A Low PAPR Subcarrier Hopping Multiple Access with Coded OFDM for Low Latency Wireless Networks

Yuta Hori and Hideki Ochiai
Department of Electrical and Computer Engineering, Yokohama National University
79-5 Tokiwadai, Hodogaya, Yokohama, Kanagawa 240-8501, Japan
Email: yuta.hori.jp@ieee.org, hideki@ynu.ac.jp

Abstract—This paper proposes a new physical layer architecture for uplink multiple access based on orthogonal frequency division multiplexing (OFDM). It achieves low peak-to-average power ratio (PAPR) and high reliability with low computational complexity at both the transmitter and receiver, targeting low-latency communications such as transmission of control information in machine-to-machine (M2M) and device-to-device (D2D) communications. Our approach is based on the judicious combination of subcarrier hopping and super-orthogonal convolutional codes (SOCC) for achieving high coding gain and frequency diversity, together with Golay complementary sequences for low PAPR signaling. By introducing non-orthogonal multiple access where the subcarriers of different users are partially overlapped, the overall bandwidth efficiency can be improved. Furthermore, the low PAPR nature improves the power efficiency and thus enhances the transmission range. Employing the successive interference cancellation at the receiver further mitigates the resulting multiple access interference.

I. INTRODUCTION

Due to an increasing demand for machine-to-machine (M2M) and device-to-device (D2D) communications, reliable control of machines and devices through wireless channels has gained significant interest. In particular, motion control of machines often requires highly reliable real-time remote control, which is challenging for current wireless communications technology. Achieving low latency without sacrificing reliability is of utmost importance for such applications.

In this paper, we address a new physical layer architecture that enables low complexity and high reliability wireless access based on orthogonal frequency-division multiplexing (OFDM) and robust channel coding. OFDM-based multiple access systems have found their applications in many wireless broadband communication systems due to their robustness against frequency-selective fading channels as well as their high bandwidth efficiency. However, OFDM has the well-known major drawback that its signal has high peak-to-average power ratio (PAPR), which forces a power amplifiers (PA) to be operated with a large back-off, resulting in a significant loss of supplied direct-current (DC) power [1], [2]. Consequently, the PA efficiency of the communication devices becomes low and the battery power consumption significantly increases. Due to this problem, OFDM-based modulation has not been considered suitable for the uplink of multi-user communications where most user terminals are assumed to be battery driven. In fact, many existing low-cost wireless systems such as sensor networks thus employ offset QPSK and FSK whose signals have constant envelope. However, these modulation schemes have major drawbacks that their bandwidth efficiency is low and they have difficulty in coping with frequency-selective fading channels associated with high data rate transmission.

In our previous work, we have proposed a novel multiple access system with OFDM modulation for the uplink which enables low complexity implementation [3]. It combines the super-orthogonal convolutional codes (SOCC) [4]–[6], Golay complementary sequence [7], and OFDM through differential encoding and differential detection. The SOCC generally has very low coding rate but has a powerful error correcting capability with simple decoder structure based on Viterbi algorithm, and the latter has a salient advantage in error rate performances at low SNR with low latency compared to capacity achieving channel codes. Moreover, the application of Golay complementary sequences to OFDM modulation results in the signal with PAPR as low as 3 dB [8], which enhances the power amplifier efficiency and thus improves the coverage of the transmitter. Similar to conventional OFDM systems, the proposed system utilizes a cyclic prefix (CP) to combat the inter-symbol interference (ISI) caused by frequency selectivity of wireless channels, which eliminates the necessity of complicated equalizer at the receiver. Furthermore, differential encoding and differential detection can make the receiver simpler, since the channel estimation is not required at the receiver side. However, the diversity order achieved in this system is limited to the length of Golay sequence over static fading channels even if the channel is multi-path rich.

In this paper, we propose a new uplink multiple access system where subcarrier hopping is applied to our previous system [3] in order to fully exploit the diversity gain provided by the multi-path rich channel with particular emphasis on low complexity receiver, targeting low latency communications of control information. Our system also allows the subcarriers of different users to be overlapped such that the spectral efficiency of multi-access channel is improved. Moreover, by employing successive interference cancellation (SIC) at the channel decoder, the multiple access interference (MAI) is significantly suppressed with low complexity, thus leading to
higher performance without sacrificing additional bandwidth.

II. SYSTEM MODEL

We consider an uplink scenario where multiple devices and machines send their signals to a single receiver. We assume that the users are transmitting their signals in a quasi-synchronous manner such that interference among users on different channels (i.e., different subcarriers of the same OFDM symbol) is negligible. The key techniques of the proposed system in this paper are the SOCC with Golay sequence, and subcarrier hopping with OFDM, which we review in what follows.

A. SOCC with Golay Sequence

The SOCC is a class of low-rate convolutional codes whose output is an orthogonal sequence. As shown in Fig. 1, the output of the encoder with constraint length $K$ is determined by current input bit and previous $K-1$ bits. The SOCC encoder uses the middle $K-2$ bits to select an orthogonal sequence of length $2^{K-2}$ and the outer two bits determine its polarity by an XOR operation. Therefore, the rate of this code is $R_c = 1/2^{K-2}$. In the original SOCC, a Walsh-Hadamard (WH) sequence is used as an orthogonal sequence. A set of WH sequences can be recursively obtained by [9]

$$H^{W}_{2N} = \begin{bmatrix} H^{W}_{N} & H^{W}_{N} \\ H^{W}_{N} & -H^{W}_{N} \end{bmatrix}, \quad H^{W}_{2} = \begin{bmatrix} + & + \\ + & - \end{bmatrix}, \quad (1)$$

where each row of the square matrix $H^{W}_{N}$ forms a sequence of length $N$, which is orthogonal to the other rows.

In this paper, we use a set of Golay complementary sequences instead of that of WH sequences as the SOCC encoder outputs. It has been well known that an OFDM signal whose subcarriers are constructed with BPSK symbols associated with Golay sequences has a PAPR as low as 3 dB [8]. Exploiting this property, several coding schemes for OFDM systems have been proposed [10]–[12]. In a similar manner to the case of WH sequences, a set of Golay sequences can be obtained by

$$H^{G}_{2N} = \begin{bmatrix} H^{G}_{N} & H^{G}_{N} \\ H^{G}_{N} & -H^{G}_{N} \end{bmatrix}, \quad H^{G}_{2} = \begin{bmatrix} + & + \\ + & - \end{bmatrix}, \quad (2)$$

where the matrix $\tilde{H}^{G}_{N}$ denotes the variant of $H^{G}_{N}$ with its right half columns reversed. For example, if $H^{G}_{N} = [A \ B]$ where $A$ and $B$ are corresponding matrices of size $N \times N/2$, then $H^{G}_{N} = [A \ B]$. From (1) and (2), we can obtain the Golay square matrix by applying bit inversion to the specific columns of the WH square matrix. Therefore, the SOCC employing Golay sequences as its outputs has the same distance spectrum (or transfer function) as that with WH sequences, and the minimum free distance $d_f$ of the code is given by [13]

$$d_f = 2^{K-3}(K+2). \quad (3)$$

It is obvious from this fact that applying Golay sequences to the SOCC does not affect the performance of the code.

The output of the SOCC encoder of length $N_a = 2^{K-2}$ is mapped onto BPSK constellation with unit average power and then allocated to equally spaced $N_a$ subcarriers in an $N_s$-subcarrier OFDM symbol. Note that equal spacing of subcarriers guarantees that the resulting OFDM signal has a 3 dB PAPR. Therefore, the maximum spacing among modulated subcarriers is $T = N_s/N_a$ which is equal to the maximum number of active users when we do not allow multiple users to share any subcarrier so as to avoid MAI.

To see how much PA efficiency improvement one can expect by this approach, Fig. 2 compares the theoretically achievable PA efficiency of class A amplifier assuming a typical solid-state power amplifier (SSPA) model between the conventional and the proposed OFDM systems for a given acceptable distortion level, i.e., signal-to-distortion power ratio (SDR). (See [14] for more details with the calculation. Note that the maximum efficiency of class A PA is 50%.) It is observed that significant efficiency improvement, which is more than twice, is achieved by this approach as long as target SDR is above 20 dB.

Since the conventional soft-decision Viterbi decoder can be used for decoding of the SOCC, we can implement the receiver with low complexity (or low latency). Moreover, considering the fact that the Viterbi decoder has been already implemented in many recent wireless communication systems, the receiver
of our proposed system can be implemented at low cost by exploiting the existing communication devices.

B. Subcarrier Allocation in OFDM Symbol with Subcarrier Hopping

We assume that the channel is static at least over $M$ OFDM symbols which consist of a single codeword. For such static channels, if the set of the subcarriers that are allocated to each user for all OFDM symbols remains the same, such as conventional orthogonal frequency-division multiple access (OFDMA) [15], [16] or interleaved frequency-division multiple access (IFDMA) [17], it fails to achieve sufficient frequency diversity gain even if the channel is multipath rich. In order to efficiently exploit the diversity gain provided by such channels, the subcarriers allocated to each user should be altered for each OFDM symbol within the transmission of $M$ OFDM symbols. Therefore, we propose a subcarrier hopping approach in this work.

Let $N_i^{(m)} = \{ k_{i,n}^{(m)} : n = 1, 2, \ldots, N_{a}\}$ denote the set of subcarrier indices which are allocated to the $i$th user in the $m$th OFDM symbol, where $k_{i,n}^{(m)}$ is the subcarrier index on which the BPSK symbol corresponding to the $n$th bit of the $i$th user’s SOCC encoder output (of length $N_{a}$) is mapped. In the conventional OFDMA system, since users have the same set of subcarriers for all OFDM symbols, $N_i^{(m)}$ is invariant for any OFDM symbol index $m$. On the other hand, in the proposed system, $N_i^{(m)}$ varies by each OFDM symbol transmission. Specifically, the initial subcarrier index $k_{i,1}^{(m)}$ is chosen randomly from the set $\{1, 2, \ldots, T\}$ and the remaining subcarrier indices are separated by the interval $T$ to guarantee transmitted OFDM signals to have low PAPR, i.e.,

$$k_{i,n}^{(m)} = k_{i,1}^{(m)} + (n - 1)T \quad \text{for } n = 2, 3, \ldots, N_{a}.$$ 

We consider the scenario where $N_{a}$ active users share $N_{a}$ subcarriers in each OFDM symbol with each user selecting its own set of $N_{a} = 2^{K-2}$ subcarriers. A cyclic prefix (CP) is added to each OFDM symbol, and we assume that the length of CP is long enough such that the effect of the ISI associated with the delay spread of the channel is negligible. Let $S_k^{(m)}$ denote the number of users simultaneously utilizing the $k$th subcarrier of the $m$th OFDM symbol. In the case of $S_k^{(m)} = 1$ for any $1 \leq k \leq N_{a}$ and $1 \leq m \leq M$ (i.e., no MAI exists), the maximum number of $N_{a}$ is equal to $T = N_{a}/N_{u}$, where all $N_{a}$ subcarriers are allocated to a certain user. This condition could be satisfied easily if each user knows the other users’ set of subcarrier indices $N_i^{(m)}$ perfectly. Since our primary interest is on achievable diversity gain and robustness against MAI in the energy-efficient and low-latency system, we assume for simplicity that all $N_{a}$ users have the same set of subcarriers for all OFDM symbols, i.e., we define

$$N^{(m)} = N_1^{(m)} = N_2^{(m)} = \cdots = N_{N_{a}}^{(m)},$$

where $N^{(m)}$ denotes the set of subcarrier indices to which $N_{a}$ users are allocated, and

$$S_k^{(m)} = \begin{cases} 
N_{a}, & k \in N^{(m)}, \\
0, & k \notin N^{(m)}, 
\end{cases}$$

for any $1 \leq m \leq M$.

III. MULTIUSER DETECTION AND DECODING

The $k$th subcarrier of the $m$th received OFDM symbol that is simultaneously shared by $N_{a}$ users is represented by

$$Y_k^{(m)} = \sum_{i \in \mathcal{U}} H_{i,k} X_{i,k}^{(m)} + N_k^{(m)},$$

where $\mathcal{U} = \{1, 2, \ldots, N_{a}\}$ represents the set of active user indices, $X_{i,k}^{(m)}$ denotes the $i$th user’s transmitted symbol, $N_k^{(m)}$ is a zero-mean complex AWGN term with variance $N_0/2$ per dimension, and $H_{i,k}$ denotes the channel coefficient of the $k$th subcarrier over the $i$th user’s channel. Note that $H_{i,k}$ is invariant for each OFDM symbol transmission since the static frequency-selective fading channel is assumed. We assume that the perfect channel state information (CSI) is available at the receiver side.

For the case of $N_{a} = 1$ where no MAI exists, the received symbol $Y_k^{(m)}$ can be directly used as a metric of the conventional Viterbi decoder designed for fading channels. On the other hand, for the case of $N_{a} \geq 2$ where the symbols of multiple users mutually interfere, multiuser detection and decoding (MUD) is necessary to mitigate or eliminate the MAI. In the following, we will describe two MUD schemes, i.e., super-trellis decoding (STD) which achieves optimum performance but with high complexity, and the decoding based on successive interference cancellation (SIC) which achieves suboptimum performance but with low complexity.

A. Super-Trellis Decoding

It is known that maximum-likelihood sequence estimation (MLSE) which jointly detects all users’ sequences is optimum in terms of error rate performance [18]. STD is an MLSE-based decoding scheme for trellis-based codes such as convolutional codes or turbo codes [19], [20]. Specifically, in STD, Viterbi algorithm performs within a super-trellis which is a single trellis representation composed of all users’ trellises to choose the most likely sequence of all the users.

A major drawback of STD is its computational complexity stemming from the large number of states of the super trellis, which in general exponentially increases with the number of users. In fact, if $N_{a}$ users have the same SOCC encoder with constraint length $K$, the super trellis has $2^{N_{a}(K-1)}$ states.

B. Successive Interference Cancellation

In the proposed SIC-based decoding, we sequentially select the target user to be decoded in the order of the received signal power. We first select the user with the highest channel gain as the target user and perform its decoding. Specifically, the target user is determined by the following rule:

$$u_s = \arg \max_{i \in \mathcal{U}} \sum_{m=1}^{M} \sum_{k \in N_i^{(m)}} |H_{i,k}|^2,$$

where $u_s$ denotes the index of the selected user. We then calculate the bit metrics and decode the signal of the target user. For the target user, the other users’ signals are regarded
as interference. In our decoding algorithm, we assume the sum of the interference and noise terms to be Gaussian, which is represented by
\[ N_k^{(m)} = \sum_{i \in \mathcal{U} \setminus \mathcal{U}_a} H_{i,k} X_{i,k}^{(m)} + N_k^{(m)}, \]
(8)
where \( N_k^{(m)} \) follows the complex Gaussian distribution with zero-mean and variance \((I_k^{(m)} + N_0)/2\), and \( I_k^{(m)} \) is given by
\[ I_k^{(m)} = \sum_{i \in \mathcal{U}_a} |H_{i,k}|^2. \]
(9)
Under this assumption, the bit metrics of \( c_{u,k}^{(m)} \) with perfect CSI can be calculated by
\[ A_{c_{u,k}}^{(m)} = \log f(Y_k^{(m)}|c_{u,k}^{(m)} = b, H_{u,k}) \]
(10)
\[ = \log \frac{1}{\pi(I_k^{(m)} + N_0)} \exp \left( -\frac{|Y_k^{(m)} - H_{u,k}(2b-1)|^2}{I_k^{(m)} + N_0} \right), \]
(11)
where \( f(\cdot) \) denotes the conditional probability density function. After obtaining the estimated symbol of the target user \( \hat{X}_{u,k} \) by Viterbi decoding with the calculated bit metrics, the estimated symbol is subtracted from the received symbol in (6), represented by
\[ Y_k^{(m)} = Y_k^{(m)} - H_{u,k} \hat{X}_{u,k}^{(m)}. \]
(12)
The resulting symbol after interference cancellation is used for decoding of the next candidate user. Note that, before proceeding to the next decoding iteration, we should update \( \mathcal{U} \) by excluding the index of the selected user.

IV. ACHIEVABLE DIVERSITY ORDER ANALYSIS

In this section, we analyze the achievable diversity order for the conventional OFDMA-based system [3] and our proposed system in order to verify that the subcarrier hopping introduced in the proposed system in fact increases the diversity gain.

To simplify our analysis, we assume the non-MAI case (i.e., \( N_a = 1 \)) and the \( L \)-tap equal-power Rayleigh fading channel.

Given the channel coefficient vector \( \mathbf{H} = [H_1, \cdots, H_N] \)
(since we consider the case that only a single user exists, we drop the user index \( i \) from \( H_{i,k} \) for simplicity), conditional pairwise error probability (PEP) associated with the minimum free distance \( d_t \) is given by [21]
\[ PEP(d_t|\mathbf{H}) = Q \left( \sqrt{2\gamma \sum_{k \in \mathcal{K}_e} |H_k|^2} \right), \]
(13)
where \( \gamma = E_s/N_0 \) represents the average SNR, and \( \mathcal{K}_e = \{e_1, \cdots, e_{d_t}\} \) denotes the set of the indices of the subcarriers onto which the erroneous bits are mapped. The Q-function is defined as \( Q(x) = \frac{1}{\sqrt{\pi}} \int_x^\infty \exp \left( -\frac{u^2}{2} \right) du \). It is obvious that \( |\mathcal{K}_e| = d_t \) and \( e_i \in \bigcup_{m=1}^M N^{(m)} \), where \( |S| \) denotes the cardinality of an arbitrary set \( S \). Let \( \mathcal{H} = \{H_{e_1}, \cdots, H_{e_{d_t}}\} \) denote the set of the channel coefficients associated with \( \mathcal{K}_e \).

Given the \( L \)-tap channel impulse response \( \mathbf{h} = [h_1, h_2, \cdots, h_L]^T \) where each element is assumed to be statistically independent and modeled as a zero-mean complex Gaussian random variable with unit variance, the channel coefficient of the \( k \)th subcarrier \( H_k \) is given by
\[ H_k = W_k^H \left( N_{e_k}^{(k)} \right) \mathbf{P} \]
(14)
where \( W_{N_{e_k}}^{(k)} = [1, W_{N_{e_k}}^{(k)}, W_{N_{e_k}}^{(2k)}, \cdots, W_{N_{e_k}}^{(L-k-1)}]^T \) is an \( L \times 1 \) column vector consisting of \( W_{N_{e_k}} \equiv e^{-\gamma 2^{2L}/N_e} \) with the superscript \((-)^H\) indicating a conjugate transpose of given matrices or vectors, and \( \mathbf{P} \) is an \( L \times L \) diagonal matrix with \( p_l \) for \( l = 1, 2, \cdots, L \), on its main diagonal. Each of the \( p_l \) takes a non-negative value and they represent the power delay profile (PDP) of the channel. From (14), it can be obtained that
\[ \sum_{k \in \mathcal{K}_e} |H_k|^2 = \sum_{k \in \mathcal{K}_e} h_k^H \left( \sum_{k \in \mathcal{K}_e} W_{N_{e_k}}^{(k)} W_{N_{e_k}}^{(k)} \right) \mathbf{P} \]
\[ = h_k^H \left( \sum_{k \in \mathcal{K}_e} W_{N_{e_k}}^{(k)} W_{N_{e_k}}^{(k)} \right) \mathbf{P} h_k \]
\[ = h_k^H \mathbf{A} \left( k \right) \mathbf{P} h_k \]
(15)
where \( \mathbf{A} \) and \( \mathbf{A}(k) \) are \( L \times L \) matrices, \( \mathbf{A} = \sum_{k \in \mathcal{K}_e} \mathbf{A}(k) \), and \( \mathbf{A}(k) = W_{N_{e_k}}^{(k)} W_{N_{e_k}}^{(k)} \mathbf{P} \mathbf{A} \). It is well known that the achievable diversity order depends on the rank of the matrix \( \mathbf{A} \), since \( \mathbf{P} \) is a nonsingular matrix. Therefore, the element selection of \( \mathcal{K}_e \) has an important role in characterizing the achievable diversity order of the system. If \( \mathcal{K}_e \) has \( d_t \) distinct elements and the corresponding elements in \( \mathcal{H} \) can be assumed to be statistically independent, the rank of the matrix \( \mathbf{A} \) is \( r = \min(L, d_t) \) [22].

In the conventional OFDMA-based system where the subcarriers allocated to users are invariant over \( M \) OFDM symbols, only \( N_a \) distinct elements are contained in \( \mathcal{K}_e \) as well as in \( \mathcal{H} \). Consequently, if \( N_a < d_t \), the diversity order is limited by \( N_a \) even if the code with larger \( d_t \) is employed and the channel is multipath rich. Moreover, since \( N_a \) is always smaller than \( d_t \) in the case of the SOCC from \( N_a = 2^{L/2} - 1 \) and (3), the rank of the matrix \( \mathbf{A} \) i.e., the achievable diversity order for the conventional system is specified by \( r = \min(L, d_t) \). The validity of this theoretical insight can be verified by the simulation results shown in [3].

On the other hand, \( \mathcal{K}_e \) of the proposed system can include more than \( N_a \) distinct indices due to the subcarrier hopping, which eliminates the \( N_a \) limitation on the achievable diversity order. Therefore, the achievable diversity order of the proposed system can be specified by \( r = \min(L, d_t) \). In order to exploit this advantage provided by subcarrier hopping, the hopping pattern should be designed carefully such that \( \mathcal{K}_e \) has \( d_t \) distinct elements. However, even in the case of random hopping, the probability that the diversity order is limited by \( N_a \) is negligibly small.
Assuming that all elements of $H$ are mutually independent, the maximum diversity order $r = \min(L, d_t)$ would be achieved in the case that $\mathcal{K}_c$ has $d_t$ distinct elements. However, in practice, they are correlated and the correlation becomes dominant as the distance of the subcarriers decreases, thus leading to performance degradation. Therefore, if we employ an appropriately designed hopping pattern such that the $d_t$ elements in $\mathcal{K}_c$ are well separated from each other, the system is expected to achieve the optimum performance with the maximum achievable diversity order.

V. SIMULATION RESULTS AND DISCUSSION

In our simulation, the SOCC with constraint length $K = 4$ is employed together with Golay sequences. Thus, we have $N_a = 4$ and $d_t = 12$. The binary length of codeword and the number of OFDM subcarriers are chosen as 3072 and 256, respectively. We assume the frequency-selective fading channel which has an $L$-tap equal-power delay profile with each tap following a statistically independent zero-mean complex Gaussian distribution (i.e., Rayleigh fading). We also assume the short frame transmission aiming at real-time communication and thus the channel is static over an entire frame consisting of 768 consecutive OFDM symbols. Therefore, the only available diversity is frequency-selectivity. Consequently, time-domain interleaving (which may lead to increasing latency) is not performed in this simulation.

A. Diversity Order Comparison for Single-User Case

In this subsection, we observe the increase of the diversity order due to the subcarrier hopping with the non-MAI case ($N_a = 1$). Figure 3 shows the BER performance of the conventional OFDMA-based system and the proposed system with subcarrier hopping over the channel with $L = 4, 8, 12, 16$ taps. For the conventional system, even if $L$ increases, no improvement is observed. This is because the achievable diversity order of the conventional system is determined by the minimum value between $N_a$ and $L$, and in this case, it is limited by $N_a = 4$. Thus, the increase of channel taps provides no additional diversity gain in the conventional system. On the other hand, it is observed that the BER of the proposed system gradually improves as the number of channel taps $L$ increases due to the subcarrier hopping.

As a reference, we also show the BER performance over an AWGN channel and theoretical lower bound of BER over Rayleigh fading channel under the assumption that the elements of $\mathcal{H}$ should be statistically independent and identically distributed (i.i.d.), which is given by [22], [23]

$$P_b \geq \frac{1}{\pi} \int_0^{\pi/2} \frac{1}{1 + \frac{2 \min(L, d_t)}{L \sin^2 \theta}} \min(L, d_t) \, d\theta. \quad (16)$$

We focus on the performance improvement between the cases of $L = 12$ and $L = 16$. As observed in Section IV, the achievable diversity order of the proposed system is $r = \min(L, d_t)$. Thus, the diversity order is limited by $d_t = 12$ for both the cases of $L = 12, 16$ and further increase of channel taps may not provide any additional diversity gain, even though the BER performance of $L = 16$ is better than that of $L = 12$. This difference stems from the fact that the BER performance in the case of $L = 12$ does not fully obtain the diversity order of $r = 12$ due to the correlation among the channel coefficients. If we employ an appropriately designed hopping scheme such that the fading correlation becomes negligibly small instead of the random hopping used in this simulation, the BER performance is expected to eventually approach the theoretical limit.

B. Performance with MAI

Figure 4 shows the BER performance of our proposed system with $N_a = 1, 2, 3$ active users over the Rayleigh
fading channel with $L = 8$ taps. Note that we consider the scenario that all $N_a$ users share the same set of the subcarriers. Therefore, in all cases except for $N_a = 1$, the MAI is observed among all the subcarriers, and thus the STD or SIC-based decoding will be performed. The performance in Fig. 4 represents average BER performance observed by a single user, i.e., the BER performance of all the users is averaged under the assumption that the decoding priority of each user is determined with equal probability.

In the case of $N_a = 2$, the performance of the SIC-based decoding is superior to that of the conventional OFDMA-based system even with twice the spectral efficiency, and it approaches the performance of the STD within 0.5 dB at the BER of $10^{-3}$. Furthermore, the computational complexity of the SIC-based decoding is much lower than that of the STD. In fact, comparing the numbers of comparison operations per information bit in the entire decoding process required for each decoding scheme, the SIC-based decoding requires only 16 comparison operations whereas the STD requires 192. Similarly, in the case of $N_a = 3$, even though the gap to the STD performance is increased (about 2.1 dB at the BER of $10^{-3}$), the SIC-based decoding shows similar performance to the conventional system in low SNR region. Note that the complexity gap between the SIC-based decoding and the STD is also increased (the SIC-based decoding has 24 comparison operations whereas the STD has 3584) since the complexity of the STD exponentially increases with $N_a$ whereas that of the SIC-based decoding increases linearly with $N_a$. The overall spectral efficiency in this case is three times higher than that with the non-MAI case and the conventional system.

We have observed that the computational complexity of the STD is much higher than that of the SIC-based decoding. However, the STD can be implemented in parallel whereas the SIC-based decoding should be processed in a serial manner, which leads to increasing latency. Therefore, if the latency issue is of primary importance given sufficient computational resources, the STD may be a preferable approach.

VI. CONCLUSION

In this paper, we have proposed a new uplink multiple access scheme based on subcarrier hopped OFDM modulation combined with SOCC and Golay complementary sequences. The SOCC offers an excellent performance in low SNR with low transmitter/receiver complexity, and the use of Golay complementary sequences guarantees low-PAPR OFDM signals. Furthermore, we have shown that the introduction of subcarrier hopping improves an achievable frequency diversity gain and thus is effective for multipath rich environment. By using the decoder based on SIC to mitigate multiple access interference, the proposed system can achieve higher spectral efficiency at the cost of slight performance loss with low complexity.

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