

Joint SIC and SCMA for NOMA-Based Uplink Transmission in 5G Systems

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Abstract— With higher access capacity, non-orthogonal multiple access (NOMA) is a promising wireless access technology to meet the demands of massive machine-type communications (mMTC) and internet of things (IoT) applications. Focused on NOMA-based uplink multiple access transmission, this paper proposes data detection schemes that integrate sparse code multiple access (SCMA) and successive interference cancellation (SIC) techniques, termed the SCMA-SIC process. Simulation comparisons of various NOMA receiver designs, including hybrid-domain NOMA and iterative detection and decoding (IDD) for coded SCMA, show that the SCMA-SIC process achieves the best system performance. In addition, with power control strategies for uplink access, the SCMA-SIC process still performs the best.

Keywords— sparse code multiple access (SCMA), message passing algorithm (MPA), successive interference cancellation (SIC), non-orthogonal multiple access (NOMA), uplink.

I. INTRODUCTION

Various application scenarios of the fifth generation (5G), including enhanced mobile broadband (eMBB), massive machine-type communication (mMTC), and ultra-reliable low-latency communication (uRLLC), have been defined by the radiocommunication sector of the international telecommunication union (ITU-R). In the mMTC scenario, which involves a large number of connected devices transmitting small amounts of data simultaneously, additional multiple access resources are required to meet the extensive connectivity demands. Hence, non-orthogonal multiple access (NOMA) technology was proposed [1] to provide higher access capacity to meet the mMTC's requirements.

NOMA schemes enable multiple users to share time and frequency resources within the same spatial layer through power domain or code domain reuse. These approaches have

been widely discussed in the literature, including power domain NOMA (PD-NOMA) [2] and sparse code multiple access (SCMA) [3]. In PD-NOMA, successive interference cancellation (SIC) [4] is used at the receiver to distinguish users. In SCMA systems, the receiver utilizes the sparsity of codewords and exploits the message passing algorithm (MPA) for multi-user data detection at the receiver.

To further improve the performance of traditional NOMA systems, some studies have proposed hybrid approaches [5], [6]. In [7] and [8], an iterative detection and decoding (IDD) method for low-density parity-check (LDPC) coded SCMA systems is proposed, integrating external channel decoders to enhance transmission reliability. However, most of the literature focused on downlink multiple access transmission, with limited discussion on uplink transmission. In this paper, we focus on uplink multiple access transmission and propose data detection schemes that integrate the concepts of IDD and SIC, called the SCMA-SIC process. Simulations compare the system performance of various data detection methods, including the IDD method and the hybrid-domain NOMA method. The results show that the SCMA-SIC process achieves superior system performance. In addition, this paper describes three different power control strategies to enhance system performance, with the SCMA-SIC process consistently demonstrating the best performance, particularly when using power control strategy C (described in Section IV.C).

The remainder of this paper is organized as follows. Section

II describes the system model. Section III reviews two different data detection methods. Section IV presents two proposed processes, i.e., the SCMA-SIC process and the SCMA-SIC group process, and describes the power control strategies. Section V presents the simulation results and performance comparison. Finally, Section VI concludes the study.

II. SYSTEM MODEL

A. Uplink Transmission and SCMA Encoder

In this study, we consider a multi-user uplink system with a base station (BS) located at the center, as shown in Fig. 1. The basic SCMA [10] encoder procedure maps a data stream of $\log_2(M)$ bits to K -dimensional codewords according to a specific codebook (CB) of size M , with the SCMA modulator mapping these bits into multi-dimensional codewords for simultaneous transmission by J users across the K resource elements. An example of an SCMA encoder procedure with $J = 6$, $M = 4$, and $K = 4$ is shown in Fig. 2.

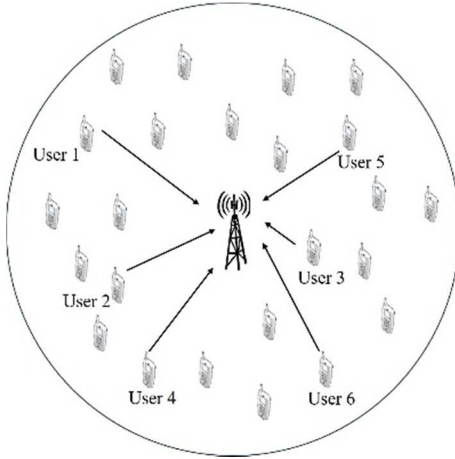


Fig. 1 Multi-user uplink transmission.

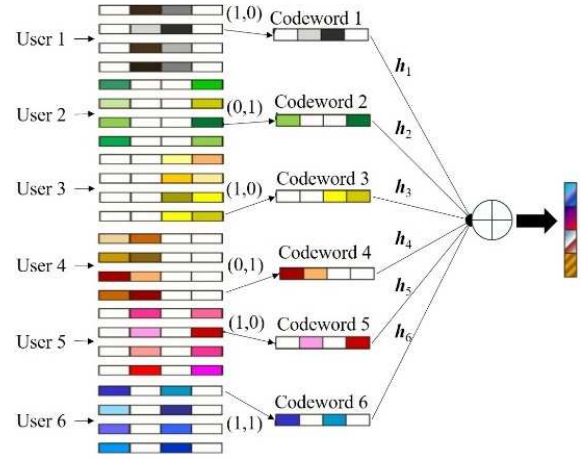


Fig. 2 SCMA encoder procedure for the uplink.

B. Uplink Coded SCMA Transmitter and Receiver

Each user's data stream is encoded with an assigned CB after channel code. The received data signal $\mathbf{y} = [y_1, y_2, \dots, y_K]^T$ over a SCMA block can be represented as (1), where J users share the K same time-frequency resource elements, as shown in Fig. 3:

$$\mathbf{y} = \sum_{j=1}^J \text{diag}(\mathbf{h}_j) \mathbf{x}_j + \mathbf{n}, \quad (1)$$

where $\mathbf{x}_j$ is the SCMA codeword for user j , $\mathbf{h}_j = [h_{j,1}, h_{j,2}, \dots, h_{j,K}]^T$ is the channel vector from user j to the BS and $\mathbf{n}$ is the white noise vector, which follows the Gaussian distribution of $CN(\mathbf{0}, \sigma^2 \mathbf{I})$.

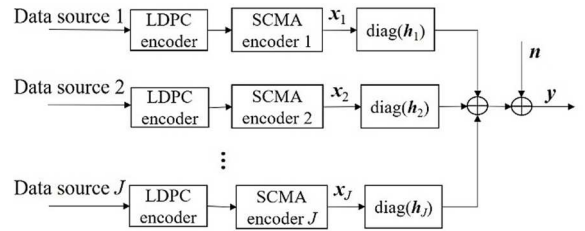


Fig. 3 Block diagram of the uplink SCMA transmitter [11].

In this work, it is assumed that the BS has the accurate information of active CBs and channel gains. Once the active CBs are correctly identified, multi-user detection for SCMA can be accomplished using the MPA [12]. The detected data is subsequently fed to the LDPC decoder for further processing, as shown in Fig. 4.

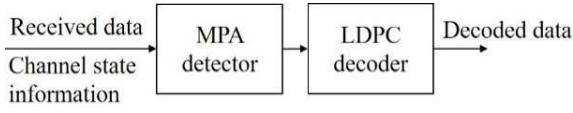


Fig. 4 Block diagram of an SCMA receiver.

III. REVIEW OF DATA DETECTION METHODS

A. Iterative Detection and Decoding (IDD)

The IDD method proposed in [7] for SCMA systems utilizes an iterative approach as shown in Fig. 5. In this method, N_{out} is the number of outer iterations, N_s is the number of SCMA iterations, and N_L is the number of LDPC iterations.

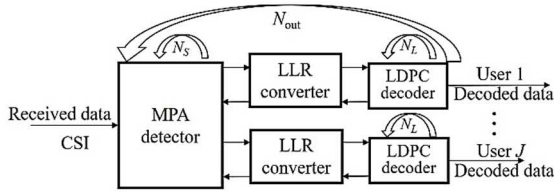


Fig. 5 An IDD method for an SCMA system.

B. Hybrid-Domain NOMA

The hybrid-domain NOMA method, proposed in [6], employs the flow chart as shown in Fig. 6. Initially, it decodes the stronger users (denoted as S), followed by SIC for these users. Subsequently, it proceeds to decode the weaker users (denoted as W). This method is noted for its lower complexity compared to other algorithms. However, it requires a significant power difference between strong and weak users.

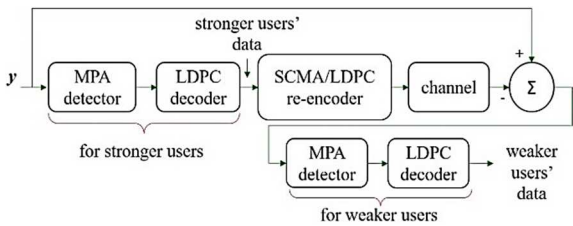


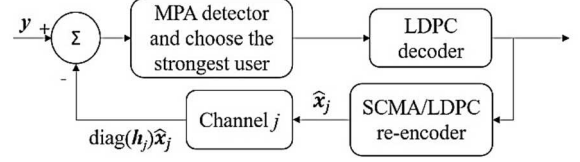
Fig. 6 The hybrid-domain NOMA method.

IV. PROPOSED DATA DETECTION SCHEMES AND POWER CONTROL STRATEGIES

A. SCMA-SIC Process

The SCMA-SIC process and flow chart are shown in Fig. 7.

The MPA detector first detects the strongest user, which is then decoded by the LDPC decoder. Using the SIC technique, the detected user's signal is subtracted from the received signal, and the remaining users are sequentially decoded according to this process. This process achieves superior performance, albeit with higher complexity.

Fig. 7 The SCMA-SIC process where $\hat{x}_j$ denotes the decision on x_j .

B. SCMA-SIC Group Process

The flow chart of the SCMA-SIC group (SCMA-SIC-G) process is shown in Fig. 8. Compared to the SCMA-SIC process, this process first requires dividing users into groups based on received signal powers. Subsequently, the LDPC decoder decodes the strongest group, and through SIC techniques, the detected group's signal is subtracted from the received signal. Finally, the remaining groups are decoded sequentially. While this process reduces complexity compared to the SCMA-SIC, it may result in some performance loss.

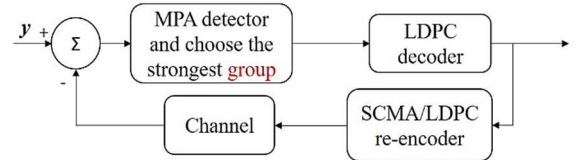


Fig. 8 The SCMA-SIC group process.

C. Power Control Strategies

For the data detection methods, we further introduce three power control strategies to differentiate between S and W (or S and W groups) in simulations. These strategies aim to optimize the allocation of transmission power based on channel conditions and user characteristics, while adhering to the constraint of the same total transmit power, as shown in Fig. 9.

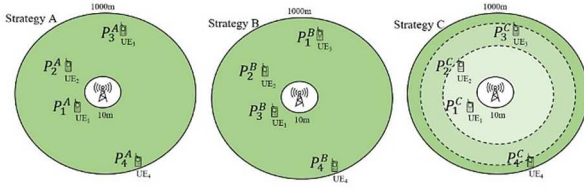


Fig. 9 The three power control strategies where user denoted as UE.

The three power control strategies are described as follows.

Strategy A achieves equal received power through power control. Specifically, strategy A sets the receive power $P_{R,j}^A$ to 1, where

$$P_{R,j}^A = P_{T,j}^A \times \|h_j\|^2 \quad (2)$$

is the receive power of the j -th user, $P_{T,j}^A$ is the transmit power of the j -th user, h_j is the channel vector of the j -th user, and the superscript A denotes strategy A. Therefore, the transmit power

$$P_{T,j}^A = \frac{1}{\|h_j\|^2}, \quad (3)$$

and

$$P_{\text{Total}} = \sum_{j=1}^J P_{T,j}^A, \quad (4)$$

where P_{Total} is total transmit power, and J is the total number of users.

Strategy B sets uniform transmit power across users (i.e., no power control), and is defined as follows:

$$P_{T,j}^B = P_{\text{Total}} \times \frac{1}{J}. \quad (5)$$

Thus, the receive power is given by

$$P_{R,j}^B = P_{T,j}^B \times \|h_j\|^2. \quad (6)$$

Strategy C involves power control with different levels of power adjustment, defined as follows. The transmit power is given by

$$P_{T,j}^C = \frac{10^{P_{T,j}^{C'}/10}}{\sum_{j=1}^J 10^{P_{T,j}^{C'}/10}} \times P_{\text{Total}} \quad (\text{Watt}). \quad (7)$$

It is a normalization of

$$P_{T,j}^{C'} = P_{T,j}^A + P_{L,j}^C \times P_{\text{step}} \quad (\text{dB}), \quad (8)$$

such that the total transmit power remains to be the (pre-specified) P_{Total} . Note in (7) that we have converted $P_{T,j}^{C'}$ from dB to the linear scale before normalizing it. In (8), $P_{T,j}^{C'}$ is set to be the sum of the baseline power $P_{T,j}^A$ (in dB) and the power adjustment term $P_{L,j}^C \times P_{\text{step}}$ (in dB), where

$$P_{L,j}^C \in \{0, 1, 2, \dots, (L-1)\} \quad (9)$$

is the number of steps of power adjustment of the j -th user and P_{step} is the step size (in dB). Thus, $P_{R,j}^C = P_{T,j}^C \times \|h_j\|^2$.

V. SIMULATION

In this section, the system evaluation of uplink multiple access transmission in a 5G system [13] is conducted based on the average probability of connection and the constraint of maintaining the same total transmission power. The system performance, in terms of block error rate (BLER), is compared across different data detection schemes: IDD method, hybrid-domain NOMA method, SCMA-SIC process, and SCMA-SIC-G process. The simulation settings and other system parameters are detailed in Table 1.

TABLE 1. System simulation parameters.

Simulation Parameter	Configuration
Transmission Direction	Uplink
Resource element per SCMA block	6
Total number of users (i.e., UEs)	2000
CB assignment	UE randomly chooses the CB
Average probability of connection	$P = 0.003$
Total number of steps of power adjustment	$L = 2$ or 3
Step size	$P_{\text{step}} = 3$ dB or 10 dB
Channel	Rayleigh (block fading channel) with path loss model [13]
Channel coding	LDPC code [14]

Using the parameter settings in Table 1, where UEs employ

random CB assignment, different UEs may choose the same CB (CB collision). Fig. 10 shows the performance impact for 4 active UEs, with and without CB collision. It is seen that decoding remains achievable even with CB collision, although there is a slight performance degradation.

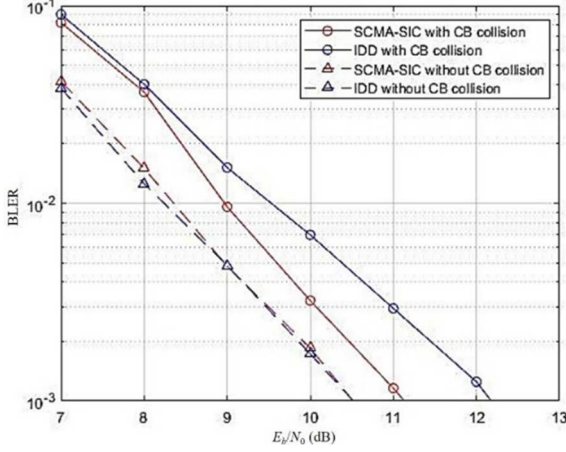


Fig. 10 Performance comparison of CB assignment with and without collision.

In the simulation environment, 2000 UEs are randomly placed within a distance range of 10 meters to 1 kilometer from the center. For an SCMA symbol using 6 resource elements, with 2000 potential UEs and an average probability of connection of 0.003, the simulation results for four different receiver designs are presented. The total number of steps of power adjustment in the simulation is 2 or 3, with power level P_{step} of 3 dB or 10 dB. Additionally, Fig. 11 demonstrates a scenario with the total number of steps of power adjustment L being 3. The area is partitioned into 3 regions: the inner circle and two outer rings. Each region corresponds to a different power adjustment. In the simulations, the 3 regions are of equal area.

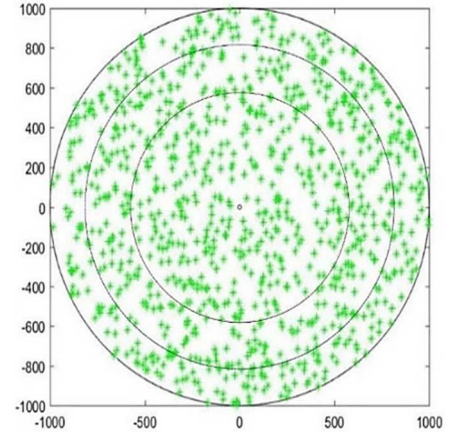


Fig. 11 Random placement of 2000 UEs and total number of steps of power adjustment $L = 3$.

The simulation results in Fig. 12 show that the SCMA-SIC process proposed in this study offers the best system performance. It is also observed that in hybrid-domain NOMA, the performance improvement for strong users diminishes when the E_b/N_0 exceeds 10 dB, indicating that the decoding performance is affected by the power gap between strong and weak users. Consequently, hybrid-domain NOMA is excluded from further performance comparisons. In Fig. 13, the simulation results demonstrate that the SCMA-SIC process consistently outperforms the other methods under various power control strategies when $L = 3$ and $P_{\text{step}} = 3$ dB, with strategy C exhibiting the best performance.

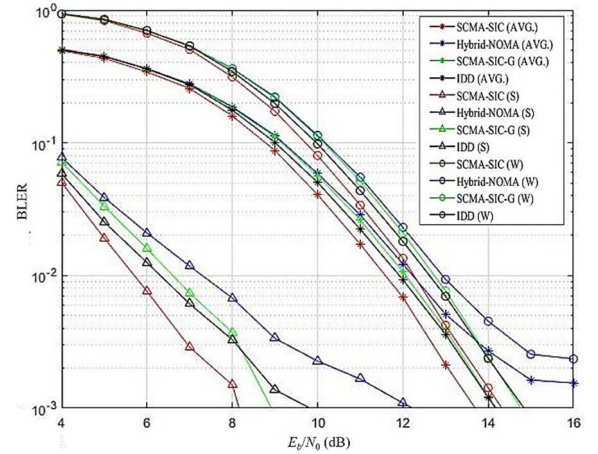


Fig. 12 The BLER with 2000 UEs, $P = 0.003$, $L = 2$, and $P_{\text{step}} = 10$ dB (without using power control).

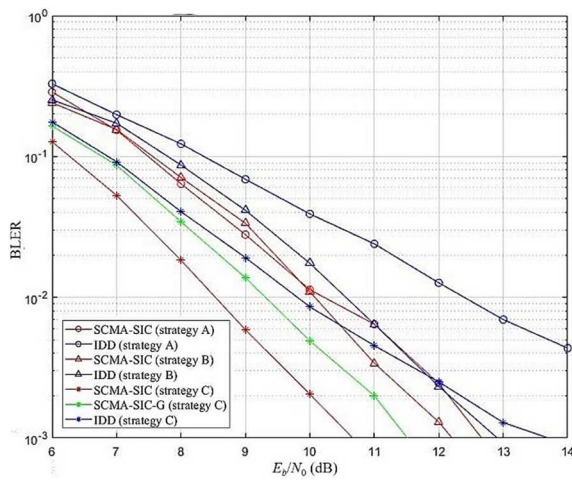


Fig. 13 The BLER with 2000 UEs, $P = 0.003$, $L = 3$, $P_{\text{step}} = 3$ dB, and with different power control strategies.

VI. CONCLUSION

In this paper, we propose an SCMA system for uplink multiple access transmission that integrates IDD and SIC techniques at the receiver, aiming to improve the accuracy of multi-user information decoding. The SCMA-SIC and SCMA-SIC-G processes are compared with existing NOMA data detection schemes (i.e., hybrid-domain NOMA and IDD methods) in terms of the system's BLER. The simulation results show that the SCMA-SIC process outperforms the other methods. Furthermore, our simulation results indicate that, when power control strategy C is adopted, the SCMA-SIC process consistently achieves the best BLER.

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