Truly Grant-Free Technologies and Protocols for 6G

Abstract: The further integration of telecommunications and industry has been considerable and is expected to bring significant benefits to society and economics in 6G. It also forms some evolution trends for next-generation communication systems, including further rises in machine-type communications (MTC), uplink-dominated systems, and decentralized structures. However, the existing access protocols are not friendly to these trends. This paper analyzes the problems of existing access protocols and provides novel access technologies to solve them. These technologies include contention-based non-orthogonal multiple access (NOMA), data features, enhanced pilot design and successive interference cancellation (SIC) of diversity. With these key enablers, truly grant-free access can be realized, and some potential modifications of protocols are then analyzed. Finally, this paper uses massive and critical scenarios in digital transformations to show the great necessity of introducing novel access technologies into future communication protocols.

Keywords: decentralization; digital transformations; future access protocols; MTC; uplink

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1 Introduction

The targets of communications vary from connecting humans to connecting everything, and digital transformations are expected to penetrate many scenarios in 6G[1–3]. Digital transformations are expected to bring significant benefits to society. Meanwhile, digital transformations raise many new requirements, as well as set the course for future communication protocols.

To support seamless and handy digital services, there are some trends in future communications, including further evolution from human-oriented communications to machine-type communications (MTC), from the downlink-dominated to uplink-dominated, and from centralization to decentralization. This paper focuses on the truly grant-free, or contention-based grant-free, technologies and protocols, which are crucial to fulfilling ultra-low latency and ubiquitous connectivity for future communications. In current 5G standards, the grant-free definition is not truly yet as it requires extra pre-configuration of grants.

Novel access technologies are required to replace the existing ones for realizing these trends, and this paper introduces four key enablers: the contention-based non-orthogonal multiple access (NOMA), the prior knowledge of data, the enhanced pilot design, and the joint use of diversity and successive interference cancellation (SIC). NOMA was first proposed in Ref. [4], and it usually requires accurate power control and resource allocation. As a comparison, the contention-based NOMA has no such requirements and achieves a higher flexibility. The prior knowledge of data can be used to improve transmission performance. Data-only transmission was proposed in Ref. [5], which is able to remove pilot overheads. Apart from the data-only scheme, a pilot is still crucial to the full use of a large receiving antenna array where the spatial combining search space is huge. Therefore, the pilot should be well designed to gain a good detection and estimation performance[6–7]. Moreover, the joint use of diversity and SIC[8] can deal with the fluctuation of loading as it is random in contention-based transmissions. This strategy is able to average the loading in different slots via iterative detection and cancellation.

With these key enablers, users are able to transmit packets without building radio resource control (RRC) connections. That is to say, a connection-free transmission can be achieved, and the transmission no longer relies on RRC connections. This great enhancement simplifies the transmission procedures a lot, as well as reduces the overheads and latency for building RRC connections. It also leads to some possible modifications of protocols in the future, which are also analyzed in this paper.

The motivation of this paper is to discuss the importance of truly grant-free technology for future communications, summarize key enablers for it, and suggest some protocol evolution considerations. The rest of this paper is organized as follows. Section 2 introduces the main trends of future radio access networks and analyzes the problems of existing access protocols. In Section 3, some novel access technologies are provided to solve the problems. Section 4 briefly introduces the impact of these technologies on future protocols. In Section 5, two important scenarios are discussed to show the advantages of the proposed schemes. Section 6 concludes this paper and provides some future research directions.

2 Three Main Trends

In this section, three main trends of future networks are introduced. The problems of existing access protocols are analyzed under these trends.

2.1 Further Rises in MTC

The first trend is that the main participants of communications vary from humans to machines. Although massive machine-type communication (mMTC) is included in 5G, more massive and critical MTC will develop and be in demand towards 2030 and beyond[1]. Unlike human communications, the potential users can be massive and the reliability requirement can be very high. However, the classical random access protocol requires a handshaking procedure, which is not suitable for the high-efficiency transmissions of massive potential users or low-latency transmissions of high-mobility networks.

2.2 Uplink-Dominated System

The second trend is that the overall performance is becoming dominated by uplink instead of downlink transmissions. For many MTC applications, uplink is the main bottleneck[9]. Moreover, in massive multiple input multiple output (MIMO) systems, time division duplex (TDD) is much easier to realize; it uses uplink-downlink reciprocity to obtain downlink channel information. Direct downlink channel estimation is very inefficient as the overheads of downlink pilots increase with the antenna number of the base station (BS)[10]. Therefore, the pilot in the uplink becomes very important for obtaining the channel information and effectively using the capability of massive antennas of the BS. In the current protocol, the uplink pilot or demodulation reference signal (DMRS) is orthogonal among users. It limits the number of pilots and is not suitable for contention-based transmission.

2.3 Decentralized Structure

The last trend is from centralization to decentralization. This trend has many aspects, including the distributed antenna or cell-free design for ubiquitous connectivity, device-to-device transmission not relying on the central controller, and decentralized information management and control, e. g. the blockchain[11]. Although network centralization has brought us many good aspects like easy management and global control, the costs should not be neglected, including coverage, latency and privacy risk. These costs greatly limit the performance and credibility of networks.

3 Novel Access Technologies

This section analyzes four novel access technologies as shown in Fig. 1. The basic idea and advantages of these technologies are discussed.

3.1 Contention-Based NOMA

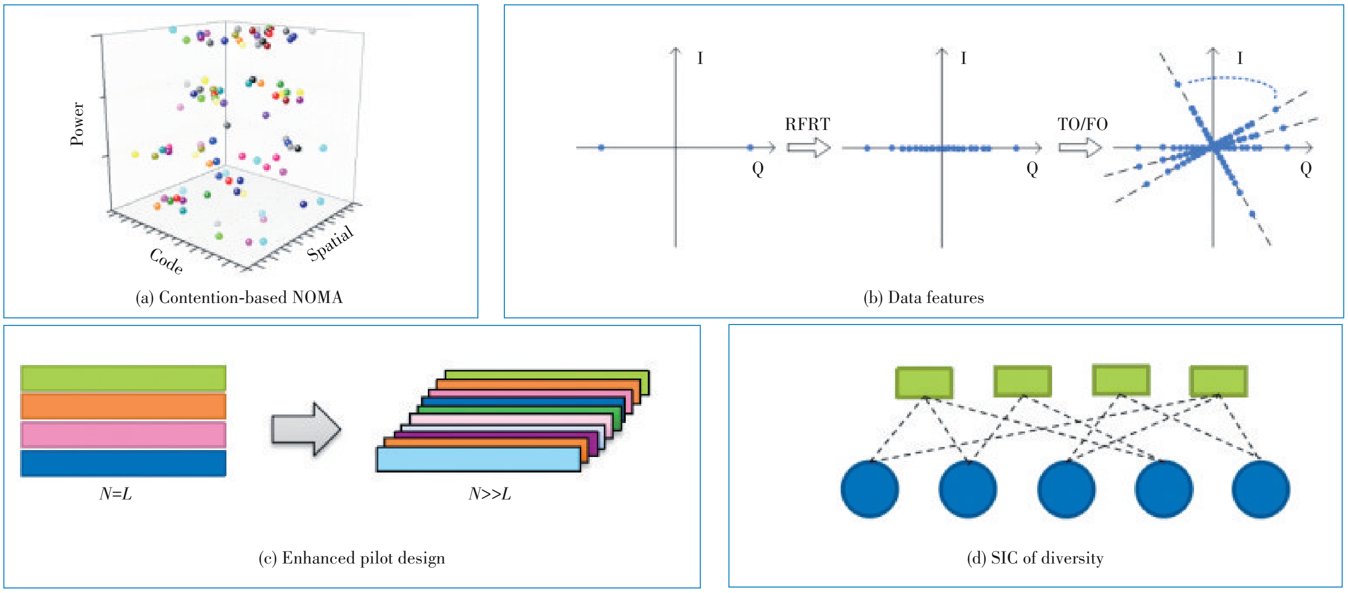
NOMA is a very effective technology to increase spectrum efficiency when there is a near-far effect. Due to the complexity limitation, a non-orthogonal power domain has not been fully utilized especially for the uplink in current protocols. NOMA still acts as an important role in the future, as the complexity limitation is expected to be solved by advanced algorithms and powerful hardware in the future.

It is complex and inefficient to implement accurate power control and resource allocation when there are massive users or the latency requirement is high. Therefore, a scheme allowing users to transmit freely is in high demand. To acquire this convenience for end devices, the transmission itself is inevitable to be non-orthogonal. In this case, extra sensing and local power control can be required to utilize the power domain[12], but it is not suitable for low-cost and low-power devices. To support a more flexible transmission not relying on any sensing and power control, a joint use of power domain, code domain and spatial domain should be considered as in Fig. 1(a).

3.2 Data Features

To get rid of pilots or reduce the pilot overheads, data features should be used. There are two mainstream ways to realize this. One is to utilize the prior knowledge and statistical information of data[5, 13], e.g. the constellation shape, correlation matrix, constant modulus, etc. This method is compatible with existing protocols, and the modification to existing standards is relatively small. The other is a data-driven method that uses deep learning (DL). The end-to-end auto-encoder is one important application of DL at the physical (PHY) layer, and Ref. [14] shows that pilot-free transmission can also be realized by an auto-encoder.

During the exploitation of data features, novel waveform potentially arises[15–16]. Discrete Fourier transform spreading orthogonal frequency division multiplexing (DFT-s-OFDM) plays an important role in 5G for its low peak to average power



▲**Figure 1. Key enablers of future access protocols**

ratio (PAPR). However, it makes the data feature hard to use. One solution is real Fourier related transform spreading OFDM (RFRT-s-OFDM)[15]. As shown in Fig. 1(b), this novel waveform can maintain the data feature. Channel equalization and time/frequency offset correction can be conducted using the data features in RFRT-s-OFDM as shown in Fig. 1(b), while the low PAPR advantage is kept.

3.3 Enhanced Pilot Design

To support mMTC and massive MIMO, novel pilot designs are proposed to support more users and reduce allocation overheads as shown in Fig. 1(c). One mainstream research area is non-orthogonal pilots based on compressed sensing (CS) [6]. The sparsity of user activities, multiple paths and angles of arrival can be used to increase the performance of user detection and channel estimation. However, a CS-based non-orthogonal pilot scheme leads to large computational complexity when the pilot pool is large or the receiving antenna array is large. Also, the inter-cell interference and time/frequency offset problems are hard to solve.

The other research direction is the special non-orthogonal pilot design with partial orthogonality. To be specific, multi-pilot[7] is proposed which consists of multiple pilots. Multiple orthogonal pilots are usually employed, although multiple non-orthogonal pilots also work. The detection of every orthogonal pilot is very simple, and the detection complexity is reduced a lot compared with general non-orthogonal pilot design. Moreover, an orthogonal pilot has been used and verified during a long period, and many existing engineering methods can be used to ensure the performance of multi-pilot use.

3.4 SIC of Diversity

The joint use of diversity and SIC was first proposed in Ref. [17], and then some novel schemes have improved the performance by optimizing a bipartite graph of Fig. 1(d). The joint use allows users to transmit multiple replica packets at any time slot, and SIC of packets is used after demodulating any packet in each round. This strategy was designed for satellite communications where the round-trip time is very long. The achievable loading of this strategy is approaching 1 with the cost of replicas. This method greatly reduces the transmission delay and increases transmission efficiency. It is also named modern random access, which is seen as one potential next-generation random access protocol[10].

Unlike satellite communications, the channel gain of different users varies a lot in widely-used terrestrial communications. Therefore, the near-far effect becomes a practical factor that requires consideration. NOMA is able to utilize the near-far effect to separate different users. The combination of NOMA and multiuser diversity with SIC requires a joint design of the medium access control (MAC) and PHY layers. An example was shown in Ref. [18] which jointly uses the code domain NOMA and diversity with SIC.

4 Impacts on Protocols

With the novel access technologies, the transmission procedure can be simplified a lot, which deeply affects the future protocols.

4.1 RRC Idle/Inactive

With the key enablers in Section 3, connection-free transmission becomes possible which enables high-efficiency and instant MTC without any connection establishment. That is to say, the transmission can be realized in an idle or inactive RRC state. These enablers can also evolve around the random access protocols with a much higher successful rate and lower latency especially in dense environment, i.e., they are beneficial for RRC connection establishment. A related standardization work is the two-step random access channel (RACH)[19]. However, it only acts as a substitution of the four-step RACH, and the collision problem has not been studied as orthogonal multiple access and orthogonal pilots are still in use. In regard to collisions, the protocols relating to multiple access and pilot sequences are expected to evolve.

4.2 Uplink and Sidelink NOMA

As mentioned before, the non-orthogonal domain has not been well utilized in 5G. Actually, the discussion of uplink NOMA has not reached a consensus in 5G standards[20]. One reason is that the performance and complexity comparison is not enough to decide a winner among different uplink NOMA schemes. The demands of mMTC should be further analyzed, and some crucial key performance indicators should be especially emphasized. The contention-based grant-free feature[21] is a potential scheme in the future as it is exceedingly friendly to low-cost and low-power MTC devices. Moreover, contention-based NOMA is also a potential standardization direction for sidelink (SL) without central control, e. g., LTE-V SL mode 4[22].

4.3 Comprehensive Synchronization

The connection-free transmission brings some synchronization (SYNC) challenges. In the current protocols, synchronization is realized by the SYNC signal and measured time advance (TA) from BS[23]. TA is hard to be obtained in connection-free transmissions, so a comprehensive SYNC is required. Some possible modifications can be based on the information of the UE status (e.g., position and speed), BS position, SYNC signals of multiple BSes, etc. Moreover, an overall framework is required to jointly use all the prior knowledge relating to SYNC which can be obtained by the end device.

5 Case Studies

Two representative cases of both massive and critical MTC are shown in this section. The advantages of novel access technologies show that they may play important roles in future standards.

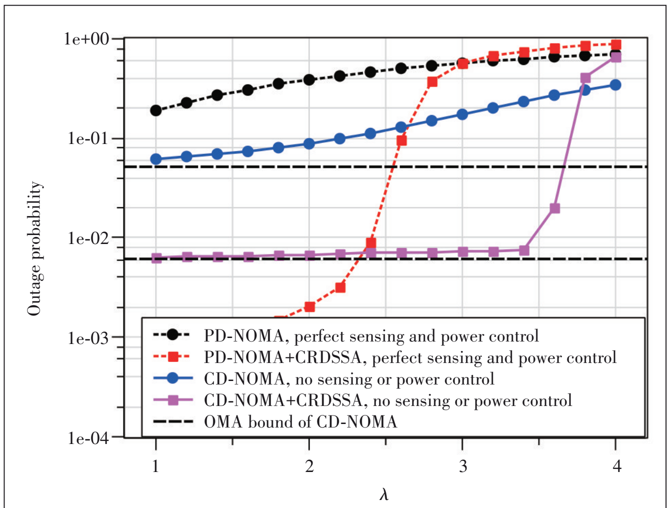
5.1 Case Study of MMTC

This case study is for mMTC, and a Poisson arrival model is used with an average arrival rate of λ. NOMA provides a large gain when there is a near-far effect, e. g., a near and strong user can reuse the channel used by a far and weak user, which greatly improves the spectrum efficiency. Therefore, the near-far effect is included in comparison. As shown in Fig. 2, the outage performances of two different contention-based grant-free NOMA schemes[12,18] are compared. As mentioned before, power domain NOMA with a contention-based feature requires extra sensing of channel gain and power control according to estimated channel gain. The aim is to make the receive power belong to some predetermined power levels. It results in an extremely high transmission power, and Ref. [12] provides sub-channel selection and distance-based methods to solve it. As a comparison, code domain NOMA[18] is just required to randomly select the spread code and can work without power control.

The simulation results show that code domain NOMA performs better than power domain. For a target outage rate of 0.1, the achievable arrival rate of power domain NOMA is less than 1 while that of code domain NOMA is greater than 2. Also, when combined with the SIC of the diversity strategy, the achievable arrival rates at the outage of 10^{-2} are 2.4 and 3.4 for the power domain and code domain NOMA. In this comparison, power domain NOMA plus SIC of diversity achieves a lower error floor because perfect sensing and power control are assumed. The outage performance of code domain NOMA is bounded by a corresponding orthogonal multiple access (OMA) transmission of perfect scheduling. As the near-far effect is utilized, code domain NOMA plus SIC of diversity achieves an arrival rate greater than 3 with the outage performance very close to the OMA bound.

5.2 Case Study of V2V

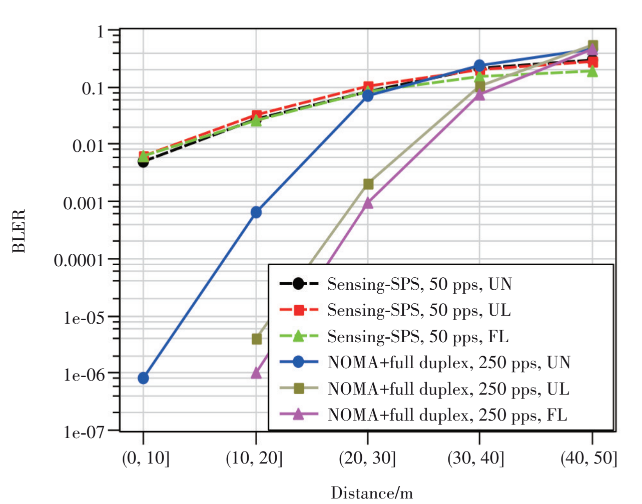
This case study is for vehicle-to-vehicle (V2V) communications without central control. V2V communications should be



CD: code domain
CRDSSA: Collision-Resolution Diversity Spreading Slotted ALOHA
NOMA: non-orthogonal multiple access
OMA: orthogonal multiple access
PD: power domain

▲ **Figure 2. Outage comparison of contention-based NOMA and their combination with SIC of diversity** extremely reliable for safety, and V2V without central control is especially important due to the robustness in a non-cellular domain and ultra-low latency requirement. In LTE-V, sensing-based semi-persistent scheduling (SPS)[22] is employed, and every user sensing the spectrum resources randomly selects idle resources in a given period. A sensing-based method is also studied and a potential candidate in 5G V2V is chosen[24]. The problem of a sensing-based method is that it is not friendly to multiple antennas, and the reliability is relatively low in ultra-dense environments. To solve these problems, Ref. [25] proposes a novel distributed antenna deployment and full-duplex contention-based NOMA transceiver scheme which jointly use power, code and spatial domains to achieve V2V communications with ultra-low latency and high reliability in ultra-dense scenarios. The block error rate (BLER) comparison is shown in Fig. 3. The channel model is based on LTE-V standards[22], and 1 500 and 700 vehicles are dropped in the urban and freeway scenarios defined in Ref. [10], respectively.

In Fig. 3, three protocol-defined scenarios are all considered, including urban non-line-of-sight (UN), urban line-of-sight (UL) and freeway line-of-sight (FL). In this comparison, the full-duplex NOMA scheme achieves a much higher reliability than the method in the current protocol. Also, the overheads of the full-duplex NOMA scheme are reduced only 1/5, which means a much more frequent transmission of 250 packets per second (pps) can be supposed, which helps to reduce the end-to-end latency once the information is generated. In this case, NOMA turns the near-far effect into advantages, and achieves a high spectrum efficiency and ultra-high reliability of near vehicles.



BLER: block error rate
FL: freeway line-of-sight
NOMA: non-orthogonal multiple access
SPS: sensing-based semi-persistent scheduling
UL: urban line-of-sight
UN: urban non-line-of-sight

▲ Figure 3. BLER comparison of sensing-based SPS in current protocols and full-duplex contention-based NOMA using novel access technologies

6 Conclusions

To fulfill digital transformations, it is necessary to make some great modifications in current protocols. One crucial aspect is to enhance the access protocols as it is a bottleneck of seamless and instant digital services. This paper provides several novel access technologies, and potential impacts on protocols are also briefly analyzed. Moreover, some typical use cases are shown to verify the necessity of these modifications of future protocols. The standardization process of novel access technologies to boost digital transformations requires a much wider application to make it more urgent, more careful considerations given to privacy and security, and a joint work of industry and academics to refine technologies.

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