CC IS NOT DEFINED USING d_v AND d_c.

Channel	Codes	d_v	d_c	Signal Constellations	Mapping Scheme
AWGN/Ray	ILDPC	2,3	4,5	16-QAM	Gray
AWGN/Ray	ILDPC	2,3	4,5	optimum	quasi-Gray
AWGN/Ray	IRA	2,3,4,5,7,8	5,6	16-QAM	Gray
AWGN/Ray	IRA	2,3,4,5,7,8	5,6	optimum	quasi-Gray
AWGN	CC	N/A	N/A	16-QAM	$M16^a$
Ray	CC	N/A	N/A	16-QAM	$M16^r$
AWGN/Ray	CC	N/A	N/A	(5,11)	quasi-MSEW

TABLE IV.
COMBINATIONS OF 16-ARY SIGNAL CONSTELLATIONS WITH DIFFERENT TYPES OF MAPPINGS FOR BOTH AWGN AND RAYLEIGH FADING CHANNELS.

Channel	Signal Constellations	Mapping Scheme	Condition
AWGN/Ray	16-QAM	Gray	A
AWGN/Ray	optimum	quasi-Gray	B
AWGN	16-QAM	$M16^a$	C
Ray	16-QAM	$M16^r$	D
AWGN/Ray	(5,11)	quasi-MSEW	E

The decoding algorithms employed by all the codes considered in this work are the message passing algorithm and BCJR algorithm. The BCJR algorithm is also known as a message passing algorithm [29]. On the other hand, the encoding complexity of IRA codes and ILDPC codes are lower than some LDPC codes, which make them good alternatives for some LDPC codes. Both IRA codes and ILDPC codes have comparatively low encoding complexity as CC, but the coding gain achieved at BER of 10^{-5} using CC is much lower in comparison with IRA codes and ILDPC codes. Both IRA codes and ILDPC codes give comparable performance with IRA codes achieving the overall best performance at a BER of 10^{-5} over both AWGN and fading channels.

A. Performance of BICM/BICM-ID Schemes over AWGN Channels

In Fig. 6, for the case of rectangular 16-QAM signal constellation, it can be seen that IRA codes with condition A provide the best BER performance using BICM and BICM-ID systems. Moreover, pertaining to condition A, the performance gain with feedback is small for both IRA and ILDPC codes as the BICM-ID and BICM schemes give comparable BER performance using the same type of iterative decodable codes at a BER of 10^{-5}. In Fig. 6, for BICM-ID schemes, IRA codes (with condition A) outperform ILDPC codes (with condition A) and CC (with condition C) by approximately 0.3 dB and 0.81 dB, at a BER of 10^{-5}.

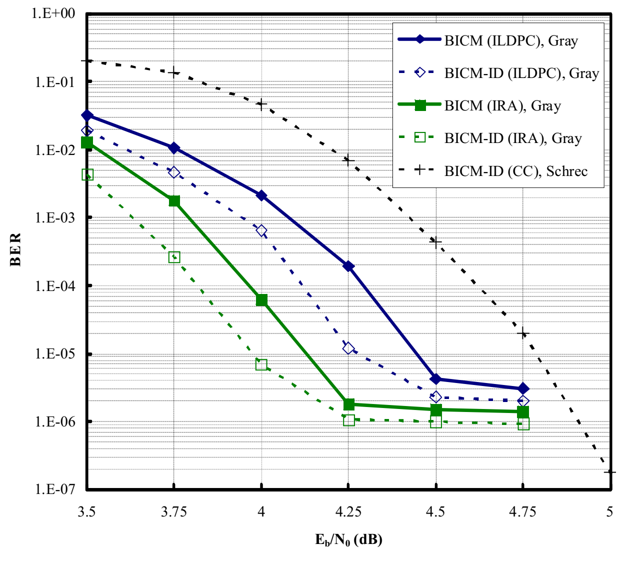

Figure 6. Performance comparison over AWGN channels among 2-bit/s/Hz BICM/BICM-ID schemes using channel codes and selected optimal combinations of rectangular 16-QAM signal constellations with mappings.

The non-rectangular 16-ary signal constellations with BICM schemes employing IRA and ILDPC codes with condition B provide comparable performance at a BER of 10^{-5} as depicted in Fig. 7. In addition, by considering condition B, the performance gain with feedback is moderate for both IRA and ILDPC codes. The BER performance gains between BICM-ID and BICM schemes using the same channel codes with condition B are approximately 0.88 dB and 1.18 dB for both IRA and ILDPC codes respectively, at a BER of 10^{-5}. Unlike the case of 16-QAM signal constellation, BICM-ID schemes using CC with condition E provide a comparable performance to that of IRA and ILDPC codes with condition B.

The effects of rectangular and non-rectangular 16-ary constellations on BICM and BICM-ID schemes are shown in Figs. 8 and 9. For BICM schemes employing iterative decodable codes such as IRA and ILDPC codes, rectangular 16-QAM achieves a better BER performance than non-rectangular 16-ary constellations and IRA codes provide the best performance. For BICM-ID schemes, both rectangular and non-rectangular 16-ary constellations give comparable performance using IRA and ILDPC codes with IRA codes giving the best marginal BER performance, at a BER of 10^{-5}. Moreover, for 16-QAM signal constellation over AWGN channels as depicted in Fig. 6, the performance gain is minimal with iterative demodulation and decoding. However, error floors were lowered with iterative demodulation and decoding over the same AWGN channels by using powerful turbo-like codes and non-rectangular 16-ary signal constellations as shown in Fig. 7. Furthermore, it can be seen that BICM-ID employing IRA codes with 16-QAM and Gray mapping performs best over AWGN channels for spectral efficiency of 2-bit/s/Hz at low SNR as shown in Fig. 9. These results agree with those provided by Tables 1 and 2. The channel capacity limit for 2 bit/s/Hz 16-QAM BICM on AWGN channels is 2.25 dB. At a BER of 10^{-5}, the gap between the capacity and the performance of BICM-ID employing IRA codes with 16-QAM Gray mapping is 1.72 dB for AWGN channels.

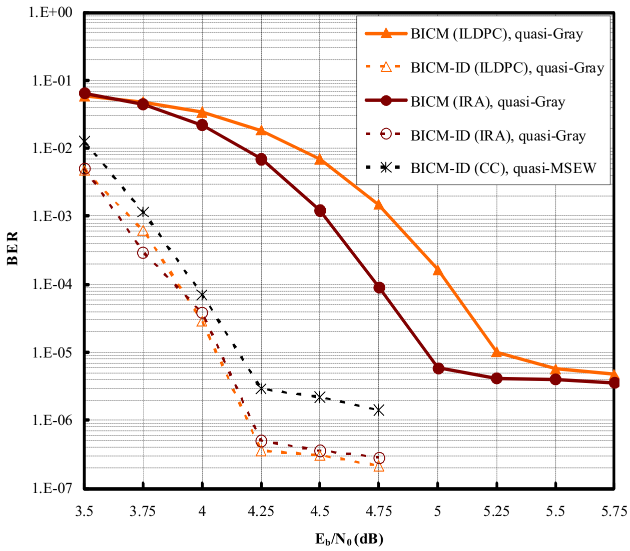

Figure 7. Performance comparison over AWGN channels among 2-bit/s/Hz BICM/BICM-ID schemes using channel codes and selected optimal combinations of non-rectangular 16-ary signal constellations with mappings. Both ILDPC and IRA codes employ optimum constellation while CC uses (5,11) constellation.

The effect of channel codes on BICM-ID schemes is show in Fig. 9. For BICM-ID employing rectangular 16-ary signal constellations, IRA codes outperforms CC at a BER of 10^{-5}. In addition, for BICM-ID employing non-rectangular 16-ary signal constellations, turbo-like codes such as IRA codes consistently perform better than CC, at a BER of 10^{-5}. Overall, computer simulation results indicated that, at a BER of 10^{-5}, the best performance for BICM-ID scheme in AWGN channels is provided by IRA codes employing rectangular signal constellation with Gray mapping.

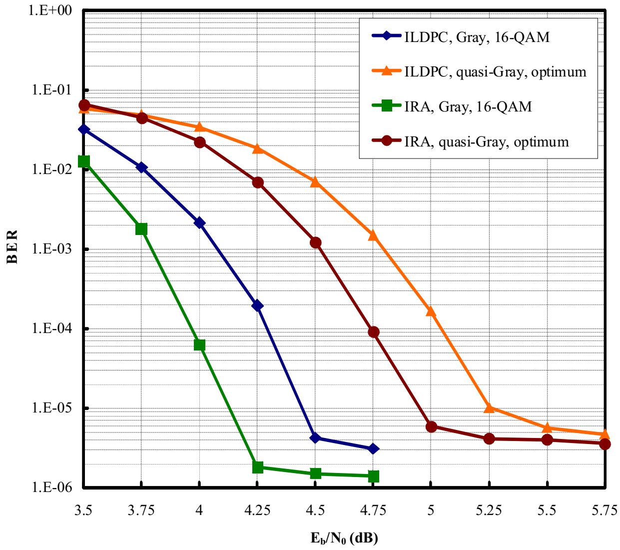

Figure 8. Performance comparison over AWGN channels among 2-bit/s/Hz BICM schemes using channel codes and selected optimal combinations of rectangular and non-rectangular 16-ary signal constellations with mappings.

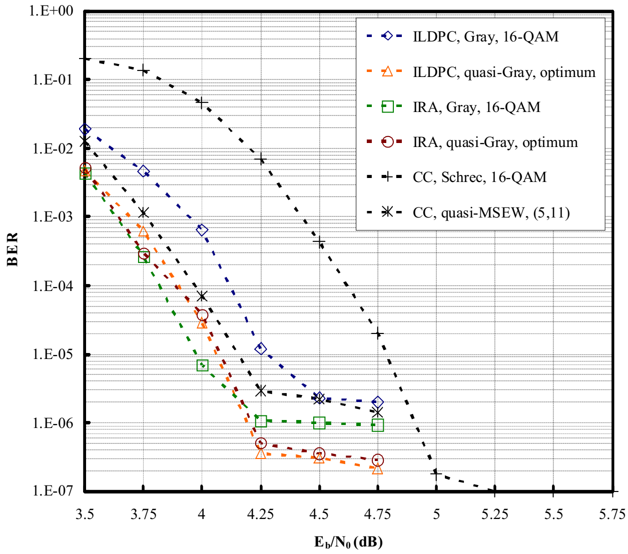

Figure 9. Performance comparison over AWGN channels among 2-bit/s/Hz BICM-ID schemes using channel codes and selected optimal combinations of rectangular and non-rectangular 16-ary signal constellations with mappings.

It is interesting to note that for BICM-ID schemes, CC with condition E achieves a comparable BER performance with both IRA and ILDPC codes. For BICM-ID schemes employing CC, nonrectangular 16-ary signal constellation (condition E) has approximately 0.63 dB performance gain over 16-QAM constellation (condition C) as depicted in Fig. 9. Error-floor occurs at BER level below 10^{-5} as shown in Fig. 8. Table V summarises the SNR required at BER = 10^{-5} for various channel codes considered and their best combinations of signal constellations and mappings in AWGN channels.

TABLE V.
SIGNAL-TO-NOISE RATIO COMPARISON (SNR) AT BER = 10^{-5} BETWEEN SEVERAL 2-BIT/S/HZ 16-ARY BICM-ID SCHEMES. NOTE THAT THE NOTATION 'N/A' IN THE TABLE INDICATES THAT THE SNR REQUIRED FOR BER = 10^{-5} IS OUT OF THE CONSIDERED SNR RANGE.

Channel	Codes	Signal Constellations	Mapping Scheme	E_b/N_0 (dB)
AWGN	IRA	16-QAM	Gray	3.97
AWGN	ILDPC	optimum	quasi-Gray	4.06
AWGN	CC	(5,11)	quasi-MSEW	4.15
Rayleigh	IRA	16-QAM	Gray	5.83
Rayleigh	ILDPC	16-QAM	Gray	5.93
Rayleigh	CC	(5,11)	quasi-MSEW	N/A

B. Performance of BICM/BICM-ID Schemes over Rayleigh Fading Channels

The influence of rectangular and non-rectangular 16-ary constellations with optimised mappings are shown in Figs. 10 and 11. In Fig. 10, IRA codes with rectangular 16-QAM constellation consistently provide the best coding gain in both BICM and BICM-ID systems at BER of 10^{-4}, which agrees with the results obtained for the AWGN channel. Moreover, BICM-ID schemes employing IRA and ILDPC codes with non-rectangular 16-ary constellations provide comparable performance at a BER of 10^{-4}. The BER performance of rectangular and non-rectangular constellations are evaluated and presented in Figs. 12 and 13 for BICM and BICM-ID schemes, respectively. It is observed that for the case of BICM schemes using iterative decodable codes, condition A outperforms condition B. Moreover, in BICM schemes, it can be seen that for both conditions A and B, IRA codes achieve a marginal performance gain over ILDPC codes at a BER of 10^{-4} as shown in Fig. 12. For the case of BICM-ID schemes using iterative decodable codes considered in this paper, the performance gain with feedback is moderate for both rectangular and non-rectangular constellations at a BER of 10^{-4} as depicted in Fig. 13. Moreover, similar to AWGN channels, 16-QAM constellation consistently outperforms the non-rectangular 16-ary constellations over Rayleigh fading channels for BICM-ID schemes using iterative decodable codes. In addition, for BICM-ID schemes using channel codes considered in this work, the BER performance gives comparable results at low SNR. In Rayleigh fading channels, BICM-ID employing IRA codes with 16-QAM and Gray mapping consistently performs best for spectral ef_ciency of 2-bit/s/Hz at low SNR. The channel capacity limits for 2-bit/s/Hz 16-QAM BICM on Rayleigh fading channels are approximately 4 dB. The gap between the capacity and the performance of BICM-ID employing IRA codes with 16-QAM Gray mapping is 1.83 dB for Rayleigh fading channels, at a BER of 10^{-5}.

Similarly, the effect of channel codes on BICM-ID schemes is shown in Fig. 13 for Rayleigh fading channels. For BICM-ID employing rectangular 16-ary signal constellations, IRA codes achieves a better performance gain than CC at a BER of 10^{-5}. For BICM-ID employing nonrectangular 16-ary signal constellations, IRA codes consistently outperform CC at a BER of 10^{-5}. Computer simulation results show that BICM-ID scheme employing IRA codes with optimal combination of rectangular signal constellation and Gray mapping offers the best performance in Rayleigh fading channels at a BER of 10^{-5}.

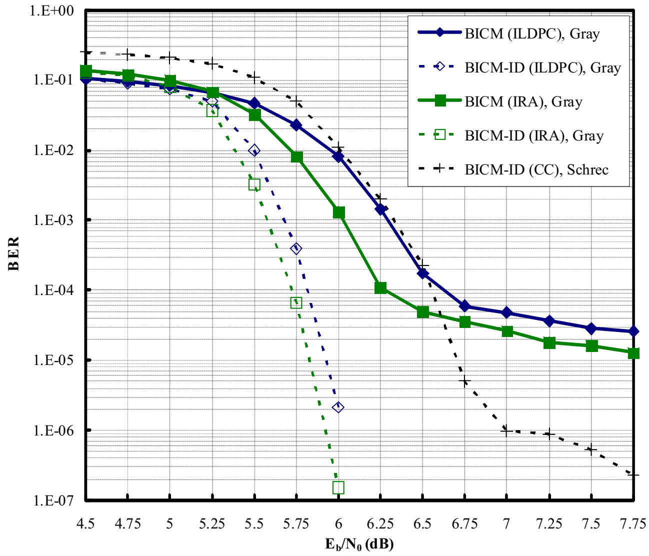

Figure 10. Performance comparison over Rayleigh fading channels among 2-bit/s/Hz BICM/BICM-ID schemes using channel codes and selected optimal combinations of rectangular 16-QAM signal constellations with mappings.

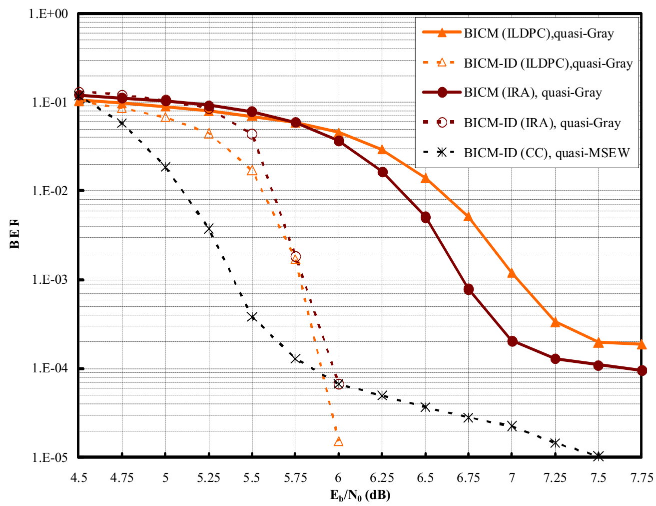

Figure 11. Performance comparison over Rayleigh fading channels among 2-bit/s/Hz BICM/BICM-ID schemes using channel codes and selected optimal combinations of non-rectangular 16-ary signal constellations with mappings. Both ILDPC and IRA codes employ optimum constellation while CC uses (5,11) constellation.

In addition, for Rayleigh fading channels, errors floors are eliminated with iterative demodulation and decoding for turbo-like codes in both rectangular and non-rectangular 16-ary constellations as depicted in Figs 10 and 11. In Fig. 13, it can be seen that although BICM-ID scheme using CC (with condition E) experiences an early convergence than IRA codes (with condition A); it suffers a large error floor. The same observation as AWGN channels is noted for BICM-ID employing CC over Rayleigh fading channels; non-rectangular constellation (condition E) has a performance improvement over rectangular constellation (condition D) by approximately 0.7 dB, at a BER of 10^{-4}. BICM-ID schemes using IRA codes with 16-QAM signal constellation and Gray mapping provide the best performance over Rayleigh fading channels, at BER level below 10^{-5}. Again, all results agree with those reported in Tables I and II.

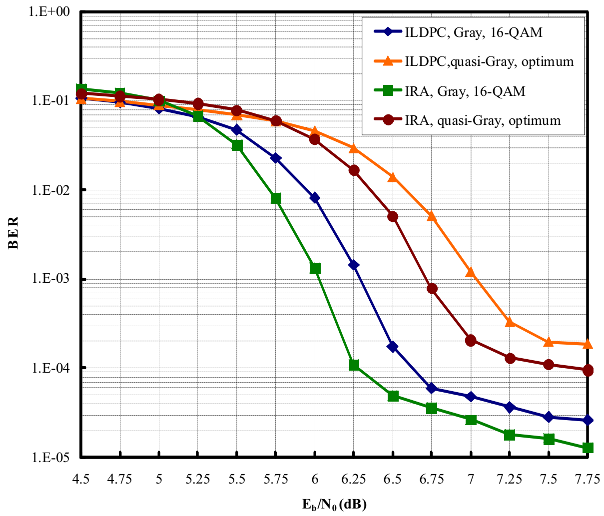

Figure 12. Performance comparison over Rayleigh fading channels among 2-bit/s/Hz BICM schemes using channel codes and selected optimal combinations of rectangular and non-rectangular 16-ary signal constellations with mappings.

Figs. 9 and 13 show that with iterative demodulation and decoding, convolutional coded BICM with condition E provides comparable performance to that of turbo or LDPC/RA coded modulation over both AWGN and Rayleigh fading channels for moderate block size. This agrees with [27].

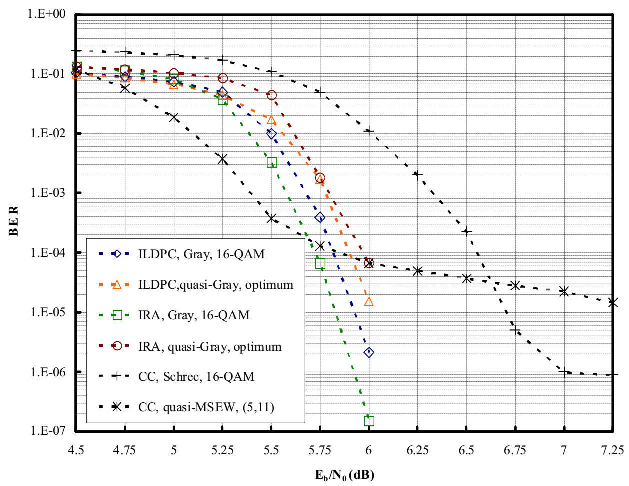

Figure 13. Performance comparison over Rayleigh fading channels among 2-bit/s/Hz BICM-ID schemes using channel codes and selected optimal combinations of rectangular and non-rectangular 16-ary signal constellations with mappings.

However as the codeword size increases to a very large value, turbo or LDPC/RA coded systems will be better [30] since the convolutional coded BICM with iterative demodulation and decoding does not have any interleaving gain as codeword size increases to a large value. Error-floor effects occurring at BER level below 10^{-3} can be noticed as shown in Fig. 12. Similarly, Table V summarises the SNR required at BER = 10^{-5} for various channel codes considered and their best combinations of signal constellations and mappings in Rayleigh fading channels.

V. BICM AND 4G

BICM is currently the most popular coded modulation for both fading and non-fading channels. BICM is a promising method to achieve high spectral efficiency over wireless communication links. BICM has been adopted in many commercial systems such as wireless and wired broadband access networks, 3G and 4G telephony, ultra-wideband (UWB) transceivers, as well as DVB, imposing itself as the de facto standard for current wireless telecommunications systems. BICM is expected to form the basis of future communication standards [31]-[35].

The combination of Orthogonal Frequency Division Multiplexing (OFDM) and BICM can be found in many standards such as IEEE 802.11 WLAN, IEEE 802.16 WiMAX, UMTS Long Term Evolution (LTE) and 4th generation mobile communication systems. Both LTE and WiMAX 4G technologies uses OFDM as the modulation scheme. In this section, single-input single-output (SISO) wireless systems are considered. The same simulation parameters and conditions are extended to BICM-ID-OFDM system. Fig. 14 depicts the BER performance of BICM-ID-OFDM scheme for two types of channel codes (IRA, CC) over quasi-static frequency-selective Rayleigh fading channels. It can be observed that powerful channel codes (IRA) achieve significant performance improvement as compared to the less powerful channel codes (CC), at a BER of 10^{-5}. It is worthy to note that for BICM-ID-OFDM (IRA), no errors were observed for E_b/N_0 greater than 16 dB within 10^7 simulated information bits.

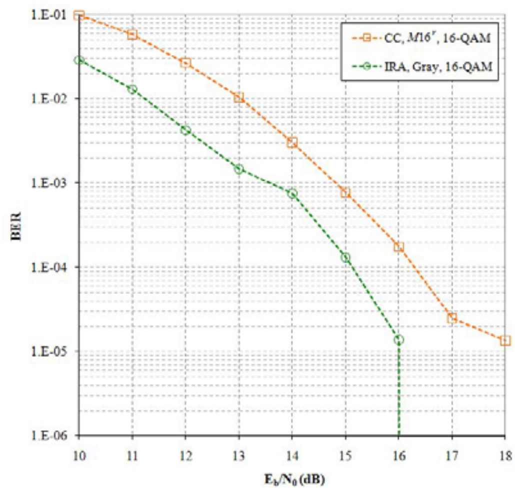

Figure 14. Performance comparison over frequency selective Rayleigh fading channels among 2-bit/s/Hz BICM-ID-OFDM schemes using channel codes considered (IRA, CC) and 16-QAM with mappings.

VI. Conclusion

Applications of BICM and BICM-ID systems with selected error-correcting codes and optimised combinations of 16-ary constellations with mappings to improve the error performance over AWGN and Rayleigh fading channels are considered in this paper. The BICM capacity for various 16-ary signal constellations has also been evaluated to determine the optimised signal constellation and mapping pair when combined with powerful error-correcting codes such as IRA codes. It has been shown that for the case of 16-ary constellations, the most attractive signal set for IRA codes is rectangular 16-QAM signal constellation with Gray mapping. Moreover, simulation results have demonstrated that the coding gains and error floors are remarkably affected by the selection of the signal constellation and bit mapping. The optimised selection of the such parameters can be used to avoid the severe performance degradation that is obtained when error floors occur. The powerful combinations of BICM-ID, OFDM and channel codes (turbo codes, LDPC codes, CC) are widely adopted in 3G/4G Wireless Systems.

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References

[1] G. Ungerboeck, "Channel coding with multilevel-phase signals," *IEEE Trans. Inform. Theory* vol. 28, no. 1, pp. 56-67, Jan. 1982.

[2] E. Zehavi, "8-PSK trellis codes for Rayleigh channel," *IEEE Trans. Commun.*, vol. 40, no. 5, pp. 873-884, May 1992.

[3] G. Caire, G. Taricco, E. Biglieri, "Bit-interleaved coded modulation," *IEEE Trans. Inform. Theory*, vol. 44, no. 3, pp. 927-946, May 1998.

[4] X. Li, J. A. Ritcey, "Bit-interleaved coded modulation with iterative decoding using soft feedback," *Electronics Letters*, vol. 34, no. 10, pp. 942-943, Mar. 1998.

[5] X. Li, A. Chindapol, J. A. Ritcey, "Bit-interleaved coded modulation with iterative decoding and 8PSK signalling," *IEEE Trans. Commun.*, vol. 50, no. 8, pp. 1250-1257, Aug. 2002.

[6] A. Chinadapol, J. A. Ritcey, "Design, analysis, and performance evaluation for BICM-ID with square QAM constellations in Rayleigh-fading channels," *IEEE J. on Selected Areas in Commun.*, vol. 19, no. 5, pp. 944-957, May 2001.

[7] S. Le Goff, "Signal constellations for bit-interleaved coded modulation," *IEEE Trans. Inform. Theory*, vol. 49, no. 1, pp. 307-313, Jan. 2003.

[8] F. Schreckenbach, G. Bauch, "Bit-interleaved coded irregular modulation," *European Transactions on Telecommunications*, vol. 17, no. 2, pp. 269-282, Feb. 2006.

[9] C. Berrou, A. Glavieux, P. Thitimajshima, "Near Shannon limit error-correcting coding and decoding: turbo-codes," in *IEEE Int. Conf. Commun. (ICC)*, Geneva, Switzerland, pp. 1064-1070, 1993.

[10] W. K. Han, S. Le Goff, B. Sharif, "Systematic repeat accumulate codes for bit-interleaved coded modulation with iterative demapping over AWGN and Rayleigh fading channels," in *IEEE 3rd Int. Symp. on Wireless Pervasive Computing (ISWPC)*, Santorini, Greece, pp. 152-155, 2008.

[11] S. Le Goff, "Bandwidth-efficient turbo coding over Rayleigh fading channels," *Int. Journal of Communication Systems*, vol. 15, no. 7, pp. 621-633, Jul. 2002.

[12] G. J. Forschini, R. D. Gitlin, S. B. Weinstein, "Optimization of two-dimensional signal constellations in the presence of Gaussian noise," *IEEE Trans. Commun.*, vol. 22, no. 1, pp. 28-38, Jan. 1974.

[13] X. Dong, N. C. Beaulieu, P. H. Wittke, "Signaling constellations for fading channels," *IEEE Trans. Commun.*, vol. 47, no. 5, pp. 703-714, May 1999.

[14] S. J. Johnson, S. R. Weller, "Constructions for irregular repeat-accumulate codes," in *Proc. IEEE Int. Symp. Inform. Theory (ISIT)*, Adelaide, Australia, pp. 179-183, 2005.

[15] S. J. Johnson, S. R. Weller, "Practical Interleavers for Systematic Repeat-Accumulate Codes," in *IEEE 63rd Vehicular Technology Conference (VTC-Spring)*, Melbourne, Australia, pp. 1358-1362, 2006.

[16] T. M. Cover, J. A. Thomas, *Elements of Information Theory 2nd edition*, Hoboken, NJ: Wiley InterScience, 2006.

[17] Y. Li, W. E. Ryan, "Bit-reliability mapping in ldpc-coded modulation systems," *IEEE Communications Letter*, vol. 9, no. 1, pp. 1-3, Jan. 2005.

[18] S. ten Brink, G. Kramer, "Design of repeat-accumulate codes for iterative detection and decoding," *IEEE Trans. Commun.*, vol. 51, no. 11, pp. 2764-2772, Nov. 2003.

[19] S. ten Brink, G. Kramer, 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.

[20] A. Ashikhmin, S. ten Brink, G. Kramer, "Extrinsic information transfer functions: Model and erasure channel properties," *IEEE Trans. Inform. Theory*, vol. 50, no. 11, pp. 2657-2673, Nov. 2004.

[21] J. Campello, D. S. Modha, S. Rajagopalan, "Designing LDPC codes using bit-filling," in *IEEE Int. Conf. Commun. (ICC)*, Saint Petersburg, Russia, pp. 55-59, 2001.

[22] M. Yang, W. E. Ryan, Y. Li, "Design of efficiently encodable moderate-length high-rate irregular LDPC codes," *IEEE Trans. Commun.*, vol. 52, no. 4, pp. 564-571, Apr. 2004.

[23] R. G. Gallager, *Low-Density Parity-Check Codes*, Cambridge, MA: MIT Press, 1963.

[24] D. J. C. Mackay, R. M. Neal, "Near Shannon limit performance of low-density parity-check codes," *Electronics Letters*, vol. 32, no. 18, pp. 1645-1646, Aug. 1996.

[25] T. K. Moon, *Correction Coding: Mathematical Methods and Algorithms*, Hoboken, NJ: John Wiley and Sons, 2005.

[26] F. Schreckenbach, N. Gortz, J. Hagenauer, G. Bauch, "Optimization of symbol mappings for bit-interleaved coded modulation with iterative decoding," *IEEE Communications Letters*, vol. 7, no. 12, pp. 593-595, Dec. 2003.

[27] J. Tan, G. L. Stuber, "Analysis and design of symbol mappers for iteratively decoded BICM," *IEEE Trans. Wireless Commun.*, vol. 4, no. 2, pp. 662-672, Mar. 2005.

[28] C. A. Nour, C. Douillard, "Performance improvement using turbo coded BICM-ID with 16-QAM over Gaussian

and flat fading Rayleigh channels," *IST Mobile and Wireless Communications Summit*, Dresden, Germany, 1-4, 2005.
[29] A. Abbasfar, *Turbo-like Codes: Design for High-Speed Decoding (1st edn.)*, Springer, 2007.
[30] D. J. C. Mackay, "Good error-correcting codes based on very sparse matrices," *IEEE Trans. Inform. Theory*, vol. 45, no. 2, pp. 399-431, Mar. 1999.
[31] R. Ghaffar, R. Knoop, " Interference Suppression for Next Generation Wireless Systems," in *69th IEEE Vehicular Technology Conf*erence *(VTC-Spring)*, Barcelona, Spain, pp. 1-5, 2009.
[32] H. Luders, A. Minwegen, P. Vary, "Low Complexity Coding and Modulation for UMTS LTE: BICM-ID with Repetition Coding," in *14th International OFDM-Workshop 2009 (InOWo'09)*, Hamburg, Germany, 2009.
[33] R. Ghaffar, R. Knoop, "Fractional Frequency Reuse and Interference Suppression for OFDMA Networks," in *8th Int. Symp. on Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks (WiOpt)*, Avignon, France, pp. 273-277, 2010.
[34] A. Nasri, R. Schober, L. Lampe, "Performance Evaluation of BICM-OFDM Systems Impaired by UWB Interference," in *IEEE Int. Conf. Commn. 2008 (ICC'08)*, Beijing, China, pp. 3616-3621, 2008.
[35] S. Stiglmayr, M. Bossert, E. Costa, "Adaptive Coding and Modulation in OFDM Systems using BICM and Rate-Compatible Punctured Codes," *European Wireless*, Paris, France, 2007.

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