Grant-Free Random Access in Machine-Type Communication: Approaches and Challenges

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Abstract-Massive machine-type communication (MTC) is expected to play a key role in supporting Internet of Things (IoT) applications such as smart cities, smart factory, and connected vehicles through cellular networks. MTC is characterized by a large number of MTC devices and their sparse activities, which are difficult to be supported by conventional approaches and motivate the design of new access technologies. In particular, in the 5th generation (5G), grant-free or 2-step random access schemes are introduced for MTC to be more efficient by reducing signaling overhead. In this article, we first introduce grantfree random access and discuss how it can be modified with massive multiple-input multiple-output (MIMO) to exploit a high spatial multiplexing gain. We then explain preamble designs that can improve the performance and variations based on the notion of non-orthogonal multiple access (NOMA). Finally, design challenges of grant-free random access towards next generation cellular systems are presented.

Index Terms—Machine-Type Communication, Random Access, Multiple-Input Multiple-Output

I. INTRODUCTION

In order to support the connectivity of a large number of devices and sensors (or things) within cellular systems, machine-type communication (MTC) has been actively studied. Thanks to MTC for massive access [1], various applications of the Internet-of-Things (IoT) with myriads of devices deployed over a large geographic area (e.g., smart factory, smart cities, and intelligent transportation) become possible.

MTC differs from human-type communication (HTC) in a number of ways. For example, MTC is expected to support massive and burst traffic due to a massive number of devices and sparse activity of each device. In particular, MTC is expected to support up to 1 million devices per km², and devices usually have low duty cycle and transmit small payloads. Clearly, HTC's transmission schemes not suitable for MTC as they result in a high signaling overhead. Therefore, it is expected that media access protocols based on random access will be preferred to provide MTC services. In addition, MTC should be very efficient in providing connectivity with limited bandwidth, since there are a large number of MTC devices and sensors. As such, there is increasing interest in the development of various new transmission methods and media access protocols with low signaling overhead and high spectral efficiency for MTC.

Random access channel (RACH) procedure is widely used in cellular systems to establish a connection from a user to its base station (BS) and to be assigned channel resources for uplink transmission by the user. RACH procedure is also used for MTC. When a device becomes active and wants to transmit its data, it can choose one of pre-defined preambles and transmit it, which is the first step of RACH procedure. Since multiple devices can be active at the same time and choose any preambles randomly, RACH procedure can be seen as a contention-based access. In particular, preamble collision happens when multiple active device chooses the same preamble. Due to multiple preambles, RACH procedure can be modeled as a multichannel (slotted) ALOHA, where each preamble can be seen as a channel. The performance of MTC is limited due to preamble collision and the probability of preamble collision grows exponentially with the number of active devices. Thus, access control and dynamic resource allocation become crucial in MTC [1].

Recently, a new random access scheme, called 2-step random access, is proposed for MTC in the 5th generation (5G) by the 3rd generation partnership project (3GPP) to further reduce signaling overhead [2] [3]. In 2-step random access, unlike RACH procedure, an active device does not wait for a response from the BS after transmitting the preamble, and immediately transmits data packet. Thus, it is expected to shorten access delay, which is desirable for low latency applications, and improve the throughput so that more devices can be supported for massive MTC. 2-step random access is also called grant-free (GF) random access, because active devices transmit data packets without obtaining any reserved channel resources.

Multiple-input multiple-output (MIMO) has been extensively investigated to improve the spectral efficiency of wireless communications over the past 30 years. In particular, the notion of massive MIMO was exploited to take advantage of the high spatial multiplexing gain of BSs equipped with largesize antenna arrays [4]. Thus, massive MIMO can also be a solution to support a large number of devices in MTC with limited bandwidth together with GF random access [5] [6]. A salient feature of GF or 2-step random access facilitated by massive MIMO is that both the two steps can be carried out on a single channel resource, which can further make GF random access simple and efficient.

Like 4-step random access, an active device is to transmit a randomly selected preamble in 2-step or GF random access, which also allows for BSs to estimate device's channel state information (CSI) or channel vector for successful decoding of data packets in massive MIMO. Consequently, preamble design becomes crucial not only for random access, but also for successful decoding in GF random access with massive MIMO. More preamble sequences are needed to support more devices in GF random access, which may require more radio resources. Thus, efficient approaches to generate more preambles are highly desirable. In addition, non-orthogonal multiple access (NOMA) [7] can be employed for the spectral efficient GF random access to improve in spectral efficiency. In this article, we present the key ideas of GF random access with improved performance by massive MIMO, semi-GF transmission facilitated by NOMA, and discuss preamble designs and the application of NOMA for variations of GF random access.

Note that a comprehensive overview of 2-step random access standardized for MTC in 5G [2] can be found in [3]. As such, in this article, we mainly focus on fundamentals of GF or 2-step random access with massive MIMO and discuss possible its variations. In addition, design challenges of GF random access are discussed from the perspective of the 6th generation (6G) [8].

In the remainder of this article, we first explain 4-step and 2-step random access schemes for MTC. We then show how massive MIMO can be employed for 2-step random access to significantly improve spectral efficiency. Since the performance of 2-step random access also depends on preambles, we discuss preamble designs. A number of variations of 2-step random access are also discussed. We also identify challenges of GF random access towards next generation of mobile networks, i.e., 6G.

II. RANDOM ACCESS PROTOCOLS IN MTC

In MTC, uplink transmissions can be carried out based on 4-step random access procedure, which is illustrated in Fig. 1. The first step is random access to establish connection to the BS with a pool of preambles consisting of L sequences. In the first step, an active user equipment (UE) transmits a randomly selected a preamble on physical random access channel (PRACH). In the second step, the BS detects the preambles transmitted by active UEs and sends responses. Once an active UE is connected to the BS, it can transmit data packets in the third step on dedicated resource blocks (RBs) or channels¹, which are physical uplink shared channel (PUSCH).

Compared with 4-step random access approaches, 2-step random access [2], which is also referred to as GF random access, can be more efficient thanks to low signaling overhead when UEs or devices have short messages to transmit. In 2-step random access, an active device does not wait for a response from the BS, i.e., Step 3 is removed and only Steps 1 and 4 in Fig. 1 are used, where Steps 1 and 3 are combined into Step 1. That is, in Step 1, an active device is to transmit a preamble on PRACH and then transmit a payload on PUSCH in a time division multiplexing (TDM) manner.

It is also possible to reserve certain preambles for UEs that require contention-free random access. In this case, the BS sends the information of reserved preambles and PUSCH assignment prior to any random access procedure to avoid collision.

III. MASSIVE MIMO FOR GF RANDOM ACCESS

In massive MIMO, thanks to a large number of service antennas co-located at a BS, the channel hardening (i.e., the

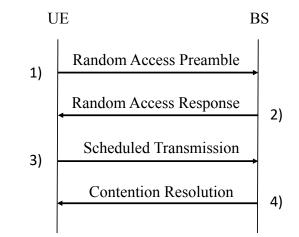


Fig. 1. 4-step random access procedure in MTC.

effect of small-scale fading is averaged out and devices' channels behave deterministic like wired channel) and favorable propagation (i.e., the propagation channels to different devices become orthogonal, which makes different devices distinguishable in space) can be exploited [4]. Taking advantage of these two features, it is possible to spatially separate signals that are simultaneously transmitted by multiple MTC devices that share the same channel in GF random access.

Massive MIMO can make GF random access further efficient by allowing transmissions of preambles and payloads on the same channel resource. In particular, for the first step that has preamble and data transmission phases, one time slot (or one channel resource) can be used as illustrated in Fig 2. Each active device chooses a preamble from a pool of L preambles uniformly at random, and transmit it in the preamble transmission phase. In the data transmission phase, a data packet is then transmitted. Since all the devices are synchronized in MTC, it is expected that the length of data packet is the same for all devices (or the length of data transmission phase is decided by the maximum length of data packet among all the devices). Because of the orthogonality among those spatial channels, the BS is able to decode each of co-existing signals transmitted by multiple active devices on the same channel resource during the data transmission phase without any orthogonal multiple access schemes (e.g., time division multiple access) [5] [6].

To decode co-existing signals via beamforming, the BS needs to estimate the spatial channels of active devices. An active device's channel can be estimated if its preamble is not transmitted by other active devices (i.e., there is no preamble collision). As a result, the performance of GF random access with massive MIMO hinges on how to minimize preamble collisions.

IV. PREAMBLE DESIGNS

Although massive MIMO can offer a high spatial multiplexing gain, the number of active devices that can successfully transmit their payloads is limited by the number of preambles, L, in GF random access. Thus, to fully exploit

¹We will use the terms resource block and channel interchangeably.

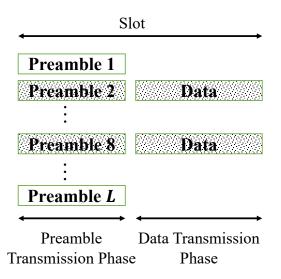


Fig. 2. A slot consisting of two phases, namely preamble and data transmission phases, for a 2-step random access scheme (the shaded blocks represent transmitted signals, i.e., there are two active devices transmitting preambles 2 and 8).

a high spatial multiplexing gain, it is desirable to generate a larger number of preambles to support a large number of devices without increasing the length of preamble transmission phase. In this section, we present a few approaches that can effectively generate more preambles.

A. Multiple Preambles

To mitigate preamble collision with a finite number of orthogonal preambles, preamble designs can be based on multi-preamble transmissions within a transmission frame [5], where a frame consists of multiple slots and a slot is further divided into two sub-slots for preamble and data transmission phases as in Fig. 2. Each device has a unique preamble-hopping pattern across multiple slots, which is assigned by the BS. Let *B* denote the number of slots per frame. Provided that there are *L* orthogonal preambles, there can be L^B different preamble-hopping patterns. In other words, up to L^B devices can be supported with different preamble-hopping patterns.

A similar multi-slot transmission structure can be found in [9], where the notion of coded random access is employed. In coded random access, each active device transmits multiple randomly selected preambles within a frame, while the same data packet is repeatedly transmitted (which differs from the approach in [5] where a device transmits different data packet in each slot). Within a frame, there can be time slots with collision-free transmissions that allow interference-free channel estimation of some devices and then successful decoding of their data packets. The BS then applies successive interference cancellation (SIC) in order to remove the signals of these devices in all the slots. After SIC, the BS can further find slots with collision-free transmissions and perform channel estimation and decoding, and so on. The same process is to be repeated until the BS cannot find any slot with collision-free transmission.

With a finite number of orthogonal preambles, these multislot transmission schemes have the potential to increase the number of active devices by mitigating/resolving the preamble and data collision in GF random access at the cost of power consumption at devices due to multiple transmissions.

B. Non-Orthogonal Preambles

A naive approach to preamble design to increase the number of preambles without increasing their length is based on non-orthogonal sequences. For example, if Zadoff-Chu sequences are used, the number of preambles can be L(L-1) with a cross-correlation of $\frac{1}{\sqrt{L}}$. Gaussian random sequences can also be used as non-orthogonal preambles, which can allow each device in the cell to have a unique non-orthogonal preamble as its signature identification, because the number of sequences can be arbitrarily large.

While making use of non-orthogonal sequences for preambles can increase the number of preambles to lower the probability of preamble collision, there is a problem in obtaining a good channel estimate that is essential in massive MIMO. Due to non-zero cross-correlation, the channel estimate is contaminated, which leads to degraded decoding performance. As a result, it is demonstrated in [10] that non-orthogonal preamble does not necessarily provide a higher success probability than its orthogonal counterpart.

It is also noteworthy that compared to orthogonal preambles, the detection of non-orthogonal preambles requires a high computational complexity and more advanced signal processing techniques [6].

In [11], in order to take both advantage of non-orthogonal and orthogonal preambles, superpositioned preambles (Spreambles) are studied. Each device uses a linear combination of few different orthogonal preambles to generate an S-preamble. For example, superposition of 2 orthogonal preambles can be considered, which can generate $\frac{L(L-1)}{2}$ Spreambles. In general, S-preambles can be viewed as structured non-orthogonal preambles. Note that unlike the approach based on multi-preamble transmissions in [5], each active device transmits one S-preamble. Therefore, the length of the preamble transmission phase in a slot does not increase. Due to the feature of S-preambles, it is possible to use lowcomplexity algorithms for the channel estimation (as the case of orthogonal preambles) with lowering the preamble collision probability (as the case of non-orthogonal preambles). Consequently, a better performance can be achieved without increasing the complexity of channel estimation.

V. SEMI-GF RANDOM ACCESS

Semi-GF transmission can offer more refined admission control compared to GF schemes [12], and yield less system overhead compared to grant-based schemes. In particular, in cellular systems, BSs can play a crucial role in providing a certain level of user coordination to improve the performance. In this section, we discuss various semi-GF approaches that can provide high spectral efficiency than pure GF approaches.

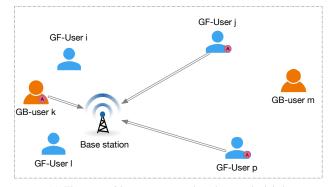
A. Semi-GF Transmission based on NOMA

The use of semi-GF transmission is motivated by the following two facts. Firstly, as mentioned earlier, in cellular systems, it is possible to take advantage of user coordination by BSs instead of relying completely on pure random access, such as GF transmission. Secondly, semi-GF transmission is able to seek more cooperation among grant-based and GF users so that limited radio resources can be more efficiently utilized. Based on these motivations, semi-GF transmission can be considered in order to encourage the spectrum cooperation among the grant-based and GF users, where the BSs are employed as an essential component for admitting GF users.

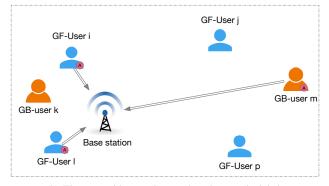
Fig. 3 describes two extreme cases which illustrate an approach of semi-GF transmission based on NOMA. In particular, in Fig. 3(a), for a case in which a grant-based user with strong channel gains is scheduled to transmit, the BS can broadcast a threshold based on the grant-based user's channel information, where only those GF users which have channel gains weaker than this threshold are allowed to compete and transmit. The BS is to decode the grant-based user's signal first prior to decoding the GF users' signals. Clearly, the BS needs to reduce the threshold in order to ensure that the grantbased user's experience is not degraded. Fig. 3(b) illustrates another extreme case, where a grant-based user with weak channel conditions is scheduled. Again the BS broadcasts a threshold. From this, only the GF users with the channel gains that are higher than this threshold can be allowed to participate in contention. The reason for this is that the BS will decode the GF users' signals first before decoding the grant-based user's signal. Again by changing the threshold, the BS is able to adaptively adjust the number of admitted GF users in a low system overhead manner.

B. Other Semi-GF Random Access Schemes

The design of preambles is crucial to the practical implementation of semi-GF transmission. In [13], a semi-GF random access with orthogonal preambles was investigated, where the BS sends the feedback after receiving preambles so that active devices with preamble collision do not transmit their data packets. This can result in a high signal-tointerference-plus-noise ratio (SINR) of the active devices that do not experience preamble collision and the increase of throughput. In [14], a compressive semi-GF random access with non-orthogonal preambles was proposed. In this scheme, compressive sensing techniques were used to detect nonorthogonal preambles that sent by devices and the information including the indices of detected transmitted preambles are feedback so that each device can be allocated a unique slot resource to transmit data packet. To achieve a higher spectral efficiency, the concept of NOMA-based GF random access was recently proposed [15]. Unlike conventional GF random access where preambles are time-multiplexed with data, i.e., preamble and data transmissions do not co-exist, NOMA-based GF random access exploits the favorable propagation of massive MIMO to allow co-existing preamble and data transmissions by two different groups of devices in each time slot; such that the resource utilization efficiency for both preamble and data



(a) The case with a strong grant-based user scheduled



(b) The case with a weak grant-based user scheduled

Fig. 3. Illustration for the principle of semi-GF transmission. For the case with a strong grant-based user scheduled, the BS invites GF users with weak channel conditions to participate in contention. For the case with a weak grant-based user scheduled, the BS invites GF users with strong channel conditions to participate in contention.

transmissions can be significantly increased, which improves the access performance for MTC devices.

VI. CHALLENGES TOWARDS 6G

The number of connected devices is expected to exceed 500 billion by 2030, while the human population is predicted to be 8.5 billion by the United Nations (UN). Clearly, the number of devices will be about 60 times the human population by 2030. Thus, MTC will play a more important role in 6G and new MTC schemes are to be developed for a variety of IoT applications using cell-free architecture, Terahertz communications, three-dimensional networking, and artificial intelligence [8]. In what follows, we will discuss potential research directions and design challenges of GF random access in 6G.

A. GF Random Access in Cell-Free Massive MIMO

Cell-free massive MIMO is regarded as a potential evolutionary technology for existing massive MIMO for 6G. In cell-free massive MIMO, the service antennas, in the form of simple and low-cost access points (APs), are distributed over a wide area without the conventional notion of cell boundaries. Several studies have shown that cell-free massive MIMO is more robust to shadow fading effect and hence can provide a better coverage than massive MIMO.

In 6G, GF random access is to be deployed with cell-free massive MIMO. However, most of the existing GF random access approaches with massive MIMO rely on the features of favorable propagation and channel hardening, which may not be applicable in cell-free massive MIMO. In particular, different from massive MIMO where the signals received at all the antennas from a device experience identical large-scale fading due to the fact that all the antennas are co-located, the signals at different antennas undergo different large-scale fading in cell-free massive MIMO. As a result, the channel hardening effect is relatively insignificant. On the other hand, cell-free massive MIMO provides other unique phenomena such as spatial sparsity and macro diversity, which are not available in massive MIMO. For example, only few antennas sufficiently close to a device can receive strong signals from the device, while the other antennas do not receive sufficiently strong signals. This spatial sparsity in cell-free massive MIMO needs to be exploited to design GF random access to support a large number of devices with their unique spatial sparsity patterns.

Another challenge is to overcome the asynchronous reception in cell-free massive MIMO for GF random access. Specifically, due to the distributed nature of the network and the differences in propagation delays, signals received from different devices at distributed antennas may not be synchronized with sufficient precision. The asynchronous reception effect may have a huge impact on the preamble detection and channel estimation, crippling the performance of GF random access. To address this issue, the preamble design that is robust to asynchronous reception can be studied together with tailored phase (or timing) estimation and compensation schemes to minimize the impact of asynchronous reception on the performance of GF random access.

B. GF Random Access for Massive URLLC

Ultra-reliable low-latency communication (URLLC) has been considered for delay-sensitive real-time applications in 5G with stringent requirements in terms of reliability and latency. In 6G, tighter requirements are expected. For example, the target error rate of 10^{-5} in 5G will be even lower to 10^{-7} in 6G. To improve reliability in 6G, various diversity techniques including multi-connectivity schemes can be employed.

In 6G, air latency is expected to be less than $100\mu s$, which makes the random access design quite challenging. To guarantee a targeted latency, contention-free random access can be used with reserved preambles in GF random access. That is, for a device with a reserved preamble, there is no re-transmission due to preamble collision and successful transmission of payload can be guaranteed within a target transmission delay time. Unfortunately, if the number of devices increases in delay-sensitive real-time applications, it can lead to a shortage of reserved preambles. Addressing this issue for massive URLLC is more challenging than massive MTC as it also needs to take the extreme reliability and latency requirements into account. To achieve a scalabilityreliability-latency tradeoff for massive URLLC, the channel inference and traffic prediction can be employed to underpin the preamble designs or management, where the temporal correlation of wireless channels and history knowledge of devices' channel and traffic states can be exploited to improve the preamble utilization efficiency, mitigate the interference originating from preamble collisions, and enhance channel estimation performance.

C. GF Random Access for 3D Networks

6G will include non-terrestrial networks (NTN) to support ubiquitous and global connectivity. In MTC, NTN will play a key role in providing global connectivity for a massive number of devices. As a result, it is necessary to develop GF random access schemes that are well-suited to threedimensional (3D) networks comprising NTN and conventional terrestrial networks. For NTN, there will be nonterrestrial nodes including unmanned aerial vehicles (UAVs), high altitude platform stations (HAPSs), and satellites. Due to the high mobility and limited energy of nonterrestrial nodes, the resulting systems exhibit different channel characteristics and deployment scenarios, which poses new challenges for random access mechanisms. In 3D networks, one major challenge is to ensure the coexistence of terrestrial and nonterrestrial devices in GF random access. As the UAVs are deployed in high altitude, the UAV-BS channels are usually dominated by lineof-sight (LoS) links, which can be significantly different from those of terrestrial devices. In addition, the deployment of UAVs in the altitude dimension also has non-negligible impact on the aerial-ground interference. Thus, new approaches to support the unprecedented aerial-ground GF random access are needed, where the channel characteristic disparity between terrestrial devices and nonterrestrial nodes, e.g., UAVs, and the deployment of UAVs in 3D networks should be taken into account in design.

In addition, in some remote areas where devices are randomly deployed (e.g., in forest for bushfire monitoring) without communication infrastructure, a swarm of UAVs can be used as gateways to collect data from randomly active devices, which results in UAV-swarm based GF random access. Different from conventional terrestrial GF random access where the locations of gateways or BSs are usually fixed on the ground, the deployment of UAV swarm in the altitude dimension can be flexibly and coordinately adjusted according to service requirements and wireless environment change. Besides, since UAVs operate under strict resource constraints such as limited battery capacity, time and energy efficiency become crucial for UAV swarm. Therefore, optimal deployment of UAV swarm needs to be carefully investigated to efficiently enable UAV-swarm based GF random access in terms of time and energy.

In 3D networks, GF random access schemes are preferred due to its spectral efficiency and low access delay, which is essential especially when devices are remotely deployed. Efficient GF random access designs therefore need to take into account channel characteristics of these networks. A crucial task for GF random access is to reduce the access delay or enhance the performance of user activity detection (UAD) and channel estimation. The joint UAD and channel estimation problem can be formulated and solved using compressive sensing or the Bayesian inference approaches for better performance.

D. Machine Learning based GF Random Access

Machine learning (ML) has been considered a powerful tool to solve complicated problems in a data-driven fashion. In GF random access, ML can be used for modeling overall processes without explicit mathematical formulations. Based on this, optimization problems for improved throughput or reliability of GF random access schemes can be formulated and solved by applying machine learning, which overcomes the difficulties due to the mathematical intractability when using non-learning methods.

Obviously, the effectiveness of ML-aided GF random access makes it a promising solution to massive access in 6G networks. However, the diverse technologies and quality-ofservice (QoS) requirements of applications that are envisioned for 6G impose challenges for ML designs. In particular, the dynamic nature in the number of active devices and services across slots becomes more significant. Thus, an efficient and unified ML framework is needed for large-scale and high dynamic 6G GF random access systems. Motivated by the fact that most devices generally fall into some types of classes where they share similar properties, e.g., the same QoS requirements, efficient ML implementations can be attained via a multi-task learning approach. In this approach, each device class is regarded as a cluster and GF resource (GFR) can be dynamically partitioned into several sub-GFRs. All devices in each cluster will select resource within each sub-GFR. Deep reinforcement learning (DRL) can be used to partition and allocate GFR adaptively. Also, the BS and devices can use ML methods to perform active device detection and GFR selection, respectively. This solution can promise to improve the training efficiency of the ML scheme, provide the flexibility of resource allocation, and reduce the complexity of data decoding.

To further improve the performance of ML-based GF random access schemes, temporal correlation characteristics of devices, i.e., sparse activities and sporadic traffic, should be exploited. Indeed, some classes of devices in practice are generally active in a regular mode with deterministic activity patterns. While the other classes of devices behave randomly, their transmit signals are usually correlated in several continuous time slots. Hence, these characteristics can be learned and predicted to some extent. One of the promising solutions to implement this is using long short-term memory (LSTM)based ML, a learning scheme that is able to remember a single event for long time periods. In particular, the history data about activities of MTC devices in previous transactions can be used to train by the BS for activity and traffic prediction in the current slot. Furthermore, devices with LSTM-based DRL algorithms can learn from their previous resource selections for efficient selections of preambles/sequences or power levels for GF random access. Finally, it would be important to take into account device activity and traffic patterns for efficient ML-based GF random access design.

VII. CONCLUSIONS

GF random access has been explained and its use with massive MIMO was discussed in this article. While GF random access can be more efficient in terms of spectral efficiency due to a high spatial multiplexing gain with massive MIMO, its performance is limited by the number of preambles. Thus, we explained a few approaches that can generate a large number of preambles. Variations of GF transmissions were also presented, which may allow us to design hybrid systems where GF and grant-based schemes can co-exist. A number of challenges of GF random access towards next generation, i.e., 6G, were identified and discussed.

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