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The Key Technological Developments of Non-Orthogonal Multiple Access (NOMA) in 5G Cellular Networks

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Abstract:

With the evolution of cellular networks, the shortage of spectrum resources remains a vital limitation for the technology. In the application of 5G, traditional Orthogonal Frequency Division Multiple Access (OFDMA) technology cannot meet the technical specifications of R17. NOMA technology introduces interference information to allow spectrum resource sharing between mass users. Therefore it improves the capacity and efficiency of the channel and is valued for its immense potential for 5G future development. This paper mainly focuses on NOMA technology. Firstly the paper introduces the technology's working principles and design concepts, then respectively elaborates on the basic principle of three mainstream technical solutions under this approach. The three technologies are MUSA, SCMA, and PDMA. The paper pointed out that NOMA realizes a non-orthogonal multi-user shared spectrum by introducing interference to differentiate different users on the same frequency resources. NOMA possesses excellent scalability and potential for enhancement, offering improved performance compared to the previous generation. However, meanwhile, the technology also faces drawbacks such as a high bit error rate under high resource utilization and limited performance improvement under low utilization. Future development of NOMA technology should mainly focus on optimizing and simplifying the code to enhance various performances. The technology can also integrate with other mature technologies for broader practical implementation. In summary, the current state of NOMA development shows great potential but faces challenges such as limited performance improvement and high bit error rates. The paper comes up with practical suggestions for optimizing NOMA to achieve mass 5G applications.

Keywords: Spectrum resources; MUSA; SCMA; PDMA; cellular network communication technology

1. Introduction

The number of devices connected within the same network sharply increases with the development of wireless cellular networks, leading to an increasingly scarce spectrum resource. Orthogonal Frequency Division Multiple Access (OFDMA), the previous generation of multiple access communication technology, can only allocate a single wireless resource to one user. Since OFDMA cannot meet the communication demand of devices in the uplink direction, Non-Orthogonal Multiple Access (NOMA) was proposed to alleviate the issue of spectrum resource scarcity.

Unlike traditional Orthogonal Multiple Access technologies, NOMA allows multiple users to share the same spectrum of resources. This significantly improves spectrum efficiency and user fairness, offering performance advantages over traditional orthogonal access methods. Moreover, NOMA possesses greater performance enhancement potential for 5G applications, thus it is more suitable for future system deployments. However, NOMA technology is currently immaturity at the coding level, with few practical application examples, which leads to challenges such as high bit error rates, significant deployment costs, and high time delay.

The successful large-scale commercialization of NOMA technology will help 5G achieve the technical specifications for massive Machine Type Communication (mMTC). This promising potential makes NOMA a popular research direction in cellular networks. But up to now, there is an scarcity of the academic summaries focusing on NOMA's principles and research status. This may make it difficult for the researchers to seek basic information about the field. This paper will systematically review the underlying technologies and research achievements of the three major NOMA solutions to prove the frequency resource reuse advantages of NOMA. It will also summarize the current state of NOMA technology development. Additionally, it will provide predictions on the future application prospects of NOMA in the field of cellular networks and offer constructive suggestions.

2. Overview of the NOMA Technical Protocol

Non-Orthogonal Multiple Access (NOMA) is a new multiple access technology developed in the 5G era to meet the massive uplink resource transmission demands of numerous users. Its basic design principle is to intentionally introduce interference information to user data. The core principle of NOMA is to modulate user data using interference information. It enables non-orthogonal data transmission for multiple users on the same channel, which significantly increases information capacity. NOMA does not represent a specific technical solution but rather a technological approach. The approach enables multi-user frequency domain resource reuse through different encoding processes at the transmitter. Compared to traditional technologies, Non-Orthogonal Multiple Access (NOMA) technology introduces specifically designed additional transmitters and receivers to handle interference. At the transmitter, the system constructs and allocates codebooks for different terminals considering the spatial position of the terminals and the type of data transmission. At the receiver end, the system uses user detection message passing algorithms, such as Successive Interference Cancellation (SIC) technology, to reconstruct the data. For instance, the Code Division Multiple Access (PDM-NOMA) technology uses specific codewords to modulate non-orthogonal multi-user data at the transmitter, realizing non-orthogonal transmission on the same frequency channel. Then the receiver uses corresponding techniques to identify the signal codewords, demodulate the signal, and restore it to the original multi-channel transmission signals. To date, there are three main Code Division Multiple Access (CDMA) solutions based on the NOMA technology framework: Multi-User Shared Access (MUSA) technology, Sparse Code Multiple Access (SCMA) technology, and Pattern Division Multiple Access (PDMA) technology.

2.1 Multi-user Shared Access (MUSA) Technology

Multi-User Shared Access (MUSA) is a Code Domain Multiplexing (CDM-NOMA) multiple access technology applied in the uplink data transmission process. The technology uses special code words to distinguish different user signals, enabling multiple users to transmit data simultaneously on the same spectrum resources. Compared to traditional technologies, MUSA has two unique technical components: the complex ternary short spreading codes at the transmitter and the Successive Interference Cancellation (SIC) technology at the receiver. The transmission principle is shown in Fig1: First, the transmitting terminal expands the spectrum resources of the user bit data by 4 times through the frequency expansion code. Then the spread frequency data sequences of different users can occupy the same spectrum resources in a non-orthogonal form during transmission. After that, the receiver demodulates different user information in the same resource block through a special code. At last, the receiver combines the same user information in multiple information blocks. Related simulations have confirmed that MUSA technology can achieve uplink access technology indicators with high efficiency and low latency in communication applications[1].

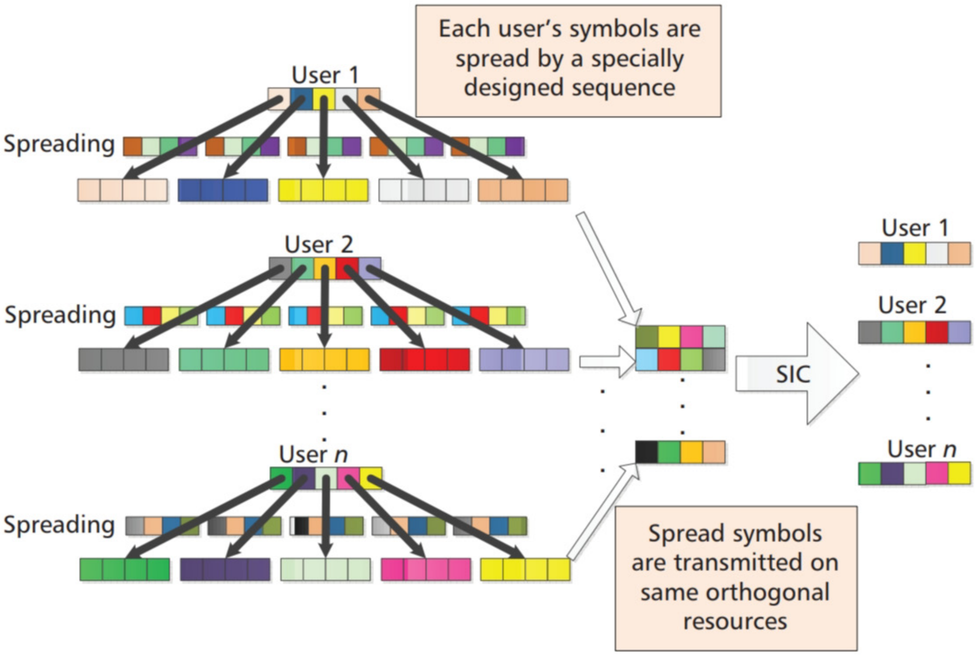

Fig.1 Schematic diagram of MUSA uplink multiple access scheme [2]

Although MUSA technology has the performance advantage of a high utilization rate of spectrum resources in multi-user reuse resource blocks, it also has drawbacks such as a complex receiver algorithm and high bit error rate. The detection algorithm of the receiver, such as multi-user detection (MUD), is more complex with higher delay and greater power consumption compared with the traditional multiple access access. Additionally, an even higher bit error rate occurs when the terminal is in high-load or fast-moving situations. Currently, researchers mostly optimized MUSA at the algorithmic level to achieve performance improvement. In specific, it means reducing the time complexity by downscale the lowest signal amplitude, but this will increase the bit error rate [3]. In practical engineering applications, performance improvement is limited because it is necessary to consider the bit error rate threshold when reducing the signal amplitude. In the subsequent development of MUSA, reduction of the threshold can be considered. Precautions such as optimizing the construction of user codebooks, increasing the differentiation of user information in the same channel, and reducing the error rate at the receiving end can be taken to lower the threshold.

2.2 Sparse Code Multiple Access (SCMA) Technology

The core technology of SCMA is the use of sparse codebooks to enable multi-user sharing resource blocks, thereby enhancing spectrum resource utilization efficiency. The SCMA system maps the bit stream of each user to the corresponding sparse codebook and uses the Message Passing Algorithm(MPA) for signal decoding detection. The biggest feature of SCMA technology is to distinguish the user data under the same channel. The core component is the design of codebooks which mainly consists of two technologies, low-density spreading techniques and high-dimensional QAM modulation. As shown in Fig.2: First, the SCMA system performs sparse coding to encode the multi-user parallel bit symbols into sparse codewords. Next, the SCMA system chooses an appropriate modulation technique, such as QPSK modulation, to modulate the signal, ensuring it meets the transmission needs of multi-user data on a single channel. When transmission, the subcarrier carries the data of multiple users. Finally, the receiver demodulates and decodes the received signal to restore the original multi-channel transmission data symbol.

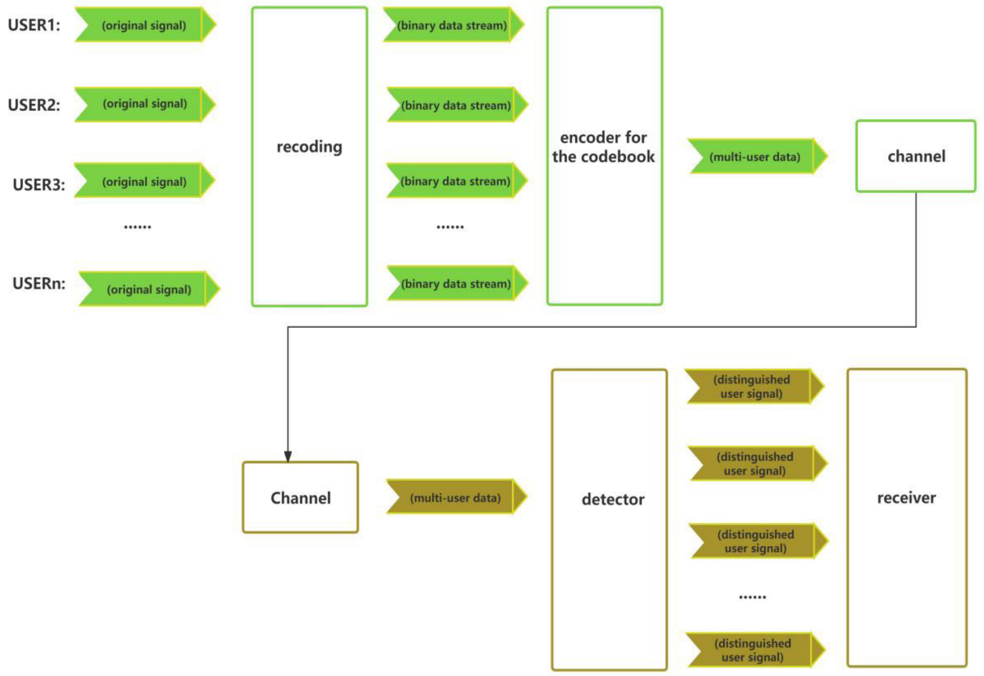

Fig.2 Upink flow diagram of SCMA system

Compared with the traditional OFDMA technology, SCMA technology achieves an increase in the transmission rate while maintaining the same number of base stations and carriers[4]. However, SCMA still faces some drawbacks. For instance, complex detection code at the receiving end, high transmission decoding latency, and high bit error rate caused by large carrier load results. The main research direction for SCMA in the future is optimizing algorithms to improve the design of sparse codes at the transmitter and enhance the performance of forward error correction code at the receiver. Besides, power allocation can be improved as well. SCMA technology shows a better expansion and is gradually applied to the fields like Internet of Things, smart homes and multimedia services.

2.3 Pattern Division Multiple Access (PDMA) Technology

PDMA technology is a kind if CDM-NOMA technology that creates unique coding for different users to realize the non-orthogonal signal modulation in the same channel. The core technology of PDMA is to achieve multi-user shared resource blocks through pattern construction and allocation. The sparse code of the PDMA technique is in the form of a pattern matrix. The user data is mapped onto a set of resources to achieve a mapping pattern with unequal diversity splitting. This is known as the PDMA coding pattern [5].

The basic transport unit of PDMA is shown in Fig 3 where time, frequency, pattern vector and pilot resource are the basic PDMA transmission units. Before data transmission, the base station selects a PDMA pattern matrix based on the user deployment scenario and the number of users. The station then allocates resources according to the unequal diversity characteristics of the PDMA pattern matrix, taking the distance between the terminals and the base station into account. In order to construct the unequal diversity characteristics, the design of the PDMA pattern mainly follows two criteria. First, the designed matrix needs to have as many groups of different diversity as possible to achieve the highest reuse ability. Second, the interference in the same diversity group shared by multiple users needs to be as small as possible to maximum the interference deletion performance.

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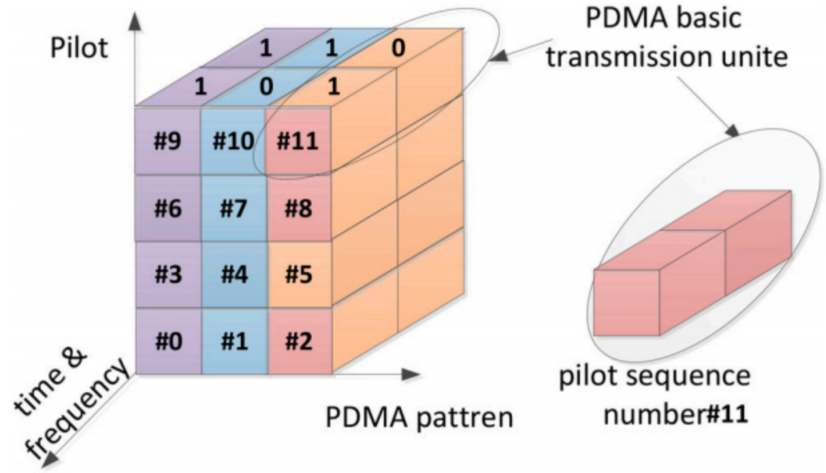
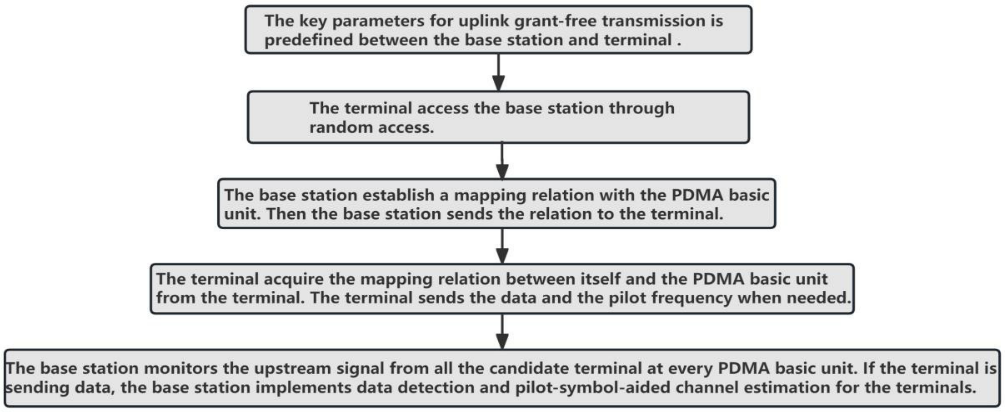


Fig.3 Schematic diagram of the PDMA basic transmission unit[6]

Compared with other NOMA technologies, the biggest improvement of PDMA technology is the introduction of three-bit space user coding, that is, the use of pattern (pattern) in the code word design process. As shown in Fig.3, the pattern data of the same user is split into different blocks of resources in the same column. At the same time, multiple user pattern data is also stored in the same resource block. User data is mapped in three dimensions to provide better discrimination. The efficient space resource utilization makes PDMA technology simplify the receiver design and significantly reduce the communication delay. In addition, the dynamic spatial characteristics also give PDMA technology better anti-interference and environmental adaptability consequently it can have excellent performance in environments such as high-speed mobile communication.

The PDMA technology transmission process is shown in Fig.4:



The key parameters for uplink grant-free transmission is predefined between the base station and terminal .

The terminal access the base station through random access.

The base station establish a mapping relation with the PDMA basic unit. Then the base station sends the relation to the terminal.

The terminal acquire the mapping relation between itself and the PDMA basic unit from the terminal. The terminal sends the data and the pilot frequency when needed.

The base station monitors the upstream signal from all the candidate terminal at every PDMA basic unit. If the terminal is sending data, the base station implements data detection and pilot-symbol-aided channel estimation for the terminals.

Fig.4 Flow chart of the PDMA transfer steps

As shown in Fig.4, PDMA technology is more complicated in the scheduling process, which requires multiple communication between the terminal and base station to complete the pattern construction allocation. This complexity extends the scheduling time. Moreover, the PDMA pattern needs to be dynamically allocated according to the real-time user requirements and channel status. This can cause the disadvantages of high time delay and high power consumption in dense users or complex channel conditions.

3. Opportunities And Challenges For NOMA

It is generally known that the existing OFDMA technology is far from the R17 technical standard, and the NOMA technical algorithm is proved to have more superior performance potential and more improvement space than the traditional technical algorithm[7]. NOMA can also avoid scheduling at the uplink resource transmission process so that the uplink user data transmission volume can theoretically be close to the system capacity [8]. To meet the demand for Massive Machine Type Communication (mMTC), NOMA is expected to be the development direction of the next-generation cellar network communication technology. However, up to now, NOMA technology is still in the early development stage, with performance defects and fails to achieve large-scale application. For example, the network interference caused by power domain multiplexing of multi-user signals can greatly reduce the reliability of cognitive radio in NOMA transmission [9]. Secondly, compared with the previous generation of OFDMA technology, technology the improvement of NOMA is limited, which cannot meet the requirements of 3 GPP usage scenarios at present[10].

In order to overcome the existing technical drawbacks of high bit error rates and limited performance improvement, for NOMA, optimization at the algorithm level is urgently needed to gradually improve the technical and theoretical performance at the simulation level. Since the NOMA technology introduces noise at the transmitter according to terminal data and spatial features, machine learning techniques can be integrated to dynamically adjust user parameters. At the same time, NOMA can be integrated with mature cellular network communication technologies. Specific implementation methods include Massive MIMO-NOMA, Cognitive Radio NOMA (CR-NOMA), Full-Duplex NOMA. NOMA technology also shows a trend of cross-field development. Related research shows its application prospect in the field of satellite communication and underwater communication[1] [11].

4. Conclusion

This paper illustrates the necessity of the Non-Orthogonal Multiple Access (NOMA) technology in the face of spectrum shortage and indicates a systematic comprehension of the value of the technology in the field of cellular networks. Then it is followed by a detailed introduction of three representative NOMA technologies with significant research achievements: MUSA, SCMA, and PDMA. Focusing on the three major technologies, this paper introduces the different underlying technical logic and technical advantages. It also lists the latest technological progress and makes predictions development. Finally, the article summarizes the opportunities and challenges of the above-mentioned NOMA technologies based on their technical characteristics. It also offers suggestions for overcoming drawbacks and further advancing NOMA technology. The future mainstream development direction of NOMA technology is to integrate existing mature technologies to further improve performance and introduce machine learning to gradually optimize algorithms. There are still some imperfections in the summary of NOMA technology. There is no detailed performance comparison between the three technologies, nor any suggestions for technical improvements at the coding or design level. Besides, another technical system of NOMA, Frequency Division Multiple Access Non-Orthogonal Multiple Access (FDMA-NOMA), is not mention in this paper. These are potential further research directions in the future.

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