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Non-Orthogonal Multiple Access Schemes for 5G

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Abstract

Multiple access scheme is one of the key techniques in wireless communication systems. Each generation of wireless communication is featured by a new multiple access scheme from 1G to 4G. In this article we review several non-orthogonal multiple access schemes for 5G. Their principles, advantages and disadvantages are discussed, and followed by a comprehensive comparison of these solutions from the perspective of user overload, receiver type, receiver complexity and so on. We also discuss the application challenges of non-orthogonal multiple access schemes in 5G.

Keywords

5G; non-orthogonal multiple access; mMTC

1 Introduction

Multiple access scheme is the key technique of wireless communications. In 3rd generation (3G) code division multiple access is applied. In 4G orthogonal frequency division multiplexing access (OFDMA) is employed. In the coming 5G, non-orthogonal multiple access schemes are hot topics because they can achieve high system capacity. Moreover, massive machine type communication (mMTC) is one of the key scenarios for 5G in which massive connection is required. In this paper, we mainly focus on the non-orthogonal multiple access schemes supporting mMTC which has the rapidest growing speed and the urgent deploy demand.

Several non-orthogonal multiple access schemes are proposed for 5G, which include multi-user shared multiple access (MUSA) [1]–[4], resource spread multiple access (RSMA) [5], sparse code multiple access (SCMA) [6]–[8], pattern division multiple access (PDMA) [9]–[11], interleaver-division multiple access (IDMA) [12], [13], and non-orthogonal multiple access (NOMA) by power domain [14]. In this paper, the principles, merits and demerits of these schemes are discussed to let readers have a full overview on that.

2 Features of 5G

5G has three main technical features, including enhanced mobile broadband (eMBB), mMTC and ultra reliable and low latency communication (URLLC). The eMBB is the evolution of MBB targeting for high data rate and can support high mobility The mMTC is characterized by massive connection with low cost terminals. High reliability and ultra-low latency are the goals of URLLC.

With the development of Internet of things, a large number of terminals will have access to the network. Therefore, mMTC needs to support one million of connections per square kilometer. The mMTC, which has the fastest growing speed and the most urgent deployment demand, will create new chances in 5G. The non-orthogonal multiple access should support at least mMTC where high user overload is the key requirement.

In LTE there are several interactive processes between base station and terminal before the data is transmitted from terminal to the base station. This makes sense for long time and continuous data transmission because signaling overhead is small by averaging over a long time. In mMTC each terminal only transmits small data and massive terminals would sporadically transmit their data to the base station. When the same access procedure like in LTE-A is applied, the signaling overhead will be comparably large and the access efficiency is very low, thus grant-free for mMTC is needed in which multiple terminals can send their data on the same resource block without multi-step negotiations with base station.

3 Non-Orthogonal Multiple Access Schemes for 5G

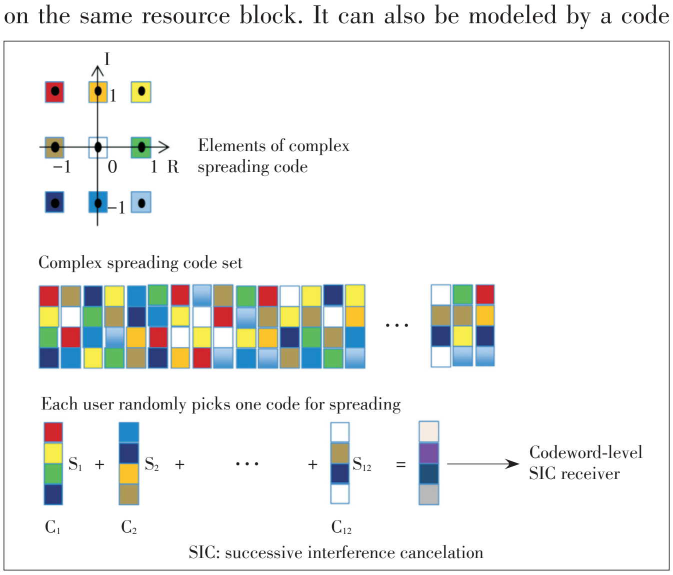
Several non-orthogonal multiple access schemes have been proposed for 5G. Based on their properties, they can be categorized to different types. Most non-orthogonal multiple access schemes use spreading codes. When such schemes have other predominant properties, such as SCMA and PDMA use code matrix to illustrate how multiple users share the same resource block, and IDMA uses interleaver for user separation, we categorize them as other kind of schemes. In the following joint detection denotes message passing algorithm (MPA) based schemes.

3.1 Non-Orthogonal Multiple Access Schemes Based on Spreading Sequences

3.1.1 MUSA

MUSA is a non-orthogonal multiple access scheme operating in code domain and power domain. Spreading code with short length is applied in MUSA to support a large number of users that share the same resource block. When the number of users is large and the length of the spreading code is small, it is difficult to design large number of spreading code with low correlation when binary element of the spreading code is assumed. For binary spreading code the element of the spreading code belongs to the set {1, -1}. Only two values are employed in the spreading code. To overcome this drawback, non-binary and complex-value spreading code is proposed in MUSA. Either the real or the image element of the non-binary spreading code belongs to the set {1, 0, -1}, there are nine values for selection. This provides much more flexibility of spreading code design. Because the real and image elements of the spreading code are 1, 0 or -1, the multiplication operation can be implemented by addition operation which will reduce the implementation complexity. **Fig. 1** shows the basic features of MUSA, where multiple users could transmit data on the same resources by using randomly selected non-orthogonal complex spreading codes with short length (e.g. 4). In this example 12 users share 4 resource blocks, and the user overload is 300%. MUSA is always modeled by multiple spreading codes superposed on the same resource block. It can also be modeled by a code matrix. The code matrix of MUSA with 300% overload is given by

$$G=\begin{bmatrix} 1+i & 1-i & -1+i & i & -i & -1-i & 1 & -1 & 1+i & 1 & 1-i & 0 \\ 1+i & 1+i & -1+i & -i & -i & -1+i & -1 & 1 & -i & -1+i & 1 & 0 \\ 1+i & i & -1 & 1 & 1+i & 1 & 1+i & 1 & 0 & 0 & 0 & 0 \\ 1 & -i & i & 1+i & 1-i & i & -1-i & -1 & 1 & 0 & 0 & 1+i \end{bmatrix}$$



▲**Figure 1. An example of MUSA with 300% user overload [4].**

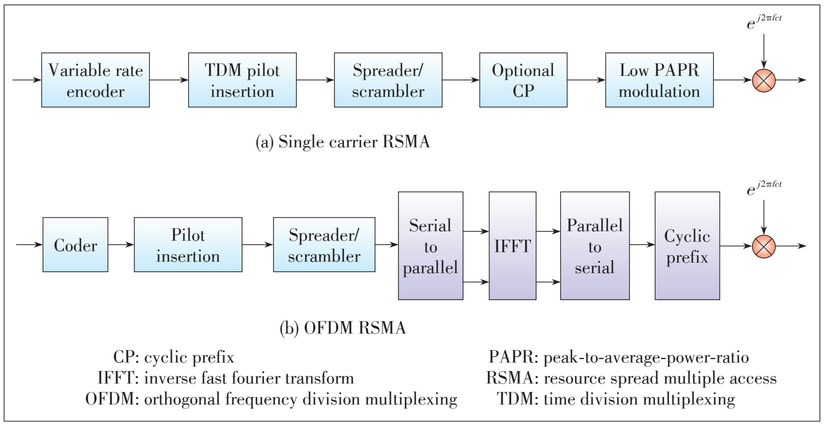
In 5G, mMTC is one important application scenario. In this scenario MUSA is preferred since grant-free transmission can be readily supported. A device terminal autonomously accesses the communication system without base station (BS) scheduling. Blind detection is applied at BS for MUSA in which active user, user spreading code and user channel would not be known before hand. Because the spreading code length is relative short and its elements have limited values, BS can generate numerous local spreading codes with low correlation. By using these local spreading codes and the received signal, we can closely approximate the optimal performance of MMSE estimator. Then the user signal with the highest signal-to-interference-plus-noise ratio (SINR) can be detected and decoded. After that user's signal is successfully decoded, it can be employed for channel estimation. After interference cancellation, the user signal with the second highest SINR is detected and decoded. During this process no pilots or preamble are needed for channel estimation, which facilitates MUSA application in mMTC because most other schemes rely on additional overhead for channel estimation. The blind detection for MUSA is verified over flat fading channel and multi-path fading channel [3], [15].

The main advantages of MUSA are reflected by high overloading factor, robust blind detection and true sense of grant-free transmission. Due to frequency-diversity gain achieved, 700% user overload can be achieved by MUSA over multi-path fading channel [15]. User detection can be carried out without the knowledge of the spreading code. User transmitted signal can be applied for enhanced channel estimation once it has been correctly decoded. Users can transmit their signals according to their demand. The possibility of collision due to the same spreading code applied is small since large number of the spreading codes can be accommodated.

Successive interference cancelation (SIC)-based receiver is applied for MUSA. It works well when there is SINR difference among the received signals. However, when the difference is small, there would be certain performance loss due to error propagation. While there is inherent SINR different in mMTC due to free power control, it is not a so serious problem for the signal detection of MUSA. The SINR difference is small, so it can be solved by using more advanced receiver, such as joint detection and decoding scheme.

3.1.2 RSMA

In RSMA (**Fig. 2**), a group of users' signals are superposed on the same resource blocks, and each user's signal is spread over the entire frequency/time resource blocks. Different users'



▲**Figure 2. RSMA block diagrams [5].**

signals within the resource blocks may be not orthogonal. Low code rate channel codes are employed to achieve large coding gain. Relative long spreading codes with good correlation property are applied to reduce the multi-user interference. Scramblers can be employed with the same purpose as the spreading codes. Interleaver is optional for RSMA according to the system requirements.

Depending on the application scenarios, it includes single carrier RSMA and multi-carrier RSMA. For the former it is optimized for battery power consumption and coverage extension for small data transactions by utilizing single carrier waveforms, very low peak-to-average-power-ratio (PAPR) modulations. It allows grant-less transmission and potentially allow asynchronous access. While for the latter it is optimized for low latency access for radio resource connection (RRC) connected users (i.e., timing with eNB already acquired) and allows for grant-less transmission.

The advantage of RSMA is that it supports asynchronous and grant-less transmission, so the signaling overhead is reduced. The disadvantage is that its user overload is limited when rake receiver is applied. By using advanced receiver, such as SIC based receiver, the overload can be enhanced.

3.2 Non-Orthogonal Multiple Schemes Based on Structured Coding Matrix

3.2.1 SCMA

Sparse codebook is applied at SCMA to reduce the detection complexity. At the same time joint detection is employed for SCMA to achieve excellent performance. The codewords are composed of multi-dimensional complex symbols, and the codewords in the same codebook have the same sparse pattern. Sparse codeword mapping utilizes low density spreading and could be referred to as sparse spreading. At the receiver, iterative multi-user detection based on MPA is used. **Fig. 3** shows an example of SCMA, where the coded bits of a data stream are directly mapped to a codeword with sparse non-zero elements from a codebook. With 6 sparse codewords transmitted over 4 orthogonal resources, the user overload is 150%. The coding matrix of Fig. 3 is given by

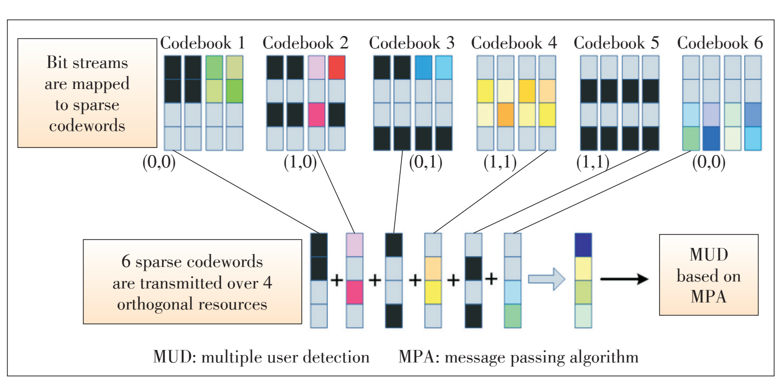
$$G=\begin{bmatrix}1&1&1&0&0&0\\1&0&0&1&1&0\\0&1&0&1&0&1\\0&0&1&0&1&1\end{bmatrix}$$

To reduce the multi-user interference and the detection complexity, sparse signature sequence is applied in SCMA for spreading. User signal is modulated by a codebook in which multidimensional modulation maps of the input coded bits to the points in the multiple complex dimensions [6]. By such operation shaping gain is achieved, which is claimed as one major property of SCMA.

The main disadvantage of SCMA is its high detection and decoding complexity even sparse signature sequence is applied. The detection and decoding complexity is even higher when large size constellation and a large number of users are employed. And additional pilots or preambles are needed for multi-user channel estimation, which may reduce system spectral efficiency. Because the size of the codebook is limited, if two users choose the same codeword, collision will happen. Collision is a serious problem for SCMA, which limits its overload capability. For example, with 6 users transmitted over 4 units, the user overload is only 150%. Although the overloading factor can be enhanced by using longer spreading codes, the detection complexity will increase significantly since the size of the codebook and the searching space is enlarged.

3.2.2 PDMA

For PDMA, the code in a code matrix is used to define mapping from data to a group of resources. Each element in the code corresponds to a resource in the resource group. PDMA can be detected by SIC type receiver. It also can be detected by MPA based scheme in the receiver. PDMA is designed for SIC-based receiver originally. The different diversity orders of different users by carefully design the code matrix facilitate the multi-user signal detection. The user with the largest diver-



▲**Figure 3. An example of SCMA with 150% user overload [8].**

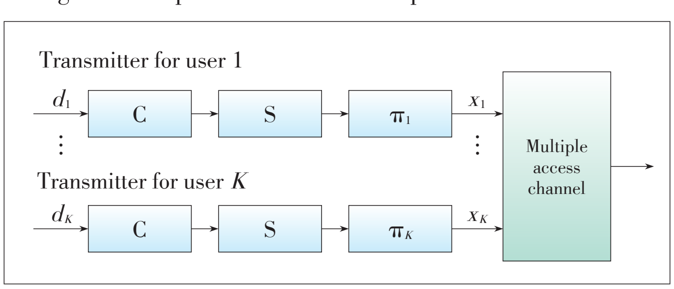
sity order is detected first, and then the user with the largest diversity order among the remaining users is detected; in this way, all users' signals will be detected.

To further improve the performance of PDMA, joint detection based scheme is proposed. In this case the unbalance weight of each column is interpreted as the irregular code weight. As we know irregular low density parity check (LDPC) code has better performance than that of the regular one. By carefully designing the code matrix with joint detection, even better performance can be obtained by PDMA compared with regular code matrix (for example non-orthogonal multiple access with low density signatures can be regards as regular code).

The main disadvantage of PDMA is its low user overload (user overload is defined by the number of user over the resource block that all users share). It is difficult to achieve overload of 400% with the 4-row code matrix (when the row of the code matrix is K, the largest user number it supported is 2^K-1 [10]).The complexity is high for high order modulation when joint-detection scheme is applied. Additional pilots or preamble are needed for channel estimation. Because the number of patterns is limited, there is high probability of collision when users are allowed to randomly select the patterns.

3.3 Non-Orthogonal Multiple Schemes Based on Interleaver

IDMA was proposed by [12], [13], in which users are separated by different interleavers. Low-rate channel decoding is applied and the coded bits are repeated multiple times to increase the SINR after accumulating the received signals. After channel coding and repetition, interleaver is employed to make the transmission bits randomly distributed. A block diagram of IDMA is shown in **Fig. 4** where C represents channel encoding, S denotes repetition and π is the interleaver. The strategy of user separation for IDMA is different from other non-orthogonal multiple access schemes. Interleaver is used for user separation and the length of the interleaver is very large (the length of the interleaver equals to the number of the bits after channel coding and repetition), thus this provides good base for a large number of users access by using IDMA. It is reported that 64 users can be supported by IDMA which share the same resource block [12]. This goal can never be achieved by other non-orthogonal multiple access schemes at present.



▲**Figure 4. IDMA block diagram [13].**

At the receiver side each user's signal is detected, demodulated and de-interleaved according to its own interleaver patterns. The soft information of decoded bits is input to elementary signal estimator (ESE) for soft information updating. After soft information updating new soft information is input to the decoder for channel decoding again. Several iterative detections between ESE and channel decoder are needed to achieve the best performance. The detection and decoding complexity does not increase exponentially with the user number and total spectral efficiency. The complexity increases linearly, which is also different from other non - orthogonal multiple access schemes which use joint detection and decoding scheme.

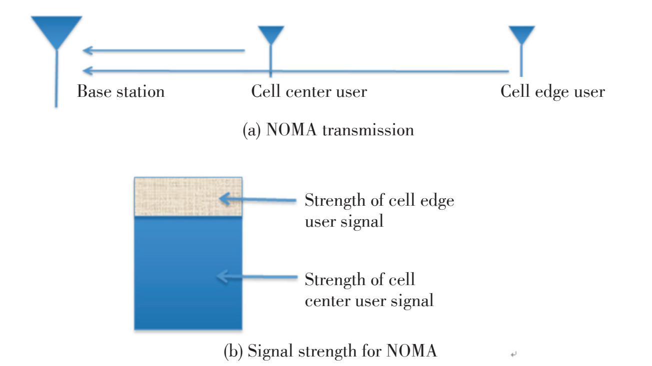
The main advantages of IDMA are its high user overload and excellent performance. And high spectral efficiency can be achieved by IDMA (as high as 8 b/s/Hz). The performance gap between IDMA simulation result and the system capacity bound is almost the same from the spectral efficiency 1 b/s/Hz to 8 b/s/Hz (this means the detection and decoding scheme is very robustness) [12]. These two merits are seldom achieved by other non-orthogonal multiple schemes simultaneously.

The main disadvantage of IDMA may be its large decoding complexity and decoding latency, especially when a large number of users are supported. The reason is that when large number of iterative detection and decoding are needed with the increasing of user number. For example, tens of channel decoder procedures are needed in the signal detection and tens of interactive actions between channel decoder and ESE detector are required. Thus high convergence algorithm is needed in the signal detection for IDMA in future. To solve the problem of large decoding complexity and decoding latency, interleaver patterns can be pre-allocate to small number of users, i.e., the relatively small pool size, so that the complexity of blind decoding and channel decoding latency can be maintained below certain level. Another disadvantage is that additional pilots or long preamble is needed to estimate the users' channels.

3.4 Non-Orthogonal Multiple Access (NOMA) Scheme Based on Power-Domain Division

Multi-user signals can be superposed together in NOMA. In NOMA, capacity or throughput improvement can be expected by sharing the same radio resources among multiple user equipments (UEs) as shown in **Fig. 5a** and **Fig. 5b**. A typical application scenario of NOMA is that a cell-center user and a cell-edge user are serviced by NOMA. Due to small path loss of cell center user, in the signal detection it is detected first and the signal of cell edge user is treated as interference. In the signal detection of cell edge user, the signal of cell center user is detected and decoded first. Then the signal of the cell center user is cancelled from the received signal and signal of cell edge user is detected and decoded.

The main advantage of NOMA is that excellent performance can be achieved when a cell center user and cell edge user are scheduled with moderate computational complexity (SIC detec-



▲Figure 5. NOMA block diagram.

tor is always applied). And a user overload of 200% is easily achieved. The main disadvantage of NOMA is that there is restriction on the scheduled users. Usually a cell center user and a cell edge user should be scheduled on the same resource block. When two cell center users or two cell edge users are scheduled and SIC-type receiver is applied, there is performance loss because one user always has low SINR due to interference from another user's signal. The NOMA is designed for eMBB originally. Thus when it is applied for mMTC, the received SINR would not be high and the number of supported users is very limited (two or three users are supported on the same resource block, which is much smaller than other non-orthogonal multiple access schemes). And additional pilots or long preamble is needed to estimate the users' channels.

A summary of these non-orthogonal multiple schemes are shown on **Table 1**. They are compared in terms of multiplexing domain, user overload, receiver type, receiver complexity and so on. Among these schemes MUSA achieves a good balance between performance and complexity, such as high user overload, low implementation complexity and flexible in grant-free transmission.

4 Application Challenges of Non-Orthogonal Multiple Access Schemes in 5G

Followings are the requirements for the non-orthogonal multiple access schemes. These factors should be considered when we design the non-orthogonal multiple access schemes.

4.1 Coverage

Coverage is an important issue for mMTC since terminals may distribute over a large area, thus it is crucial for non-orthogonal multiple access schemes to support terminals with different received power due to path loss. And the non-orthogonal multiple access schemes should have the ability of robustness to the high interference. To increase the coverage, low code rate channel coding or large spreading factor could be considered. High efficiency power amplifier is appealing for coverage

▼Table 1. Summary of different non-orthogonal multiple access schemes

	MUSA	RSMA	SCMA	PDMA	IDMA	NOMA
Multiplexing domain	Spreading	Spreading/ scramble	Codebooks	Pattern	Interleaver	Power
User overload	High	Low	Middle	Middle	High	Low
Receiver type	SIC	Raker or SIC	Joint detection	SIC or joint detection	Iterative detection and decoding	SIC
Receiver complexity	Low	Low	High	Low for SIC High for joint detection	High*	Low
Grant-free transmission	Users can randomly pick up spreading sequence	Power control needed	Codeword for each user is predefined and known at BS. Codeword collision is a problem due to limited number of codewords	Pattern is predefined and known at BS. User collision is a problem due to limited number of patterns	Interleaver patterns are known at BS	Grant-based

* Unlike joint detection scheme whose complexity increases exponentially as the number of the users and spectral efficiency increases, the complexity of IDMA only linear increases with the number of users and the spectral efficiency. The high complexity is due to large number of iterative detection and decoding.

MUSA: multi-user shared multiple access
RSMA: resource spread multiple access
SCMA: sparse code multiple access
PDMA: pattern division multiple access
IDMA: interleaver-division multiple access
NOMA: non-orthogonal multiple access
SIC: successive interference cancelation
BS: base station

extension, which requires transmit signals with low PAPR.

4.2 PAPR

When the non-orthogonal multiple access scheme is applied for uplink, PAPR should be considered to increase the transmission efficiency and reduce the transmission power thus save the battery life. The battery life is desired to be 10 years for mMTC, so it puts a big challenge on the non-orthogonal multiple access scheme. The signal of the non-orthogonal multiple access schemes which have low PAPR will be preferred in practical implementation. Filtered π/2-binary phase shift keying (BPSK) and Gaussian filtered minimum shift keying (GMSK) have good property of low PAPR and are employed for PAPR reduction in RSMA [16].

4.3 Implementation Complexity

The implementation complexity includes two parts: transmitter implementation complexity and receiver implementation complexity. Because multi-user detection is carried out at receiver side, which has the highest complexity over the entire signal processing chain, the main implementation complexity is at the receiver side. Two types of receivers are always applied for non-orthogonal multiple access schemes: SIC-based receiver and joint-detection-based receiver. The former can achieve a good balance between performance and complexity. As the number of user increases, the complexity only increases linearly. While it suffers performance loss in some cases, such as the path-losses among different users are the same. Joint-detection-based receiver achieves excellent performance at the cost of high computational complexity. Although by some designs, such as sparse coding matrix, the decoding complexity is reduced significantly, however, as the constellation size and the number of users increase, the decoding complexity grows exponentially. This bottleneck should be solved before such scheme is employed in practical systems.

4.4 Combination with Multiple-Input Multiple-Output (MIMO)

By applying MIMO technique large system capacity or high transmission/receiver reliability can be achieved. It had been proved that MIMO is a very effective technique in wireless communication systems. The non-orthogonal multiple access schemes should be amiable for MIMO. As the first step, SISO is assumed in the research of the new non-orthogonal multiple access schemes. However, compatibility with MIMO should be considered in the next research step.

4.5 Flexibility

The non-orthogonal multiple access schemes should have flexibility. It can change its parameters to support different use scenarios. For example, in some cases high user overload is the system design target, while in other cases coverage is the most important factor. This imposes requirements on the non-orthogonal multiple access scheme design. By changing the parameter of the non-orthogonal multiple access schemes, different targets can be achieved. Another example is that non-orthogonal multiple access schemes should support both multi-carrier system and single-carrier systems to facilitate its application scenarios.

5 Conclusion

This article reviews the main non-orthogonal multiple access schemes for 5G. Their principles and unique properties are discussed. MUSA can support high user overload with low implementation complexity and is more suitable for grant-free transmission. RSMA is suitable for single-carrier system and multi-carrier system. It has good property of large coverage. SCMA can achieve additional shaping gain and PDMA has the flexibility in the patterns design. IDMA can accommodate very high user overload and support high spectral efficiency at the cost of large decoding complexity and decoding latency. NOMA works well for large SINR difference among the non-orthogonal multiple users. At the same time they have their own disadvantages. It is important to integrate the advantages of different schemes to make the final designed scheme fulfill the challenging requirements of coming 5G.

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