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RESEARCH ARTICLE

An Uplink Random Access Scheme Based on ALOHA System Assisted by Gain Division Multiple Access

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ABSTRACT Gain division multiple access (GDMA) is a non-orthogonal multiple access (NOMA) technique for uplink communications. In GDMA, the receiver employs both the magnitudes and phases of channel gains associated to the users to separate users. In the power-domain NOMA, the receiver employs the power levels associated to users to separate users. We apply the GDMA concept together with orthogonal frequency division multiple access (OFDM) to combat the collision problem in the ALOHA system. Our goal is to minimize the complexity of the devices (users) required for coordination and to obtain high throughput simultaneously in the random access protocol. For the proposed unslotted OFDM-GDMA-ALOHA, each user randomly chooses a Zadoff-Chu (ZC) sequence as its preamble for the transmitted packet so that the receiver can simultaneously obtain the information for timing and the information for coarse channel estimation. Moreover, fine channel estimation is obtained by using a cluster-based method. Simulation for a coded unslotted OFDM-GDMA-ALOHA system with BPSK modulation demonstrates that the obtained throughput performance can be better than that obtained by the slotted ALOHA system without using GDMA. We also provide simulation for slotted OFDM-GDMA-ALOHA, which shows that very high throughput can be achieved if the synchronization of slots can be obtained.

INDEX TERMS Gain division multiple access (GDMA), non-orthogonal multiple access (NOMA), ALOHA, cluster-based channel estimation.

I. INTRODUCTION

The Internet of Things (IoT) is an important feature for modern life. In order to support the connectivity of a large number of devices and sensors, the machine-type communication (MTC) protocol is essential. One possible characteristic of MTC is considered as an opportunistic access in which the devices and sensors are sparsely active. Hence, random access protocol such as the ALOHA protocol [1] and carrier sensing multiple access with collision avoidance (CSMA/CA) [2] can be considered for the uplink MTC applications. Since the devices (or users) in CSMA/CA needs to continuously monitor the channel, the required power consumption does not meet the low-power requirement for the devices in MTC. The primitive (pure or unslotted) ALOHA scheme [1], [3] for random access system is unslotted and needs the least effort for coordination. Slotted ALOHA [4], [5], which requires the synchronization of slots, can help increase the system throughput.

In [6] and [7], the slotted ALOHA protocol is applied to the MTC. The technique of spread spectrum has been combined to the ALOHA protocol [8] to deal with the collision problem, where the price is the increased bandwidth. The concept of power-domain (PD) non-orthogonal multiple access (NOMA) has been incorporated into the ALOHA system [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], denoted as PD-NOMA-ALOHA, by exploiting the power domain superposition with successive interference

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cancellation (SIC) at the receiver. For PD-NOMA-ALOHA, there is a high probability of successful decoding at the receiver when a collision of the transmitted packets occurs. By contrast, a failed decoding is declared as long as a collision occurs in the conventional ALOHA. Hence, PD-NOMA-ALOHA can achieve better throughput. Most of the works for PD-NOMA-ALOHA are designed based on the slotted ALOHA.

To resolve the collision in the PD-NOMA-ALOHA, channel state information (CSI) for uplink transmission is necessary for both the base station (receiver) and the devices (users), where the users need the CSI in order to appropriately choose their power levels for supporting SIC. Moreover, for slotted PD-NOMA-ALOHA, the synchronization of packets from different users to arrive in the same slot requires significant effort. As a possible method [13], the base station periodically broadcasts beacons to help power control, time synchronization and the reciprocal channel estimation for users.

Gain division multiple access (GDMA) [19] is also a NOMA technique for recovering the data of multiple users in the same channel. For PD-NOMA, the users must transmit their packets with coordinated power levels according to their channel information. SIC decoding together with their channel information is then performed at the receiver side. For GDMA, the users with equal power for transmitted packets are distinguished by the channel gains (including magnitudes and phases) which are expected to be distinct through the fading environment. No coordination of their power levels is needed. Moreover, a random phase can be manually added by each device to enhance the variety of channel gains. Joint decoding with their channel information is then performed at the receiver side.

This paper proposes to integrate GDMA into the ALOHA system, denoted as GDMA-ALOHA, to combat the collision problem. One advantage of GDMA-ALOHA is that the CSI is needed only by the base station while the CSI for the power-domain NOMA-ALOHA is needed by each user and the base station. Orthogonal frequency division multiplexing (OFDM) arrangement can be applied to GDMA-ALOHA. The resultant protocol is denoted OFDM-GDMA-ALOHA. For the simplicity of the devices in the MTC, we only consider the BPSK modulation.

A blind channel estimation scheme [20] has been proposed to achieve the CSI for GDMA without using pilots. Suppose that the constellation size of each symbol x_u transmitted from user u, where $u \in \{1, 2, \ldots, U\}$ is 2^m. By excluding the added noise, the superposition of U transmitted symbols is $\sum_{u=1}^{U} h_u x_u$, which will be one of the $L = 2^{mU}$ points in the signal space, where h_u is the channel gain between the receiver and user u. In [20], the receiver firstly collects a sufficient number of received symbols, which are divided into 2^{mU} groups by applying a clustering algorithm [21]. The centroids of the L groups will be used as estimates of the L possible $\sum_{u=1}^{U} h_u x_u$ points. Then, each channel gain h_u can be estimated.

We propose an unslotted OFDM-GDMA-ALOHA protocol for which the timing and CSI are estimated by the receiver. Each user randomly chooses a Zadoff-Chu (ZC) sequence as its preamble for its transmitted packet. The ZC preamble can be used for the receiver to obtain timing and preliminary channel estimation. Clustering can further enhance the channel estimation. In this way, the complexity of the device for the coordination is virtually free. Simulation shows the throughput of unslotted OFDM-GDMA-ALOHA with estimated timing and CSI is better than that obtained by the conventional slotted ALOHA system without resolving the collision.

To see the effect of various coordination effort required by the devices, we also study the unslotted OFDM-GDMA-ALOHA and slotted OFDM-GDMA-ALOHA for which the perfect timing and perfect CSI are partly or totally available to the receiver. We derive the limit of throughput of ALOHA protocol when the assumption of synchronization for slots and perfect CSI can be achieved. The proposed slotted OFDM-GDMA-ALOHA with perfect CSI and timing can achieve throughput very close to the derived limit.

In the following section, we will provide an overall picture of contributions of this paper and brief introduction of some of the many related works. In Section III, the condition of collision in the uplink communication is discussed. The integration of OFDM-GDMA into the ALOHA protocol is studied in Section IV. Concluding remarks are provided in Section V.

II. CONTRIBUTIONS AND THE RELATED WORKS

The goal of this paper is to design uplink random access which has the merits of high throughput and low complexity for the devices. Contributions of this paper to realize our goal are summarized below.

- We propose multi-carrier GDMA-ALOHA denoted OFDM-GDMA-ALOHA for uplink MTC which employs GDMA to resolve the collision in the ALOHA system. The collision of packets from devices A, B, C, ... can be resolved by the receiver through the knowledge of channel gains h_A, h_B, h_C, ... respectively, where the magnitudes and phases of h_A, h_B, h_C, ... respectively will be employed.
- For the proposed OFDM-GDMA-ALOHA for uplink MTC, the variety of channel gains for separating users is acquired through the different fading channels or through the random phase rotations of the transmitted signals. There is no need for each device to acquire the knowledge of the channel before transmitting its packet. By contrast, the devices of PD-NOMA-ALOHA needs the CSI to determine the transmitted power level.
- We propose unslotted OFDM-GDMA-ALOHA for uplink MTC for which a preamble sequence is appended in each transmitted packet. The information of timing and CSI can be obtained by the receiver through the preamble and the clustering method. The coordination among the devices and the receiver is minimized.

- We propose pilot-free slotted OFDM-GDMA-ALOHA for uplink MTC for which the knowledge of channel gains can be estimated using the clustering [20], [21]. Hence, there is no need for the coordination between each device and the receiver regarding the CSI and the transmitted power level which is needed in the PD-NOMA-ALOHA. However, the coordination of timing is needed.
- We propose slotted OFDM-GDMA-ALOHA for uplink MTC for which the knowledge of CSI and timing are available to the receiver. Although the coordination effort needed for the devices is significant, we can see the limit of the throughput.

Contention resolution diversity slotted ALOHA (CRDSA) [22] is a brilliant idea to randomly assign repeated packets to different slots to reduce the likelihood of collision. It is natural to consider integrating CRDSA into PD-NOMA, which is proposed in [14] and many other works. The concept of CRDSA is extended to irregular repetition slotted ALOHA (IRSA) [6], [23]. In [15] and [16], the concept of IRSA is applied to NOMA.

The dimension of multiple channels can be applied to slotted ALOHA [24], where a packet will occupy one or several of the available channels at each time slot and hence the probability of collision can be reduced. In [17] and [18], the technique of multi-channel slotted ALOHA is combined with the NOMA technique for performance improvement.

Throughput analysis for slotted NOMA-ALOHA can be found in [9] and [12].

Throughput analysis for unslotted ALOHA based on Poisson approximation was first introduced in [25]. Then, there are many works studying the unslotted ALOHA protocol. A recent work [26] analyzes the throughput and random access delay and investigates their optimization. However, in these works, the NOMA technique is not used to mitigate the collision conditions. The only unslotted PD-NOMA-ALOHA we have observed by now appears in [27], where a 5-phase frame structure is used for the coordination among the receiver and the many devices.

III. COLLISION DETECTION

In this section, we first review the GDMA technique which was proposed in [19] for recovering the messages transmitted from multiple users over independent fading channels. Then, we will consider the condition of unaligned OFDM-GDMA.

A. GAIN DIVISION MULTIPLE ACCESS (GDMA)

Assuming a perfect timing alignment, the signals from U users are transmitted to the receiver through independent fading channel. At the receiver side, let $r = \{r(1), \ldots, r(N)\}$ represent a packet which is a sequence of N received symbols, where the ith received symbol is

$$r(i) = \sum_{u=1}^{U} h_u x_u(i) + w(i) = s(i) + w(i), \qquad (1)$$

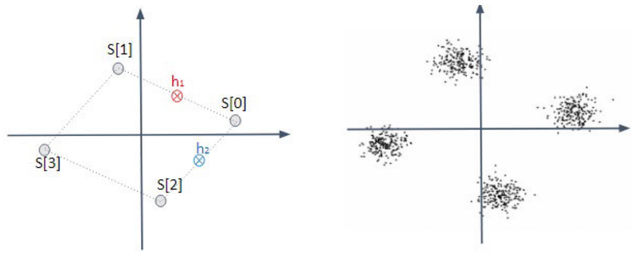

FIGURE 1. An example of superimposed symbols and the clustering of received symbols for $m = 1$ and $U = 2$.

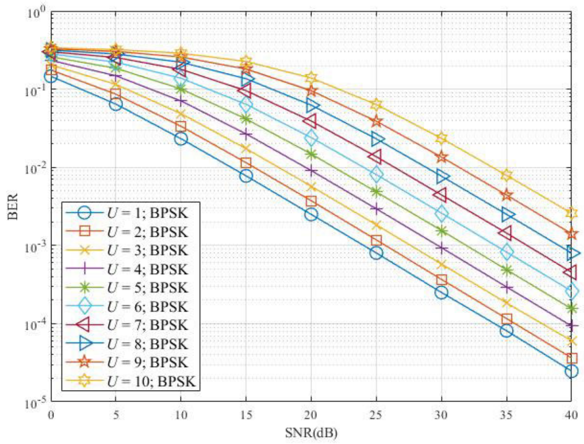

FIGURE 2. BER performances of BPSK-GDMA over quasi-static Rayleigh Fading Channels.

where $x_u(i)$ is the ith symbol transmitted by user u, h_u is the complex channel gain between user u and the receiver, $w(i)$ is the complex AWGN with variance $\sigma_w^2 = N_0/2$ in each dimension and $s(i) = \sum_{u=1}^{U} h_u x_u(i)$ is a superimposed signal. In the rest of this paper, we remove the symbol index i to simplify the notations. In addition, there are $L = 2^{mU}$ possible outcomes (levels) in s. We denote the lth level of s by $S[l]$, where $l = 0, 1, \ldots, L-1$. An example for $m = 1$ and $U = 2$ are illustrated in the left side of Fig. 1.

The idea of GDMA [19] is that the collision detection can be implemented by calculating the *a posteriori* probability (APP) p_l for each $S[l]$ and then apply the MAP (maximum *a posteriori*) decision, where

$$p_l = \Pr\{s = S[l] | r\}. \qquad (2)$$

For maximum likelihood decision, the detection is simply to find the $S[l]$ which is nearest to r. The bit error rate (BER) performances for the BPSK modulated GDMA with perfect CSI for $U = 1, 2, \ldots, 10$ are provided in Fig. 2, where each user goes through an independent quasi-static frequency-flat Rayleigh fading channel. We see that even for the collision of $U = 4$ users, the BER is still below 10^{-2} at $E_b/N_0 = 20$ dB.

1) OFDM-GDMA

The above detection concept can be extended to an orthogonal-frequency division multiplexing (OFDM). For each $j \in \{0, 1, \ldots, N/(mQ) - 1\}$, the subblock $[x_u(jQ+1), x_u(jQ+2), \ldots, x_u((j+1)Q)]$ is converted into time domain

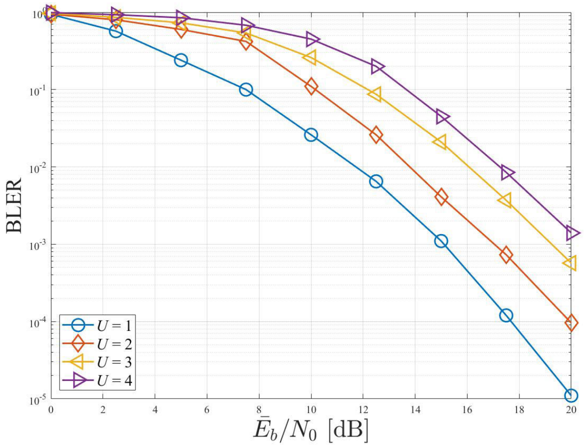

FIGURE 3. BLER of BPSK modulated OFDM-GDMA over 5-tap Rayleigh fading channels encoded by (1008,504) LDPC code.

signals through the Q-point inverse fast Fourier transform (IFFT). A cyclic prefix (CP) is inserted so as to avoid inter-symbol interference (ISI) and inter-carrier interference (ICI). On the receiver side, following CP removal and the Q-point FFT process, the frequency domain signal is then sent to implement the GDMA detection. Let $H_u(q)$ be the channel gain between user-u and the receiver over the q-th sub-channel for $q \in \{1, \ldots, Q\}$. For the frequency domain signal, the component in the q-th sub-channel is

$$r(jQ+q) = \sum_{u=1}^{U} H_u(q)x_u(jQ+q) + W(jQ+q), \quad (3)$$

where $W(jQ+q)$ is the AWGN. Consider an example for which a 504-bit message is encoded by a (6,3) regular (1008,504) LDPC code. The 1008 code bits are mapped to 63 BPSK OFDM symbols. Each OFDM symbol contains a cyclic prefix (CP) of length 4 and its Q is 16. Each user goes through a 5-tap Rayleigh fading channel that has exponentially decay power in taps. From Fig. 3, we see that for the collision of $U = 4$ users, the block error rate (BLER) is around 10^{-3} at $E_b/N_0 = 20$ dB, where CSI is available to the receiver.

2) PILOT-FREE CHANNEL ESTIMATION

GDMA has the advantage that it is suitable for pilot-free channel estimation using the clustering technique. In [20], the set $\{r(1), \ldots, r(N)\}$ are divided into L groups according to the clustering technique, where the centroids of the L groups are the estimates of the superimposed signals $S[0], S[1], \ldots, S[L-1]$. Then, the estimates of channel gains $h_1, h_2, \ldots, h_U$ are obtained from the estimates of $S[0], S[1], \ldots, S[L-1]$. Illustration of the clustering can be found in the right side of Fig. 1. We see that the centroids of the four groups can be used to estimate $S[0], S[1], S[2], S[3]$, which will enable us to recover h_1 and h_2. The accuracy of the clustering estimation for GDMA depends on the number of received symbols and the specific clustering technique. In this paper, a modified k-means++ [20], [21] will be used for clustering.

TABLE 1. Settings of the collision detection for user 1, $m = 1$.

Case	Parameter Setting	Collision Condition
1	$\sigma_w = \sigma_{\text{awgn}}; L = 4$ $j = 0, 1, \cdots \frac{N}{Q} - 1$	$0 \leq \tau_2 - \tau_1 \leq \text{CP}$
2	$\sigma_w = \sigma_{\text{awgn}}; L = 2$ $j = 0, 1, \cdots i - 1$	$iN_s \leq \tau_2 - \tau_1 \leq iN_s + \text{CP}$
	$\sigma_w = \sigma_{\text{awgn}}; L = 4$ $j = i, i+1, \cdots, \frac{N}{Q} - 1$	
3	$\sigma_w = \sigma_{\text{awgn}}; L = 2$ $j = 0, 1, \cdots, i - 1$	$iN_s + \text{CP} < \tau_2 - \tau_1 < (i+1)N_s$
	$\sigma_w = \sigma_{\text{adjust}}; L = 4$ $j = i, i+1, \cdots, \frac{N}{Q} - 1$	

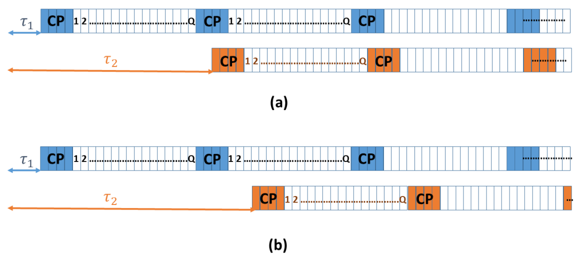

FIGURE 4. Asynchronous OFDM packets (a) case 2 (b) case 3.

B. UNALIGNED COLLISION IN THE OFDM SCHEME

The OFDM-GDMA can be applied to cope with the collision in the un-slotted (asynchronous) system. Consider the condition of $U = 2$ and two packets collided in a channel. The packet of user 1 arrived at time τ_1 and the packet of user 2 arrived at time τ_2, where $\tau_2 > \tau_1$. User 1 is assumed to be a desired user, and the receiver is aligned to user 1. Let $p_{q,l}$ be the APP of the qth subchannel at the lth level. With equally likely *a priori* probabilities, we have $p_{q,l} = \frac{1}{2\pi\sigma_w{}^2} \exp\left(-\frac{|r-S[l]|^2}{2\sigma_w{}^2}\right); l = 0, 1, \cdots L-1; q = 1, 2, \cdots, Q$. Since only BPSK modulation is considered in this paper, we set $m = 1$. In addition, the parameters σ_w and L may vary according to different conditions which are shown in Table 1. For clearly discussing the detection under different time drifts, we classify it into three cases which are shown in Table 1.

Consider case 1 for which we have $0 \leq \tau_2 - \tau_1 \leq CP$. In a slotted system, all devices are synchronized before transmitting packets. However, it may be difficult to guarantee that all the devices are perfectly aligned to receiver. Multiple users can be detected by conventional GDMA if the timing drifts are restricted in a tolerance range specified by the cyclic prefix (CP), where the timing drift in the time domain corresponds to only a phase shift in the frequency domain. Hence, such a collision can be resolved to recover message from both user 1 and user 2 just like the case of perfect timing. Note that, increasing the tolerance range, i.e., CP, will decrease the transmission rate.

In the un-slotted system, each device for transmission may not be synchronized with the receiver. For the detection of messages from user 1, the collision condition can be any of cases 1, 2 and 3. The illustration of case 2 and case 3 is provided in Fig. 4.

For case 2, we have $i \cdot N_s \leq \tau_2 - \tau_1 \leq i \cdot N_s + \text{CP}$; $i = 1, 2, \cdots, \frac{N}{Q}, N_s = \text{CP} + Q$. Although each of the packet for user 1 and user 2 contains $\frac{N}{Q}$ subblocks, the superposition of the two packets must be described by $\frac{N}{Q} + i$ subblocks. For $j = 0, 1, \cdots, i-1$, there is no collision for the symbol of user 1. Hence, we set $U = 1$ in applying the APP detector. For $j = i, i+1, \cdots, \frac{N}{Q} - 1$, the symbols of user 1 and user 2 collide. Hence, we set $U = 2$ and apply the GDMA detector.

For $U = 2$, the timing drift between the two collided subblocks is within the range of CP. Like case 1, such a timing drift will only results in a phase shift in the frequency domain.

For case 3, we have $i \cdot N_s + \text{CP} < \tau_2 - \tau_1 < (i+1) \cdot N_s$, where $i = 0, 1, \cdots, \frac{N}{Q}$. If $j = 0, 1, \cdots, i-1$, there is no collision for the symbol of user 1. Hence, we set $U = 1$ in applying the APP detector. If $j = i, i+1, \cdots, \frac{N}{Q} - 1$, the symbols of user 1 and user 2 collide. Hence, we set $U = 2$ and apply the GDMA detector.

Unlike case 2, for $U = 2$, the timing drift between the two collided subblocks is not within the range of CP.

By treating the OFDM symbol of user 1 in a subblock as a complete OFDM symbol, the OFDM symbol of user 2 is not a complete OFDM symbol. This will generate multiple access interference (MAI). Hence, we also need to consider the MAI variance for APP detector. The σ_w^2 for detecting APPs must be modified as $\sigma_w^2 = \text{MAI variance} + \text{AWGN variance}$. Since the MAI noise is dependent on the signal-to-noise ratio (SNR) condition, we adjust σ_w^2 according to the SNR, which is expressed as $\sigma_w^2 = (\sigma_{AWGN} + \nu \cdot \sqrt{\text{snr(dB)}})^2$, where $\text{snr(dB)} = 10 \cdot \log(\frac{E_s}{2 \cdot R \cdot \sigma_w^2})$ and ν is a predefined parameter obtained through simulation. This SNR can also be obtained through estimation.

For both cases 2 and 3, after the messages from user 1 are recovered, the contribution of user 1 in $\{r(1), \ldots, r(N)\}$ can be removed and then the messages from user 2 can be retrieved.

In the random access, the collision incurred by more than two users may occur. When more than two users collide, the system will first treat the packets transmitted by users other than user 1 and user 2 as noise. After the packets of user 1 and user 2 are recovered, we can process the detection of the packets of other users by removing the interference from the packets of users 1 and users 2.

IV. GDMA ASSISTED RANDOM ACCESS SCHEME

We now propose to integrate OFDM-GDMA into the ALOHA protocol, denoted OFDM-GDMA-ALOHA, with various degrees of coordination effort required by the devices, including (i)unslotted OFDM-GDMA-ALOHA with estimated channel information and estimated timing, (ii) unslotted OFDM-GDMA-ALOHA with estimated channel state information (CSI) and perfect timing, (iii) slotted OFDM-GDMA-ALOHA with estimated CSI and (iv) slotted OFDM-GDMA-ALOHA with perfect CSI. For the unslotted OFDM-GDMA-ALOHA with estimated channel information and estimated timing, the required coordination can be minimized. For the slotted OFDM-GDMA-ALOHA with perfect CSI, the needed coordination effort is more than the other three systems while the throughput will be the best. Note that we consider BPSK modulation only.

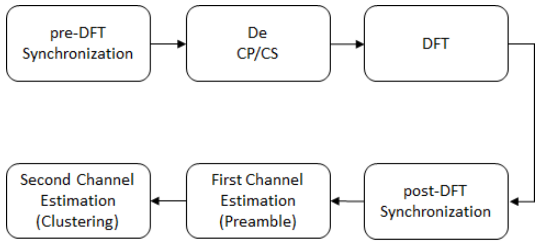

FIGURE 5. Synchronization and channel estimation process.

A. UNSLOTTED OFDM-GDMA-ALOHA

For the unslotted OFDM-GDMA-ALOHA with estimated channel information and estimated timing, a preamble sequence is used to obtain coarse timing synchronization and coarse channel estimation, while fine timing synchronization is obtained through finding the strongest tap gain estimate and fine channel estimation is obtained through the clustering used for GDMA.

1) PREAMBLE AND ESTIMATION

There are some widely used preamble sequences, Zadoff-Chu (ZC) sequence, maximum-length sequence (m-sequence), Gold sequence, etc. For our uplink application, a large number of sequences are needed for the pool of preamble sequences so that the numerous devices can select the sequences with little probability of collision. For a given sequence length, the number of available m-sequences is much less than the number of available ZC sequences. In addition, in our uplink application, the cross-correlation between different sequences should be small. The property of cross-correlation for the Gold sequence does not meet this requirement. Hence, we use Zadoff-Chu (ZC) sequence [28] as preamble sequence. The ZC sequence is also used in the 3GPP NR as Primary Synchronization Signal(PSS), random access preamble(PRACH), etc.

The Zadoff-Chu sequence at position n is given by

$$\begin{aligned} z_p[n] &= e^{-j\pi pn(n+1)}, \quad 0 \leq n \leq N_{ZC} - 1 \\ p &\in \{1, \cdots, N_{ZC} - 1\}, \quad \forall \gcd(N_{ZC}, p) = 1, \end{aligned} \tag{4}$$

where p is the root index.

Suppose that each user randomly chooses a preamble sequence from the set $\{z_p : p \in \{1, \cdots, N_{ZC} - 1\}, \gcd(N_{ZC}, p) = 1\}$. Fig. 5 is the flow chart of synchronization and channel estimation, where pre-DFT synchronization is the coarse-timing estimation, and post-DFT synchronization is the fine-timing estimation. The channel estimation can also be divided into two steps, where the first channel estimation only uses the preamble sequence to derive coarse gain estimation. The second channel estimation uses the clustering technique to acquire fine gain estimation based on the first channel estimation result.

2) COARSE TIMING ESTIMATE

Coarse synchronization in this paper is implemented by the cross-correlation method, where the received signal is cross-correlated with receiver-generated preamble symbol sequence z_p. Estimated rough time offset is derived by choosing the mean of timing metric trajectory peak.

Define the timing metric $c[n]$ by

$$c[n] = \frac{\sum_{i=0}^{N_{ZC}} (z_p[i] - \bar{z}_p)^* (y[n+i] - \bar{y})}{\sqrt{\sum_{i=0}^{N_{ZC}} (z_p[i] - \bar{z}_p)^2 \sum_{i=0}^{N_{ZC}} (y[n+i] - \bar{y})^2}}, \quad (5)$$

where $y[i]$ is the received sample at time i, $\bar{y}$ is the mean of y, $\bar{z}_p$ is the mean of z_p. The timing metric has absolute value less than 1, i.e., $|c[n]| < 1$. If the timing metric is greater than a threshold μ at time $\widehat{\theta}$, then the Time offset is estimated as $\widehat{\theta}$.

In an AWGN channel, the coarse estimated time offset is close to the exact timing point, but in multipath channels it would be shifted (delayed) due to the channel dispersion.

3) FINE TIMING ESTIMATE

For deriving a more accurate timing offset in a multipath channel, the fine time offset is necessary. The coarse timing estimate may be erroneously estimated at one of the delayed path (tap) rather than the first path (tap). If the delay in channel estimate can be found, the effect of the multipath channel response on the timing estimation can be removed from the coarse-timing estimation. In other words, the coarse timing estimate can be fine-tuned by adding the delay of the first actual channel tap. Define the fine time offset $\hat{\epsilon} = \hat{\theta} - \theta$, where θ is the exact timing offset. For finding the delay of the first actual channel tap [29], firstly, the strongest tap gain estimate $\hat{h}_{max}$ is found as

$$\hat{h}_{\max} = \max_{l}\{h[l] : l = 0, 1, \cdots, K^{\dagger} - 1\}. \quad (6)$$

Then, the delay estimate of the first actual channel tap $\hat{\epsilon}$ is given by

$$\hat{\epsilon} = \arg\max_{l}\{E_h(l) : l = 0, 1, \cdots, K^{\dagger} - K'\} \quad (7)$$

where

$$E_h(j) = \begin{cases} \sum_{k=0}^{K'-1} |\hat{h}[l+k]|^2, & \text{if } ||\hat{h}[l]|| > \mu \cdot |\hat{h}_{\max}| \\ 0, & \text{otherwise.} \end{cases} \quad (8)$$

and $E_h(l)$ is the channel energy estimation contained in a length-K' window starts from the tap l with the condition that the channel energy estimate of the tap should be greater than threshold μ and $K^{\dagger}$ is a preset parameter. The channel gain $\hat{h}[k]$ is obtained by (9) and (10) by initially setting $\hat{\epsilon} = 0$. After $\hat{\epsilon}$ is obtained though (7), then iterative operation is implemented to update $\hat{\epsilon}$.

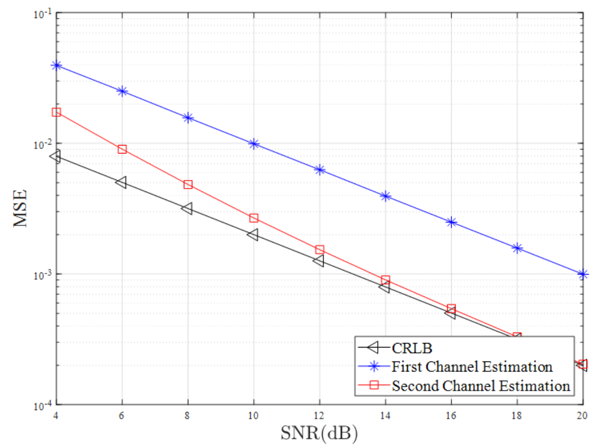

FIGURE 6. Comparison of MSE for the first (coarse) channel estimation and the second (fine) channel estimation in the unslotted OFDM-GDMA-ALOHA systems.

4) HYBRID CHANNEL ESTIMATION

Once obtaining the fine time offset $\hat{\epsilon}$, we can find the first tap of time-domain channel gains $\hat{h}[k]$ and derive the frequency domain channel gains $\hat{H}[k]$ directly by the following equations.

$$\hat{H}[k] = \frac{Y[k]}{Z_p[k]} e^{\frac{j2\pi k \hat{\epsilon}}{N}}, \quad k = 1, \cdots, N_{ZC} \quad (9)$$

$$\hat{h}[k] = \mathrm{IDFT}_{N_{ZC}}(\hat{H[k]}), \quad k = 1, \cdots, N_{ZC} \quad (10)$$

where $Y[k]$ and $Z_p[k]$ are obtained by the DFT of $y[k]$ and $z_p[k]$ respectively. Usually, the preamble length N_{ZC} is different from the sub-carrier size Q. Apparently, the estimated channel gains $\hat{H}[k]$ will not be the same as sub-carrier channel gains $\tilde{H}$, which can be derived as

$$\tilde{H}[k] = \mathrm{FFT}_Q(\hat{h[k]}), \quad k = 1, \cdots, Q, \quad (11)$$

where first Q symbols out of the $\hat{h[k]}$ sequence of length N_{ZC} are used.

Now we have the coarse channel estimation $\tilde{H}[k]$. In [20], it has been proposed that using the clustering technique, we are able to find pilot-free channel estimation. The basic idea of the clustering technique is to firstly divide a sequence of received symbols into $L = 2^{mU}$ groups, and then find the centroid of each group as the estimate of the noise-free collide symbol. The estimated channel gains can then be obtained by the set of the estimated noise-free collided symbols. In the clustering technique, the centroids are obtained iteratively. The choice of initial centroid(s) is essential. Since we have the coarse channel estimation, we can set initial centroids with substantial reliability. Hence, we are able to find the final centroids with much ore reliability. Then, we can have the fine channel estimation, denoted by $\breve{H}[k]$.

5) SIMULATION

In the simulation, each packet has identical setting and contains a preamble sequence and OFDM sequence. For each packet, a 504-bit message is encoded by a (6,3) regular

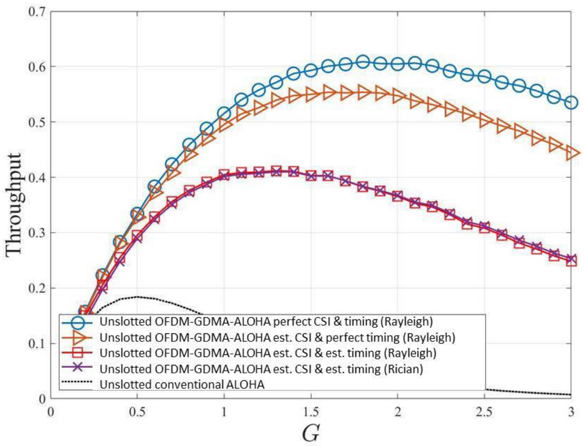

FIGURE 7. **Throughput performances of unslotted OFDM-GDMA-ALOHA and the conventional unslotted ALOHA.**

(1008,504) LDPC code. The 1008 code bits are mapped to 63 BPSK OFDM symbols. Each OFDM symbol contains a cyclic prefix (CP) of length 4 and its Q is 16. The preamble sequence is composed of a CP of length 4 and a CS (cyclic suffix) of length 4 and a Zadoff-Chu sequence of length 63 with $N_{ZC} = 63$ and $p = 25$. In the time domain, a packet length is $T_p = (CP + N_{NC} + CS) + (CP + Q) \times P = (4 + 63 + 4) + (4 + 16) \times 63 = 1331\ T_s$, where T_s is time unit, CP, CS and P are the lengths of cyclic prefix, cyclic suffix, and the number of OFDM symbols respectively.

- We first examine the mean-square-error (MSE) performance of first (coarse) and second (fine) channel estimation. Consider the environment of two users in collision, where the difference between the beginning time of the two collided packets is uniformly distributed within the time of a packet length T_p. Using the 5-tap Rayleigh fading channel that has exponentially decay power in taps, Fig. 6 shows the MSE performance of first and second channel estimation for various SNR values. Note that the second estimation is very close to the Cramer-Rao lower bound (CRLB) at SNR = 20 dB, where perfect timing estimation is assumed.
- We next examine the throughput performance at SNR = 20 dB. Assume that packets transmission is a Poisson process having an average rate of λ packets/s at receiver. The normalized channel traffic G, is defined as $G = \lambda \cdot T_p$ packets/duration, where the duration is the period of a packet. Let TR be the random variable representing the number of transmitted packets from various devices within a time duration. For a time duration, the probability of there being k transmitted packets is

$$P(\mathrm{TR} = k) = \frac{G^k e^{-G}}{k!} \tag{12}$$

We use the exponential distribution $f(x) = Ge^{-Gx}$, $x \geq 0$ to simulate the time offset at receiver, e.g., the difference between i-packet and $i+1$-packet is $T_p \cdot f(x)$.

The throughput performances at SNR = 20 dB are shown in Fig. 7. One of the curve is implemented based on Rician channel. There are three curves implemented based on a 5-tap Rayleigh fading channel that has exponentially decay power in taps. Compared to the conventional unslotted ALOHA, the unslotted Aloha assisted by GDMA (OFDM-GDMA-ALOHA) has significant improvement of throughput performance. For the conventional unslotted ALOHA, the largest throughput $S \approx 0.1839$ packets/T_p can be observed at $G = 0.5$. For OFDM-GDMA-ALOHA with perfect timing and perfect CSI, the largest throughput $S \approx 0.6088$ can be observed at $G = 1.8$. For OFDM-GDMA-ALOHA with both timing estimation and channel estimation, the largest throughput $S \approx 0.4107$ can be observed at $G = 1.4$. This throughput is still much better than the conventional unslotted ALOHA. For conventional slotted ALOHA, its largest throughput is 0.368 which occurs at $G = 1$.

B. SLOTTED OFDM-GDMA-ALOHA

The lack of synchronization of slots in the unslotted OFDM-GDMA-ALOHA limits its throughput even if perfect CSI and perfect timing are available. To see the power of the assumption of perfect synchronization of the arrival of packets from various users, we provide the throughput simulation of slotted OFDM-GDMA-ALOHA in Fig. 8 where the settings are identical to those for the unslotted case in the last subsection except for the fact that there is no need for Zadoff-Chu sequences as preambles for timing estimation and channel estimation. Since there is no ZC sequence as preamble in the slotted case, the channel estimation is implemented solely based on the clustering technique.

The throughput of any ALOHA protocol can be calculated by

$$\eta = \sum_{k=1}^{\infty} \sum_{i=1}^{k} i \cdot P(\mathrm{NSP} = i | \mathrm{TR} = k) P(\mathrm{TR} = k) \tag{13}$$

where NSP denotes number of successful packets. Consider the extreme limit of which every packet can be successfully recovered, i.e.,

$$P(\mathrm{NSP} = k | \mathrm{TR} = k) = 1, \tag{14}$$

Hence,

$$\sum_{i=1}^{k} i \cdot P(\mathrm{NSP} = i | \mathrm{TR} = k) = k. \tag{15}$$

We find that η equals the mean of TR, i.e.

$$\eta = \sum_{k=1}^{\infty} k \cdot P(\mathrm{TR} = k) = G. \tag{16}$$

From Fig. 3, we see that even for $U = 4$ collided packets, the BLER is around 10^{-3}. That means $P(\mathrm{NSP} = k | \mathrm{TR} = k) \approx 1$ for $k = 1, 2, 3, 4$. Hence, it is not surprising to

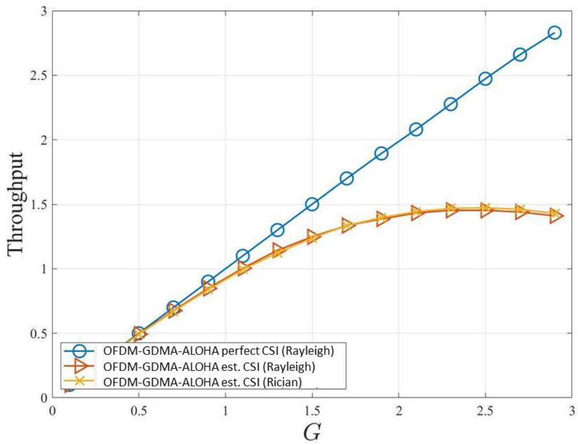

FIGURE 8. **Throughput performances of slotted OFDM-GDMA-ALOHA.**

see that the curve in Fig. 8 with perfect CSI, shows that the throughput η of slotted OFDM-GDMA-ALOHA is close to G. As G increases beyond 2, the throughput for slotted OFDM-GDMA-ALOHA with estimated channel begins to decrease. This phenomenon can be explained by the condition that when more users collided in a slot, the channel estimation using clustering is less accurate and hence the BLER of OFDM-GDMA is worse.

C. UPLINK CHANNELS

The resolution of collision in the OFDM-GDMA-ALOHA depends on the difference of channel gains between every pair of devices. In Section IV-A and IV-B, each of the uplink channels is assumed to be a 5-tap Rayleigh fading channel that has exponentially decay power in taps. In each of Fig. 7 and Fig. 8, there is a curve simulated based on assumption that each uplink channel is the Rician channel model which is obtained by adding a direct path (i.e., a line of sight path) to the 5-tap Rayleigh fading channel, where the signal of direct path contains 50% of the total power. Directly applying the direct path for each user in the GDMA is not appropriate for distinguishing users. To combat this drawback, signal transmitted by each user (device) is randomly rotated. This arrangement will avoid the condition (or reduce the probability) of similar channels associated to different devices. From Fig. 7 and Fig. 8, we see that the simulation results both the Rayleigh fading channel and the Rician fading channel are very close.

In the mobile communications, the movement of vehicles will result in time-varying fading channels. In the MTC, the devices for communications are not operated by the human and usually are not moving. Hence, in this paper, we only consider fading channels which are not time-varying. However, the applications of MTC may be extended to include moving devices. Hence, in the future work of OFDM-GDMA-ALOHA should include time-varying channels. One of the possible problems is that the clustering around the centroid $\sum_{u=1}^{U} h_u x_u$ can be implemented for only a short time period where each h_u remains constant. The other problem is that the ZC sequence is vulnerable the carrier frequency offset (CFO) caused by Doppler shift [30]. This will in turn deteriorate the timing estimation and coarse channel estimation. Solving these two problems will be a challenging work.

V. CONCLUDING REMARKS

We apply OFDM-GDMA to combat the collision problem in the ALOHA system. System throughput and the coordination effort required by all the devices and the receiver are two factors to be considered. Systems with various degrees of coordination effort are provided. For unslotted OFDM-GDMA-ALOHA using Zadoff-Chu (ZC) sequence as preamble for timing estimation and channel estimation, the devices require the least coordination effort. Although the throughput performance is worst of all the OFDM-GDMA-ALOHA systems in consideration, such throughput performance is still much better than the conventional unslotted ALOHA without resolving the collision. For slotted OFDM-GDMA-ALOHA with perfect timing and CSI, the devices require the most coordination effort, while the associated throughput performance shows the upper limit of all the systems in consideration.

The usage of ZC sequence for timing and coarse channel estimation is independent of the modulation for data transmission. The fine channel estimation will utilize the received data, where the clustering method divide the sequence of received symbols into $L = 2^{mU}$ groups and then finding the centroid of each group. In this paper, the simulation is implemented for only BPSK modulation for which $m = 1$. The concept of this paper can be extended to other modulations. For example, we may use QPSK modulation for which $m = 2$. However, increasing m will result in the deterioration of the performance of fine channel estimation.

In this paper, we consider the Rayleigh fading channel and the Rician fading channel, where for each device the expected value of the associated channel gain is equal to the expected value of any other device and the transmitted power is equal to the transmitted power of any other device. In practical applications, there may be a weak user (device) for which the expected value of the associated channel gain is much less than the expected values of others. Hence, the weak user needs to increase its transmitted power to roughly make up for the loss of channel gain. Note that for each device the in OFDM-GDMA-ALOHA, the information of the exact power level is not necessary. Only the knowledge of a rough power level is needed. In contrast, for each device in PD-NOMA-ALOHA, knowledge of accurate power level is needed.

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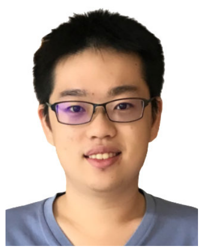

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