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Potential Solutions, Challenges and Implementation Issues for NOMA in 5G Communications

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ABSTRACT

Non-Orthogonal Multiple Access (NOMA), a promising radio access technology for 5G and beyond networks, has recently attracted a lot of interest because of its higher spectral efficiency and capacity to serve multiple users simultaneously while maintaining the same time and frequency resources. 5G mobile networks will be able to accommodate at least 100 billion connections between devices, a 1000-fold growth in system capacity, improved coverage, high data rates, and ultra-low energy consumption. A base station (BS) can serve numerous users at the same time, frequency, and code resource thanks to NOMA, which implements multiple access (MA) by utilizing a new dimension - the power domain. One of the fundamental NOMA methods that performs successive interference cancellation (SIC) at the receiver and superposition coding (SC) at the transmitter is the power domain NOMA. In this study, the use of MIMO techniques with NOMA systems is discussed. Additionally, it compares and contrasts Orthogonal and Non-Orthogonal Multiple Access strategies.

Keywords: 5G, NOMA, MIMO, SC, SIC, Spectral Efficiency,

INTRODUCTION

For battery-powered devices, such as smart phones, energy-efficient communication is essential because higher energy usage will cause the battery to discharge more quickly. Therefore, it is essential and significant to make efforts to maximize energy-saving potentials and enhance the energy efficiency of cellular networks. A new radio access and core network, as well as new kinds of devices and applications, are all part of the 5G mobile network standard. It represents the entire (virtualized) ecosystem, comprising core networks, backhaul, management, and effective end-to-end application delivery, as well as the consolidation of wireless, fixed, and satellite access networks.

Future radio access networks (5G and beyond) are expected to offer applications with extremely high rates, ultra-low latency, enormous connections, and high levels of mobility. The researchers strongly suggest and look into NOMA to achieve these goals. By permitting users to share the same radio resources, NOMA facilitates dense networks and achieves great spectrum efficiency.

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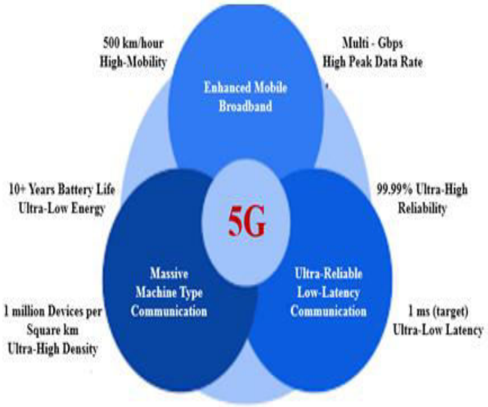

Figure 1: The 5GVision

Multiple Input and Multiple Output (MIMO)

A MIMO system is considered with N_t transmitting antennas and N_r receiving antennas in figure 2.

Greater data can be added to the wireless channels, which is one of the system's major advantages. Therefore, this strategy can increase dependability, spectrum efficiency, and energy efficiency. MIMO allows antennas to integrate data streams coming from several directions and at various times to significantly boost receiver signal receiving power. When striving to achieve maximum data throughput in channels with constrained bandwidth, it is possible to combat the negative impacts of multipath and fading by using several antenna arrangements. Higher Data Rates, Range, and Reliability are provided by MIMO.

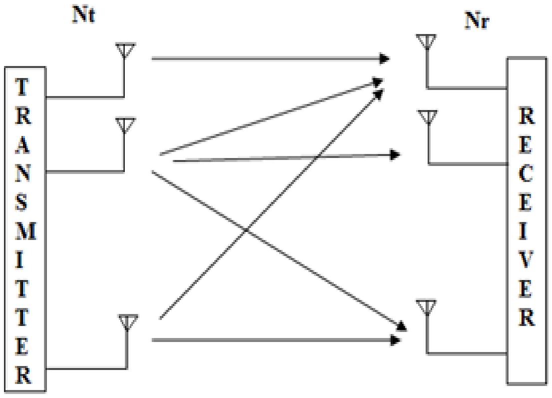

Figure 2: MIMO System

MIMO – Spatial Diversity and Spatial Multiplexing

MIMO can be set up in one of two ways depending on how data is carried over a particular channel. Different propagation paths exists in a system if there are multiple antennas.

Spatial Diversity: Sending the same data through many propagation (spatial) pathways aims to increase the system's dependability. We refer to this as spatial diversity. A signal path from transmitter to receiver is provided by each set of transmit and receive antennas. Multiple independently-faded copies of the data symbol can be generated at the receiving end by delivering the SAME data across various pathways, resulting in more trustworthy reception.

Spatial Multiplexing: Different parts of the data can be sent on various data propagation pathways in an attempt to enhance the system's data rate (spatial-multiplexing).

MULTIPLE ACCESS (MA) TECHNIQUES

A suitable MA scheme enables large mobile devices to effectively use the constrained network resources and achieve the highest system performance. In essence, a radio access network uses a channel access approach to interconnect mobile terminals to the core network.

Orthogonal multiple access (OMA) and non-orthogonal multiple access (NOMA) are two general categories for multiple access techniques.

Orthogonal Multiple Access (OMA)

Using various basis functions, an orthogonal technique enables a perfect receiver to completely remove undesired signals from the required signal. The cell capacity is restricted by traditional OMA protocols, which distribute resources to each user either in time, frequency, or code. OMA techniques include time division multiple access (TDMA) and orthogonal frequency-division multiple access (OFDMA). In TDMA, many users time-share the usage of the same frequency channel. With the use of the orthogonal frequency-division multiplexing (OFDM) method, which involves selecting subcarrier frequencies so that the subcarriers are orthogonal to one another, OFDMA enables multi-user communications.

Non - Orthogonal Multiple Access (NOMA)

In comparison to OMA, NOMA enables the simultaneous allocation of a single frequency channel to a number of users within a single cell. It also offers other benefits, such as increased spectral efficiency (SE), higher cell-edge throughput, flexible channel feedback, and lesser transmission latency. The two types of NOMA approaches that are currently available are power domain and code-domain NOMA. The power-domain NOMA that superimposes numerous users in the power domain and takes use of the diversity in channel gains amongst multiplexed users is the subject of this study. Signals from different users are superimposed at the transmitter side, and the resultant signal is then transmitted over the identical channels. Multiuser detection (MUD) techniques like SIC are used at the receiver sides to discover the desired signals.

For delay-sensitive applications in fading scenarios, non-orthogonal systems allow for non-zero cross-correlation between the signals from various users and outperform orthogonal ones in terms of spectral - power efficiency. Exploring the power domain to implement MA on mobile networks is the core principle of NOMA. The same time, code, and frequency channel is used by a BS to service NOMA users in a single cell, and their signals are multiplexed using various power allocation coefficients.

PRINCIPLES OF NOMA

Numerous NOMA solutions exist, but they can mainly be divided into two basic categories. Code-domain NOMA achieves multiplexing in the code domain, as opposed to power-domain NOMA, which does so in the power domain. The full pool of time and frequency resources are shared by code-domain NOMA, just like in the fundamental code division multiple access (CDMA) systems. The user-specific spreading sequences used in code-domain NOMA, on the other hand, are either sparse sequences or non-orthogonal cross-correlation sequences with lower correlation coefficient.

The innovative aspect of NOMA is its ability to opportunistically distribute transmit power among various users by taking advantage of their various channel circumstances. The users who have good channel conditions will employ the SIC method, whereby they first decode the messages of the users who have worse channel conditions, and then they decode their own messages by omitting the information from the previous users.

NOMA aims to establish a compromise between fairness and throughput. Compared to LTE designs, 5G network architecture will be distinct. The NOMA in LTE allows significant performance gains in system throughput and capacity when compared to OMA. The idea behind NOMA is that several user signals in the code or power domain might share the same frequency resource, leading to non-orthogonality in user access. Multi-user detection and SIC are used for signal separation at the receiver side by depending on highly advanced receivers.

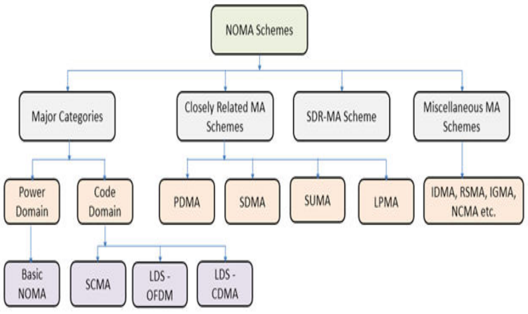

Figure 3: A simple classification of NOMA techniques

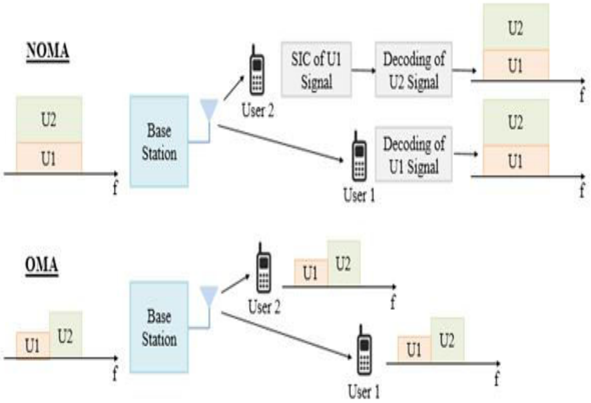

Figure 4: NOMA vs. OMA

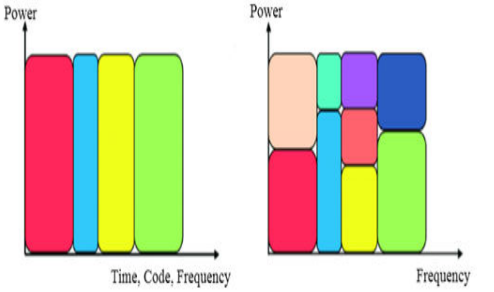

Figure 5: Illustration for OMA and NOMA in the power as well as frequency domain

The number of sub channels in OMA determines the maximum number of User Equipments (UEs) that can access the sub channels simultaneously. The number of concurrently multiplexed UEs in NOMA can be significantly more than in OMA.

An example of single-cell OMA and NOMA in the power (and frequency) domain is shown in the accompanying figure 5. While each sub-channel in NOMA can accept more UEs, each UE in OMA has dedicated access to the radio resource.

Two fundamental methods, SC and SIC, are crucial for comprehending the class of NOMA that this work focuses on.

Superposition Coding (SC)

Information can be sent from one source to many receivers at once using the SC approach. The broadcasting of a television signal to several receivers and delivering a speech to a crowd of individuals with various backgrounds and abilities are two instances of superposed communications.

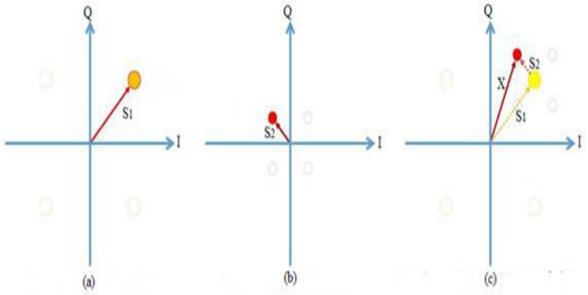

Figure 6: An example of SC encoding; (a) Signal constellation of user 1; (b) Signal constellation of user 2; (c) Constellation of superposed signal

Successive Interference Cancellation (SIC)

The main principle of SIC is the successive decoding of user signals. Before the signal from the following user is deciphered, the signal from the previous user is subtracted from the combined signal. When SIC is used, one user signal is decoded while the second user signal is treated as an interference. However, the latter user signal is then decoded with the advantage of the interference from the former signal having previously been eliminated. Before SIC, users are arranged according to the intensity of their signals, allowing the receiver to decode the stronger signal first, take it out of the combined signal, and then separate the weaker signal from the rest.

It should be noted that each user decodes the signals received from the other interfering users as noise. On the receiving end, the method for decoding the superposed signal is shown in figure 7. First, the signal received is processed to reveal the constellation point of user 1. The constellation point of user 2 is then decoded in relation to the constellation point of user 1 that has already been decoded.

The order of signal or power strength is important for SIC. In other words, the user or receiver can decode one of most powerful or active message, subtract it from the original combined signal, and decode the other messages using less power while treating other user signals as interference.

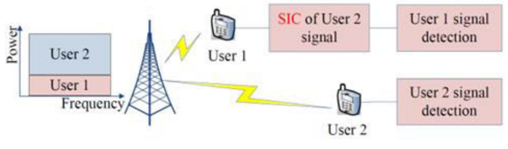

Figure 7: SIC at the receiver

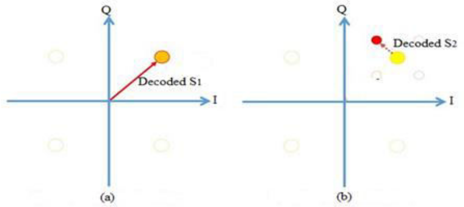

Figure 8: An example of SC decoding; (a) decoding the signal of user 2; (b) decoding the signa
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Channel Capacity with SIC

Let's compare the wireless channel capacity with and without SIC for the typical receiver case shown in figure 9.

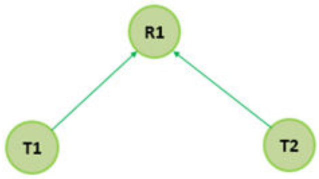

Figure 9: Two transmitters sharing a common receiver

Let S_{11} and S_{12} represent the received signal strengths from two transmitters T_1 and T_2 at a single receiver R_1; B represent the bandwidth, and N_0 represent the channel noise. When T_1 and T_2 broadcast at the same time, R_1 must decode the stronger signal - say let's S_{11} - first and treat the weaker signal - say let's S_{12} - as interference.

(i) Since only one of T1 or T2 can transmit simultaneously without SIC, the channel's capacity, C-SIC, is

$$C_{-SIC} = \max\left\{B\log_2\left(1+\frac{S_{11}}{N_0}\right), B\log_2\left(1+\frac{S_{12}}{N_0}\right)\right\}$$

Receiving two signals at once is possible using SIC. In accordance with SIC, the corresponding channel capacity

$$C_{+SIC} = B\log_2\left(1+\frac{S_{11}+S_{12}}{N_0}\right)$$

The important finding is that, with SIC, the channel capacity is at all times higher than the individual capacities of any one transmitter, and that the relative gain is greater when the received signal strengths (RSSs) are identical.

PROSPECTIVE NOMA SOLUTIONS

Prospective solutions for challenges with the adoption of NOMA in 5G are presented in this section.

NOMA with MIMO and Beam forming

Thus, the combination of NOMA with multi-user Beam Forming (NOMA-BF) has the potential to achieve the benefits of both NOMA and BF. Two users can share a single beam forming vector using the NOMA-BF approach. NOMA-BF includes a clustering and power allocation algorithm based on correlation among users and channel gain difference in order to eliminate inter-beam interference and intra-beam interference. In comparison to the traditional multi-user beam forming system, the NOMA-BF system increases the total capacity. Additionally, NOMA-BF ensures weak users' ability to maintain user fairness.

Energy-Efficient NOMA

Through non-orthogonal resource allocation, NOMA uses some regulated interference and achieves overloading at the expense of a marginally more complex receiver. As a result, NOMA for 5G can reach greater SE. Reducing energy consumption has become of utmost importance to academics in recent years due to the surge in interest in green communications, and 5G has also targeted EE as one of the primary factors to be achieved.

Co-operative NOMA (C-NOMA)

Cooperative communications and NOMA can be combined to increase the capacity and dependability of the system. The cooperative NOMA (C-NOMA) technique takes advantage of historical data present in NOMA systems. By acting as relays for distant users with weak channels to the BS who are at the cell edge, close users with better channel conditions to the BS decode information for others and enhance the reliability of their own reception. The outage probability is a crucial C-NOMA metric for system characterization.

In particular, C-NOMA is split into two phases the cooperation phase and the transmission phase. The BS transmits superimposed messages (users' signal) to NOMA users during the transmission period. The users will do subsequent detection at the end of this phase. There are (n-1) time slots in the cooperation phase. At the i-th time slot, $(1 < i < (n-1))$ the (n-i+1) th user broadcasts the combination of the (n-1) messages. Implementing optimal power allocation strategies will improve C- NOMA's performance even more.

Path Loss's Effect

Future radio access may benefit from the power-domain user multiplexing strategy known as NOMA. The path loss performance of NOMA in a cellular network with randomly distributed users can be assessed in two scenarios. Each user has a targeted data rate in the first scenario, which is determined by the allocated quality of service (QoS). In the alternative case, channel circumstances are taken into account while assigning users' rates.

However, under NOMA, the transmission power is divided among strong and weak users. Inter-user interference also appears in NOMA. As a result, NOMA users encounter changes in both the signal and interference powers, which could lead to a different rank from the reported RI presuming full transmission power.

NOMA in a Coordinated System

In cellular systems, a user at the cell edge often has a lower data rate than a user close to the base station. Transmission speeds to cell-edge users are typically increased by using coordinated multipoint (CoMP) transmission and reception systems, where many BSs support cell-edge users collectively. A coordinated SC (CSC)-based NOMA technique was developed to address this issue by taking into account SC for downlink broadcasts to a number of cell-edge users and users close to the BS concurrently with a common access channel.

Fairness in NOMA

The NOMA plan is a practical means of enhancing user fairness and allows for a more flexible administration of the users' achievable rates. Data charges for NOMA subscribers are inequitable. The fact that NOMA distributes more power to the weaker users is an important characteristic. As a result, NOMA is able to ensure an alluring trade-off between the fairness among users in terms of their throughput. The cooperative NOMA scheme and intelligent PA policies are two examples of complex methods for maintaining fairness for NOMA.

Under two presumptions, the power allocation issue can be approached from the perspective of fairness:

a. Since the BS features flawless CSI, user data rates automatically adjust to channel conditions; and

b. Under a typical CSI, users have specified targeted data rates.

These presumptions allow for the development of low-complexity algorithms that produce globally optimal results.

Network NOMA

The direct deployment of single-cell NOMA solutions will not be suitable to deal with inter-cell interference and mutual interference between cell edges users when using NOMA in a multi-cell situation; single-cell NOMA needs to be extended to network NOMA. Using joint pre-coding of user signals across nearby cells is one potential way to reduce the aforementioned interferences in network NOMA. Dynamic user selection is required for each NOMA pair in the correlation-based pre-coder design.

NOMA in Visible Light Communications (VLC)

In addition to being a potential candidate for next-generation wireless communications, NOMA's viability in VLC is also a topic of discussion. It is practical to use a NOMA scheme to increase the throughput that can be achieved in high rate VLC. A potential MA downlink method in VLC networks is NOMA.

NOMA User Pairing

Multiple groups of users may be created, each with its own NOMA implementation and OMA allocation to other groups. Selecting users whose channel circumstances are more pronounced would further boost the performance advantage of NOMA with fixed power allocation over traditional OMA. On the basis of proportional fairness (PF), a two-step strategy for user matching was presented. The power allocation for each candidate user set is optimized to identify the best scheduling measure in the first stage. A further phase involves scheduling the ideal user pair, or single user with the maximum metric.

NOMA CHALLENGES

Number of researchers have sought to develop and use NOMA techniques as well as to address numerous technological issues related to such methods. NOMA considerably boosts performance gains and is compatible with MIMO, relaying, and cooperative communications. In order to address the issues with the multi-cell network, wireless link adaption, EE-SE trade-off, and user pairing, this article has identified a number of practical NOMA solutions. Researchers have developed a method whereby the poor service quality and low data rate that cell-edge customers encounter may readily be enhanced by implementing NOMA-based coordination. This section aims to offer some suggestions for further research for academics who want to look into NOMA in further detail.

Consequences of Transmission Distortion

The outage probability affects information capacity and distortion. It is clear that an outage probability that optimizes the outage rate may not deliver the least amount of distortion anticipated. The outage probability for which a NOMA method may deliver the maximum outage rate with acceptable distortion can be optimized through research.

NOMA with Several Antennas

A critical factor in the assessment of MIMO NOMA is the channel matrix rank. It is crucial to research MIMO NOMA design while taking rank-deficient channel matrices into account. To enhance MIMO NOMA performance, rank adjustment for NOMA can be used. To further improve performance, rank and transmission power assignment optimization can be integrated.

Interference's Effect

Wireless personal area network (WPAN) operations present a severe interference threat to Bluetooth (BT) radio in cellular communications. When a user is in the discovery phase, BT interference reduces coverage and throughput, results in frequent or complete loss of connectivity, and makes pairing challenging. Since NOMA pairs its users based on CSI, a self-organizing scatter net used to manage BT nodes must be modified to work with NOMA. Because users are mobile, interference changes with time. An attractive topic will thus be the performance evaluation of a cooperative NOMA scheme in this dynamic interfering scenario.

Adaptive User Pairing

Due to the fact that several users share the same time, frequency, and spreading code, co-channel interference is a significant issue with NOMA systems. To maximize the advantages provided by NOMA, dynamic user pairing/grouping systems must be designed. Performance increases are improved by the UPPA scheme. However, NOMA is only able to schedule a maximum of two users. A power allocation technique in the multi-user NOMA system where the scheduler permits more than two users would be a promising extension of the UPPA scheme. Additionally, more study is needed to apply UPPA schemes and adaptations to a real-world system that uses an appropriate modulation and coding scheme.

Analysis of Outage Probability

The capacity that can be reached depends on user outage behaviour. The likelihood that consumers may experience an outage will change when NOMA includes beam shaping. On that basis, NOMA-outage BF's performance analysis can be looked into. By creating a pre-coder, Network NOMA primarily concentrates on minimizing inter-cell interference. But in order to comprehend how cell-edge users behave during outages, precise study is required. To examine outage performance, additional research can be done on other NOMA works, such as NOMA with VLC and NOMA with coding.

Resource Allocation

5G systems should be able to provide huge data speeds at extremely low latency and in efficient ways in order to serve a variety of traffic demands. In order to manage the system BW in a communications system effectively, the entire BW is first separated into a number of portions. Then, like in the case of NOMA, each chunk is given to a specific user or a group of users. Additionally, each user's total quantity of packets changes over time. A complex algorithm is therefore needed for user pairing and optimal power distribution among users in NOMA in order to deliver the best performance while utilizing the fewest resources. Another fascinating area of study is power distribution in NOMA-based cognitive radio networks.

Heterogeneous Networks

A wireless network made up of nodes with various transmission power and coverage sizes is known as a heterogeneous network (HetNet). The HetNet offers sufficient capacity and coverage, as well as low energy consumption, for next-generation wireless networks. The performance of NOMA will also be impacted by the spatial distribution of mobile users, which is not uniform. Therefore, research into ergodic capacity, user fairness, and outage performance in NOMA schemes with spatial user distribution may also be worthwhile.

Uniform Fairness

mmW cellular, the majority of locations encounter a signal failure at a distance greater than 175 m. It would be good work to develop a NOMA scheme that offers users (especially those situated at a distance larger than 150 m up to the cell border, in the case of mmW cellular) consistent outage experiences..

NOMA with Antenna Selection

An efficient Transmit Antenna Selection (TAS) technique uses a single RF chain for transmission and opportunistically chooses the optimal antenna from among various antennas. This finally results in a reduction in system complexity, cost, size, and power consumption at the cost of tolerable performance loss. Research should be done to find an innovative TAS-NOMA system for downlink communications from a BS in this regard.

Practical Channel Model

A massive amount of BW is available in the millimeter wave (mmW) frequencies between 30 and 300 GHz, which constitute a new horizon for cellular networks. Therefore, it is crucial to comprehend the difficulties of mmW cellular communications in general and channel behaviour in particular. This is a prerequisite for creating 5G mobile systems and backhaul technologies. The studies that have already been done on NOMA assume that the wireless links between transmitter and receiver have an AWGN Rayleigh fading channel. If the measured path loss and delay spread values could be taken into account to represent the radio channel in the mmW band, a more accurate analysis would be presented.

Other Challenges

To achieve robust performance, one needs an appropriate CSI feedback mechanism, a suitable channel estimation scheme, and an appropriate reference signal architecture. When the transmitter must operate with faulty CSI and/or little feedback, proper user selection and power allocation algorithms are required. To choose the methods that will produce the optimum NOMA performance, it is essential to consider the impact of PAPR.

IMPLEMENTATION ISSUES

The system's operation and design are included in the NOMA implementation. This section explains issues like computational complexity and error propagation that can be crucial when evaluating NOMA performance.

Decoding Complexity

When opposed to orthogonal methods, SIC signal decoding requires more complex implementation since the receiver must first decode the information of other users before decoding its own. As the number of users in the targeted cell grows, complexity also grows. The execution of SC/SIC can then take place within each group after the users are clustered into a number of groups. A trade-off between performance improvement and implementation complexity is essentially offered by this group-wise SC and SIC operation.

Power Allocation Complexity

The transmit power allotted to a user has an impact on the throughput the user can achieve. The capacity that other users can achieve is also impacted by this specific power allocation. It takes a brute-force search of all potential user pairings with dynamic power allocation to obtain the best throughput performance in NOMA.

Quantization Error

For an analog-to-digital (A/D) converter to accurately quantize a weak signal when the user's received signal strength varies, the converter must support a very large full-scale input voltage range and have high resolution. This is because the ADC's quantization noise power decreases with the number of levels it uses. Arbitrarily high-resolution ADC has a limit, though, because of the expense, length of the conversation, and complexity of the technology.

Signaling and Processing Overhead

Comparing NOMA to its orthogonal counterparts reveals various sources of increased signaling and processing cost. NOMA signal processing involves additional energy overhead due to dynamic power allocation and encoding and decoding for SC and SIC.

Error Propagation

It makes sense that once an issue in SIC happens, all other user data will probably be decoded incorrectly as well. The NOMA performance may be slightly impacted by error propagation. The issue is because during NOMA scheduling, a user with poor channel gain is allocated to a user with good channel gain. Although there are publications that analyze the SIC error propagation in fundamental MIMO systems, there isn't much well-known research that explains how faulty SIC affects NOMA schemes mathematically.

Limited Number of User Pairs

Power-domain multiplexing is utilized by NOMA to provide its advantages. A typical NOMA scheme can only accommodate a certain number of user pairs, which gradually limits the capacity gain of NOMA. It is crucial to identify the best signal detection and decoding method that maximizes the number of user pairings.

Residual Timing Offset

Since NOMA users are spatially distributed and mobile communications channels are typically dynamic, perfect synchronization between NOMA users is impractical on uplink. OFDM symbols from the superposition-coded users are time-aligned in asynchronous communications. As a result, the performance of NOMA users is significantly influenced by the relative time offset between interfering users.

NOMA Deploying Environment

Small cells are also becoming more significant and are being researched for 5G networks in addition to microcells. Fortunately, even in a small cell where NOMA gives a bigger performance increase than OMA, the NOMA gain is still attainable. It's also vital to remember that NOMA growth in tiny cells is higher in terms of cell throughput than in macro cells. As a result, NOMA can be used equally well in small- and macro-cell contexts.

CONCLUSION

An innovative and promising power-domain user multiplexing method for future radio access is called NOMA. Enhanced spectrum efficiency is one of the appealing advantages provided by NOMA. The network-level and user-experienced data rate needs of 5G technologies can both be met with NOMA in an efficient manner.

One can anticipate that NOMA with a SIC applied to the receiver side will provide a superior trade-off between system efficiency and user fairness than OMA, based on information theory. When there are significant differences in the channel conditions among the users who are not orthogonally multiplexed, this improved performance becomes extremely significant. The near-far effect that occurs in cellular environments can be effectively exploited by NOMA.

To fully benefit from NOMA, optimal power allocation, QoS-oriented user fairness, proper user pairing, and effective link adaptation are also necessary in addition to excellent SC at the transmitter and error-free SIC at the receiver. Further study on NOMA in 5G is anticipated to be based on a number of significant concerns, including dynamic user pairing, distortion analysis, interference analysis, resource allocation, heterogeneous networks, carrier aggregation, and transmit antenna selection.

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