Research on Sparse Code Multiple Access Technology

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Abstract: As an important port technology in mobile communication, multiple access can effectively improve the number of user access in the communication system. However, the Orthogonal Multiple Access (OMA) technology has been unable to meet the higher requirements of spectrum efficiency and system capacity in the future, so it is of great practical significance to study and design a new multiple access technology. Sparse Code Multiple Access (SCMA), as a new non-orthogonal multiple Access (NOMA) scheme, improves the number of user access and spectrum utilization by superposition of multi-user information on the same time-frequency resource. And it can well adapt to all kinds of new application scenarios in 5G. This paper introduces SCMA technology from four aspects: basic principle, system model, key technology and its combination with other systems.

1. Introduction
Reviving the development history of mobile communication, from The First Generation (1G) to The Fourth Generation (4G), multiple access technology has always been a symbol of the evolution of mobile communication system[1]. Frequency Division Multiple Access (FDMA) in 1G, Time Division Multiple Access (TDMA) in The Second Generation (2G), Code Division Multiple Access (CDMA) in The Third Generation (3G) and Frequency Division Multiple Access (OFDMA) in The Long Term Evolution (LTE) technology—representative of The Orthogonal system of 4G. Their performance is constantly improving, but no matter in time, frequency or code domain, orthogonality is required, means that each resource can only be allocated to one user. Therefore, these OMA schemes severely limit the number of users' access, and gradually become difficult to meet the higher requirements of The Fifth Generation(5G) system in the number of user connections, system capacity, communication rate and other indicators. As a result, NOMA technology, represented by stacking transmission, came into being. Compared with OMA, NOMA technology has obvious advantages in enhancing spectrum efficiency, improving the user's connection ability and reducing the time delay of in-port transmission.

NOMA means that users can reuse the same physical resources for communication. By superimposing and transmitting multi-user information, the system capacity is greatly improved. In addition, NOMA can achieve scheduling-free transmission, which helps to achieve a 1ms air interface transmission delay index [2]. It can also use multi-dimensional modulation and code domain extension to achieve higher spectrum efficiency. At present, more than ten NOMA schemes have been proposed, and the ones that have been extensively studied include Power Domain Non — Orthogonal Multiple Access (PD-NOMA technology, Multi-User Shared Access (MUSA), Pattern Division Multiple Access (PDMA) technology and SCMA technology, this paper mainly introduces the SCMA technology.
2. The basic principles of SCMA

SCMA is a new NOMA technology proposed by Huawei and evolved from Low Density Signature (LDS) technology. In order to better understand the basic principles of SCMA, compare it with LDS.

2.1. LDS technology

LDS is a special code domain non-orthogonal multiple access method. It achieves a balance between capacity and interference by introducing low-density tag sequences [3]. At the same time, compared with CDMA spreading codes, LDS introduces zero elements to make the codeword appear sparse, which not only improves the overload gain but also reduces the number of different users after superposition. The collision between code words effectively improves the system performance.

![Figure 1](image1.png)

Figure 1 shows the basic scenario for LDS. After the transmitter completes the channel coding, the data of each data layer is firstly processed by QAM high-order modulation, and then transmitted directly by linear sparse spread spectrum and non-orthogonal superposition. Finally, the receiver adopts the low-complexity message passing algorithm for multi-user joint iterative decoding.

2.2. SCMA technology

In the SCMA system, each user has its own codebook, users map the input bit information into codewords according to its codebook. These codewords are multiplexed on shared subcarriers for transmission, thereby realizing multiple access for multiple users.

![Figure 2](image2.png)

Figure 2 shows the basic scheme for SCMA. Compared with LDS, SCMA combines multidimensional modulation and sparse spread spectrum into a codeword mapping module. On the one hand, this change does not have much impact on the receiver, on the other hand, it can be globally optimized from the modulation and spread spectrum modules to get a better codebook.

3. SCMA system model

Mobile cellular communication systems are usually divided into uplink and downlink. Uplink refers to the physical communication path between the mobile terminal and the base station, while downlink refers to the physical communication path between the base station and the mobile terminal.
3.1. SCMA uplink model

Figure 3 SCMA uplink model

Figure 3 shows the uplink SCMA model. Suppose there are J users in total in the system. First, in order to ensure the reliability of the symbols, the binary bit data input by the user is encoded according to the channel. Secondly, the bit stream output by the channel coding enters the SCMA encoder module, the SCMA encoder generates a proprietary codebook for each household, and selects the corresponding complex code word from the corresponding codebook. Finally, the received signal is sent to the SCMA decoder at the base station side for multi-user signal separation, and the original data is restored through channel decoding.

3.2. SCMA downlink model

Figure 4 SCMA downlink model

Figure 4 shows the downlink SCMA model. The data stream sent by the base station undergoes channel coding and SCMA coding to obtain code words, and then the code words of each user are superimposed and transmitted on the link between the base station and the user. In the downlink, the received signal is multi-user aliased data, so it needs to be equipped with a multi-user detector on the user receiver side. After each user detector separates its own symbol data, the original data is restored through channel decoding.

4. SCMA key technology

Optimized codebook and efficient multi-user detection algorithm are the key to SCMA technology's many advantages, and it is also a breakthrough to achieve further improvement of system performance. Therefore, the codebook design scheme of the transmitting end and the decoding algorithm of the receiving end are the two major aspects of the SCMA system.

4.1. Codebook design

The SCMA system multiplexes resource blocks by assigning different codebooks to different users. Figure 5 shows a transmission scenario where 6 users multiplex 4 subcarriers in the SCMA system.
Because there are multiple users transmitting on the same carrier, the SCMA system exhibits an overload characteristic. The system overload rate in Figure 5 is $6/4=1.5$.

Although sparse codewords can bring overload gain, it also brings great interference, so codebook design is particularly important. A good SCMA codebook can increase the resolution of codewords superimposed, thereby reducing the complexity of the receiving end detection algorithm Degree and bit error rate (BER). The basic idea of SCMA codebook design is: firstly generate the mother constellation diagram, and then perform different constellation diagram operations on the parent constellation diagram to generate each codebook, where the constellation diagram operations include phase rotation, conjugate transposition, and so on [5]. The mother constellation diagrams of the same codebook set are the same, and each codebook is obtained by performing different constellation diagram operations on the mother constellation diagram. The structure of an SCMA codebook can be expressed as:

$$V^*, C^* = \arg \max_{V,C} f(\delta(V, C; J, M, N, K))$$

(1)

f is the code book design criteria, V is the mapping matrix, C is the multi-dimensional constellation, J is the number of users, M is the size of the code book, N is the number of non-zero elements in the code word, and K is the dimension of the code word. Since codebook design is a complex multi-dimensional problem, the optimal design scheme is still in the unknown state.

In order to improve the reliability of codewords, a new SCMA codebook algorithm using Star Quadrature Amplitude Modulation (STAR-QAM) Modulation constellation is proposed in Literature [6], Based on the criterion of obtaining the maximum and minimum Euclidean distance between codebooks, each constellation of the parent codebook is optimized. The simulation results show that the constructed codebook has obvious gain in BER. Literature [7] designed large SCMA codebook with high coding gain based on grid constellation. Simulation results show that the constructed codebook has excellent performance, especially the gain is more obvious at high signal-to-noise ratio.

In order to reduce the complexity of multi-user detection algorithm, a symmetric SCMA codebook was designed based on the visible light communication system of SCMA in Literature [8] according to the maximized minimum Euclidean distance criterion, which can not only reduce the complexity of the codebook design, but also reduce the complexity of the detection algorithm of the receiver. Literature [9] studied the SCMA-ZF scheme combining Zero force Precoding (ZF) with MIMO-SCMA system. On this basis, ZF technology was replaced with an improved nonlinear precoding technology to further improve the advantages in user data rate and receiver complexity.

In addition, literature [10] provides a method to allocate codebook, rate and power for multi-user SCMA systems from the perspective of fairness. This method is based on cooperative game theory to
allocate codebook, which ensures fairness among users while increasing system and rate. Literature [11] proposes an optimal iterative algorithm for joint power allocation and codebook allocation to solve the problem of large transmission power consumption in SCMA, which can effectively reduce the transmission power consumption and computational complexity of the system.

4.2. Multi-user detection algorithm

After the high-dimensional modulation signal generated by the transmitter of SCMA system is transmitted to the receiver through the channel, the receiver uses the MPA algorithm to complete the data detection. MPA is a confidence propagation algorithm, which mainly uses factor graph model to solve probabilistic inference problems [12]. Factor diagram is usually used to represent the relationship between users and resource blocks. The process of information transmission between resource nodes and user nodes can be clearly seen in the factor diagram. Figure 6 shows the factor diagram of SCMA model with 6 users and 4 carriers.

![Factor Diagram Example](image)

Due to the sparsity of SCMA, MPA algorithm needs multiple iterations when there are many users superimposed on the same resource or in multi-antenna scenes, which increases the detection complexity. Therefore, how to reduce the detection complexity is a hot topic of current research. In Literature [13], a low-complexity Discretized Message Passing Algorithm (DMPA) is proposed based on the Probability Density Function (PDF) of discrete variable nodes. Compared with the traditional MPA algorithm, the computational complexity of updating the check node information is reduced from exponential level to polynomial level, which effectively reduces the detection complexity. Literature [14] proposed a SC-EPA detection algorithm with lower complexity based on the extended-factor diagram based on the user's uplink MIMO-SCMA system with multiple antennas and the characteristics of Sparse channel (SC). The sparsity of the channel was used to reduce the transmission of information on the extended-factor diagram, thus accelerating the convergence rate.

5. Integration of SCMA with other systems

Device-to-Device (D2D) and multiple-input multiple-output (MIMO) are two promising technologies in 5G New Radio, which can effectively increase the communication system capacity and spectrum efficiency. The combination of SCMA technology and them has also attracted widespread attention.

Multiple Inlet Multiple Output (MIMO) is an antenna system that uses multiple antennas at both the sender and the receiver to form multiple channels between the receiver and the receiver. By using space resources, it gains both reliability and effectiveness, but the price is to increase the processing complexity of the sender and receiver. To solve the problem of high complexity of signal detection in MIMO-SCMA system, literature [14] proposed an initialization method with accelerated convergence based on the expected propagation framework of extended factor graph, and proposed a new message passing method between variable nodes on this basis, which effectively reduced the algorithm complexity. The literature [15] focuses on SCMA systems that use antennas (or space) as parallel
resources to transmit overlay signals. In order to eliminate Antenna interference and separate users, proposed a joint Zero-Forcing (ZF) and/or minimum mean square error (MMSE) message passing algorithm (MPA). Simulation results show that the BER performance and channel capacity of the proposed system are improved.

D2D communication is a communication mode in which the neighboring devices in the cellular network transmit information directly without passing through the base station. The multiplexing of cellular spectrum can effectively improve the capacity and throughput of the system. Reasonable resource allocation scheme is the key issue to determine its gain. Based on the D2D underlying cellular network in the uplink multi-cell SCMA system, Literature [16] aims to optimize the system throughput, proposes a novel Mode selection and User Preference Matching (MUPM) algorithm based on the matching theory, which effectively increases the system throughput and ensures the fairness of users. In literature [17], codebook and power joint optimization in downlink D2D cellular network of SCMA system is studied. Aiming at codebook allocation, a codebook selection scheme based on conflict graph is proposed. For power distribution, an iterative power distribution scheme based on geometric water charging method is proposed, and the effectiveness of the proposed scheme is verified by simulation.

6. Conclusions

With the development of the mobile Internet and the Internet of Things, the number of access devices in the network has increased sharply. Traditional OMA solutions limit the number of user connections to ensure orthogonality. To solve this problem, Noma technology was proposed. As one of many NOMA schemes, SCMA has become a multi-access scheme with great application prospect in the future due to its advantages such as high frequency utilization, low latency, high transmission rate and the ability to provide massive communication connections. Its combination with various new technologies in 5G has also attracted extensive attention. However, the codebook optimization and decoding simplification of SCMA technology are still the problems hindering its continued development and popularization. Further research and discussion are needed to give full play to the efficiency of SCMA technology.

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