A Highly Efficient Multi-Carrier Transmission Scheme with Message-Driven Idle Subcarriers

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***Abstract*—This paper develops a highly efficient multi-carrier transmission scheme by using message-driven idle subcarrier identification. The basic idea is to carry part of the information, named carrier bits, through idle subcarrier selection while transmitting ordinary bits regularly on all the other subcarriers. When the number of subcarriers is much larger than the adopted constellation size (e.g., in most OFDM systems), a high spectral efficiency as well as power efficiency can be achieved. This is because that the number of carrier bits transmitted through each idle subcarrier is larger than the number of ordinary bits carried by a regular symbol, and all the carrier bits are transmitted with no power consumption through idle subcarrier selection. When applied to the OFDM framework, the proposed scheme can achieve an even higher spectral efficiency than OFDM, while keeping a higher power efficiency. We further enhance its security and error-tolerance using secure subcarrier assignment, secure symbol mapping and bit vector rearrangement. Both theoretical analysis and numerical results are provided to demonstrate the performance of the proposed scheme.**

***Index Terms*—multi-carrier transmission, message-driven idle subcarriers, secure subcarrier assignment, secure symbol mapping, bit vector rearrangement.**

I. INTRODUCTION

In conventional multi-carrier transmission systems, spectral overlaps are usually avoided to eliminate inter-carrier interference (ICI). When it was realized that the spectral efficiency could be significantly increased by allowing spectral overlaps between orthogonal subcarriers [1], especially after a low-cost implementation using IFFT/FFT blocks was proposed [2], orthogonal frequency division multiplexing (OFDM) becomes one of the most effective ways in modern communications and is adopted by many recent standards, e.g., LTE and WiMAX. Besides the robustness to multipath fading over frequency selective channels, the very first advantage making OFDM prevalent is its high spectral efficiency, which is so far believed to be the highest. There is always a question which greatly attracts the interest of many researchers: can the spectral efficiency of a system be even higher than OFDM?

In this paper, we develop a highly efficient multi-carrier transmission scheme, which offers a positive answer to the question above. Our approach is motivated by the concept of message-driven frequency hopping (MDFH), which was initiated in [3]. In MDFH, the hopping carrier frequency is specified by the message itself and recovered by a filter bank at the receiver. Several revised versions of MDFH were proposed and analyzed in [4]–[6]. By transmitting information through hopping frequency selection, MDFH can increase the spectral efficiency of conventional frequency hopping (FH) systems [7] by multiple times.

Note that MDFH only transmits information through the active hopping carriers, but keeping most channels idle. In this paper, we consider the opposite. That is, using part of the information bits, named carrier bits, to specify idle subcarriers while transmitting ordinary bits regularly on all the other subcarriers. In this way, if the number of subcarriers is much larger than the adopted constellation size (e.g., in most OFDM systems), we can transmit more information bits at an even lower power consumption. This is because that the number of carrier bits transmitted through each idle subcarrier is larger than the number of the ordinary bits carried by a regular symbol, and all the carrier bits are transmitted with no power consumption through idle subcarrier selection. When applied to the OFDM framework, i.e., using orthogonal subcarriers and IFFT/FFT blocks, the proposed scheme can achieve an even higher spectral efficiency than OFDM, while keeping a higher power efficiency. The existence of idle subcarriers can also decrease possible inter-carrier interference between their neighboring subcarriers. We further enhance its security and error-tolerance using secure subcarrier assignment, secure symbol mapping and bit vector rearrangement. Both theoretical analysis and numerical results are provided to demonstrate the performance of the proposed scheme. The contributions of this paper are summarized as follows:

1) We propose a new multi-carrier transmission scheme which can achieve higher spectral and power efficiency than OFDM;

2) We enhance its security and error-tolerance using secure subcarrier assignment, secure symbol mapping and bit vector rearrangement;

3) We provide theoretical analysis on efficiency maximization of the proposed scheme.

The rest of the paper is organized as follows. In Section II, the system structure of the proposed scheme is provided. The issues on security and error-tolerance are discussed in Section III. Theoretical performance analysis is presented in Section IV. Numerical evaluation is conducted in Section V and we conclude in Section VI.

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II. SYSTEM STRUCTURE OF THE PROPOSED SCHEME

The main idea of the newly proposed scheme, which distinguishes itself from MDFH [3]–[6], is that part of the information bits are used to select the idle subcarriers instead of active subcarriers. The active subcarriers carry ordinary bits as usual, while for the idle ones, we actually transmit the carrier bits without power consumption. Moreover, we can implement it through the OFDM framework to achieve a higher spectral efficiency.

A. Transmitter Design

Let N_c be the total number of available subcarriers, with $\{f_0, f_1, ..., f_{N_c-1}\}$ being the set of all available subcarrier frequencies. Here we assume N_c is exactly a power of 2 for the convenience of OFDM implementation. Subcarrier grouping is allowed for design flexibility and efficiency maximization, which will be discussed later. The number of groups, N_g, can also only be a power of 2 and no more than $\frac{N_c}{2}$. In each group, there is only one idle subcarrier and the rest will carry regular symbols as usual. The number of subcarriers in each group would be $N_f = \frac{N_c}{N_g}$, and therefore the number of bits required to specify an idle subcarrier in a group is $B_c = \log_2 N_f = \log_2 \frac{N_c}{N_g}$. We name the bits used to specify idle subcarriers as carrier bits, and then the total number of carrier bits to determine idle subcarriers in all groups would be $N_g B_c = N_g \log_2 \frac{N_c}{N_g}$.

Let Ω be the selected constellation that contains M symbols, and each symbol in the constellation represents $B_s = \log_2 M$ bits. We name the bits carried in regular symbols as ordinary bits, and the total number of ordinary bits carried on all the active subcarriers is $(N_c - N_g)B_s = (N_c - N_g)\log_2 M$.

We divide the data stream into blocks of length $L = N_g B_c + (N_c - N_g)B_s$. Each block is partitioned into N_g groups and each group contains $B_c + (N_f - 1)B_s$ bits. The information block structure is shown in Fig. 1. We will transmit the entire block I_n, which contains L bits, in one single OFDM symbol period.

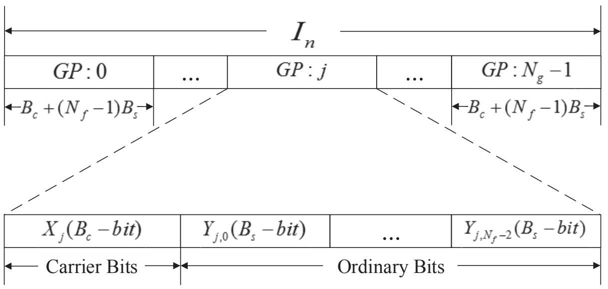

Fig. 1. Information Block Structure for the Proposed Scheme.

Before introducing the transmitter structure, we discuss subcarrier grouping first. Subcarrier grouping can either be fixed or dynamic. As will be discussed in Section III-A, dynamic grouping with secure subcarrier assignment can enhance the security of the scheme. Suppose that after grouping, subcarrier i will be numbered as the kth subcarrier in the jth group, written as $i = G_{j,k}$, for $i = 0, 1, ..., N_c - 1$, $j = 0, 1, ..., N_g - 1$, $k = 0, 1, ..., N_f - 1$. If the subcarrier grouping is a direct segmentation of $\{0, 1, ..., N_c - 1\}$ and keeps fixed, we get $G_{j,k} = jN_f + k$. If dynamic subcarrier grouping is required, $G_{j,k}$ can be obtained by performing a subcarrier assignment algorithm, as will be illustrated in Section III-A.

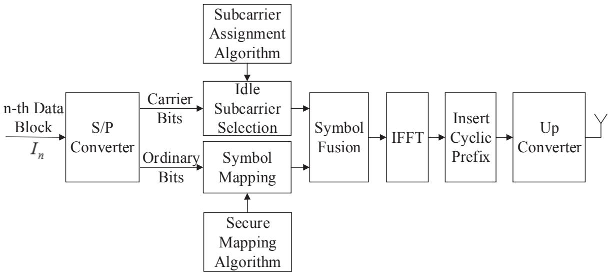

Fig. 2. Transmitter Structure.

The transmitter structure is illustrated in Fig. 2. According to the information block structure, the Serial-to-Parallel (SP) converter fetches carrier bits and ordinary bits from the information block. The carrier bits are used to determine the idle subcarrier in each subcarrier group. The index of idle subcarrier in the jth group can be calculated by converting the carrier bit vector into a decimal value, i.e.,

$$k_j = bin2dec(X_j), \quad j = 0, 1, ..., N_g - 1, \tag{1}$$

where X_j is the carrier bit vector for the idle subcarrier in the jth group. The ordinary bits are mapped to symbols which are carried by the active subcarriers. Usually the mapping table is fixed; however, as will be seen in Section III-B, if we introduce dynamic and secret mapping, the transmitted messages would become invisible to any eavesdroppers.

Once the idle subcarriers and regular symbols are determined, we transmit the carrier bits and ordinary bits using the OFDM framework [2]. The key step is to perform symbol fusion and it works in the following way: for each subcarrier, assign a zero symbol if it is idle; otherwise assign a regular symbol we obtained earlier. For $i = 0, 1, ..., N_c - 1$, the symbol corresponding to subcarrier i is

$$d_i = d_{G_{j,k}} = \begin{cases} \mathcal{M}(Y_{j,k}), & k < k_j, \\ \mathcal{M}(Y_{j,k-1}), & k > k_j, \\ 0, & k = k_j, \end{cases} \tag{2}$$

where $\mathcal{M}(Y_{j,k})$ and $\mathcal{M}(Y_{j,k-1})$ are symbols mapped from the ordinary bit vectors $Y_{j,k}$ and $Y_{j,k-1}$, respectively. The nth OFDM symbol corresponding to I_n can then be written as [2]

$$s_n(t) = \sum_{i=0}^{N_c-1} d_{n,i} e^{j2\pi f_i t}, \quad t \in [nT_s, (n+1)T_s), \tag{3}$$

where $f_i = \frac{i}{T_s}$ and T_s is the OFDM symbol period. Note that the subscript n is added in $d_{n,i}$ to indicate that $d_{n,i}$ corresponds to the nth information block I_n.

The sampled version of (3) corresponds to the IFFT block. To eliminate Inter-Symbol Interference (ISI) and Inter-Carrier

Interference (ICI) caused by multipath signals, a guard time with Cyclic Prefix (CP) is inserted before up-conversion and signal emission.

B. Receiver Design

The receiver structure is shown in Fig. 3. The nth received OFDM symbol can be written as

$$r_n(t) = s_n(t) * h(t) + n(t), \tag{4}$$

where $*$ stands for convolution, $h(t)$ is the channel impulse response, and $n(t)$ denotes additive white Gaussian noise (AWGN). Sample the OFDM symbol and remove the cyclic prefix, we get

$$r_{n,l} = r_n(t_l), \quad t_l = nT_s + l\frac{T_s}{N_c}, \quad l = 0, 1, ..., N_c - 1. \tag{5}$$

Performing FFT, we have

$$R_{n,i} = \sum_{l=0}^{N_c-1} r_{n,l} e^{-j2\pi f_i t_l}, \quad i = 0, 1, ..., N_c - 1. \tag{6}$$

Let $\mathbf{H} = [H(0), ..., H(N_c - 1)]$ be the frequency domain channel impulse response vector. After channel estimation, the nth symbol for the ith subcarrier can be estimated as

$$\hat{d}_{n,i} = \frac{R_{n,i}}{H(i)}. \tag{7}$$

Without loss of generality, the subindex n in $\hat{d}_{n,i}$ is omitted in the following discussions.

Next we conduct symbol defusion to recover the carrier bits and the ordinary bits. For each subcarrier group, detect the idle subcarrier by finding the symbol with minimum power, i.e.,

$$\hat{k}_j = \underset{0 \leq k \leq N_f - 1}{\arg\min} \; |\hat{d}_{G_{j,k}}|^2, \tag{8}$$

where $\hat{k}_j$ is the estimated index of the idle subcarrier in the jth group and $G_{j,k}$ can be obtained in the same way as in the transmitter. Note that the subcarrier grouping information is shared between the transmitter and receiver. Now the carrier bit vectors can be estimated as

$$\hat{X}_j = dec2bin(\hat{k}_j), \qquad j = 0, 1, ..., N_g - 1. \tag{9}$$

After the idle subcarriers are determined, ordinary bit vectors can be estimated as

$$\begin{cases} \hat{Y}_{j,k} &= \mathcal{M}^{-1}(\hat{d}_{G_{j,k}}), \quad k < \hat{k}_j, \\ \hat{Y}_{j,k-1} &= \mathcal{M}^{-1}(\hat{d}_{G_{j,k}}), \quad k > \hat{k}_j, \end{cases} \tag{10}$$

where $\mathcal{M}^{-1}(\cdot)$ represents the demapping operator, $\hat{Y}_{j,k}$ and $\hat{Y}_{j,k-1}$ are the recovered ordinary bit vectors. Hence, the entire block $\hat{I}_n$ is recovered.

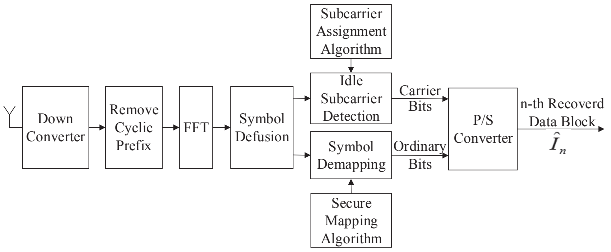

Fig. 3. Receiver Structure.

C. Further Discussions

Due to the introduction of message-driven idle subcarriers, the newly proposed scheme has the following features:

1) Using idle subcarriers to transmit part of the information bits, the system has a chance to achieve a higher efficiency, i.e., transmitting more bits with less power consumption. As will be illustrated in Section IV-A, subcarrier grouping provides the design flexibility to maximize its efficiency, which challenges the most efficient system we believe so far, OFDM.

2) This scheme can directly employ the OFDM framework, which ensures easy implementation and smooth upgrade of existing OFDM systems. The existence of idle subcarriers can also decrease possible inter-carrier interference between their neighboring subcarriers.

3) From the security perspective, we can increase its anti-interception ability by introducing dynamic and secure subcarrier grouping as well as symbol mapping through secure subcarrier assignment and symbol mapping algorithms.

4) We introduce our system assuming one user only; however, it can be easily extended to multi-user applications by assigning one or multiple groups to each individual user. The users can obtain different transmission rates, depending on the number of subcarrier groups they can occupy.

III. SECURITY AND ERROR-TOLERANCE REINFORCEMENT

Under the current scheme, we need to assume that the opponents can perform OFDM demodulation to access information on all the subcarriers. As a result, fixed subcarrier assignment and symbol mapping make the system fragile to eavesdropping. Moreover, an error in idle subcarrier detection may crash the information recovery in the whole subcarrier group, since the ordinary bits carried by active subcarriers may not be recovered in the correct order. In this section, we try to address the security and error-tolerance issues.

A. Secure Subcarrier Assignment

As mentioned earlier, the proposed message-driven scheme itself requires subcarrier grouping. From the security perspective, we need to perform dynamic and secret subcarrier grouping. Basically, we have the following requirements on the subcarrier grouping strategy:

1) All available subcarriers should be involved, and there are no frequency overlaps in any grouping period;

2) The secure grouping information is shared only by the authorized transmitter and receiver, and should be secure under all known attacks;

3) The implementation cost should be low enough to allow frequent subcarrier regrouping.

A secure subcarrier assignment algorithm was proposed in [8] to avoid frequency collisions in OFDM-based FH systems. Its security is guaranteed by the Advanced Encryption Standard (AES), which has been proven to be immune to all known attacks. This algorithm was originally designed to assign subcarriers randomly to different users in multi-user FH systems. We find that it meets all the aforementioned requirements. The core part of the secure subcarrier assignment is a secure permutation algorithm. The detailed procedure of this algorithm is omitted here, please refer to [8]. However, to make it concrete, we would like to illustrate what we can finally obtain from the algorithm through the following simple example.

Example 1: Assume that the total number of available subcarriers is N_c = 8, and they are supposed to equally divided into M = 2 groups. The algorithm actually performs a secret and random permutation among the subcarrier indexes $\{0, 1, 2, 3, 4, 5, 6, 7\}$. Suppose we get the final permutation as $\{3, 7, 0, 4, 2, 5, 6, 1\}$. In this case, the subcarrier groups are $\{3, 7, 0, 4\}$ and $\{2, 5, 6, 1\}$, respectively. For instance, for the first group, if the specified idle subcarrier index is 1 (note that we start from 0), then subcarrier 7 will be the one unused and the rest $\{3, 0, 4\}$ will work as active subcarriers.

Secure subcarrier assignment can effectively prevent the eavesdroppers from recovering the carrier bits, even if they successfully locate the idle subcarriers. Regarding the ordinary bits, they can recover bits from the symbols, but cannot sort them in the correct order without knowing the grouping information.

B. Secure Symbol Mapping

Though not in the correct order, the ordinary bits recovered by eavesdroppers can still be properly sorted by an aggressive attacker, e.g., by exploiting the information relevance or redundancy. This motivates us to develop a secure symbol mapping algorithm to completely hide the ordinary bits at minimum cost.

To secure the mapping operation, we can simply make the constant mapping table dynamic and secret. As shown in Fig. 4, for a constellation of size M, keeping a fixed-order symbol list $\mathcal{D} = \{d_0, d_1, ..., d_{M-1}\}$, we randomly and secretly adjust the corresponding bit vectors of these symbols. More specifically, define $\mathcal{A} = \{0, 1, ..., M-1\}$, and denote the secure permutation operation as $\mathcal{P} : \mathcal{A} \rightarrow \mathcal{A}$. Then for any $l \in \mathcal{A}$, the bit vector obtained from $dec2bin(\mathcal{P}(l))$ is mapped to symbol d_l. The demapping operation can be performed accordingly.

For the implementation of the secure symbol mapping, note that typically $M <= N_c$, so we do not need to generate new AES-encrypted permutations, but can derive permutations of $\{0, 1, ..., M-1\}$ simply by sorting the elements in the order of their appearances in permutations of $\{0, 1, ..., N_c - 1\}$, which have already been generated in secure subcarrier assignment.

In this way, a secure symbol mapping is implemented at little extra cost except maintaining a dynamic mapping table. Note that this approach prevents us from constantly employing the best mapping table, in which closer symbols are always mapped to closer bit vectors. Here symbol closeness means shorter distances in constellation and bit vector closeness corresponds to smaller Hamming distances.

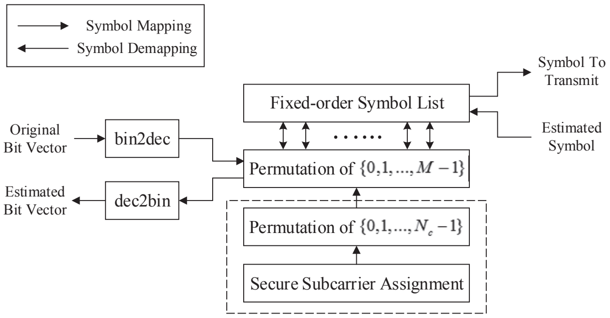

Fig. 4. Secure Symbol Mapping and Demapping.

C. Bit Vector Rearrangement

One possible issue with the proposed scheme is that: under low SNRs, an error in idle subcarrier detection may occur and lead to bit vector disorder in the whole subcarrier group, even if each symbol is recovered correctly from its corresponding subcarrier. To solve this problem, we develop a bit vector rearrangement (BVR) algorithm, which is illustrated in Table I and Fig. 5. Note that each information block contains N_g groups, and BVR is performed group by group rather than block by block.

TABLE I
THE BIT VECTOR REARRANGEMENT (BVR) ALGORITHM.

Rearrangement in the transmitter:

1) Fetch $B_c + N_f B_s$ bits and determine the idle subcarrier in the current group using the first B_c bits;
2) Evacuate the B_s bits at the location of the idle subcarrier and place them at the beginning of next group;
3) Transmit the remaining $(N_f - 1)B_s$ ordinary bits on the active subcarriers of the current group;
4) Repeat the above procedures till the end of the bit stream.

Restoration in the receiver:

1) Recover both the carrier bits and ordinary bits from the current group;
2) Reserve a B_s-bit space at the location of the idle subcarrier according to the carrier bit vector in the current group;
3) Recover the next bit group and fill its first B_s bits into the reserved space in the current one;
4) Make the new group the current one and repeat from 2).

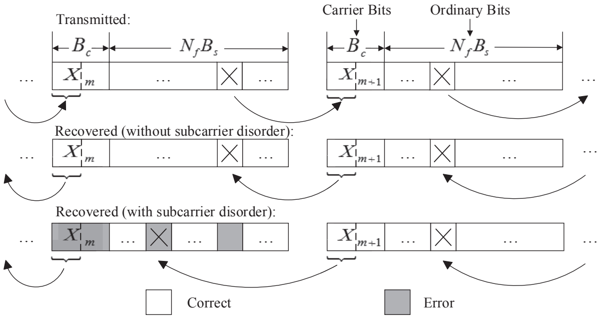

Fig. 5. Illustration of The Bit Vector Rearrangement (BVR) Algorithm.

BVR is designed to keep the order of most ordinary bits from being influenced by an error in idle subcarrier detection. Note that the evacuated B_s bits in the current group will be placed at the beginning of the next one and form a carrier bit vector together with the successive $B_c - B_s$ bits. On the receiver side, each group removes its first B_s bits and fills them into the previous group, simultaneously acquiring B_s bits from the next group. As a result, the length of each group remains unchanged as $B_c + (N_f - 1)B_s$ bits. Unlike channel coding, no redundancy is introduced here, so no spectral efficiency is sacrificed.

As shown in Fig. 5, with BVR, if an error in idle subcarrier detection occurs, only one[1] of the ordinary bit vectors in the group will be influenced, but the remaining would not. This contributes a lot to save the ordinary bits under possible idle subcarrier detection errors, especially when the group size is large. In the worst case, if the carrier bits of the current group is corrupted, the first B_s bits of the next group will be placed at a wrong location. As a result, it will also lead to errors, even if they themselves are correctly recovered. However, when the group size is relatively large, the impact is insignificant comparing with the saved ordinary bits. In the case of a small group size N_f = 2, this approach is not recommended since no ordinary bits can be saved. BVR is designed to enable the proposed scheme to work in the worst case (i.e., at low SNRs), but we would like to emphasize that idle subcarrier detection errors are very unlikely to occur at reasonable or high SNRs.

IV. PERFORMANCE ANALYSIS

In this section, we evaluate the performance of the proposed scheme and compare it to that of OFDM.

A. *Spectral Efficiency*

The spectral efficiency η is defined as the ratio of the information bit rate R_b (bits/s) to the transmission bandwidth W (Hz), i.e., $\eta = \frac{R_b}{W}$ (bits/s/Hz). Since the proposed scheme is implemented on the OFDM framework, both OFDM and the proposed scheme have the same total bandwidth $W = (N_c + 1)R_s$, where R_s is the OFDM symbol rate.

Considering both the carrier bits and the ordinary bits, the bit rate of the proposed scheme can be calculated as

$$R_{b,P} = R_s[N_g \log_2 \frac{N_c}{N_g} + (N_c - N_g)\log_2 M]. \tag{11}$$

To maximize the bit rate, we differentiate (11) over N_g,

$$\frac{dR_{b,P}}{dN_g} = R_s \log_2 \frac{N_c}{N_g M e}, \tag{12}$$

where e is the Euler's number. Set (12) to zero, we get $N_g^* = \frac{N_c}{Me}$. Unfortunately, N_g can only be a power of 2, so we select two candidates nearest to N_g^*: $N_{g,1}^* = \frac{N_c}{2M}$ and $N_{g,2}^* = \frac{N_c}{4M}$. Substituting them into (11), we obtain exactly the same value, which forms the maximum bit rate for the proposed scheme,

$$R_{b,P}^* = R_s N_c[\log_2 M + \frac{1}{2M}]. \tag{13}$$

It then follows that the maximum spectral efficiency of the proposed scheme is given by

$$\eta_P^* = \frac{N_c}{N_c+1}[\log_2 M + \frac{1}{2M}] \approx \log_2 M + \frac{1}{2M}. \tag{14}$$

The bit rate and spectral efficiency of OFDM are respectively represented in (15) and (16),

$$R_{b,OFDM} = R_s N_c \log_2 M, \tag{15}$$

$$\eta_{OFDM} = \frac{N_c}{N_c+1}\log_2 M \approx \log_2 M. \tag{16}$$

Comparing (14) with (16), obviously the proposed scheme has a higher efficiency than OFDM, and it is increased by

$$\Delta\eta \approx \frac{1}{2M}. \tag{17}$$

According to (17), compared with OFDM, the improvement achieved by the proposed scheme in efficiency only depends on the constellation size M, and it would be as high as 25% with M = 2. To be concrete, we offer the following example.

Example 2: Assume that the total number of available subcarriers is N_c = 64 and the constellation size is M = 4. For the proposed scheme, $N_{g,1}^*$ = 8 and $N_{g,2}^*$ = 4, which both lead to the maximum bit rate $R_{b,P}^* = 136R_s$ and spectral efficiency $\eta_P^* \approx 2.125$; while for OFDM, the bit rate $R_{b,OFDM} = 128R_s$ and spectral efficiency η_{OFDM} = 2. Consequently the bit rate and spectral efficiency are increased by $8R_s$ and 6.25%, respectively.

B. *Bit Error Rate and Capacity*

As will be shown in the numerical results, the proposed scheme has a slightly worse BER performance than OFDM. This is because that the modulation of the carrier bits is actually FSK, which is known to be worse in BER performance than PSK or QAM. It should be noted that the spectral efficiency only considers nominal bit rates, without excluding the corrupted bits. The capacity of a system, however, evaluates the number of bits that are correctly transmitted per second. A more complete theoretical analysis of BER and capacity is left for future work. Here we simply try to demonstrate when the proposed scheme will outperform OFDM in terms of capacity, i.e., the number of correctly transmitted bits per second.

The capacity of the proposed scheme can be estimated as

$$C_P = R_{b,P}^*(1 - P_{e,P}), \tag{18}$$

where $P_{e,P}$ is the BER of the proposed scheme. Likewise, the capacity of OFDM is

$$C_{OFDM} = R_{b,OFDM}(1 - P_{e,OFDM}), \tag{19}$$

where $P_{e,OFDM}$ is the BER of OFDM. A sufficient while not necessary condition for $C_P > C_{OFDM}$ is

$$P_{e,P} < \lambda_{TH} \triangleq 1 - \frac{R_{b,OFDM}}{R_{b,P}^*}. \tag{20}$$

This means any SNRs which guarantee (20) will make the proposed scheme preferable to OFDM in capacity. Actually (20) can be easily satisfied, because λ_{TH} is at the level of 10^{-2} or even higher for a typical $R_{b,P}^*$ and $R_{b,OFDM}$.

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[1] Note that in Fig. 5, only the middle shaded box is counted as ordinary bit errors, while the other two shaded ones are counted as carrier bit errors.

V. NUMERICAL RESULTS

In this section, the performance of the proposed scheme under AWGN channels is evaluated and compared with that of OFDM. For the following evaluation, we assume $N_c = 64$, $N_g = N^*_{g,2} = 4$ and $R_s = 100$. Except for the spectral efficiency part, we employ QPSK modulation with a constellation of size $M = 4$ for both OFDM and the proposed scheme.

1) Spectral Efficiency: Based on the theoretical analysis, the spectral efficiency of OFDM and the proposed scheme is numerically shown in Table II for different constellation size M. The proposed scheme, with maximized efficiency, is always more efficient than OFDM, while the efficiency gap decreases with an increase on the constellation size.

TABLE II
COMPARISON OF SPECTRAL EFFICIENCY WITH DIFFERENT M.

Constellation Size(M)	2	4	8	16
OFDM(bits/s/Hz)	1	2	3	4
Proposed(bits/s/Hz)	1.25	2.125	3.0625	4.03125

2) Bit Error Rate: The BER performance of OFDM and the proposed scheme (with and without BVR) is presented in Fig. 6. The BER performance of the proposed scheme is slightly worse than OFDM, because the modulation of the carrier bits is actually FSK which is not so good as PSK modulation. We can also see that, compared with the version without BVR, the proposed scheme with BVR has a better performance which is even closer to that of OFDM.

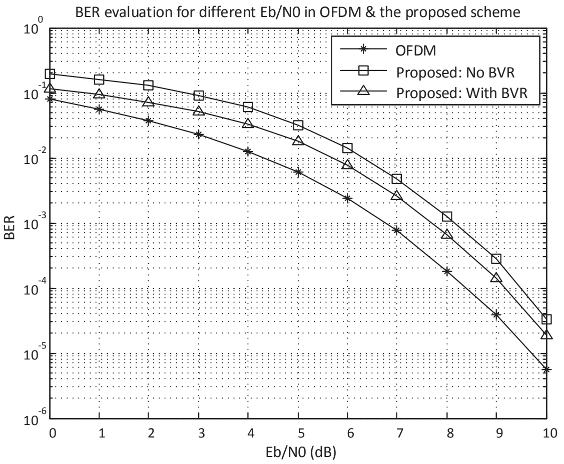

Fig. 6. Bit Error Rates for OFDM and the proposed scheme.

3) Capacity: Considering capacity, we would like to compare the number of correctly transmitted bits per second. Fig. 7 shows the capacity of OFDM and the proposed shceme using the same bandwidth. It can be seen that the proposed scheme would be more superior at high SNRs. Moreover, BVR contributes much in saving ordinary bits from disorder at low SNRs. If a larger constellation size is used (not shown in the figure), the same result holds except that the SNR threshold which guarantees the superiority of the proposed scheme will be relatively higher.

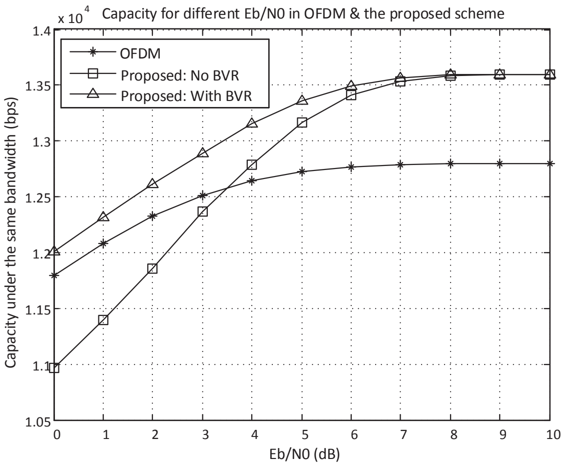

Fig. 7. Capacity for OFDM and the proposed scheme.

VI. CONCLUSIONS

In this paper, we proposed a highly efficient multi-carrier transmission scheme, which leaves one idle subcarrier in each group to be specified by the carrier bits, but transmits ordinary bits regularly on all the other subcarriers. This scheme imposes no extra cost on bandwidth but resulting in both efficiency increase and power saving. We enhance its security and error-tolerance using secure subcarrier assignment, secure symbol mapping and bit vector rearrangement. Both theoretical analysis and numerical results demonstrate that, in spite of a slightly worse BER performance, the proposed scheme has a higher spectral efficiency, which makes it outperform OFDM in terms of capacity.

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