Abstract—We consider a new uplink multiple access system based on orthogonal frequency-division multiplexing (OFDM), subcarrier hopping, and super-orthogonal convolutional codes (SOCC) that can achieve high coding gain and frequency diversity without sacrificing latency. Such a system is of significant importance for future wireless communications targeting motion controls of machines and vehicles. In order to improve the spectral usage, multiple users should share the same subcarriers with multiuser detection and decoding (MUD) at the receiver. In this work, we focus on super-trellis decoding (STD) and successive interference cancellation (SIC) in the framework of our proposed multiple access system. Through the extensive analysis based on simulations, we reveal that 1) properly designed SIC can achieve almost the same performance as the optimum STD with much lower complexity than the STD, and 2) our proposed system with SIC can outperform the conventional orthogonal frequency-division multiple access (OFDMA) with twice as much spectrum efficiency as OFDMA. The major drawback of SIC is its increased latency as the number of the users increases. Therefore, we also propose an alternative multiple access approach based on STD that can achieve optimum performance and low latency.

I. INTRODUCTION

Due to the recent demand for machine-to-machine (M2M) and device-to-device (D2D) communications, a reliable control of machines and devices through wireless channels has gained significant interest. In particular, motion control of vehicles such as unmanned aerial vehicles requires a realization of highly reliable real-time communications. Achieving a good trade-off between reliability and latency is thus of utmost importance for such applications.

In our previous work, we have proposed a new uplink multiple access system that achieves low complexity and high reliability based on orthogonal frequency-division multiplexing (OFDM) with robust channel coding [1]. OFDM has the well-known drawback that its signal has high peak-to-average power ratio (PAPR), which forces a power amplifier (PA) to be operated with a large back-off, resulting in a significant loss of supplied direct-current (DC) power [2], [3]. In order to solve the high PAPR problem, our system combines super-orthogonal convolutional codes (SOCC) [4]–[6] with Golay sequence [7]. The SOCC generally has very low coding rate but has a powerful error correcting capability with simple decoder structure based on Viterbi algorithm, which is a salient advantage in error rate performance at low SNR with low latency compared to capacity achieving channel coding such as low-density parity check (LDPC) code and turbo code. Furthermore, the use of Golay sequence for OFDM modulation results in the signal with PAPR as low as 3 dB [8], which improves the PA efficiency and thus improves the coverage area 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.

In our recent work [9], subcarrier hopping is applied to the multiple access system proposed in [1] in order to fully exploit the frequency diversity gain provided by the multipath channel. It also allows the subcarriers of different users to overlap such that the overall spectrum efficiency of multiple access channel improves, but it causes multiple access interference (MAI) due to the subcarrier collisions among users. Consequently, our system can be considered as a class of non-orthogonal multiple access systems based on subcarrier hopping. In particular, when a group of users employ an identical hopping pattern, their signals perfectly overlap (i.e., perfect non-orthogonality is achieved) whereas their subcarriers could be partially overlapped, if their hopping patterns are not identical (partial non-orthogonality). However, only the perfectly overlapped case is considered in [9] for simplicity of analysis since its main focus was on the increase of diversity gain achieved by the newly introduced subcarrier hopping.

In this paper, we consider a more practical scenario where each user independently determines its hopping pattern in a random manner and thus achieving partial non-orthogonality. In such a scenario, we compare the two commonly adopted multiuser detection and decoding (MUD) approaches, i.e., successive interference cancellation (SIC) and super-trellis decoding (STD), in terms of their error rate performance and decoding complexity. Moreover, we discuss the decoding latency of these approaches and propose an alternative multiple access strategy that enables the use of STD with optimum performance and low decoding latency, which is suitable when the number of users is large.
II. SYSTEM MODEL

We consider an uplink of multiuser communications where multiple terminals transmit their signals to a single receiver. We assume that the users transmit 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 that realize the proposed system are the SOCC with Golay sequence and subcarrier hopping with OFDM, which we brieﬂy review in what follows.

A. SOCC with Golay Sequence

The SOCC is a class of low-rate convolutional codes whose output consists of an orthogonal sequence. Encoder structure of the SOCC is depicted in Fig. 1. The SOCC encoder with constraint length \( K \) assigns the middle \( K - 2 \) bits for selection of 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 [10]

\[
H_{2N}^W = \begin{bmatrix} H_N^W & H_N^W \\ H_N^W & -H_N^W \\ \end{bmatrix}, \quad H_2^W = \begin{bmatrix} + & + \\ + & - \\ \end{bmatrix},
\]

(1)

where each row of the square matrix \( H_N^W \) forms a sequence of length \( N \) which is orthogonal to the other rows.

In order to generate a low PAPR OFDM signal, we use a set of Golay sequences instead of that of WH sequences as the SOCC encoder outputs. It is well known that an OFDM signal with subcarriers constructed with Golay sequences has a PAPR as low as 3 dB [8]. Exploiting this property, several coding schemes for OFDM systems have been proposed [11]–[13]. Similar to the case of WH sequences, a set of orthogonal Golay sequences can be obtained by

\[
H_{2N}^G = \begin{bmatrix} H_N^G & H_N^G \\ H_N^G & -H_N^G \\ \end{bmatrix}, \quad H_2^G = \begin{bmatrix} + & + \\ + & - \\ \end{bmatrix},
\]

(2)

where the matrix \( H_N^G \) denotes the variant of \( H_N^W \) with its right half columns reversed. For example, if \( H_N^G = [A \ B] \) where \( A \) and \( B \) are the corresponding matrices of size \( N \times N/2 \), then \( H_N^G = [A \ -B] \). From (1) and (2), we can identify that the Golay square matrix is obtained by applying bit inversion to the specific columns of the WH square matrix. Consequently, the SOCC employing Golay sequences as its outputs has the same distance spectrum (and transfer function) as that with WH sequences, and its minimum free distance \( d_l \) is given by [14]

\[
d_l = 2^{K-3}(K + 2).
\]

(3)

This fact implies that application of Golay sequences to the SOCC does not affect the performance of the code.

The output of the SOCC encoder of length \( N_u = 2^{K-2} \) is mapped onto BPSK constellation with unit average power and then allocated to equally spaced \( N_u \) subcarriers in an \( N_u \)-subcarrier OFDM symbol. Note that equal spacing of subcarriers guarantees that the resulting OFDM signal has a 3 dB PAPR. In this work, the space among modulated subcarriers is set as the maximum spacing given by \( T = N_u/N_s \) in order to fully achieve the frequency diversity (i.e., eliminate the correlation among modulated subcarriers).

Since the conventional soft-decision Viterbi decoder can be used for decoding of SOCC, we can implement the receiver with low complexity (and 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 Hopping

Since our proposed system aiming at real-time communications based on short-frame transmission, we assume that the channel is static at least over \( M \) OFDM symbols consisting of a single codeword. Over such a static fading channel, if the set of subcarriers allocated to each user remains the same for all OFDM symbols such as conventional orthogonal frequency-division multiple access (OFDMA) [15], [16] or interleaved frequency-division multiple access (IFDMA) [17], it fails to fully achieve frequency diversity gain even if the channel is multipath rich. In order to efﬁciently exploit the diversity gain provided by such channels, the set of subcarriers allocated to each user should be altered for each OFDM symbol within the transmission of \( M \) OFDM symbols. Therefore, our system employs subcarrier hopping approach.

We consider the scenario where \( N_u \) active users share \( N_s \) subcarriers in each OFDM symbol with each user selecting its own set of \( N_u = 2^{K-2} \) subcarriers with the space \( T \). Let \( u \) denote the set of subcarrier indices allocated to the \( i \)th user in the \( nth \) OFDM symbol, where \( k_{i,n}^{(m)} \) is the subcarrier index onto which the BPSK symbol corresponding to the \( i \)th bit of the \( nth \) user’s SOCC encoder output (of length \( N_u \)) is mapped with \( i \in \{1, 2, \cdots, N_u \} \) represents the set of the active user indices. In the conventional OFDMA system, since users utilize the same set of subcarriers over all OFDM symbols, \( u_i \) is invariant for any OFDM symbol index \( m \). On the other hand, in the proposed system, \( u_i^{(m)} \) varies by each OFDM symbol transmission. Specifically, the initial subcarrier index \( k_{i,1}^{(m)} \) is chosen randomly from the set \( \{1, 2, \cdots, T \} \) and
the remaining subcarrier indices are separated by the interval $T$ to guarantee transmitted OFDM signals to have low PAPR, i.e., $k_{i,n} = k_{i,1} + (n - 1)T$ for $n = 2, 3, \ldots, N_u$.

A CP is added to each OFDM symbol, and we assume that the length of CP is long enough such that the effect of ISI associated with delay spread of the channel is negligible. Let $S_k^{(m)} = \{i_1, i_2, \ldots\}$ denote the set of the user indices allocated to the $k$th subcarrier of the $m$th OFDM symbol. For example, in the case of $|S_k^{(m)}| = 1$ for any $1 \leq k \leq N_s$ and $1 \leq m \leq M$ (i.e., no MAI exists) where $|A|$ represents the cardinality of an arbitrary set $A$, the maximum number of $N_a$ is equal to $T = N_s/N_u$ where all $N_s$ subcarriers are allocated to a certain user.

In our recent work [9], in order to analyze the achievable diversity gain provided by the introduction of subcarrier hopping, we have considered a simple scenario where all $N_s$ users share the identical set of subcarriers for all OFDM symbols. Specifically, we have considered the case

$$\mathcal{N}^{(m)} = \mathcal{N}_1^{(m)} = \mathcal{N}_2^{(m)} = \cdots = \mathcal{N}_{N_a}^{(m)},$$

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

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

for any $1 \leq m \leq M$. Note that this scenario can be considered as the worst case in terms of error rate performance since MAI exists in all allocated subcarriers. In practice, however, one may consider the system where all the users’ hopping patterns need not be identical by allowing them to choose their patterns independently, and in such a system some subcarriers may experience collision while the others may not. Therefore, we consider the case that each user’s hopping pattern is determined randomly, independent of the other users’ hopping patterns. Specifically, $\mathcal{N}_i^{(m)}$ is independently and randomly determined for any pair of $i$ and $m$, and thus $S_k^{(m)}$ is also independent for any pair of $k$ and $m$, where $1 \leq i \leq N_s$, $1 \leq k \leq N_a$, and $1 \leq m \leq M$.

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

$$Y_k^{(m)} = \sum_{i \in S_k^{(m)}} H_{i,k} X_i^{(m)} + N_k^{(m)},$$

where $X_i^{(m)}$ 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. We note that in order to achieve real-time communications based on short-frame transmission, channel estimation with reduced overhead (i.e., pilot symbols) is essential. Development of such channel estimation is important, which is left as future work.

In the case of $|S_k^{(m)}| = 1$ for any $1 \leq k \leq N_s$ and $1 \leq m \leq M$ where no MAI exists, the received symbol $Y_k^{(m)}$ can be directly used in a metric calculation for the conventional Viterbi decoder designed for fading channels. On the other hand, in all the other cases 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 representative MUD schemes, i.e., super-trellis decoding (STD) and the decoding based on successive interference cancellation (SIC). The former achieves optimum performance at the cost of high complexity, whereas the latter generally 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 leads to optimum 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 the STD, Viterbi algorithm is performed over a super-trellis which is a single trellis representation composed of all users’ trellises to choose the most likely sequence of all the users. Figure 2(b)

![Fig. 2. Single- and super-trellis representation of SOCC with $K = 3$, where $s_i$ denotes the state, $u_i$ denotes the input bit, and $c_{i,n}$ denotes the $n$th output bit of the $i$th user.](image-url)
shows an example of super-trellis consisting of two users’ trellises where each user employs the SOCC with K = 3 and its trellis is represented by Fig. 2(a). Note that in Fig. 2(b), not all branches are shown for visibility.

In the scenario of our partially overlapping system where both collided and non-collided subcarriers exist, the bit metric calculation depends on the number of overlapping users, i.e., the bit metrics are calculated independently when the users do not overlap whereas they are calculated jointly when the users do overlap. For instance, let us focus on the branch from the state 00/00 to the state 00/10 in Fig. 2(b). Let us denote the corresponding branch metric by

\[ \lambda = \lambda_{01}^1 + \lambda_{01}^2, \]  

(7)

where \( \lambda_{01}^1 \) and \( \lambda_{01}^2 \) represents the metrics of the first and second outputs with their corresponding outputs given by \((c_{1,1}, c_{2,1}) = (0, 1)\) and \((c_{1,2}, c_{2,2}) = (0, 1)\), respectively. If the first outputs of the two users do not overlap, then \( c_{1,1} \) and \( c_{2,1} \) are detected from the distinct received symbols denoted by \( Y_{c_{1,1}} \) and \( Y_{c_{2,1}} \), respectively. The metric \( \lambda_{01}^1 \) is then expressed by the sum of the metric of each user calculated independently:

\[
\lambda_{01}^1 = \log f(Y_{c_{1,1}} | c_{1,1} = 0, H_{c_{1,1}}) \\
\quad + \log f(Y_{c_{2,1}} | c_{2,1} = 1, H_{c_{2,1}}) \\
= \log \frac{1}{\pi N_0} \exp \left( -\frac{|Y_{c_{1,1}} + H_{c_{1,1}}|^2}{N_0} \right) \\
+ \log \frac{1}{\pi N_0} \exp \left( -\frac{|Y_{c_{2,1}} - H_{c_{2,1}}|^2}{N_0} \right),
\]  

(8)

where \( f(\cdot) \) denotes the conditional probability density function and \( H_{c_{1,1}} \) and \( H_{c_{2,1}} \) are the corresponding user’s channel coefficients. On the other hand, if both users do not overlap, then \( c_{1,1} \) and \( c_{2,1} \) are detected by the same received symbol \( Y_{\text{col}} \), the metric \( \lambda_{01}^1 \) should be calculated jointly:

\[
\lambda_{01}^1 = \log f(Y_{\text{col}} | c_{1,1} = 0, c_{2,1} = 1, H_{c_{1,1}}, H_{c_{2,1}}) \\
= \log \frac{1}{\pi N_0} \exp \left( -\frac{|Y_{\text{col}} + H_{c_{1,1}} - H_{c_{2,1}}|^2}{N_0} \right).
\]  

(10)

Note that \( \lambda_{01}^2 \) and all the other metrics are calculated in the similar manner. Exploiting these metric calculations, Viterbi algorithm is performed over the super-trellis shown in Fig. 2(b).

The major drawback of STD is its computational complexity stemming from the large number of states of the super trellis, which in general increases exponentially with the number of users. Specifically, if \( N_u \) users have the same SOCC encoder with constraint length \( K \), the super trellis has \( 2^{N_u(K-1)} \) 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 \( u_s \in U \) is determined by the following rule:

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

(12)

We then calculate the bit metrics and decode the signal of the target user. For this 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

\[ N_{k}^{(m)} = \sum_{i \in S_k^{(m)} \setminus u_s} H_{i,k}X_{i,k}^{(m)} + N_{k}^{(m)}, \]  

(13)

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

\[
I_k^{(m)} = \sum_{i \in S_k^{(m)} \setminus u_s} |H_{i,k}|^2.
\]  

(14)

Under this assumption, the metric of the bit carried by the \( k \)th subcarrier of the user \( u_s \), denoted by \( c_{u_s, k}^{(m)} \), can be calculated as

\[
\lambda_{c_{u_s, k}}^{(m)} = \log f(Y_{k}^{(m)} | c_{u_s, k} = b, H_{u_s, k}) \\
= \log \frac{1}{\pi(I_k^{(m)} + N_0)} \exp \left( -\frac{|Y_{k}^{(m)} - H_{u_s, k}(2b-1)|^2}{I_k^{(m)} + N_0} \right).
\]  

(16)

After obtaining the estimated symbol of the target user \( \hat{X}_{u_s, k}^{(m)} \) by Viterbi decoding with the calculated bit metrics, the estimated symbol is subtracted from the received symbol of (6), represented by

\[ Y_{k}^{(m)} = Y_{k}^{(m)} - H_{u_s, k}\hat{X}_{u_s, k}^{(m)}. \]  

(17)

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 \( U \) by excluding the index of the selected user.

**IV. Simulation Results and Discussion**

In our simulation, the SOCC with constraint length \( K = 4 \) is employed together with Golay sequences. Thus, we have \( N_u = 4 \) and \( d_f = 12 \). The binary length of the codeword and the number of OFDM subcarriers are chosen as 3072 and 64, respectively. We assume the frequency-selective fading channel which has an 8-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 \( M = 768 \) consecutive OFDM symbols. Therefore, the only available diversity is the frequency diversity offered by the frequency-selectivity of the channel. Consequently, time-domain interleaving (which may lead to increasing latency) is not performed in this simulation.
A. Comparison between STD and SIC

In this subsection, we compare STD and SIC in terms of bit error rate (BER) and complexity. Figure 3 shows the BER performance of STD for the number of active users $N_a = 2, 4$ and SIC for $N_a = 2, 4, 8, 16$. As a reference, the BER performance of no-MAI case and that of SIC in the perfect overlapping scenario is also presented. As we described in Section III-A, since STD is based on MLSE criterion, it shows the optimum performance which is the same as that of the no-MAI case regardless of $N_a$. However, since the number of states of the corresponding super-trellis exponentially increases with $N_a$, simulations for $N_a > 4$ turned out to be difficult to perform. (In the case of $N_a = 8$, the number of states is as large as $2^{24}$ in our simulation settings.) On the other hand, the SIC also shows almost the same performance as that of the no-MAI case even though it is suboptimum. This stems from the fact that the number of the subcarriers that experience overlapping is small for $N_a = 2, 4, 8$ and thus even the simple SIC can suppress the MAI successfully. In fact, the performance of $N_a = 16$ where the number of the overlapping subcarriers increases is slightly degraded, and in the case that all $N_a$ users utilize the same set of subcarriers (i.e., all the signals of $N_a$ users perfectly overlap), the performance of SIC significantly degrades even in the small $N_a$ case. Comparing the numbers of comparison operations per information bit in the entire decoding process of STD and SIC, STD requires 192 and 61440 for $N_a = 2$ and 4, respectively, while SIC requires 16 and 32. Consequently, we may conclude that SIC is a better choice in terms of performance and complexity when the number of users is relatively small compared to the number of subcarriers available.

B. Comparison with OFDMA

Figure 4 shows the BER performance of SIC for the number of active users $N_a = 4, 8, 16, 32$ and that of the conventional OFDMA system without the subcarrier hopping. Due to the lack of the subcarrier hopping, the diversity order achieved by OFDMA is less than our proposed system with SIC. In the case of OFDMA, the users utilize their specific predetermined sets of subcarriers such that no user experiences the overlap of their signals. Therefore, $N_a = N_s/N_u = 16$ users can be allocated to one OFDM symbol without MAI. Our proposed system with SIC for $N_a = 16$ has the same spectrum efficiency as OFDMA, but its BER performance is significantly superior to that of OFDMA. Furthermore, even in the scenario of $N_a = 32$ where the proposed system achieves twice as much spectrum efficiency as OFDMA, it still outperforms OFDMA. However, its performance has a slight gap from the optimum performance due to the increasing number of the overlapping subcarriers.

C. A Design Strategy for Low Latency Applications

As shown in the previous subsection, SIC can achieve near optimum performance when the number of users is relatively small. On the other hand, when the number of users is large, the use of SIC results in not only degraded performance but also increased latency due to its serial architecture. In particular, the latency issue is a critical for real-time applications where the latency requirement is given high priority.

Contrary to SIC, STD always achieves optimum performance, i.e., its performance is not affected by the number of users and the user overlapping rate. The major issue of STD is its prohibitive computational complexity stemming from the exponential increase in the number of the super-trellis states as the number of potential users increases. Nevertheless, unlike SIC, since STD is processed within one trellis, it can be implemented based on the parallel architecture and thus its decoding latency can be suppressed considerably. Moreover, the user overlapping rate does not affect the computational complexity of STD. (The number of branches to be compared in the super-
trellis is determined not by the number of overlapping users but by that of the active users.)

From the above observations, we propose a strategy to develop an alternative multiple access approach employing STD and user grouping, aiming at reliable real-time applications with large number of users. The main concept is to put a limitation on the number of active users allocated to the same subcarrier resources such that the implementation of STD is possible. Specifically, we separate all $N_a$ active users into $\left[ N_a/N_p \right]$ groups where $[x]$ is the minimum integer greater than or equal to $x$, and $N_p < N_a$. Each group consists of at most $N_p$ users and the users in the same group employ the identical hopping patterns (i.e., $N_p$ users perfectly overlap). Note that the different groups must be designed to be orthogonal such that the number of the super-trellis states does not increase. This user grouping contributes to the reduction of the number of the super-trellis states from $2^{N_a (K-1)}$ to $2^{N_p (K-1)}$. Furthermore, the computational complexity does not increase by the perfect user overlapping and the optimum BER performance is achieved for any $N_p$. The decoding latency can be suppressed by parallel implementation. Consequently, our design strategy with STD based on the user grouping can achieve low decoding latency and optimum performance without sacrificing the spectrum efficiency. Note that the combination of user grouping and SIC also alleviates the latency of SIC, but it leads to significant performance degradation due to perfect user overlapping as shown in Fig. 3. Therefore, we may conclude that when the number of users are large such that the use of SIC does not satisfy a latency requirement of a given application, the proposed strategy with STD and user grouping should be a better choice. Note that, in this proposed strategy, the number of available users depends on the processor performance of the receiver (i.e., $N_p$) and the available orthogonal resources (i.e., $N_a/N_p$), and thus the optimum setting of them depends on the application.

V. CONCLUSION

In this paper, we have examined the performance of the MUD based on STD and SIC in the framework of SOC encoded OFDM with subcarrier hopping as a new low-latency uplink multiple access scheme. In the scenario where the small number of users independently determine their hopping patterns in a random manner, even simple SIC can approach to the optimum performance without MAI with much less decoding complexity than STD. We have also shown that our proposed system with SIC outperforms the conventional OFDMA system while achieving twice as much spectrum efficiency as OFDMA. However, when the number of users is large, it is difficult to achieve low decoding latency with the SIC-based MUD due to its inherent serial processing architecture. Therefore, we have proposed an alternative multiple access approach based on STD and user grouping for such cases. It will achieve optimum performance and low decoding latency by parallel implementation without decreasing the spectrum efficiency. Further analysis of the proposed STD-based system, together with its real-time implementation using FPGA, is our future work.

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