

Regular and Irregular Multiple Serially-Concatenated Multiple-Parity-Check Codes for Wireless Applications

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Abstract—Multiple Serially-Concatenated Multiple-Parity-Check (M-SC-MPC) codes are a class of structured Low-Density Parity-Check (LDPC) codes, characterized by very simple encoding, that we have recently introduced. This paper evidences how the design of M-SC-MPC codes can be optimized for their usage in wireless applications. For such purpose, we consider some Quasi-Cyclic LDPC codes included in the mobile WiMax standard, and compare their performance with that of M-SC-MPC codes having the same parameters. We also present a simple modification of the inner structure of M-SC-MPC codes that can help to improve their error correction performance by introducing irregularity in the parity-check matrix and increasing the length of local cycles in the associated Tanner graph. Our results show that regular and irregular M-SC-MPC codes, so obtained, can achieve very good performance and compare favorably with standard codes.

Index Terms— Error Correcting Codes, Mobile WiMax, M-SC-MPC Codes, QC-LDPC Codes.

I. INTRODUCTION

The scenario of forward error correction has dramatically changed in the last decades, thanks to the introduction of codes based on the so called “turbo principle”, like turbo codes [1] and Low-Density Parity-Check (LDPC) codes [2], [3]. The turbo principle consists in an iterated exchange and updating of reliability values referred to each received bit. More generally, iterative soft decoding algorithms use, as input, the soft information from the channel in the form of *a priori* probabilities on the status of each received bit, and iteratively update such values based on the parity-check constraints imposed by the code. Hence, the algorithm can produce *extrinsic* messages, to be used as starting values for the next iteration, and *a posteriori* probabilities, that represent the updated reliability values [4].

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LDPC codes, in particular, have been proved to be able to approach the ultimate channel capacity limits [5], and are experiencing an increasing diffusion in many telecommunication standards and practical applications.

Very good LDPC codes can be obtained through a constrained random design of the parity-check matrix, but this, together with the need to adopt large codes for achieving good performance, can yield difficulties in their hardware implementation. For this reason, an increasing interest has been devoted to *structured* LDPC codes, that have characteristic matrices with a very simple inner structure, in such a way as to facilitate their implementation.

Structured LDPC codes can be found in several recommendations and practical applications, as, for example, the DVB-S2 [6] and the IEEE 802.16e (or Mobile WiMax) standard [7]. A very important class of structured LDPC codes is represented by Quasi-Cyclic (QC) LDPC codes, having parity-check and generator matrices formed by circulant blocks [8]. This form of the characteristic matrices allows efficient encoding and decoding, without penalizing the code performance. However, the design of QC-LDPC codes is *block-wise* oriented, thus yielding some constraints on the choice of the code parameters.

As an alternative, we have recently proposed Multiple Serially Concatenated Multiple Parity-Check (M-SC-MPC) codes, that allow to design structured LDPC codes without losing flexibility in the choice of their parameters [9]. M-SC-MPC codes are obtained as the serial concatenation of very simple component codes, named MPC codes, that are a generalization of Single Parity-Check (SCP) codes. This allows to design a concatenated encoder based on very simple circuits. The parity-check matrix of an M-SC-MPC is lower triangular and has columns with almost uniform Hamming weights. Under suitable hypotheses, such parity-check matrix can be sparse and free of short cycles; so, M-SC-MPC can be seen as LDPC codes and their decoding can be accomplished through efficient LDPC decoding algorithms based on the *belief propagation* principle.

In this paper, we show how M-SC-MPC codes can be designed for practical applications and compare them with standard QC-LDPC codes.

We refer to the IEEE 802.16e standard and give some design examples of M-SC-MPC codes with the same parameters as standard QC-LDPC codes, in order to compare their simulated error correction performance. Furthermore, we present a very simple technique to introduce some form of irregularity in the parity-check matrix of an M-SC-MPC code. Irregular LDPC codes, in fact, have been proved to be better than regular ones, especially for low code rates [10]. For this reason, we propose a solution to design irregular M-SC-MPC matrices, that can also have longer local cycles in the associated Tanner graph. Simulations prove that irregular M-SC-MPC codes can actually outperform almost regular ones.

The paper is organized as follows. Section 2 describes the QC-LDPC codes adopted in the IEEE 802.16e standard. Section 3 summarizes the characteristics of our recently proposed M-SC-MPC codes and introduce a solution for designing irregular M-SC-MPC codes. Section 4 reports some design examples of regular and irregular M-SC-MPC codes. Section 5 describes the results of numerical simulations of the designed codes and their performance comparison with standard QC-LDPC codes. Finally, Section 6 concludes the paper.

I. QC-LDPC CODES IN MOBILE WiMAX

The IEEE 802.16e Mobile Wireless MAN standard, approved in 2005 [7], includes, as an option, the possibility of adopting LDPC codes for forward error correction (FEC). As common in wireless applications, the FEC scheme must be able to adapt itself against variable channel conditions, providing different solutions as tradeoffs between error correction capability and spectral efficiency.

For this reason, a family of channel codes with different rates must be provided. In addition, all standards in the IEEE 802 family deal with packet switched networks having variable length blocks; so, flexibility in the block length is a mandatory requirement for channel codes to be used in these systems.

In order to fulfill such needs, the IEEE 802.16e standard adopts a family of QC-LDPC codes having variable code rate ($R = 1/2, 2/3, 3/4, 5/6$), and length (n) ranging between 576 and 2304 bits by a step of 96 bits. These codes are used in conjunction with the following modulation schemes: QPSK, 16-QAM and 64-QAM.

Standard QC-LDPC codes have parity-check matrices formed by $z \times z$ circulant permutation blocks or null blocks. The parity-check matrix of each standard QC-LDPC code can be represented as shown in (1), where $\mathbf{I}_{p(i,j)}$, $0 \leq i \leq r_b - 1$, $0 \leq j \leq n_b - 1$, is the $z \times z$ circulant permutation matrix corresponding to the cyclic shift $p(i,j) \in [0; z - 1]$.

$$\mathbf{H} = \begin{bmatrix} \mathbf{I}_{p(0,0)} & \mathbf{I}_{p(0,1)} & \cdots & \mathbf{I}_{p(0,n_b-1)} \\ \mathbf{I}_{p(1,0)} & \mathbf{I}_{p(1,1)} & \cdots & \mathbf{I}_{p(1,n_b-1)} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{I}_{p(r_b-1,0)} & \mathbf{I}_{p(r_b-1,1)} & \cdots & \mathbf{I}_{p(r_b-1,n_b-1)} \end{bmatrix}. \quad (1)$$

This allows to obtain a synthetic representation of the parity-check matrices: if each null block is conventionally associated to \mathbf{I}_1 , matrix \mathbf{H} in (1) can be represented in an alternative form through a *base matrix*, \mathbf{H}_{bm} , having size $r_b \times n_b$, that contains the $p(i,j)$ values associated to each block. For the IEEE 802.16e standard codes, it is $n_b = 24$, while r_b varies according with the code rate.

Two examples of \mathbf{H}_{bm} are reported in (2), for the rate 3/4 “B” standard code, and in (3), for the rate 5/6 standard code. From the structure of the base matrix we notice that, for both rates, the parity-check matrices of the codes have a dual-diagonal form, that is, contain two diagonals of symbols 1 in their rightmost part. This property can facilitate encoding, when accomplished through the parity-check matrix [11], without yielding the penalization in minimum distance that would be due to the inclusion of identity blocks. The same also occurs for the other base matrices provided by the

$$\mathbf{H}_{\text{bm}}^{R34B} = \begin{bmatrix} -1 & 81 & -1 & 28 & -1 & -1 & 14 & 25 & 17 & -1 & -1 & 85 & 29 & 52 & 78 & 95 & 22 & 92 & 0 & 0 & -1 & -1 & -1 & -1 \\ 42 & -1 & 14 & 68 & 32 & -1 & -1 & -1 & -1 & 70 & 43 & 11 & 36 & 40 & 33 & 57 & 38 & 24 & -1 & 0 & 0 & -1 & -1 & -1 \\ -1 & -1 & 20 & -1 & -1 & 63 & 39 & -1 & 70 & 67 & -1 & 38 & 4 & 72 & 47 & 29 & 60 & 5 & 80 & -1 & 0 & 0 & -1 & -1 \\ 64 & 2 & -1 & -1 & 63 & -1 & -1 & 3 & 51 & -1 & 81 & 15 & 94 & 9 & 85 & 36 & 14 & 19 & -1 & -1 & -1 & 0 & 0 & -1 \\ -1 & 53 & 60 & 80 & -1 & 26 & 75 & -1 & -1 & -1 & -1 & 86 & 77 & 1 & 3 & 72 & 60 & 25 & -1 & -1 & -1 & -1 & 0 & 0 \\ 77 & -1 & -1 & -1 & 15 & 28 & -1 & 35 & -1 & 72 & 30 & 68 & 85 & 84 & 26 & 64 & 11 & 89 & 0 & -1 & -1 & -1 & -1 & 0 \end{bmatrix} \quad (2)$$

$$\mathbf{H}_{\text{bm}}^{R56} = \begin{bmatrix} 1 & 25 & 55 & -1 & 47 & 4 & -1 & 91 & 84 & 8 & 86 & 52 & 82 & 33 & 5 & 0 & 36 & 20 & 4 & 77 & 80 & 0 & -1 & -1 \\ -1 & 6 & -1 & 36 & 40 & 47 & 12 & 79 & 47 & -1 & 41 & 21 & 12 & 71 & 14 & 72 & 0 & 44 & 49 & 0 & 0 & 0 & 0 & -1 \\ 51 & 81 & 83 & 4 & 67 & -1 & 21 & -1 & 31 & 24 & 91 & 61 & 81 & 9 & 86 & 78 & 60 & 88 & 67 & 15 & -1 & -1 & 0 & 0 \\ 50 & -1 & 50 & 15 & -1 & 36 & 13 & 10 & 11 & 20 & 53 & 90 & 29 & 92 & 57 & 30 & 84 & 92 & 11 & 66 & 80 & -1 & -1 & 0 \end{bmatrix} \quad (3)$$

standard, for different code rates. The standard base matrices for the lowest code rates (1/2 and 2/3) have an additional property: a row permutation can exist through which they can be transformed to have only orthogonal adjacent rows. This is a desirable property, for example, when implementing layered decoding [12].

As concerns the block length, each standard base matrix can be expanded into 19 parity-check matrices with different size, thus defining as many codes with different length. Each code corresponds to a different *expansion factor* (z_f), that coincides with the size of the circulant blocks forming the parity-check matrix. The longest block provided by the standard is formed by $n = 2304$ bits, and corresponds to the expansion factor $z_0 = 96$. The other values of z_f are smaller than z_0 by multiples of 4, that is:

$$z_f = z_0 - 4f, \quad f = 0 \dots 18. \quad (4)$$

Once z_f has been fixed, the code length (n) and dimension (k) directly follow as:

$$\begin{cases} n = n_b z_f, \\ k = (n_b - r_b) z_f. \end{cases} \quad (5)$$

Table 1 shows the values of n and k as functions of the expansion factor, z_f , and the code rate.

TABLE I
PARAMETERS OF IEEE 802.16e STANDARD CODES

n	z_f	k			
		$R = 1/2$	$R = 2/3$	$R = 3/4$	$R = 5/6$
576	24	288	384	432	480
672	28	336	448	504	560
768	32	384	512	576	640
864	36	432	576	648	720
960	40	480	640	720	800
1056	44	528	704	792	880
1152	48	576	768	864	960
1248	52	624	832	936	1040
1344	56	672	896	1008	1120
1440	60	720	960	1080	1200
1536	64	768	1024	1152	1280
1632	68	816	1088	1224	1360
1728	72	864	1152	1296	1440
1824	76	912	1216	1368	1520
1920	80	960	1280	1440	1600
2016	84	1008	1344	1512	1680
2112	88	1056	1408	1584	1760
2208	92	1104	1472	1656	1840
2304	96	1152	1536	1728	1920

The permutations corresponding to each circulant block can be obtained from the base matrix through the following relations:

$$p(i, j, f) = \begin{cases} p(i, j) & \text{for } p(i, j) \leq 0, \\ \left\lfloor \frac{p(i, j) z_f}{z_0} \right\rfloor & \text{for } p(i, j) > 0, \end{cases} \quad (6)$$

where $\lfloor x \rfloor$ represents the *floor function*, that gives the greatest integer smaller than or equal to x . Expressions (6) are slightly changed for the rate 2/3 "A" standard code [7].

II. M-SC-MPC CODES

Multiple Serially-Concatenated Multiple-Parity-Check codes are a class of structured LDPC codes we have recently proposed [9]. They exploit the serial concatenation of very simple component codes, in such a way as to obtain LDPC codes with good performance and very good flexibility in the code design. Furthermore, the component codes have a very simple inner structure, that facilitates the encoder implementation.

The serial concatenation of very simple components was already exploited in M-SC-SPC codes, first proposed by Tee et al. [13], that are based on SPC components. M-SC-MPC codes instead adopt, as components, MPC codes, that are a generalization of SPC codes (more precisely, they represent subcodes of SPC codes). The adoption of MPC components allows to represent M-SC-MPC through LDPC matrices, and to adopt efficient belief propagation algorithms for their decoding.

A. Structure of M-SC-MPC codes

Fig. 1 shows the scheme of the serial concatenation at the basis of M-SC-MPC codes. It adopts M component codes, each with length n_i , dimension k_i and redundancy r_i , $i = 1 \dots M$. As it is evident from the figure, serial concatenation is systematic, and each component code simply appends its r_i redundancy bits to the input codeword.

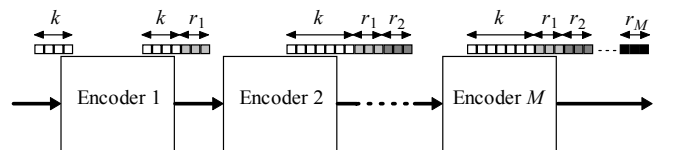


Fig. 1. Serial concatenation in M-SC-MPC codes.

So, the serially concatenated code has dimension k (that coincides with the number of information bits given as input to the first component code) and redundancy

$$r = \sum_{i=1}^M r_i. \quad (7)$$

As anticipated, the distinctive feature of M-SC-MPC codes is the form of their components, named MPC codes. The i -th MPC component code calculates its j -th redundancy bit as the parity-check of the codeword bits whose indexes are smaller than j by an integer multiple of r_i .

It follows from its definition that an MPC code can be encoded by using a circuit as that reported in Fig. 2 for the i -th component of the serial concatenation.

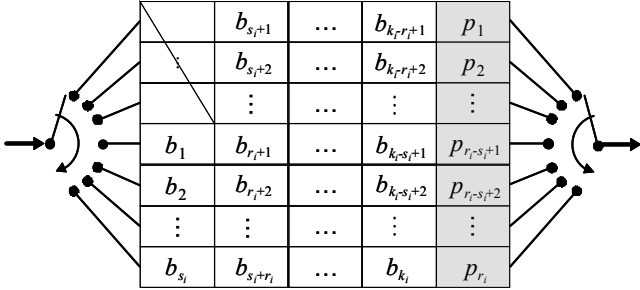


Fig. 2. Encoder for the i -th MPC component code.

This circuit is formed by a rectangular matrix having r_i rows and $\lceil k_i/r_i \rceil + 1$ columns, where $\lceil x \rceil$ represents the *ceiling function*, that gives the smallest integer greater than or equal to x . The white cells in the matrix are filled with the information word input to the i -th MPC code, in column-wise order, from top left to bottom right. The first $r_i - s_i$ cells, with $s_i = k_i \bmod r_i$, are unused, whereas used cells are denoted in the figure by their corresponding information bit index. When the j -th row is full, $j = 1 \dots r_i$, the parity bit p_j is calculated, by XORing the elements of the row, and its value is stored in the last column, at the same row (grey cells in the figure). When all the parity bits have been calculated and the last column is full, the encoder outputs the codeword by reading its content in the same order used for the input, but including also the parity bits at the end of the codeword.

It follows from the definition and the encoder structure of an MPC code that its parity-check matrix has a very simple form, almost coincident with a single row of $r_i \times r_i$ identity matrices. Fig. 3 shows its form for the i -th MPC component code in the serial concatenation. In the figure, diagonals represent symbols 1, whereas all other symbols are null.

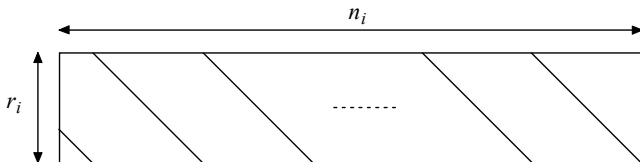


Fig. 3. Parity-check matrix of the i -th MPC component code.

The component parity-check matrices (having the form shown in Fig. 3) can be combined to obtain a valid parity-check matrix for the serially concatenated code, that has the form shown in Fig. 4 (for the case with $M = 3$). Such matrix has $r = \sum_{i=1}^M r_i$ rows, and the maximum Hamming weight of its columns is M . So, it is immediate to observe that, for large r_i values, the parity-check matrix is sparse, and M-SC-MPC codes can be seen as LDPC codes.

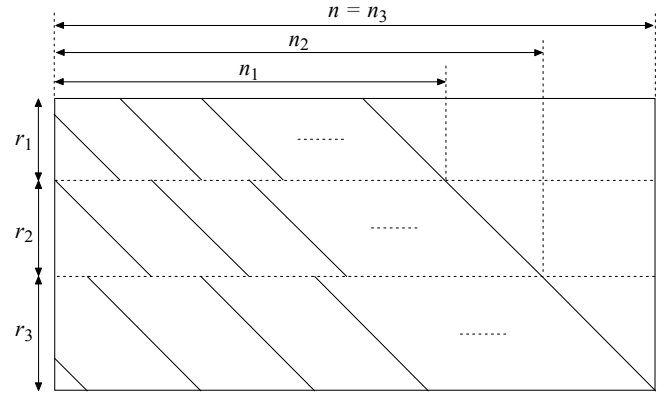


Fig. 4. Parity-check matrix of an M-SC-MPC code with $M = 3$.

Even more noticeably, it can be proved that, for distinct, coprime and increasingly ordered r_i 's, the matrix is free of length-4 cycles when the following condition is satisfied [9]:

$$n \leq n_{\max} = r_1 r_2 + \sum_{i=2}^M r_i; \quad (8)$$

so, efficient belief propagation algorithms can be adopted for decoding M-SC-MPC codes as LDPC codes.

Condition (8) allows great flexibility in the code design, since the value of n_{\max} is rather large (for common choices of the r_i values) and each value of length $n \leq n_{\max}$ is theoretically feasible. Moreover, the very simple structure of the parity-check matrix, together with its lower triangular form, allows easy encoding when accomplished through standard techniques, like *back substitution*, instead of adopting concatenated MPC encoders.

B. Nodes degree distributions

From the definition of M-SC-MPC codes, and from the structure of their parity-check matrices, it follows that such codes are almost regular. In other terms, their associated Tanner graphs have almost constant variable and check nodes degrees. In order to represent variable and check nodes degree distributions, we can refer to the notation introduced in [10]. According with that notation, an irregular bipartite graph with maximum variable nodes degree \bar{d}_v and maximum check nodes degree \bar{d}_c is specified by two sequences, $(\lambda_1, \dots, \lambda_{\bar{d}_v})$ and $(\rho_1, \dots, \rho_{\bar{d}_c})$, such that λ_i (ρ_i) is the fraction of edges connected to variable (check) nodes with degree i . These two sequences can be used as the coefficients of two polynomials, $\lambda(x)$ and $\rho(x)$, describing the edge degree distributions:

$$\begin{cases} \lambda(x) = \sum_{i=1}^{\bar{d}_v} \lambda_i x^{i-1}; \\ \rho(x) = \sum_{i=1}^{\bar{d}_c} \rho_i x^{i-1}. \end{cases} \quad (9)$$

Equivalently, other two polynomials, $v(x)$ and $c(x)$, can be used, that describe the degree distributions of the variable nodes and check nodes, respectively. The polynomials $\lambda(x)$ and $\rho(x)$ can be easily translated into $v(x)$ and $c(x)$ through the following relations:

$$\begin{cases} v_i = \frac{\lambda_i/i}{\sum_{j=1}^{\bar{d}_v} \lambda_j/j}; \\ c_i = \frac{\rho_i/i}{\sum_{j=1}^{\bar{d}_c} \rho_j/j}. \end{cases} \quad (10)$$

For M-SC-MPC codes, the very simple structure of the parity-check matrix permits to derive explicit expressions for $v(x)$ and $c(x)$. In fact, it is easy to observe that the triangular part of the matrix is formed by: r_M columns with degree 1, $r_M - 1$ columns with degree 2, and so on, up to r_2 columns with degree $M - 1$; the remaining $n_1 = k + r_1$ columns have degree M . So, the polynomial $v(x)$ of an M-SC-MPC code can be expressed as follows:

$$v(x) = \frac{1}{n} \left(\sum_{i=1}^M r_i x^{M-i} + kx^{M-1} \right). \quad (11)$$

The fact that M-SC-MPC codes have variable nodes with almost regular degree also results from Eq. (11): the term kx^{M-1} , in fact, is often dominant (especially for high rate codes, in which $k \gg r_i, \forall i$), meaning that the Tanner graph contains many variable nodes with degree M . As concerns check nodes, we can observe that each *layer* of r_i rows in the parity-check matrix contains $(n_i \bmod r_i)$ rows with weight $\lceil n_i/r_i \rceil$, whereas the remaining $r_i - (n_i \bmod r_i)$ rows have weight $\lfloor n_i/r_i \rfloor$. So, for M-SC-MPC codes, the polynomial $c(x)$ can be expressed as follows:

$$c(x) = \frac{1}{r} \sum_{i=1}^M \left\{ (n_i \bmod r_i) x^{\lfloor n_i/r_i \rfloor - 1} + [r_i - (n_i \bmod r_i)] x^{\lceil n_i/r_i \rceil - 1} \right\}. \quad (12)$$

C. Irregular M-SC-MPC Codes

As M-SC-MPC codes are almost regular, their $v(x)$ and $c(x)$ polynomials often correspond to a peaked distribution, especially for high code rates. This will be confirmed, through numerical examples, in the next section.

Regular distributions have been proved to be non-optimal [10], and the polynomials $\lambda(x)$ and $\rho(x)$ (or, equivalently, $v(x)$ and $c(x)$) can be optimized in such a way as to improve the performance of belief propagation decoding algorithms. This can be done by using the *density evolution* approach [10], [14], that permits to obtain capacity approaching degree distributions under the hypothesis of large block length.

So, at least in principle, the performance of M-SC-MPC codes could be improved by introducing some form of irregularity in their parity-check matrices. The approach we propose is aimed at increasing irregularity of the parity-check matrix though preserving its structured character and the very simple encoder implementation reported in Fig. 2. Our solution consists in cancelling some of the identity blocks included in one or more matrix layers. This is equivalent to *switch off* some columns in the encoder shown in Fig. 2, in such a way that the input bits in those columns do not participate anymore in a parity-check equation.

Under the performance viewpoint, it would be more efficient to cancel single 1 symbols without any constraint, that would also permit to optimize the nodes degree distributions. However, we prefer to maintain the structural simplicity of M-SC-MPC codes and, in this perspective, canceling whole identity blocks facilitates the implementation of irregular codes.

It should be noted that the cancellation of some blocks within the parity-check matrix reduces the code minimum distance, since the corresponding MPC encoder has no more effect on the input bits corresponding to such blocks. For this reason, in order to obtain codes with rather good minimum distance though cancellations, it can be required to increase the value of M (i.e. the number of concatenated codes) with respect to the case without cancellations.

D. Length of Local Cycles

The almost regular structure of the M-SC-MPC parity-check matrices is also responsible for the appearance of local cycles with length 6. The existence of shorter cycles is avoided through condition (8), but length-6 cycles can still exist. Even if their presence is not sure, they often occur due to linear relations that may be established among the different r_i values.

In principle, the length of local cycles could be increased by adding an interleaver between each pair of MPC encoders. This would recall the original proposal by Tee et al., who introduced M-SC-SPC codes based on interleavers [13]. On the contrary, the proposed technique, based on the cancellation of some blocks in the parity-check matrix, can increase the length of local cycles by maintaining the structural simplicity of MPC codes, without the need of further components. This is due to the fact that the cancellation of some blocks avoids the existence of some pairs of symbols 1 whose positions differ by an integer multiple of an r_i value. This way, some of the local cycles due to linear relations existing among the r_i values are avoided, and this facilitates the convergence of the decoding algorithm.

As highlighted in the previous subsection, however, the cancellation of some blocks reduces the code minimum distance, so the efficiency of the decoding algorithm is improved at the expenses of the code structural characteristics. However, it often occurs that LDPC codes with not very high minimum distance are able to achieve better performance in the waterfall region with respect to codes with higher

TABLE II
PARAMETERS OF THE SIMULATED CODES WITH LENGTH $n = 1632$

Code	R	Type	$[r_1, \dots, r_M]$	$[h_1, \dots, h_M]$	$v(x)$	$c(x)$
1	1/2	Q	-	-	$0.208x^5 + 0.333x^2 + 0.458x$	$0.333x^6 + 0.667x^5$
2	1/2	M	[153, 155, 159, 167, 182]	-	$0.594x^4 + 0.095x^3 + 0.097x^2 + 0.102x + 0.112$	$0.369x^8 + 0.301x^7 + 0.205x^6 + 0.125x^5$
3	1/2	M	[87, 89, 93, 101, 117, 149, 180]	-	$0.553x^6 + 0.055x^5 + 0.057x^4 + 0.062x^3 + 0.072x^2 + 0.091x + 0.110$	$0.203x^{11} + 0.327x^{10} + 0.217x^9 + 0.252x^8$
4	1/2	iM	[87, 89, 93, 101, 117, 149, 180]	[0, 4, 4, 4, 4, 3, 3]	$0.146x^5 + 0.275x^4 + 0.248x^3 + 0.058x^2 + 0.053x + 0.221$	$0.04x^{10} + 0.066x^9 + 0.328x^7 + 0.359x^6 + 0.206x^5$
5	2/3	Q	-	-	$0.667x^3 + 0.042x^2 + 0.292x$	$0.125x^{10} + 0.875x^9$
6	2/3	M	[113, 127, 149, 155]	-	$0.736x^3 + 0.078x^2 + 0.091x + 0.095$	$0.388x^{10} + 0.588x^9 + 0.024x^8$
7	2/3	M	[71, 83, 101, 127, 162]	-	$0.710x^4 + 0.051x^3 + 0.062x^2 + 0.078x + 0.099$	$0.042x^{16} + 0.088x^{15} + 0.147x^{14} + 0.061x^{13} + 0.131x^{12} + 0.134x^{11} + 0.121x^{10} + 0.276x^9$
8	2/3	iM	[71, 83, 101, 127, 162]	[4, 0, 3, 2, 0]	$0.292x^4 + 0.415x^3 + 0.116x^2 + 0.078x + 0.099$	$0.147x^{14} + 0.006x^{13} + 0.042x^{12} + 0.088x^{11} + 0.208x^{10} + 0.410x^9 + 0.099x^8$
9	3/4	Q	-	-	$0.292x^5 + 0.5x^2 + 0.208x$	$0.667x^{14} + 0.333x^{13}$
10	3/4	M	[59, 73, 113, 163]	-	$0.786x^3 + 0.045x^2 + 0.069x + 0.099$	$0.108x^{21} + 0.037x^{20} + 0.103x^{18} + 0.076x^{17} + 0.277x^{12} + 0.005x^{10} + 0.395x^9$
11	3/4	M	[73, 75, 79, 87, 94]	-	$0.795x^4 + 0.046x^3 + 0.048x^2 + 0.053x + 0.057$	$0.125x^{18} + 0.618x^{17} + 0.257x^{16}$
12	3/4	iM	[73, 75, 79, 87, 94]	[4, 0, 3, 2, 0]	$0.423x^4 + 0.359x^3 + 0.107x^2 + 0.053x + 0.058$	$0.054x^{18} + 0.213x^{17} + 0.147x^{16} + 0.216x^{15} + 0.191x^{14} + 0.137x^{13} + 0.042x^{12}$
13	5/6	Q	-	-	$0.458x^3 + 0.417x^2 + 0.125x$	x^{19}
14	5/6	M	[37, 53, 73, 109]	-	$0.856x^3 + 0.033x^2 + 0.045x + 0.067$	$0.103x^{37} + 0.033x^{36} + 0.07x^{27} + 0.125x^{26} + 0.232x^{20} + 0.037x^{19} + 0.390x^{14} + 0.011x^{13}$
15	5/6	M	[43, 45, 49, 57, 78]	-	$0.860x^4 + 0.028x^3 + 0.03x^2 + 0.035x + 0.048$	$0.129x^{32} + 0.195x^{31} + 0.099x^{30} + 0.081x^{29} + 0.055x^{27} + 0.154x^{26} + 0.265x^{20} + 0.022x^{19}$
16	5/6	iM	[43, 45, 49, 57, 78]	[12, 11, 0, 6, 4]	$0.156x^4 + 0.458x^3 + 0.286x^2 + 0.052x + 0.048$	$0.993x^{30} + 0.081x^{29} + 0.239x^{21} + 0.235x^{20} + 0.059x^{19} + 0.265x^{16} + 0.022x^{15}$

minimum distance.

III. CODE EXAMPLES

In this section, we provide some examples of codes with the aim to compare M-SC-MPC codes and their irregular versions with IEEE 802.16e standard QC-LDPC codes. For this purpose, we consider codes having all values of rate specified by the standard ($R = 1/2, 2/3, 3/4$ and $5/6$) and length $n = 1632$. We have designed some M-SC-MPC codes and irregular M-SC-MPC codes with exactly the same length and rate.

Table 2 reports the parameters of the codes considered in our examples, that are of three types: QC-LDPC codes compliant with the IEEE 802.16e standard (Q), M-SC-MPC codes (M) and irregular M-SC-MPC codes (iM). In the latter case, the table also reports the number (h_i) of blocks canceled in each matrix layer (that is, the number of columns switched off in each component encoder). Such values, that form what we call a *nulling pattern*, have been found on a heuristic basis; so, margins may exist for their further optimization.

More precisely, for a given nulling pattern, the choice of the blocks to cancel in each layer has been made through a constrained random search, based on two criteria: i) avoiding the appearance of very low weight columns in the non-

triangular part of the matrix (denoted by $d_v(i)$ the weight of the i -th column, we fixed $d_v(i) \geq 3, i \in [1; n_1]$) and ii) increasing the length of local cycles. For all code rates, different values of M have been considered for the design of M-SC-MPC codes. This allows to highlight the effect of varying the number of components codes. Codes with lower M have lower column degree of their parity-check matrices and smaller minimum distance. These two facts yield a rather good waterfall performance, that usually begins at lower signal-to-noise ratio with respect to codes with higher M . On the other hand, a small minimum distance produces rather high error floors, that cause a slope change in the error rate curves. When the number of component codes is increased, both the parity-check matrix column weight and the minimum distance are increased. This makes the waterfall begin at higher signal-to-noise ratios, but the error floor is lowered as well. So, the error rate curves for codes with low and high M tend to intersect at intermediate values of the signal-to-noise ratio. By applying block cancellations to codes with high M , the advantages of both low and high M can be joined, and codes can achieve good error rate performance both in the waterfall and in the error floor region. The simulation results of some specific cases will be discussed in the next section.

Table 2 also reports, for each code, the polynomials $v(x)$

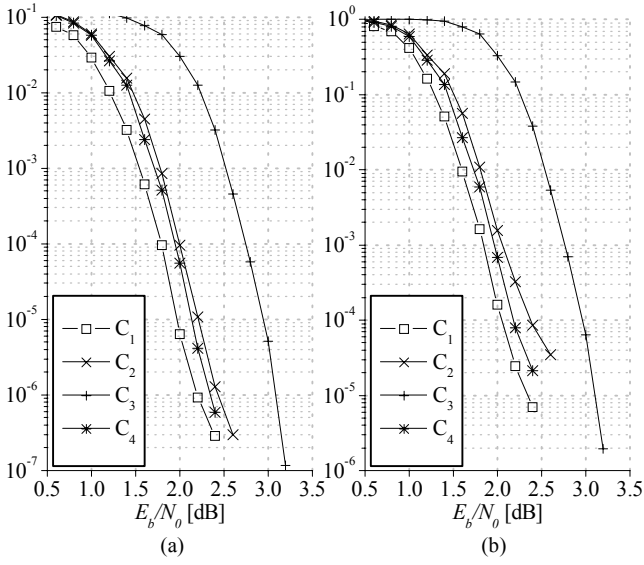


Fig. 5. Simulated BER (a) and FER (b) for codes with rate 1/2.

and $c(x)$, that describe the nodes degree distributions. By looking at polynomials $v(x)$, we notice that, as expected, M-SC-MPC codes have peaked degree distributions for their variable nodes (except for rate 1/2 codes, more than 70% of the variable nodes have degree M). By applying block cancellations, instead, the variable nodes degree distribution becomes more uniform, since the fraction of nodes with degree $< M$ is increased. This results in polynomials that are more similar to those of standard codes, that have coefficients never exceeding 0.7.

We remind that, in our examples, the degree polynomials have not been optimized but, instead, they have been obtained as the result of optimization of the block cancellations, based on the two criteria described above. Further improvements could be possible by aiming at optimizing also the degree

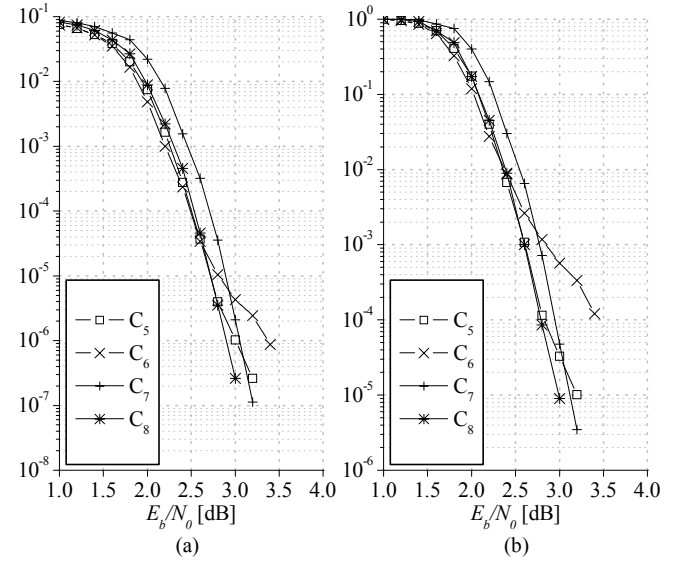


Fig. 6. Simulated BER (a) and FER (b) for codes with rate 2/3.

polynomials.

IV. SIMULATION RESULTS

The codes we have considered in Section 4 have been assessed through simulation of transmission over the AWGN channel, with BPSK modulation. Decoding has been implemented by using the log-domain version of the sum-product algorithm [4]. The simulation results are shown and compared in the next subsections, where codes with the same rate are grouped together. We remind that all codes considered in our examples have length $n = 1632$.

A. Codes with rate 1/2

Fig. 5 reports the simulated performance of the considered codes with rate 1/2. As we observe from the figure, the

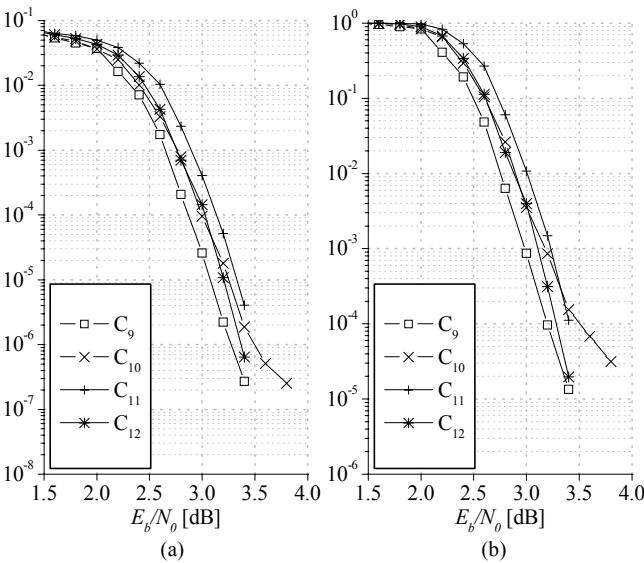


Fig. 7. Simulated BER (a) and FER (b) for codes with rate 3/4.

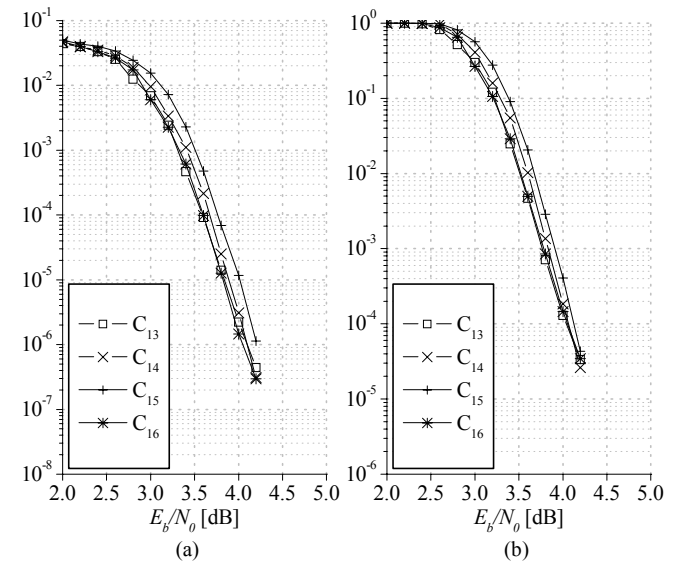


Fig. 8. Simulated BER (a) and FER (b) for codes with rate 5/6.

standard QC-LDPC code (C_1) achieves very good performance, and its curves are the leftmost ones. The M-SC-MPC code with $M = 5$ (C_2) has a rather good performance, yielding a loss of about 0.2 dB with respect to the standard code. However, especially in its FER curve, an error floor effect is observed, that tends to deteriorate its performance for increasing signal-to-noise ratios.

The error floor can be mitigated by adopting a higher value of M : the M-SC-MPC code with $M = 7$ (C_3) exhibits a more favorable slope in its error rate curves for increasing signal-to-noise ratio. On the other hand, the adoption of such a high value of M gives a worse performance in the waterfall region, requiring higher signal-to-noise ratios for reaching the same error rate with respect to codes having lower M . Applying the cancellation of some blocks helps to mitigate such an effect: we observe that the irregular M-SC-MPC code (C_4), though still exploiting $M = 7$ component codes, has good performance in the waterfall region, with a slight improvement with respect to C_2 . Moreover, in the error floor region, the performance of C_4 tends to further improve that of C_2 , especially for the FER curve, in which the error floor effect is mitigated. So, the irregular M-SC-MPC code, obtained by canceling some blocks in the parity-check matrix of the M-SC-MPC code with $M = 7$, is able to join the advantages of both low and high M , and to achieve better performance both in the waterfall and in the error floor region. Its curves approach those of the standard code, with a loss of some fraction of dB with respect to them.

B. Codes with rate 2/3

The simulation results are quite similar for codes with rate 2/3: also for such code rate, irregular M-SC-MPC codes are able to achieve very good performance. Moreover, in this case, they can become even better than standard codes.

This can be observed in Fig. 6, where we notice that both the standard QC-LDPC code (C_5) and the M-SC-MPC code with $M = 4$ (C_6) show an error floor. On the contrary, the M-SC-MPC code with $M = 5$ (C_7) has no error floor, but its waterfall performance is worse than the others. The irregular M-SC-MPC code with $M = 5$ (C_8), instead, is able to improve the waterfall performance without losing its curve slope in the error floor region.

C. Codes with rate 3/4

A similar conclusion can be drawn from the analysis of codes with rate 3/4, shown in Fig. 7: the M-SC-MPC code with low M (C_{10}) has good waterfall performance, but a rather high error floor. On the contrary, the M-SC-MPC code obtained by increasing M (C_{11}) has better error floor performance at the expense of the waterfall behavior. The adoption of an irregular M-SC-MPC code (C_{12}) allows to improve the error floor performance without loss in terms of error floor, so approaching the performance of the standard QC-LDPC code (C_9).

D. Codes with rate 5/6

For codes with rate 5/6, the difference among the

considered design techniques is less evident. The simulation results, reported in Fig. 8, show that both the M-SC-MPC code with $M = 4$ (C_{14}) and the irregular M-SC-MPC code with $M = 5$ (C_{16}) are able to approach the performance of the standard code (C_{13}). The M-SC-MPC code with $M = 5$ (C_{15}) has instead a worse waterfall behavior. In this case, the usage of an irregular M-SC-MPC code does not give any significant improvement with respect to the classic M-SC-MPC solution.

V. CONCLUSION

In this paper, we have presented a design technique for codes intended for wireless applications. We have referred to QC-LDPC codes included in the IEEE 802.16e standard, and we have designed codes with the same parameters in order to compare their characteristics and performance with those of standard codes.

Our analysis has started from the M-SC-MPC codes design technique, we have recently proposed, and a new variant of it has been introduced, that is aimed at designing irregular codes. Both techniques are able to produce very good codes, with performance that can be comparable or even better with respect to standard codes.

We have shown that, in some cases, classic M-SC-MPC codes still have performance comparable with that of the new irregular M-SC-MPC codes. Our analysis brings to the conclusion that further margins of improvement may exist, that are probably related with the optimization of the nodes degree polynomials. This could be a point worth to be studied in future works.

Another interesting cue for future work is to deepen the investigation of the link between Quasi-Cyclic and M-SC-MPC codes, in such a way to assess whether the M-SC-MPC structure can also be adapted to design QC codes.

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