An Interleaver Optimization for BICM-OFDM with Convolutional Codes over Frequency-Selective Block Fading Channels

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***Abstract*— Bit-interleaved coded modulation (BICM) system combined with orthogonal frequency-division multiplexing (OFDM) has been adopted in many recent wireless standards, where the random interleaver is commonly assumed due to its simplicity of analysis for BICM. On the other hand, the recent results have shown that BICM using convolutional code without any interleaving shows better performance than that with bit interleaving over an AWGN channel without fading. Nevertheless, the interleaver design suitable for BICM with convolutional code over general fading channels has not been well studied. In this paper, we propose an approach for optimizing conventional block interleavers in the framework of BICM-OFDM and demonstrate its effectiveness over frequency-selective Rayleigh and Ricean fading channels.**

I. Introduction

Due to the growing demand for high data-rate wireless communications under the scarcity of bandwidth, the use of coded modulation together with effective channel coding is a prerequisite for recent wireless and mobile communication standards. Also, in order to gain robustness against frequency-selective fading channels with feasible receiver complexity, orthogonal frequency-division multiplexing (OFDM) technique has become a *de facto* standard for such systems. By applying a suitable channel coding to OFDM, the frequency diversity effect provided by the frequency-selective nature of channels can be achieved efficiently without complex equalization.

Among several coded modulation techniques, bit-interleaved coded modulation (BICM) [1], [2] has become popular due to its simplicity of coding and constellation design over fading channels. In fact, BICM is known to outperform trellis coded modulation (TCM) [3] over certain fading channels in terms of cut-off rate and bit error rate (BER) [2]. Therefore, the combination of BICM and OFDM has been considered as a promising approach in the recent standards that target high bandwidth efficiency and high reliability over frequency-selective fading channels with limited receiver complexity.

In general, the performance of BICM depends on the channel as well as a constituent binary channel coding. If the channel is ergodic and the channel interleaver can provide almost independent fading effect on each quadrature amplitude modulation (QAM) symbol, capacity approaching channel codes such as low-density parity-check (LDPC) and turbo codes are desirable since they can approach ergodic capacity of the fading channels [4], [5]. On the other hand, if the interleaver does not provide enough diversity as in the case of real-time data transmission, the channel will be characterized as block-fading, and the channel coding within each block may not be necessarily effective [6], [7]. In this case, the minimum Hamming distance of the channel code becomes important as it determines the achievable diversity order provided by the channel [8].

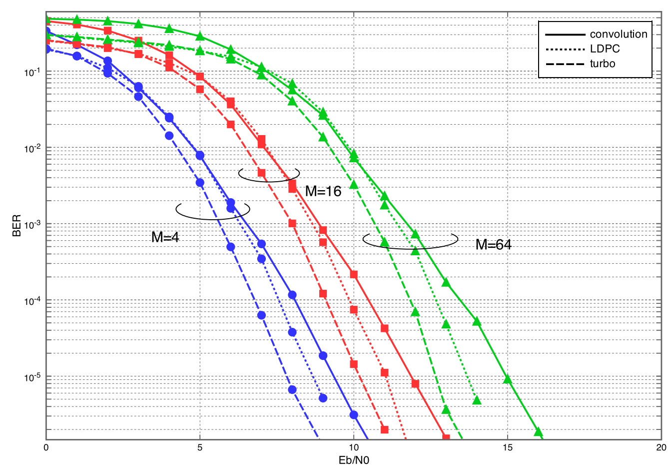

Fig. 1. BERs for BICM-OFDM using LDPC code, turbo code, and convolutional code with random interleaver over frequency-selective Rayleigh fading channels.

For a BICM-OFDM system, if the interleaver cannot be applied to multiple OFDM symbols that are subject to independent channel fading, a similar conclusion applies; the capacity approaching channel codes may not be necessarily effective. To see this, Fig. 1 compares the BER performances of BICM-OFDM system with rate-1/2 LDPC code, turbo code, and convolutional code over frequency-selective Rayleigh fading channels where a single codeword of length 3096 is transmitted as one OFDM symbol with each subcarrier modulated by M-ary QAM, M ranging from 4 to 64. (The detailed parameters of LDPC encoder and decoder are provided in the later section. For the turbo code results, the original rate-

1/3 turbo code is punctured and log-MAP decoder is used for iterative decoding.) In all the results, considering the burst error nature of fading channels, random interleavers are adopted as an example of channel interleaver that disperses correlated fading coefficients.

Even though the BER performances of the convolutional code is inferior to those of the LDPC and turbo codes, they show similar diversity gain (as observed from the slope of the BER curves) and, furthermore, the encoding and decoding complexities of the convolutional codes are much lower than those of the other two codes. Considering the requirement of lower complexity as well as lower latency receiver implementation in the real-time wireless communication applications, we will focus on the performance of the convolutionally coded BICM-OFDM throughout this paper. In particular, we will demonstrate that the performance of BICM-OFDM system in the case of the convolutional codes considerably depends on interleaver structures. We show that when the diversity order provided by the frequency-selective channel is limited, the performance of the convolutional codes approaches that of LDPC codes, provided that the interleaver is properly designed. That is, the performance gap between the LDPC and convolutional codes observed in Fig. 1 can be made even smaller. (Note that the performance of LDPC code is not much affected by the interleaver structures in our scenario where a single codeword is transmitted over a single OFDM symbol or fading is static over multiple OFDM symbols where a single codeword is assigned.)

As mentioned above, for frequency-selective Rayleigh fading channels, the performance of BICM-OFDM is largely determined by the diversity order of channels and the minimum distance of channel codes as shown in [8]. On the other hand, in the case of additive white Gaussian noise (AWGN) channels without fading, it has been recently shown that BICM without interleaver outperforms that with interleavers (whether they are random or block) [9], [10], which justifies that BICM with any interleaver may become suboptimal. This is because of noise correlation (dependency invoked by the same noise realizations) in the log likelihood ratio [9]. The question that may arise at this point is whether the channel interleaver is necessary or not when the fading is characterized by Ricean, which balances between severe Rayleigh fading and AWGN (no fading) channels. To the best of the authors' knowledge, this aspect has not been well investigated in the literature. Therefore, in this paper, we study a suitable design of interleavers in the framework of BICM-OFDM over frequency-selective channels with various fading conditions. We will show that there is a trade-off between the achievable diversity gain by interleaving and sub-optimality of the interleaver associated with BICM. We note that rigorous theoretical analysis of optimal interleavers is challenging and thus our study is mostly based on simulations. However, we provide some theoretical insights and derive a general interleaver design guideline in our framework.

The rest of the paper is organized as follows. The BICM-OFDM system and channel models considered in this work are given in Section II. Section III is devoted to the description and design of interleavers suitable for our scenario. Simulation results that justify our observation and design guideline are given in Section IV. Finally, Section V concludes this work.

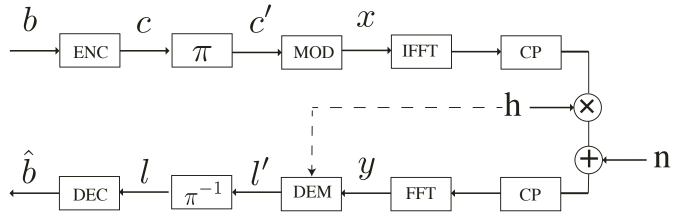

Fig. 2. BICM-OFDM system.

II. System Model

A. BICM-OFDM

The system model of BICM-OFDM considered throughout this paper is shown in Fig. 2. A binary information sequence of length $N/2$, denoted by $\mathbf{b} = [b_1, \cdots, b_{N/2}]$, is fed to the binary channel encoder (ENC) and encoded as $\mathbf{c}$. In this work, unless stated otherwise, we employ the binary convolutional code of rate $R = 1/2$ with the constraint length $K_c = 7$, where its generator polynomial is given by (133,171), which is well known as the optimal distance spectrum convolutional code [11].

The resulting codeword $\mathbf{c} = [c_1, \cdots, c_N]$ of length N is then permuted by a bit interleaver Π and the interleaved sequence is denoted by $\mathbf{c}'$. The detailed description of the interleavers adopted in this paper is given in Section III. The modulator (MOD) maps the interleaved sequence $\mathbf{c}'$ onto the QAM symbols with constellation size of M, each labeled by Gray labeling. We denote the set of M-QAM symbols by $\mathcal{X}$ and $m = \log_2 M$ as the number of bits constituting one QAM symbol.

Let N_{sc} denote the number of subcarriers for each OFDM symbol, and we assume that each subcarrier is modulated by M-QAM. The resulting QAM vector that represents one OFDM symbol is expressed as $\mathbf{x} = [x_1, \cdots, x_{N_{sc}}]$ where $x_k \in \mathcal{X}$ for any $k \in \{1, 2, \ldots, N_{sc}\}$. In this paper, we consider a *low-latency system implementation scenario* where the set of QAM symbols corresponding to each codeword is matched to one OFDM symbol, i.e., *a codeword-matched OFDM system*. Specifically, since the N_{sc}-subcarrier OFDM, each modulated by M-QAM, can carry $N_{sc}m$ bits, we set the codeword length as

$$N \equiv N_{sc} \log_2 M. \tag{1}$$

In this manner, the detection of OFDM (i.e., FFT operation) and decoding of codeword can be implemented in a pipelined fashion such that the decoding latency at the receiver can be significantly reduced. Even though we only focus on this particular system, we emphasize that if the channel is time invariant over multiple OFDM symbols, which is often the case with practical OFDM systems with low mobility, the resulting performance may not be affected even if a single codeword is spread over multiple OFDM symbols as no additional diversity will be provided by the time-domain interleaving.

B. Decoding of BICM

Since our primary interest in this work is the achievable coding gain and diversity order offered by frequency-selective channels, it is assumed that the cyclic prefix (CP) added to each OFDM symbol is long enough such that the effect of inter-symbol interference (ISI) associated with the delay spread is negligible. In this case, for the transmitted symbol on the kth subcarrier, the corresponding received symbol is expressed as $y_k = h_k x_k + n_k$, where n_k is a zero-mean, complex AWGN term with variance $N_0/2$ per dimension and h_k is the frequency response of the corresponding channel. Assuming that the perfect knowledge of the channel state information (CSI) is available at the receiver, we calculate the log likelihood ratio $\boldsymbol{l'}$ of the entire coded and interleaved bit sequence. Specifically, the log likelihood ratio of the ith bit of the kth subcarrier to be calculated at the demodulator is expressed as

$$l'_{k,i} = \log \frac{p(y_k | c_{k,i} = 1)}{p(y_k | c_{k,i} = 0)}, \quad (2)$$

where $c_{k,i}$ is the coded bit corresponding to the ith bit position on the kth subcarrier. A set of the bit metrics (2) is then permuted by the bit deinterleaver Π^{-1} to obtain that of the original order, denoted by $\boldsymbol{l}$, and this is fed to the Viterbi decoder. The Viterbi decoder then determines the maximum likelihood (ML) path (i.e., the most likely coded sequence) $\hat{\mathbf{c}}$, which is expressed as

$$\hat{\mathbf{c}} = \arg\max_{\mathbf{c} \in \mathcal{C}} \left\{ \sum_{k=1}^{N_{sc}} \sum_{i=1}^{m} l_{k,i} \right\}, \quad (3)$$

where $\mathbf{c}$ is the candidate codeword and $\mathcal{C}$ is a set of the entire codewords.

C. Channel Model

In this paper, we focus on the frequency-selective fading channels without time variation, which is the situation where neither the transmitter nor the receiver moves rapidly. We further consider that the channel is Ricean fading in order to deal with the case where the line-of-sight (LOS) path is available. Let us assume that there are one direct path and L indirect paths that are characterized by statistically independent Rayleigh distribution. Ricean fading is characterized by Ricean factor K which represents the ratio of the power of the direct wave to the sum of those of Rayleigh waves. Therefore, $K = 0$ corresponds to the Rayleigh fading channel and $K = \infty$ corresponds to the AWGN channel without fading.

III. Interleaver Design Based on Block Interleaving

A. Regular Block Interleaver

In the literature, a random interleaver is usually considered for BICM due to its simplicity of performance analysis [2]. However, when a random interleaver is applied to a convolutionally coded system, there is a certain probability that the bit metrics that have correlated fading coefficients may be clustered in the same trellis segment such that the achievable diversity gain is reduced. A so-called block interleaving is effective for reducing the occurrence of such cases. In a general block interleaver for a binary codeword of length $N = N_r \times N_c$, where N_r and N_c correspond to the numbers of row components and column components, respectively, each bit of the original codeword is stored in the row direction, and the stored bits are read in the column direction. In this manner, the adjacent bits in the original order are separated exactly by N_r bits in the interleaved codeword. We refer to this type of interleaver as a *regular block interleaver* in what follows.

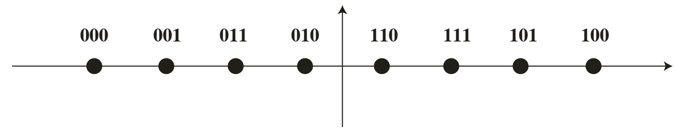

Fig. 3. Gray labeling for the in-phase of 64QAM (8-ASK).

B. Bit Location Optimization for Block Interleaver

In the BICM system with high-order QAM and Gray labeling, the reliability of each coded bit depends on the bit positions [12]; some bits are relatively robust against noise, whereas some bits are sensitive. Since the QAM symbols are affected by AWGN where its in-phase (I) and quadrature phase (Q) components are statistically independent, we can decompose the square (M-ary) QAM signaling into the two identical amplitude shift keying (ASK) constellations of size $\sqrt{M}$. Therefore, in what follows, we only consider the ASK with Gray labeling. For example, in the case of square 64-QAM, the equivalent 8-ASK constellation (as its in-phase component) is shown in Fig. 3. It is easy to observe that the bit at the first position (the leftmost bit) has the highest protection among the three bits, whereas the bit at the third position (the rightmost bit) has the lowest protection.

In general, with $i = 1, \cdots, m/2$ denoting the bit position of the Gray labeled $\sqrt{M}$-ASK symbol, we can arrange such that the bit reliability decreases as i increases, i.e., the first bit is most reliable, whereas the $(m/2)$th bit is most unreliable. By concatenating the two identical ASK to form the square M-ary QAM, the ith and $(i + m/2)$th bits have the equal bit reliability.

In the case of the regular block interleaver, some unreliable bits may happen to be assigned to the same trellis segment. For example, if we choose N_r as a multiple of m for M-QAM, i.e., $N_r = J\,m$ where J is an integer, the resulting interleaver may be expressed as in Fig. 4. Here, we denote $x_{k,i}$ as the ith bit position of the kth QAM symbol (subcarrier) x_k. In this case, the bits modulated by the same bit position of the QAM are arranged consecutively in the same row. Since the deinterleaved sequence to be decoded at the receiver is read in the row direction, this interleaver array structure results in

$$
N_r = Jm \overset{N_c}{\begin{bmatrix} x_{1,1} & x_{J+1,1} & \cdots & x_{(N_c-1)J,1} \\ x_{1,2} & x_{J+1,2} & \cdots & x_{(N_c-1)J,2} \\ \vdots & \vdots & \ddots & \vdots \\ x_{J,m} & x_{2J,m} & \cdots & x_{N_cJ,m} \end{bmatrix}}
$$

Fig. 4. The interleaver array where N_r is chosen as a multiple of m for M-QAM in the regular block interleaver. The element $x_{k,i}$ represents the ith bit position of the kth QAM symbol (subcarrier).

the occurrence of the clusters of the most unreliable bits in the $j\,(m/2)$th and $j\,m$th rows for $j = 1, \cdots, J$.

To avoid the occurrence of such clusters with unreliable bits, we now propose an optimization of block interleavers. Our optimization process is; 1) to break the consecutiveness of the unreliable bits, and 2) to minimize the variance of the bit metrics such that the overall performance is improved [13]. To achieve this goal, the most unreliable bit must be paired with the most reliable bit in the same trellis segment, and the second unreliable bit must be paired with the second reliable bit. Note that the above-mentioned pairing approach is applicable even if the constellation size M is large.

To better understand the concept, we start with an example of our interleaver optimization process before describing a general algorithm. Consider the case with 64-QAM that has the three different bit reliability and let the first and fourth bits be most reliable, whereas the third and sixth bits be most unreliable. Then one can consider several optimal bit position orders as an input to the Viterbi decoder; for example, $[\bar{1}, \underline{6}, \underline{3}, \bar{4}, 5, 2, \cdots]$ and $[\bar{1}, \underline{3}, 5, 2, \bar{4}, \underline{6}, \cdots]$, where the notation $\bar{x}$ emphasizes the fact that the element is chosen from the most reliable bits whereas $\underline{x}$ denotes that it is chosen from the most unreliable bits. In this case, we can choose the former order $[1, 6, 3, 4, 5, 2, \cdots]$ since it is most similar to the original bit position order without interleaving (i.e., $[1, 2, 3, 4, 5, 6, \cdots]$, which is optimal when the channel suffers from no fading) as our candidate. Choosing this order simplifies the optimization operation compared to the other orders, since the generating most similar order requires fewer permutation steps from the original order. In our example of 64-QAM, we can generate the target order by permuting only the second bits and the sixth bits of the original order. Permuting all second bits and all sixth bits is equivalent to permuting the second label and the sixth label of 64-QAM symbols [12].

Following the process outlined above, we provide our interleaver optimization algorithm in a general form as follows.

Optimization Algorithm

We begin with the block interleaver with N_r rows and N_c columns, where both values are larger than m for M-QAM. Let $i \in \{1, 2, \ldots, N_r\}$ and $j \in \{1, 2, \ldots, N_c\}$ denote the row and column indices, respectively, and we define the two parameters d_r and d_c as

$$
\begin{aligned}
d_r &= N_r \bmod m && (4) \\
d_c &= N_c \bmod m. && (5)
\end{aligned}
$$

First, we attempt to retrieve the original order in each row by cyclically shifting the coded bits in the same column. This process depends on how chosen N_r is related to m, i.e., the value of (4) as follows:

- If $d_r = 0$, cyclically shift all the elements in the jth column downward by the amount of $(t_j \bmod m)$ positions where $t_j = (j-1) \bmod m$.
- If $d_r = 1$, no shift is performed.
- If $d_r \geq 2$, cyclically shift all the elements in the jth column downward by the amount of $(t_j(m-d_r+1) \bmod m)$ positions where $t_j = (j-1) \bmod m$.

After the above operation, all the rows have the original order, but the first positions (the bit positions at the leftmost bits) differ by each row. The above differences may cause undesirable pairs in the trellis segment. (As observed in our previous example of 64-QAM, the first and second bits, the third and fourth bits, and the fifth and sixth bits are not assigned to the same trellis segment in the original order.)

Note that whether the above pairing issue occurs or not depends on the value of N_c and m, or (5). Therefore, we can choose the operations as follows

- If $d_c = 0$, cyclically shift all the elements in the ith row rightward by the amount of $(t_i \bmod m)$ positions where $t_i = (i-1) \bmod m$.
- If $d_c = 1$, no shift is performed.

Note that in the case of $d_c \geq 2$, there may be no general operation that can avoid the occurrence of the undesirable pairs by simple row shifting. Therefore, upon initial construction of the block interleaver structure, it is suggested that N_c should be chosen such that the condition of $d_c = 0$ or 1 is met, whereas N_r can be chosen arbitrarily.

This optimization algorithm can be applied to any modulation schemes or codeword length and the optimized block interleaver can be designed for all cases. In our numerical results in the next section, we specifically consider the case of $N = 3096$ as our example, but we have observed that the result is insensitive to the codeword length.

IV. Simulation Results

A. Simulation Settings

The convolutional code described in Section II-A is used, whereas for LDPC code, (3,6) regular LDPC code is employed with log domain sum-product decoder due to the simplicity of implementation. We assume that the codeword length is $N = 3096$, and the number of subcarriers is determined by (1); since we assume M-QAM modulation for $M = 16, 64$, and 256, the numbers of the subcarriers are determined as $N_{sc} = 774, 516$, and 387, respectively. Both Rayleigh and Ricean fading channels are considered where both channels have $L = 15$ independent Rayleigh fading paths. As an example, we assume that the delay profile is uniformly distributed so that

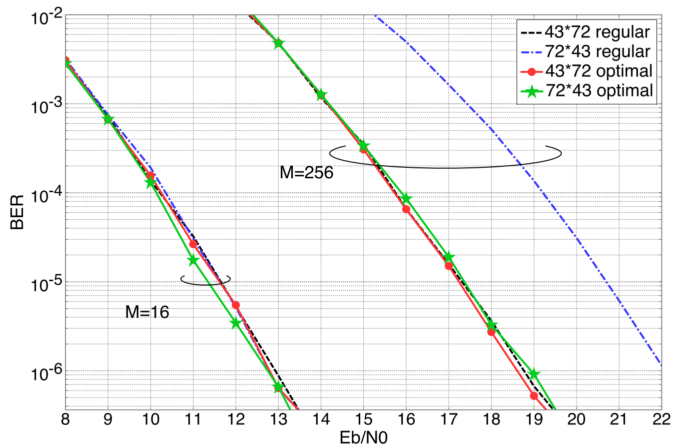

Fig. 5. BERs for BICM-OFDM with convolutional code with regular and optimal block interleavers over Rayleigh fading channels with equal delay intervals.

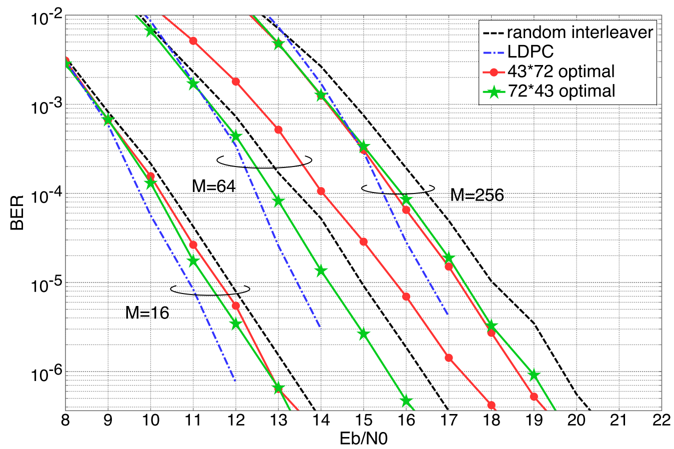

Fig. 6. BERs for BICM-OFDM with convolutional code with random interleaver and optimal block interleavers and LDPC code over Rayleigh fading channels with equal delay intervals.

the time intervals of the adjacent paths are all equal and given by $\Delta\tau$. We consider the three types of interleavers described in Section III; random, regular block, and optimized block interleavers. In the regular and optimized block interleavers, we choose the following two block structures; $(N_r, N_c) = (43, 72)$ and $(N_r, N_c) = (72, 43)$. We refer to them as 43*72 interleaver and 72*43 interleaver, respectively.

B. Performance Comparison over Rayleigh Fading Channels

In this subsection, we will show the effect of optimization of block interleaver over Rayleigh fading channels. The BER performances of the BICM-OFDM system with convolutional code with regular and optimized block interleaver are compared in Fig. 5. Moreover, the BER performances of the BICM-OFDM system with convolutional code with random and optimized block interleaver and LDPC code are compared in Fig. 6.

Comparing the performances between optimized and regular

$$N_c = 72$$
$$N_r = 43 \begin{bmatrix} x_{1,1} & x_{8,2} & \cdots & x_{509,6} \\ x_{1,2} & x_{8,3} & \cdots & x_{510,1} \\ \vdots & \vdots & \ddots & \vdots \\ x_{8,1} & x_{15,2} & \cdots & x_{516,6} \end{bmatrix}$$

Fig. 7. An example interleaver array with 43*72 regular block interleaver and 64-QAM.

block interleavers in the case of 72*43, we observe that the former outperforms the latter, and the gain achieved by optimization increases as M increases. This is because the difference of reliabilities between the most reliable bit and the most unreliable bit becomes dominant as M increases.

On the other hand, in the case of using 43*72 block interleavers, optimized and regular block interleavers result in the same performance for any M. This stems from the fact that N_r is not a multiple of m for all M values investigated here. For example, if we use 43*72 regular block interleaver and 64-QAM ($m = 6$), the resulting interleaver is expressed as in Fig. 7. In this case, the resulting bit position order is equal to that of the original one, i.e., the regular block interleaver does not satisfy the perfect condition that reliable bit and unreliable bit are paired in the same trellis segment, but it can avoid the worst case that the unreliable bits are paired. Therefore, 43*72 regular block interleaver is suboptimal and may not be improved by the proposed optimization process. Furthermore, from the above results, we observe that the most important factor that contributes to the improvement by the optimization is the avoidance of the consecutive unreliable bits, and the minimization of the variance of the bit metrics is of second importance. In other words, breaking the consecutiveness of unreliable bits is a crucial factor for block interleaver optimization.

Comparing both the optimized interleavers, 72*43 block interleaver shows better performance than 43*72 block interleaver for $M = 64$, but both perform almost equal for $M = 16$ and 256. Since both the interleavers have the same optimized bit position order, the difference between them is the symbol (subcarrier) interval of the bits in the same trellis segment. Let us now recall the assumption that the channel has statistically independent Rayleigh waves with an equal interval $\Delta\tau$. In this case, the frequency response is also periodic with the period determined by the interval. If the corresponding delays $k\Delta\tau$, where $k = 1, 2, \ldots,$ happen to match the symbol intervals between the bits in the same trellis segment, they are affected by the same fading coefficient. This results in the performance degradation since the bits in the same trellis segment suffer from identical fading and thus the achievable diversity gain is reduced. Conversely, if, for example, the delays $(k - 1/2)\Delta\tau$ match the symbol intervals, one can avoid the case where the deeply faded bits are assigned in the same trellis segment. Therefore, the delay profile of the channel also affects the performance of the optimized block interleavers.

If we compare the performance of the optimized block interleaver with that of the LDPC code, we observe that with judicious interleaving optimization, even the performance of convolutionally coded BICM with a slightly modified block interleaver can approach that of the LDPC code, especially in the case of $M = 256$ where the effect of the delay profile $\Delta\tau$ becomes negligible. Note that the random interleaver is applied to LDPC code in this example, but the results do not depend on the type of the channel interleavers in the case of LDPC code in our scenario as expected, since the entire OFDM symbol forms a single LDPC codeword.

C. Performance Comparison over Ricean Fading Channels

The previous subsection has demonstrated that the optimization can significantly improve the BER performance over Rayleigh fading channels. In this subsection, we focus on the Ricean fading channels with different Ricean factors K that balance between Rayleigh and AWGN channels and investigate the corresponding BER performance of BICM-OFDM with random and optimized block interleavers as well as without interleaving. The corresponding BER results for $M = 256$ are shown in Fig. 8 in the cases of $K = 4$ and 12. We observe that the optimized block interleaver outperforms the random interleaver regardless of the value of K, which indicates that the optimization process is valid not only over Rayleigh fading channel but also over other types of fading channels.

We now compare the results with those without interleaving. In the case of $K = 4$, it is apparent that even the use of random interleaver can outperform those without interleaving due to the fact that the interleaving provides diversity effects over the channels where the diversity order determines the performance such as frequency-selective block Rayleigh fading channels. On the other hand, for $K = 12$, the performance of the system without interleaving outperforms the others. This is because the statistical properties of the channels approach those of AWGN, where the use of interleaving leads to suboptimal performance [9]. Therefore, in the case of Ricean fading channels, there is a trade-off between the diversity effect achieved by interleaving and the improvement due to the noise correlation achieved by absence of interleaving. Nevertheless, the optimized block interleavers show good performance for both the cases.

V. Conclusion

We have proposed an optimization for the block interleavers in the framework of BICM-OFDM and investigated its performance in terms of BER over frequency-selective block Rayleigh and Ricean fading channels. Simulation results have revealed that the optimized block interleaver always outperforms random and regular block interleavers. However, as the channels approach that of AWGN without fading (i.e., large Ricean factor K), that without interleaving outperforms the others. We have shown that there is a trade-off between the

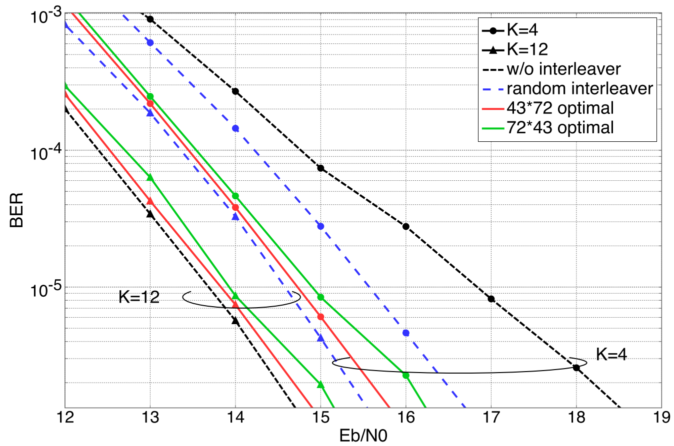

Fig. 8. BERs for BICM-OFDM for $M = 256$ with convolutional code with random interleaver, optimal interleavers, and without interleaver over Ricean fading channels.

diversity effect provided by interleaving and the noise correlation effect lost by interleaving. Nevertheless, the optimized block interleaver can achieve good performance for both cases and thus is a promising approach when the channel interleavers cannot be adaptively switched based on the channel conditions.

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