A Novel Codebook Construction and Blind Detection Method for Grant-Free mMTCs

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Abstract. The grant-free transmission supports user devices to activate and transmit at any time without requiring a connection establishment beforehand, therefore it is well-suited for massive machine type communications. The existing grant-free schemes suffer from a small codebook size and consequently a high collision probability of spreading sequences among users. To address this issue, this paper proposes a novel method for constructing the codebook by concatenating sequences for a potentially large number of users. The codebook size is significantly increased while the low-correlation property is maintained. To guarantee a low complexity at the receiver, two types of blind phased detection schemes are proposed as well, which deal with the blind user recognition in a successive or parallel manner. The phased detection greatly reduces the complexity compared with the traditional multiuser detection through sequence traversal. Simulation results are provided, which verify the advantages of the proposed scheme in collision probability, user recognition and block error rate.

Keywords: massive machine type communication (mMTC) · non-orthogonal multiple access (NOMA) · grant-free (GF) · codebook design · blind multiuser detection (MUD)

1 Introduction

Massive machine type communication (mMTC) is an important application scenario in future wireless communication networks, which is characterized by sporadic short packet transmission, low cost, and low power consumption [1]. It offers large-scale and effective connectivity for numerous Internet of Things (IoT) devices [2]. Non-orthogonal multiple access (NOMA) is one of the key candidate techniques for mMTC, which allows multiple users to simultaneously transmit data on a single channel to meet the needs of massive access, high-frequency spectral efficiency, and low latency [3,4]. NOMA designs specific multiple access signatures based on the multiplexing of time domain, frequency domain, code domain, power domain, etc. A variety of NOMA schemes have been proposed or

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rediscovered, such as multi-user shared access (MUSA) [5], sparse code multiple access (SCMA) [6], pattern division multiple access (PDMA) [7], interleave division multiple access (IDMA) [8], which differ from their signature designs or resource reuse manners.

The above schemes are generally classified into two types of uplink NOMA transmission: grant-based NOMA and grant-free (GF) NOMA. The former incurs significant signaling overhead and latency, making it unsuitable for burst short-packet communication scenarios with large-connected devices. The GF transmission can support user devices to activate and transmit at any time, without requiring a connection establishment with the base station (BS) through handshaking or other procedures. This feature is well-suited for mMTC scenarios with sporadic short-packet characteristics. In this paper, we adopt a competitive GF scheme that simplifies the access procedure and reduces time-frequency resource consumption, signaling overhead and latency.

The GF uplink transmission usually applies spreading sequences to distinguish users, therefore it is critical to design codebooks with low cross-correlation [9]. In general, a large codebook size can support high user overload but also increase inter-user interference and system complexity. Short spreading sequences can reduce complexity from both the transmitter and the receiver, but the codebook size is limited. Therefore, a tradeoff between the codebook size and the length of the spreading sequence is required. Additionally, complex spreading sequences can be more advantageous than binary or real spreading sequences, as they can facilitate better cross-correlation [10].

The existing GF NOMA [11,12] usually suffers from a small codebook size. Considering that the user equipments (UEs) compete with each other for the resources in the competitive GF access system, collisions are inevitable. Furthermore, these collisions markedly degrade the efficacy of multi-user detection. As a result, the number of UEs accessing simultaneously is very limited [13]. One solution to support massive potential GF access is to expand the codebook size by increasing the number of spreading sequences while maintaining the low-correlation property [14].

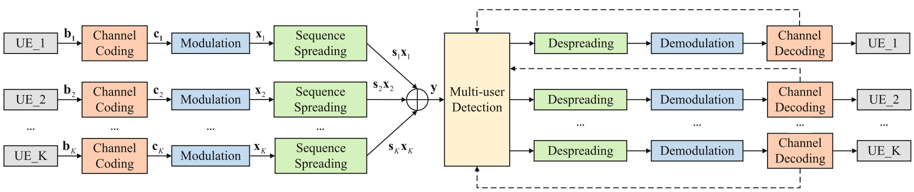

Fig. 1. The structure of transmitters and receivers for GF multiple access.

In this paper, we propose a method for designing codebooks for GF mMTC scenarios featured by a large number of potential users and sporadic short packet transmissions. By properly concatenating short spreading sequences, the size of codebook is enlarged while the low correlation is maintained. For the concatenated codebook, we propose two types of blind phased detection, namely successive-phased detection and parallel-phased detection at the receiver. The proposed scheme achieves lower collision probability, higher user recognition rate, and better blind detection performance in the competitive GF scenario. We take the existing MUSA sequences as an example to construct the new codebook and carry out simulations, which verify the advantages of the proposed scheme.

The remainder of the paper is organized as follows: In Sect. 2, we briefly describe the system model of GF transmission. In Sect. 3, we propose the construction of codebook by concatenating and then analyze the probability of collision and the correlation of the spreading sequences. In Sect. 4, we introduce the blind phased detection schemes for the proposed codebook. In Sect. 5, simulation results and discussions are provided. Finally, Sect. 6 concludes the paper.

2 System Model

An uplink GF multiple access system is illustrated in Fig. 1. We assume that the system has K active UEs sending packets during a certain period, while other UEs remain silent. The signals from the K UEs are superimposed on the same subcarrier in the transmission, and then the information is separated and recovered by the receiver. Each active UE randomly selects a spreading sequence with length L from the codebook, multiplies each symbol with the spreading sequence, and then transmits the spreaded symbols onto the L continuous Resource Elements (REs). Considering an overloaded transmission where $K \geq L$, the load of the system is defined as $OF = \dfrac{K}{L}$.

The received signal can be written as

$$\mathbf{y}_j = \sum_{k=1}^{K} h_k \mathbf{s}_k x_{k,j} + \mathbf{n}_j, \tag{1}$$

where $x_{k,j}$ represents the j-th transmitted symbol from user k, h_k denotes the channel fading from the user k to the receiving antenna, $\mathbf{s}_k = [s_{k,1}, s_{k,2}, \cdots, s_{k,L}]^T$ is the spreading sequence selected by user k, $\mathbf{n}_j$ is additive Gaussian noise with zero mean and variance σ^2 and $\mathbf{y_j}$ denotes the superimposed symbol vector received at the BS. In this paper, we consider an uncorrelated flat Rayleigh fading channel and each user's subchannels have the same fading coefficients. We assume that both channel gain h_k and spreading sequence $\mathbf{s}_k$ are unknown at the receiver. Note that $(\cdot)^T$ and $(\cdot)^H$ represent the transpose and the conjugate transpose of a matrix, respectively.

The BS receives GF superimposed signals without any pilot. Consequently, it lacks information on user activation and channel conditions. The receiver has to perform a blind multiuser detection (MUD), which involves user recognition and data recovery. The blind detection first recognizes the spreading sequence, and then conducts in turn the multi-user interference cancellation, demodulation and decoding.

The system applies an advanced minimum mean square error based successive interference cancellation (MMSE-SIC) MUD architecture at the receiver as in [10]. As shown in Fig. 2, the blind MUD consists of four key components. First, blind user recognition is performed to identify M spreading sequences with the highest probability. Then, blind MMSE despreading is applied using the selected M sequences to suppress the multi-user interference. After that, each data stream is equalized to restore the constellation shape. We select the top F streams with the highest signal-to-interference plus noise ratio (SINR) for demodulation and decoding. In the end, the demodulated and decoded bits undergo the CRC check. If the check passes, the receiver reconstructs the transmitted symbols and carries out the interference cancellation.

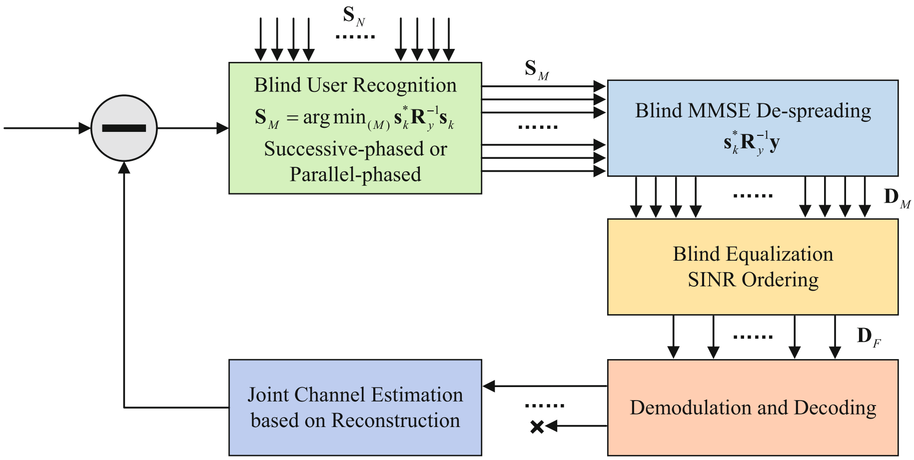

Fig. 2. Blind multiuser detection.

3 The Proposed Codebook Design

In this section, we propose a concatenation method for generating multiuser codebooks to address issues such as UE collisions and the limited ability to accommodate a large number of UEs. This method expands the size of the codebook by increasing the length of the spreading sequences. This structured concatenation facilities the ease of detection.

3.1 Concatenated Codebook Design

We start with an existing codebook $\tilde{\mathbf{S}} = [\tilde{\mathbf{s}}_1, \tilde{\mathbf{s}}_2, \ldots, \tilde{\mathbf{s}}_N]$ with a spreading sequence length of L and a codebook size of N. We then select $T(T \geq 1)$ candidate codebook groups $\left[\hat{\mathbf{S}}_1, \hat{\mathbf{S}}_2, \ldots, \hat{\mathbf{S}}_T\right]$ based on $\tilde{\mathbf{S}}$, where $\hat{\mathbf{S}}_i = [\hat{\mathbf{s}}_1, \hat{\mathbf{s}}_2, \ldots, \hat{\mathbf{s}}_{W_i}], i = 1, 2, \cdots T$. The candidate codebooks concatenate T times of $\tilde{\mathbf{S}}$, resulting in a new codebook $\mathbf{S} = [\mathbf{s}_1, \mathbf{s}_2, ..., \mathbf{s}_{N \times \prod_{i=1}^{T} W_i}]$. Based on the original spreading sequence $\tilde{\mathbf{S}}$, the first L bits of the new spreading sequence $\mathbf{S}$ are

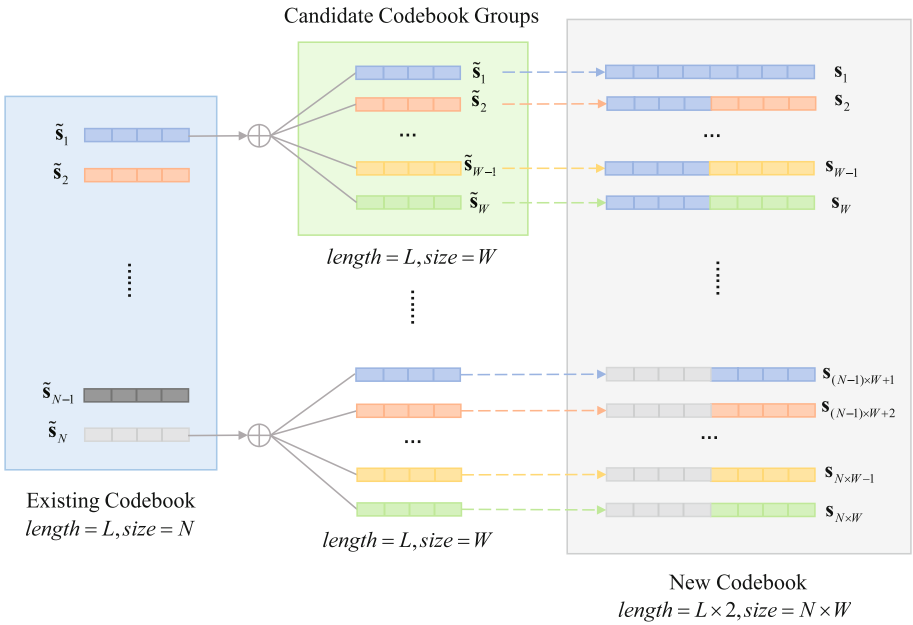

Fig. 3. The principle of the concatenated codebook construction.

determined. Additionally, based on the spreading sequence $\hat{\mathbf{S}}$ from the i-th candidate codebook group, the $(L*i+1)$-th to $(2L*i)$-th bits of $\mathbf{S}$ are determined. That is, each spreading sequence in the original codebook is concatenated with W_i spreading sequences in each candidate codebook group to obtain a total of $N \times \prod_{i=1}^{T} W_i$ new spreading sequences. The new codebook $\mathbf{S}$ has a spreading sequence length of $L \times (T+1)$ and a codebook size of $N \times \prod_{i=1}^{T} W_i$, allowing more UEs to access the system with reduced collisions.

The spreading sequences in $\hat{\mathbf{S}}$ can be randomly selected from those in $\tilde{\mathbf{S}}$, or in a predetermined order. Alternatively, they can be chosen according to other rules. The length of the new spreading sequence is determined by the number of candidate codebook groups T. For instance, if there is only one candidate codebook group, the length will be $2L$; if there are two candidate codebook groups, the length will be $3L$, and so on. If $T = 1$ and there are W spreading sequences in the candidate codebook, the above codebook construction will yield $N \times W$ new spreading sequences. In the case $T = 2$, assuming the candidate codebook groups are $\hat{\mathbf{S}}_1 = [\hat{\mathbf{s}}_{1_1}, \hat{\mathbf{s}}_{2_1}, \ldots, \hat{\mathbf{s}}_{W_1}]$ and $\hat{\mathbf{S}}_2 = [\hat{\mathbf{s}}_{1_2}, \hat{\mathbf{s}}_{2_2}, \ldots, \hat{\mathbf{s}}_{W_2}]$ and the first original spreading sequence is $\tilde{\mathbf{s}}_1$, the newly designed spreading sequences can be generated as follows: first, concatenate $\tilde{\mathbf{s}}_1$ with each sequence in $\hat{\mathbf{S}}_1$ to obtain W_1 intermediate spreading sequences. Then, each of these W_1 intermediate sequences is concatenated with each sequence in $\hat{\mathbf{S}}_2$ to obtain in total

$W_1 \times W_2$ new spreading sequences. Similar procedure is applied for $\tilde{\mathbf{s}}_2, \ldots, \tilde{\mathbf{s}}_N$, and $N \times W_1 \times W_2$ new spreading sequences are obtained. The above concatenation can be generalized straightforwardly. If the size of each candidate codebook group is the same as that of the original codebook, i.e., $W_i = N$, then the maximum number of new spreading sequences obtained through the concatenation is N^{M+1}. The construction principle of the codebook is illustrated in Fig. 3 for $T = 1$. The former L bits of the newly constructed spreading sequences correspond to the original spreading sequence, while the latter L bits correspond to the concatenated spreading group sequence.

3.2 Collision Analysis

In GF scenarios, when the number of potential user devices is large, there is an increased likelihood of multiple users selecting the same spreading sequence, leading to collision issues. Collision may still exist with the newly generated codebook $\mathbf{S}$, as either the 1st (the former L bits of the spreading sequence) or 2nd (the latter L bits of the spreading sequence) segments of the codeword may overlap, as shown in Fig. 4.

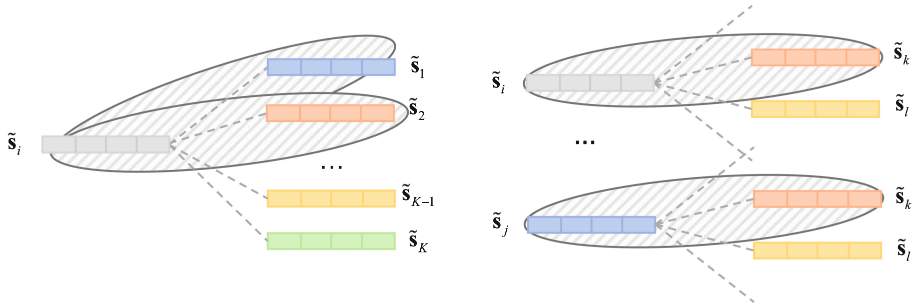

Fig. 4. The 1st or the 2nd segment spreading sequence collision.

It should be noted that in cases where UEs experience only the 1st or 2nd collision mentioned above, they can still be distinguished at the receiver as long as the entire spreading sequences do not collide. The probability of collision for the entire spreading sequence is directly dependent on the size of the codebook, which is denoted by $P_{N,K}$ as

$$P_{N,K} = 1 - \frac{A_N^K}{N^K}, \tag{2}$$

where A represents the full permutation operator and K represents the number of UEs randomly selecting signatures from the codebook of size N.

The collision probability for different numbers of active users and different codebook sizes is shown in Fig. 5. It can be seen that the collision probability decreases as the size of the codebook increases when the spreading sequences are selected competitively by UEs.

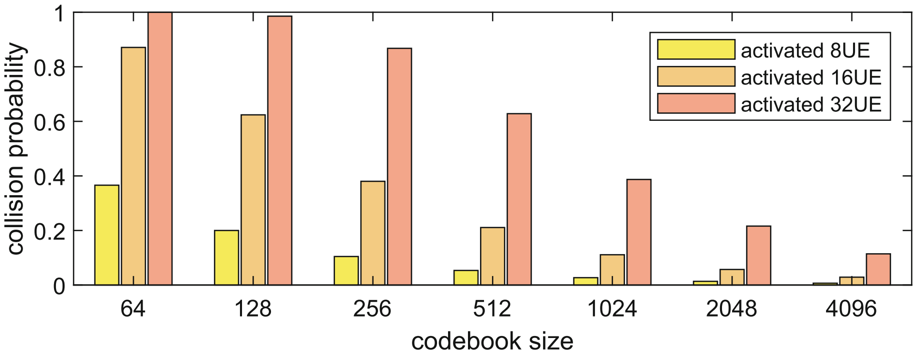

Fig. 5. The collision probability for different numbers of active users and different codebook sizes.

3.3 Correlation Analysis

For multiuser transmission, the cross-correlation property of the codebook is crucial. In the following, we evaluate the correlation of the newly proposed codebook by calculating the average modulus cross-correlation between spreading sequences using

$$\mathbf{S} = \underset{\mathbf{s}_i,\mathbf{s}_j \in \mathbf{S}}{\arg\min} \sum_{i=1}^{N} \left| \frac{1}{N-1} \sum_{j=1, j\neq i}^{N} \left\| \mathbf{s}_i^H \mathbf{s}_j \right\| - C \right|, \tag{3}$$

where N represents the size of the codebook, $\mathbf{s_i}$ and $\mathbf{s_j}$ are spreading sequences in the codebook $\mathbf{S}$, and the constant C represents the ideal average modulus cross-correlation value.

Assuming that there are two distinct spreading sequences, $\tilde{\mathbf{s}}_a$ and $\tilde{\mathbf{s}}_b$, in the original codebook $\tilde{\mathbf{S}}_N$ such that $\tilde{\mathbf{s}}_a \neq \tilde{\mathbf{s}}_b$, we randomly select two other spreading sequences, $\tilde{\mathbf{s}}_c$ and $\tilde{\mathbf{s}}_d$, to form the concatenated group $\tilde{\mathbf{S}}_W$ as

$$\begin{aligned} \mathbf{s}_i &= [s_{i,1}, \cdots, s_{i,2L}] = [\tilde{s}_{a,1}, \cdots, \tilde{s}_{a,L}, \tilde{s}_{c,1}, \cdots, \tilde{s}_{c,L}] \\ \mathbf{s}_j &= [s_{j,1}, \cdots, s_{j,2L}] = [\tilde{s}_{b,1}, \cdots, \tilde{s}_{b,L}, \tilde{s}_{d,1}, \cdots, \tilde{s}_{d,L}], \end{aligned} \tag{4}$$

where $\mathbf{s}_i$, $\mathbf{s}_j$ are the new codewords generated by the concatenation. Then the cross-correlation modulus between $\mathbf{s}_i$ and $\mathbf{s}_j$ is

$$\begin{aligned}\left\|\mathbf{s}_i^H\mathbf{s}_j\right\| &= \left\|\sum_{n=1}^{2L} s_{i,n}^* s_{j,n}\right\| \\ &= \left\|\sum_{n=1}^{L} \tilde{s}_{a,n}^* \tilde{s}_{b,n} + \sum_{n=1}^{L} \tilde{s}_{c,n}^* \tilde{s}_{d,n}\right\| \\ &\le \left\|\sum_{n=1}^{L} \tilde{s}_{a,n}^* \tilde{s}_{b,n}\right\| + \left\|\sum_{n=1}^{L} \tilde{s}_{c,n}^* \tilde{s}_{d,n}\right\| \\ &= \left\|\tilde{\mathbf{s}}_a^H\tilde{\mathbf{s}}_b\right\| + \left\|\tilde{\mathbf{s}}_c^H\tilde{\mathbf{s}}_d\right\|.\end{aligned} \tag{5}$$

We can see that the low correlation property of the original spreading sequences is maintained after the concatenation, which satisfies the requirements of user recognition in blind detection receivers.

Taking the MUSA spreading sequence as an example, we calculated the average modulus cross-correlation between codebooks of different sizes, as shown in Table 1, where ω denotes the modulus cross-correlation per subcarrier. The results demonstrate that the proposed codebook construction guarantees a low correlation between spreading sequences, enabling multi-user blind detection at the receiver.

Table 1. Cross-correlation between codewords.

pool size	64	256	512	1024	4096
ω	0.43832	0.34532	0.34927	0.34899	0.35369

4 Blind Phased Detection for the Proposed Codebook

In the scenario of GF multiple access, user recognition is a crucial component of the MUD receiver since the BS is unaware of the activity of UEs. We evaluate the SINR of a symbol stream corresponding to a spreading sequence $\mathbf{s}_k$ using measure A_k as

$$A_k = \mathbf{s}_k^* \mathbf{R}_y^{-1} \mathbf{s}_k, \tag{6}$$

where $\mathbf{R}_y = \frac{1}{J}\sum_{j=1}^{J} \mathbf{y}_j \mathbf{y}_j^*$ is the correlation matrix of the received signal and J is the number of modulation symbols corresponding to a channel code block. Generally, the smaller the A_k, the higher the SINR. Therefore, in each round of SIC user recognition, the M smallest spreading sequences are selected from $\mathbf{S}_N$ to form $\mathbf{S}_M$ based on this measure.

In this section, we propose two types of blind phased detection schemes, namely "successive" phased detection and "parallel" phased detection, based on the structure of the codebook. These schemes aim to reduce the complexity of detection for the blind receiver.

4.1 Successive-Phased Detection

Blind activity detection typically involves traversing all spreading sequences in the codebook and selecting the M spreading sequences with the highest likelihood of successful decoding based on correlation, which can be computationally expensive due to a large number of matrix operations involved. Therefore, we propose a successive-phased detection that picks out the spreading sequence with the highest SINR in two rounds, as shown in Fig. 6.

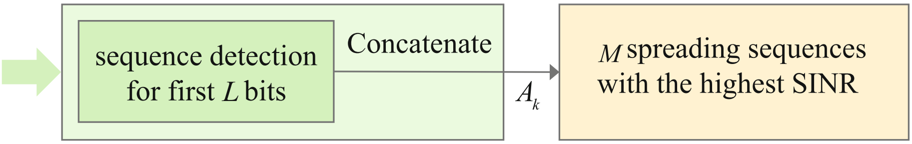

Fig. 6. Successive-phased detection.

We use a codebook $\tilde{\mathbf{S}}_N$ with sequence length $2L$ and codebook size N as an example. In the successive-phased detection scheme, the first round involves traversing the original codebook $\tilde{\mathbf{S}}_N$ using the upper left corner $(L \times L)$ matrix of ${\mathbf{R}_y^{-1}}_{(2L\times 2L)}$ and selecting the M_1 sequences with the highest SINR to determine the first L bits of the UE's spreading sequence. Then, we concatenate the M_1 spreading sequences selected in the first round with the W spreading sequences in each candidate codebook group to obtain $M_1 \times W$ transitional codebook sequences. In the second round, the ${\mathbf{R}_y^{-1}}_{(2L\times 2L)}$ is used to traverse the spreading sequence in the $2L$-length and $(M_1 \times W)$-size codebook based on picking out the M_1 sequences, and then M spreading sequences with the highest SINR are selected. The final step involves using the activated M spreading sequences for de-spreading, equalization, and decoding.

Compared to the traditional detection method that employs ${\mathbf{R}_y^{-1}}_{(2L\times 2L)}$ to traverse a $(L \times 2)$-length and $(N \times W)$-size codebook, the proposed method does not require any change in the matrix inversion dimension. It effectively reduces the number of blind sequence detections by selecting the M_1 spreading sequences with high probability, which serves as a priori information for the sequence detection. This significantly reduces the algorithm's complexity.

In blind activity detection, we used A_k to select M spreading sequences with the highest SINR, where

$$
\begin{aligned}
A_k &= \mathbf{s}_k^* \mathbf{R}_y^{-1} \mathbf{s}_k \\
&= \begin{bmatrix} s_{k,1}^* \cdots s_{k,2L}^* \end{bmatrix} \begin{bmatrix} r_{1,1} & \cdots & r_{1,2L} \\ \vdots & \ddots & \vdots \\ r_{2L,1} & \cdots & r_{2L,2L} \end{bmatrix} \begin{bmatrix} s_{k,1} \\ \vdots \\ s_{k,2L} \end{bmatrix} \\
&= (s_{k,1}^* r_{1,1} + \cdots + s_{k,2L}^* r_{2L,1}) s_{k,1} + \cdots + (s_{k,1}^* r_{1,2L} + \cdots + s_{k,2L}^* r_{2L,2L}) s_{k,2L}.
\end{aligned} \tag{7}
$$

When using the correlation matrix $\mathbf{R}_y^{-1}{}_{(2L\times 2L)}$ to detect the first L bits of the UE's spreading sequence, we may limit our focus to the first L bits of s_k, where the last L bits have been set to a value of zero. Therefore (7) can be rewritten as

$$A'_k = \left[s_{k,1}^* \cdots s_{k,L}^* \; 0 \cdots 0\right] \begin{bmatrix} r_{1,1} & \cdots & r_{1,2L} \\ \vdots & \ddots & \vdots \\ r_{2L,1} & \cdots & r_{2L,2L} \end{bmatrix} \begin{bmatrix} s_{k,1} \\ \vdots \\ s_{k,L} \\ 0 \\ \vdots \\ 0 \end{bmatrix}$$
$$= (s_{k,1}^* r_{1,1} + \cdots + s_{k,L}^* r_{L,1}) s_{k,1} + \cdots + (s_{k,1}^* r_{1,L} + \cdots + s_{k,L}^* r_{L,L}) s_{k,L}. \quad (8)$$

Then, it can be further simplified as

$$A'_k = \left[s_{k,1}^* \cdots s_{k,L}^*\right] \begin{bmatrix} r_{1,1} & \cdots & r_{1,L} \\ \vdots & \ddots & \vdots \\ r_{L,1} & \cdots & r_{L,L} \end{bmatrix} \begin{bmatrix} s_{k,1} \\ \vdots \\ s_{k,L} \end{bmatrix}. \quad (9)$$

It is evident that the correlation result obtained from using the upper left $L \times L$ matrix of the correlation matrix $\mathbf{R}_y^{-1}{}_{(2L\times 2L)}$ in (9) agrees with the result obtained by computing (8). Consequently, the original spreading codebook sequence of length L and size N can be directly traversed using the upper left corner matrix of $\mathbf{R}_y^{-1}{}_{(2L\times 2L)}$ to complete the first round.

4.2 Parallel-Phased Detection

We also propose a parallel-phased detection scheme based on the concatenated codebook, as shown in Fig. 7.

In the first round of the proposed parallel-phased detection scheme, we traverse the original codebook $\tilde{\mathbf{S}}_N$ using the upper left corner $L \times L$ matrix of $\mathbf{R}_y^{-1}{}_{(2L\times 2L)}$ and to select the M_1 sequences with the highest SINR from $\tilde{\mathbf{S}}_N$ to determine the former L bits of the spreading sequence. In the second round, we traverse the candidate codebook $\hat{\mathbf{S}}_W$ using the lower right corner $(L \times L)$ matrix of $\mathbf{R}_y^{-1}{}_{(2L\times 2L)}$ to select the M_2 sequences with the highest SINR from

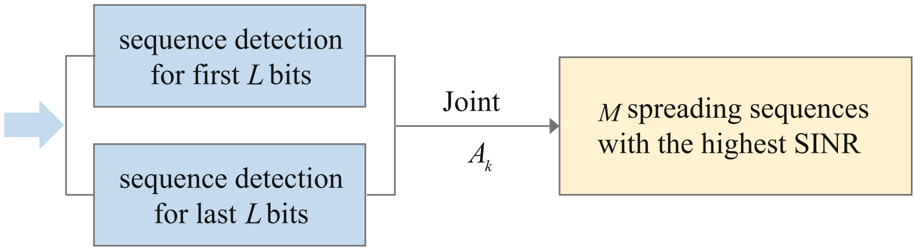

Fig. 7. Parallel-phased detection.

$\tilde{\mathbf{S}}_W$ to determine the latter L bits of the spreading sequence. We then concatenate the M_1 and M_2 sequences to obtain the $\mathbf{S}_{M_1 \times M_2}$ spreading sequence. Then, the $\mathbf{R}_y^{-1}{}_{(2L \times 2L)}$ is used to traverse the spreading sequence in the $(L \times 2)$-length and $(M_1 \times M_2)$-size codebook based on A_k, and then M spreading sequences with the highest SINR are selected and then used for despreading, equalization, and decoding. The multiplication and other operations of the $(L \times L)$-matrix are less complex than the traditional $(2L \times 2L)$-matrix operations, reducing the complexity of the blind receiver.

5 Simulation Results and Discussions

The simulations were conducted under the following assumptions. A number of K UEs were assumed to use equal power in the transmission, and the length of information bits was set to 1000. A 5G-NR LDPC channel coding with rate of 1/3 was employed, and BPSK modulation was used. The new codebook $\mathbf{S}_{N \times W}$ was constructed based on the MUSA codebook $\tilde{\mathbf{S}}_{N=64}$ using the concatenation method, and the spreading sequence length was set to $L = 8$. The number of sequences for blind user recognition was set to $M = K + 4$. The simulation was conducted under two cases: one without collision of spreading sequences and the other allowing for collision. The performance of the system was evaluated based on the block error rate (BLER). The MUSA codebook of 4-length and 64-size was used for comparison.

We choose a scenario in which the overload factor $OF = 1$. The codebook size is $W = 16$ in the concatenated group, and a new codebook $\mathbf{S}_{N=1024}$ is obtained by using the MUSA sequences. The receiver uses the successive-phased detection scheme, and the user recognition rate is illustrated in Fig. 8. It can be observed that the user recognition rate is slightly lower than the traditional method of complete traversal, and it approaches 100% under high SNRs. Note that by using the successive-phased detection, the complexity is significantly reduced than the traversal method.

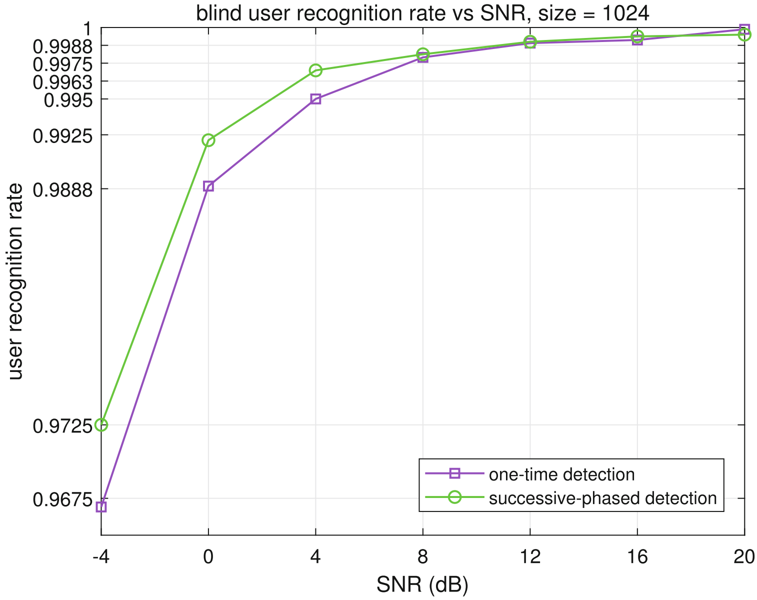

Fig. 8. User recognition rate by successive-phased detection with the codebook size of 1024.

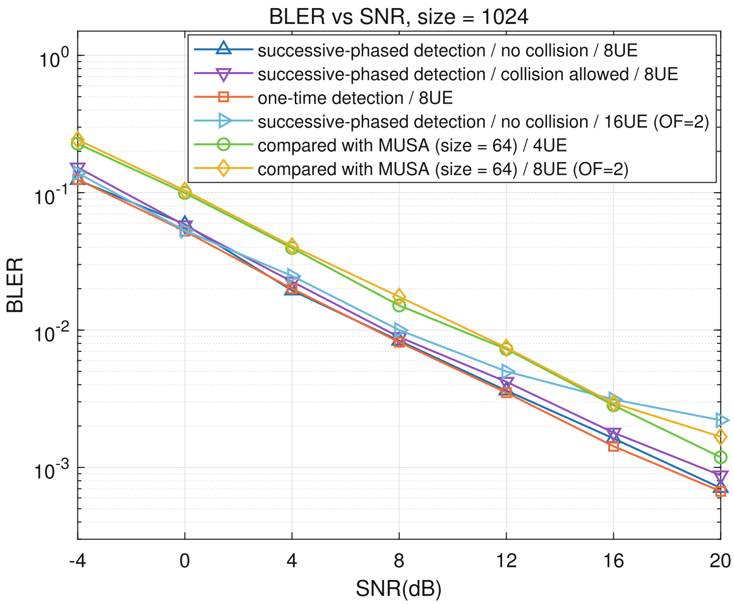

Fig. 9. BLER of the successive-phased detection with the codebook size of 1024.

The BLER performance is plotted in Fig. 9. It can be seen that the performance of the successive-phased detection is similar to that of the traditional traversal detection. The performance of colliding allowed is slightly worse than that of no colliding when they both use the successive-phased detection. Due to the lower correlation of the newly proposed codebook, the above BLERs generally outperform the MUSA scheme by about 2 dB for the same overload. Moreover, for $OF = 2$, as illustrated in Fig. 9, the performance under conditions of a low SNRs is approximately 2 dB better optimal than that of the MUSA scheme with a comparable load. The performance is marginally compromised relative to the MUSA scheme under high SNRs, primarily due to the pronounced effects of inter-user interference.

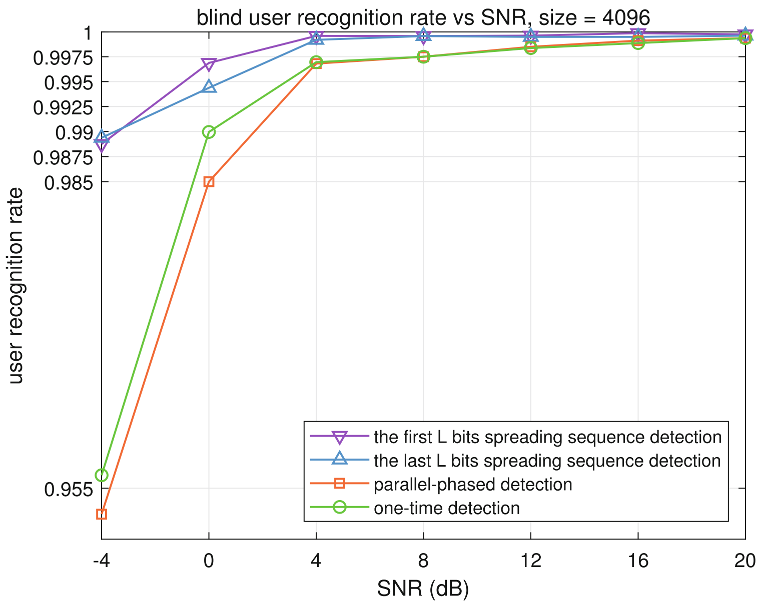

Fig. 10. User recognition rate by parallel-phased detection with the codebook size of 4096.

A similar construction can be extended to a larger codebook size. When the codebook size of the concatenated group is $W = 64$, a codebook $\mathbf{S}_{N=4096}$ is obtained. For this setup, the receiver adopts the parallel-phased detection scheme for the purpose of an even lower complexity. The blind user recognition rate is depicted in Fig. 10, and the BLER performance is compared in Fig. 11. As for the codebook of size 1024, the performance of the parallel-phased detection scheme is comparable to that of the traditional traversal detection method at low SNRs, and their BLER performance is slightly degraded for high SNRs. Similarly, the performance of this scheme is approximately 2 dB better than that of the MUSA under the same overload.

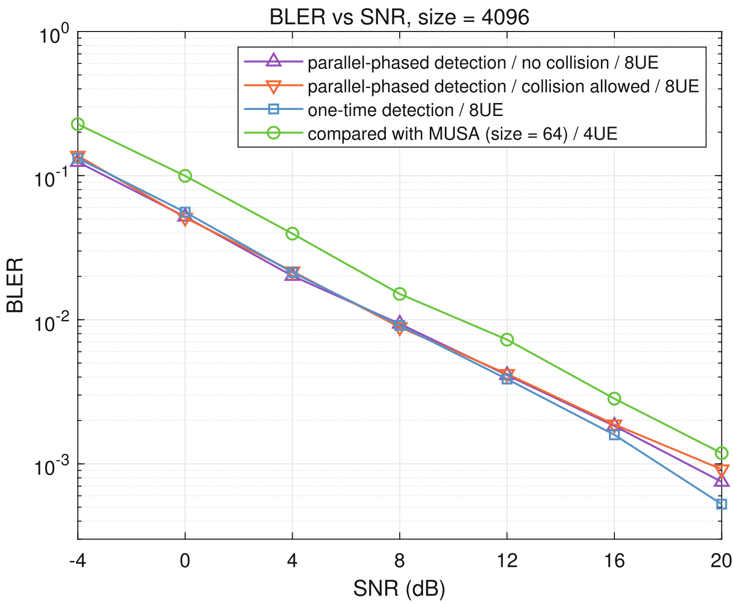

Fig. 11. BLER of the parallel-phased detection with the codebook size of 4096.

6 Conclusions

The spreading sequence plays a crucial role in the multi-user transmission in GF multiple access systems. The codebook design should take into account the codebook size, the correlation among sequences and the detecting complexity, etc. In this paper, we have proposed a method for designing codebooks for GF mMTC scenarios. By properly concatenating short spreading sequences, the size of the codebook has been significantly enlarged while the low correlation has been maintained. For the concatenated codebook, we also proposed two types of blind phased detection, namely successive-phased detection and parallel-phased detection, respectively. The proposed scheme has achieved low collision probability, high user recognition rate, good blind detection performance, and low detecting complexity for the competitive GF scenarios.

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