NOMA and Its Applications: A Survey

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ABSTRACT

Non-orthogonal multiple access (NOMA) has been recognized as an emerging technology that can enhance spectral efficiency, throughput, data rate, and latency in future 5G wireless networks. Thus, NOMA has been considered by many researchers in the last decade. In this paper, we present an overview of NOMA technology and its application in cellular networks and unmanned aerial vehicles (UAVs). In addition, we also describe in detail the superposition coding (SC) and successive interference cancellation (SIC) mechanisms. Furthermore, the performance metrics of the NOMA based wireless networks, including outage probability, throughput, and energy efficiency, are analyzed. Finally, the challenges in NOMA network systems in terms of imperfect SIC and imperfect CSI are provided. Therefore, this survey provides the fundamentals of NOMA for findings of this latest technology.

Index Terms – NOMA, Superposition Coding, Successive Interference Cancellation, Cellular Networks, NOMA Aided UAV, Outage Probability, Energy Efficiency, Throughput, Imperfect Channel State Information.

1. INTRODUCTION

Recently, NOMA plays a potential role in the exploitation of emerging technologies to serve 5G and future networks. This is because that this technique shows superior features over previous and current 4G technologies such as increased user data rate, massive connections, reduced end-to-end latency, more energy efficient communications as well as increased system capacity [1]. NOMA, belonging to a non-orthogonal multiple access mechanism group, carries out sharing the same frequency/time resource for multiple users. Two mechanisms are exploited in NOMA including superposition coding (SC) and successive interference cancellation (SIC) [2], [3]. In contrast, OMA technology utilizes many techniques such as TDMA, FDMA, CDMA, OFDM [4], [5] which are orthogonal multiple access among subcarriers. Users in the OMA system are served in a single carrier. Although OMA has been proved its advantages in the past many decades, with spectral scaring, latency decreased requirement, and fairness among users, NOMA has been demonstrating superior advantages over OMA.

Many studies have pointed out that NOMA can be exploited in a huge number of applications. These applications spread from cellular communications, wireless sensor networks, UAV networks. In [6], a new radio resource allocation strategy combined with the NOMA scheme was investigated. The proposed strategy has demonstrated that it can improve cell-edge user throughput as well as spectral efficiency and is robust in the case of communications in congested areas. [7] developed a new NOMA technique for multi-cell multiple input multiple output (MIMO) by utilizing the interfering channel alignment method. Based on the proposed scheme for a given system parameter, the user number maximization problem for supporting within each cell was derived. The issues of channel assignment and power control were analyzed for a device-to-device (D2D) NOMA cellular network [8]. With SIC decoding order constraints, a maximum sum rate of two-D2D groups can be achieved with the satisfaction of minimum rate requirements of the users.

In this survey, we first overview NOMA and the main techniques for NOMA. Furthermore, we discuss schemes NOMA in the power domain (PD) and code domain (CD). We address superposition coding and SIC mechanisms in NOMA. The set of NOMA system performance parameters, including outage probability, throughput, and energy efficiency, are analyzed. Finally, two challenges, including imperfect SIC and imperfect channel state information (CSI), are analyzed in this overview. This survey provides an overview and key issues for finding NOMA.

2. FUNDAMENTALS OF NOMA

What is NOMA? First, we consider the multiple access concept. This concept refers to the communication channel sharing mechanism among multiple users. It is a part of the heart of cellular communication systems. The cellular network generations from the first to the fourth employed different multiple access schemes, known as the OMA technique. However, on the receiver side, it only uses one common theme for orthogonal signals for multiple users. Multiple access schemes for OMA consist of FDMA, TDMA, CDMA, OFDMA, and SDMA. For instance, the orthogonal rules for different users in OFDMA scheme relate to the frequency and/or time domains. This means that each user can only be allocated one OFDM resource block. In contrast, the

NOMA technique allows the same frequency/time/space/code resource to be allocated to multiple users, resulting in frequency reuse.

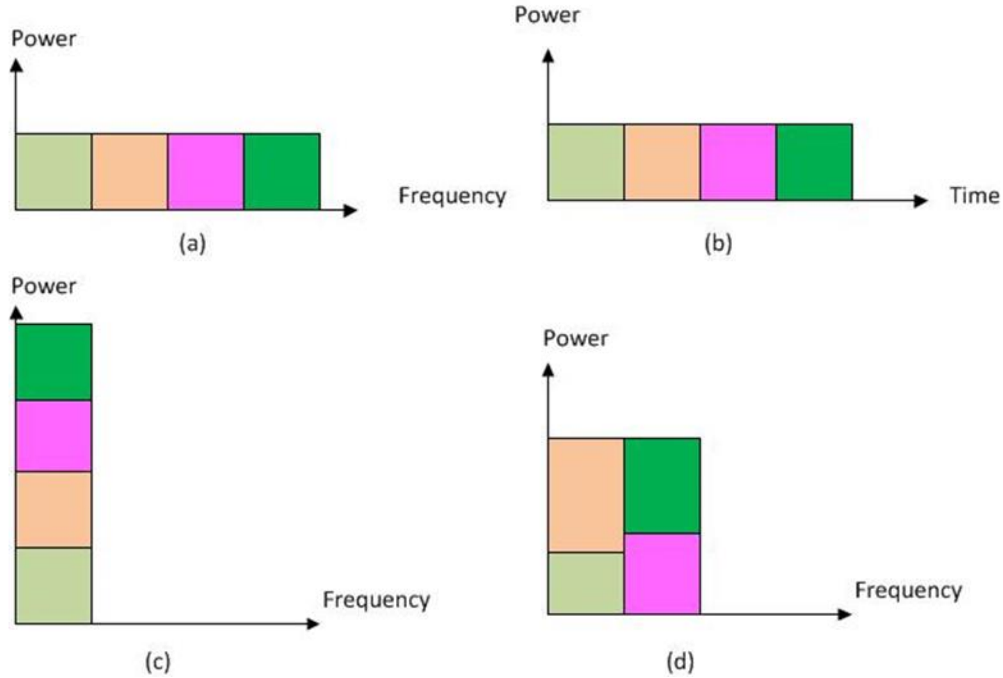

Figure 1: Multiple Access Scheme Illustrations (a) FDMA, (b) TDMA, (c) CDMA and (d) PD NOMA

Although released in the 1980s, the user capacity has hugely increased from the first to fifth cellular network generations (named 1G, 5G, respectively), as shown in Figure 2. While 1G and 2G achieve small user capacity, 3G has a higher user capacity and this capacity is exponentially increased in 4G. In particular, the capacity depicted for 5G in 2020 is more and more. This is because there will be a huge number of wireless communication devices connecting to these 5G networks. They can be cellular devices, smart devices, wireless sensors, and so on. These devices need to access the resources for transferring high data rates, communicating voice and video calls. Therefore, it has been expected to open several chances for the delivery of innovative products.

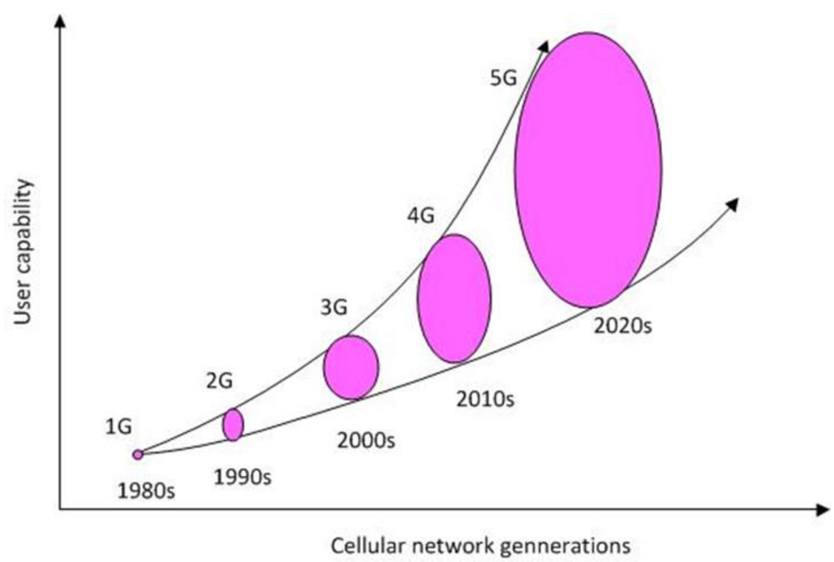

Figure 2: User Capabilities Versus Cellular Network Generations

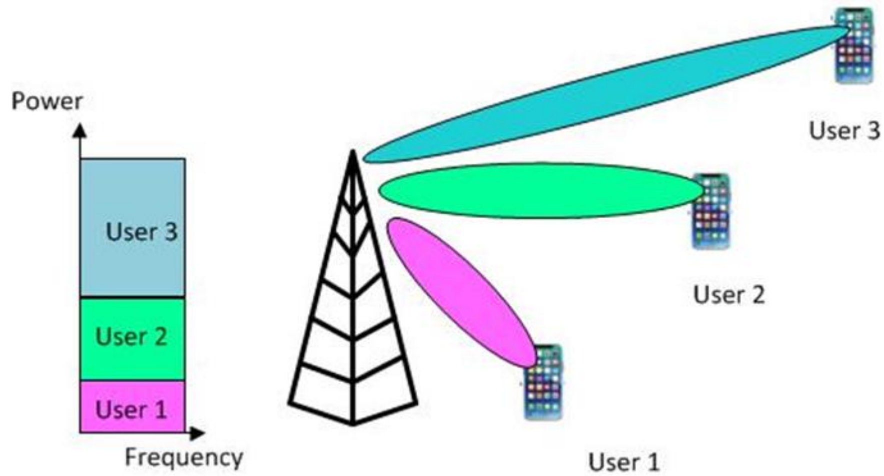

Figure 3: The Resource Allocation of the Three-User PD NOMA Based System with Three Users

The NOMA technology utilizes superposition coding to sum individual signals from transmitting users into a composite signal. In uplink NOMA, signals are summed at the base station (BS). For downlink NOMA, the users receive superimposed signals from the BS. Then, this composite signal is decoded using the SIC method. The categorization of NOMA includes PD NOMA, CD NOMA, and hybrid NOMA [9], [10], [11], [12]. However, there are some different classifications such as channel based NOMA, e.g. NOMA with and without relaying. In the PD NOMA, the differences in the channel strengths among different users is a principle for the power allocation to each user. The users get different power levels from the source node/BS. The far user with poor channel condition receives more power from BS than the near user with stronger channel condition. Thus, this multiple access technique can optimize the achieved system capacity. The PD NOMA with spectral and power allocation graph is plotted in Figure 3. However, in the CD NOMA, a detection technique for multiple users which has a low complexity is exploited, as shown in Figure 4. The schemes such as Sparse code multiple access (SCMA), interleave division multiple access (IDMA), and low-density spreading (LDS)-CDMA belong to this type of NOMA. Hybrid NOMA is the combination between PD NOMA and CD NOMA. However, this scheme has not been investigated by researchers yet.

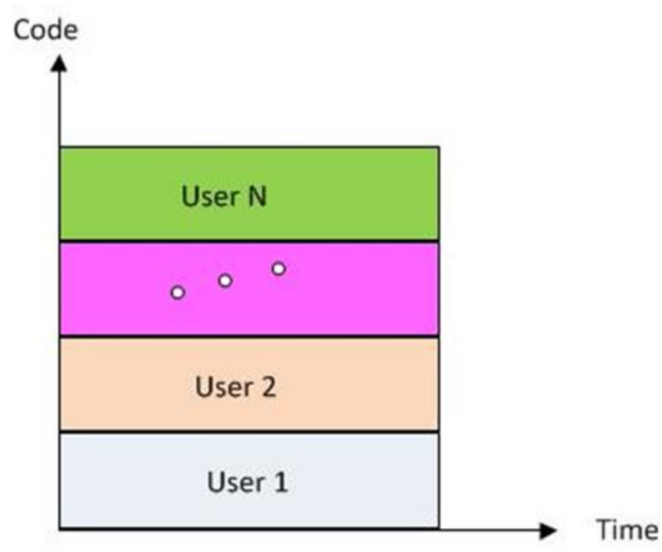

Figure 4: PD NOMA Resource Allocation for a Three-User NOMA System

Let us consider a NOMA system with two users and one BS to clarify SC and SIC techniques as shown in Figure 5. The operating principles of this system are summarized as follows. Before sending a superimposed signal to users, the BS has to code all signals received from each user using the superposition coding mechanism. Assume that the signal which is transmitted from the BS to the near user is denoted by x1, the transmitted signal to the far user is represented by x2.

The signal at the BS is given by

$$x_T = \sum_{i=1}^{2} \sqrt{P_i} x_i \tag{1}$$

Where Pi stands for the power which is allocated to both users by the BS, respectively.

For each user, the expression of its received signal is calculated by

$$x_i = h_i x_T + n \tag{2}$$

Where, hi represents the channel coefficients. n is the additional white Gausian noise (AWGN) with variance and mean zero.

After receiving, the signal is decoded by users. The weaker user detects its own signal while the information cancellation of the weak user is carried out by the stronger user using SIC. To decode this strong user's message, SIC is also utilized.

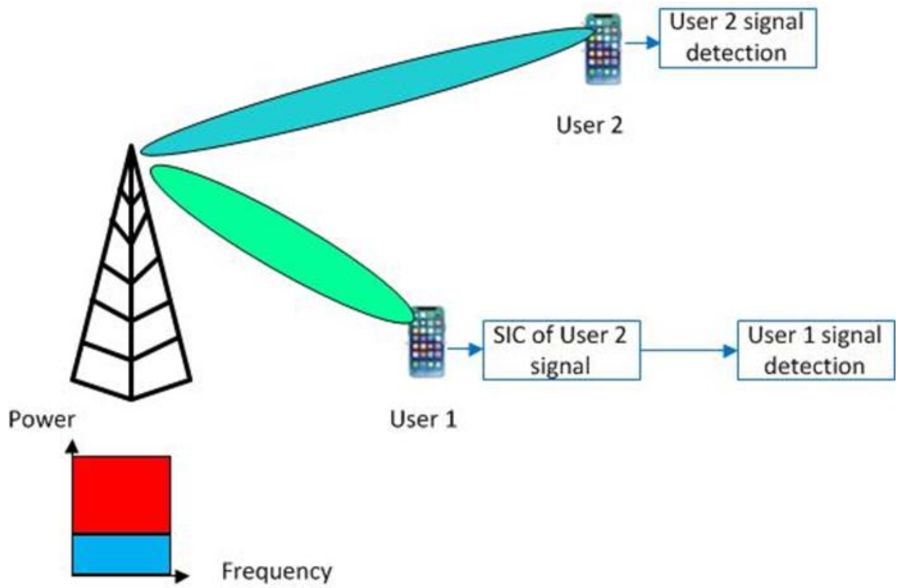

Figure 5: A PD NOMA based Two-User System in Downlink

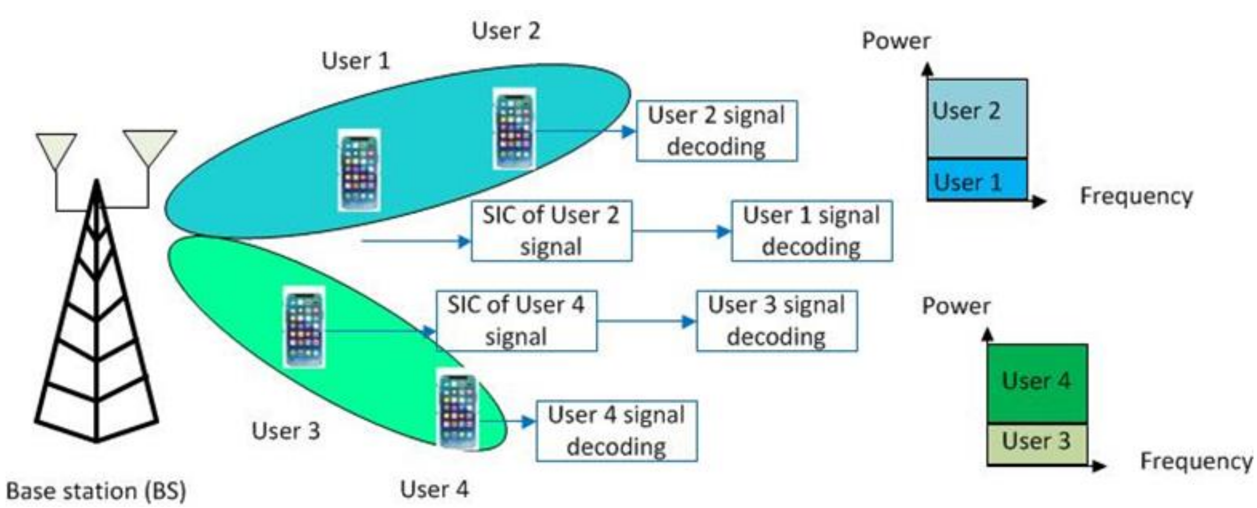

Figure 6: Illustration of a Four-User One-BS Downlink MIMO-NOMA System using Power Domain NOMA Scheme

Figure 6 also shows a MIMO-NOMA system consisting of one BS and four users. As shown in the figure, user 1 employed the SIC for the signal of user 2 and user 3 employed the SIC for the signal of user 4.

In general, SC and SIC processes can be described as follows.

2.1. Superposition Coding

This scheme was proposed in [13]. It is a technique where information can be communicated simultaneously via a single source to many users. Therefore, at the same time, the messages of multiple users are simultaneously transmitted. An illustration of communication in superposed type is the broadcasting of television signals from a broadcast station to multiple receivers. In practice, the transmitter side needs to encode messages relevant to each user for SC.

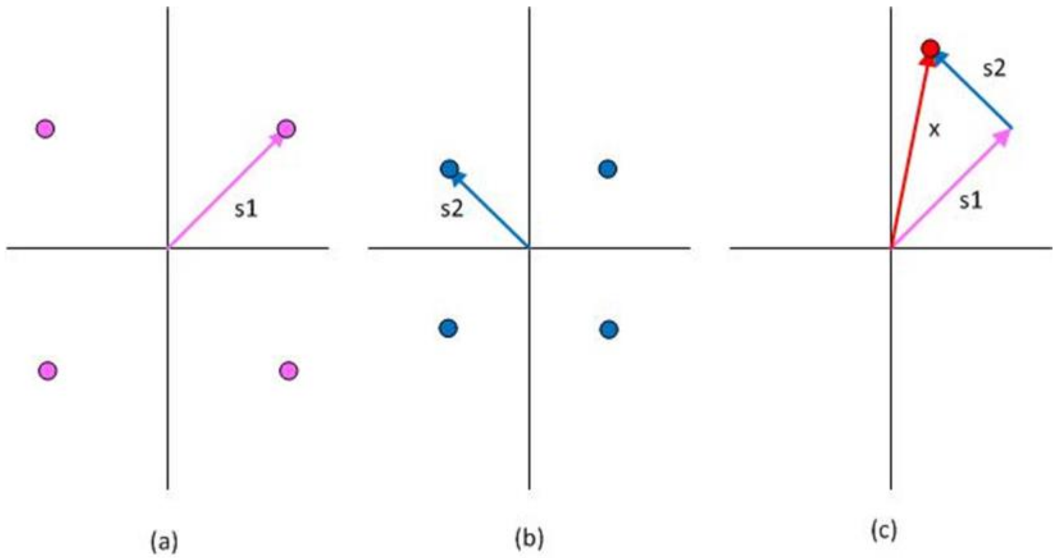

Figure 7: An Illustration of SC Technique (a) User 1's Signal Constellation (b) User 2's Constellation, and (c) Constellation of Combined Signal

Figure 7 illustrates a two user scenario with QPSK modulation in which user 1's constellation has a greater transmitting power and user 2's constellation has a smaller transmitting power and how to perform SC for two constellations. Thus, two point to point encoders are required on transmitter side to map between the respective inputs and complex-valued sequences of the two-user signal.

2.2. Successive Interference Cancellation

The SIC technique was first proposed by Cover [13]. The SIC mechanism is to exploit the different characteristics of the signal strength among the interested signals. According to the SIC principle, the signals of users are successively decoded. It means that after decoding the signal of one user, a substraction between this signal and the composite signal is carried out before decoding the signal of the next user. As a result, the SIC user considers other user signals as interference, while the latter is decoded with the benefit of the former's signal having already been removed. It is noted that the arrangement of user order with the corresponding signal strengths needs to be performed before deploying SIC. Therefore, the stronger signal at the receiver is first decoded, after which it is subtracted from the combined signal and the weaker signal is isolated from the residual. As the incoming signal is decoded in SIC, each user perceives the other interfering users as noise. In general, the process of superposed messages described in math can be expressed by [14].

At near user, the message x1(n) is decoded by a single user decoder in which the message x2(n) is treated as noise.

A far user successively recovers its information by utilizing the received signal y2(n) by performing a procedure as follows. First, it decodes the message of a near user x1(n) based on a single decoder. After this step, it subtracts $\sqrt{P_1}h_2x_1(n)$ from the y2(n) to obtain $y_2^{'}(n) = y_2(n) - \sqrt{P_1}h_2x_1(n)$, where h2 is the complex channel gain of a strong user. Finally, the message x2(n) of the strong user is decoded by employing another single user decoder on $y_2^{'}(n)$

In addition, in this section, we also summarize some major NOMA schemes in non-cooperative NOMA, e.g. PD NOMA, SCMA, MUSA, LDS-CDMA, and LDS-OFDM as shown in Figure 8.

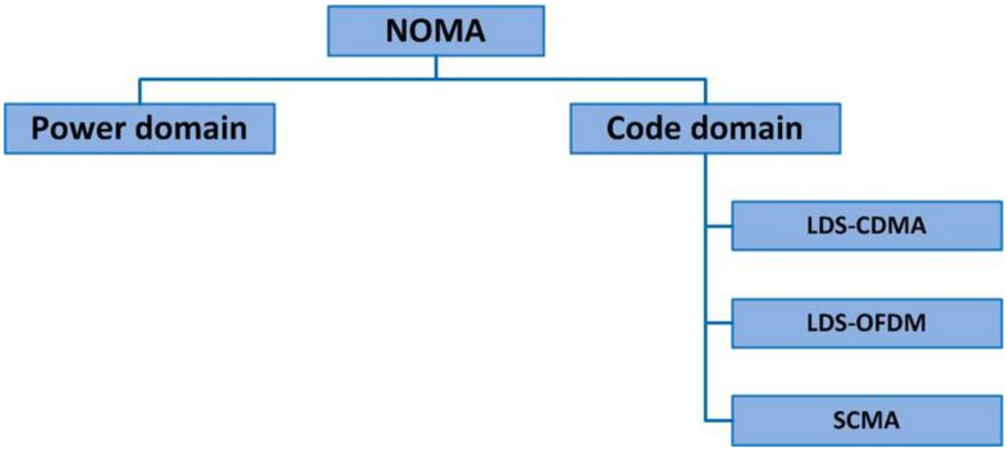

Figure 8: A Simple Category of NOMA Techniques

2.3. Power Domain NOMA

This is a leading candidate for 5G NOMA. Two SC and SIC techniques are key principles in the PD NOMA. The transmitted signal in the PD NOMA is summed by SC technique in the PD. It exploits the inverse proportional principle in user power allocation, in which the farther the user, the more power is given. Therefore, users are guaranteed fairness and this results in enhanced quality of service (QoS). Figure 8 illustrates the power allocation with different levels for N users in the power domain NOMA technique.

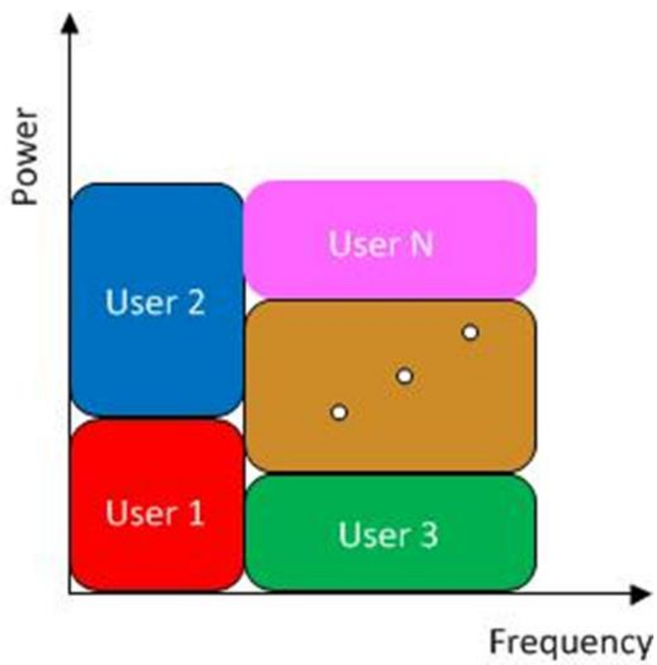

Figure 9: Power Allocation in Power Domain NOMA Scheme

Although a larger difference in the power level can make a better performance, the fairness of user throughput is low because when the difference between the rates of weaker and stronger users is substantial, the weaker users achieve a significantly lower rate than the stronger users. This is the limitations of the PD NOMA.

An extended version of the power domain NOMA is known as cooperative NOMA. In this type of NOMA, one user which has better channel conditions is chosen as a relay. The purpose of this relay is to forward the message from the transmitting user to the desired user. Relaying users can be one user or a group of users.

Code domain NOMA is an enhanced version of Coding Division Multiple Access (CDMA). In CDMA, the transmission of multiple users is allowed to happen on a network simultaneously. The background theory of the CDMA technique is a multiplication between the data in each user and one of W unique spreading sequences [15], [16]. The main disadvantage of CDMA is its bandwidth expansion because N chips need to be utilized to compose the spreading code. The signal which is received on the the receiver side is then despreaded back to its original bandwidth via a prior knowledge of the spreading codes. We consider two schemes for CDMA based code domain NOMA as follows.

2.4. Low-Density Spreading (LDS)-CDMA

LDS-CDMA [17] is an enhanced scheme of CDMA. Instead of using conventional dense spreading sequences, sparse spreading sequences are used in this scheme [18]. In comparison to conventional CDMA, LDS CDMA has fewer non-zero spreading sequences. Multiple user detection (MUD) at the receiver can be carried out using a SIC or a message-passing algorithm (MPA) based sequence detector. A received signal at each chip is referred to as a factor node in MPA, whereas the transmitted symbol is referred to as a variable node. Symbol reliability is exchanged between nodes, resulting in an improvement in error performance. In particular, the conversion from LDS CDMA to LDS OFDM can be directly performed by replacing the subcarriers in OFDM with the chips [19]. Figure 10 shows the coding process of LDS-CDMA with users but only 4 employed subcarriers.

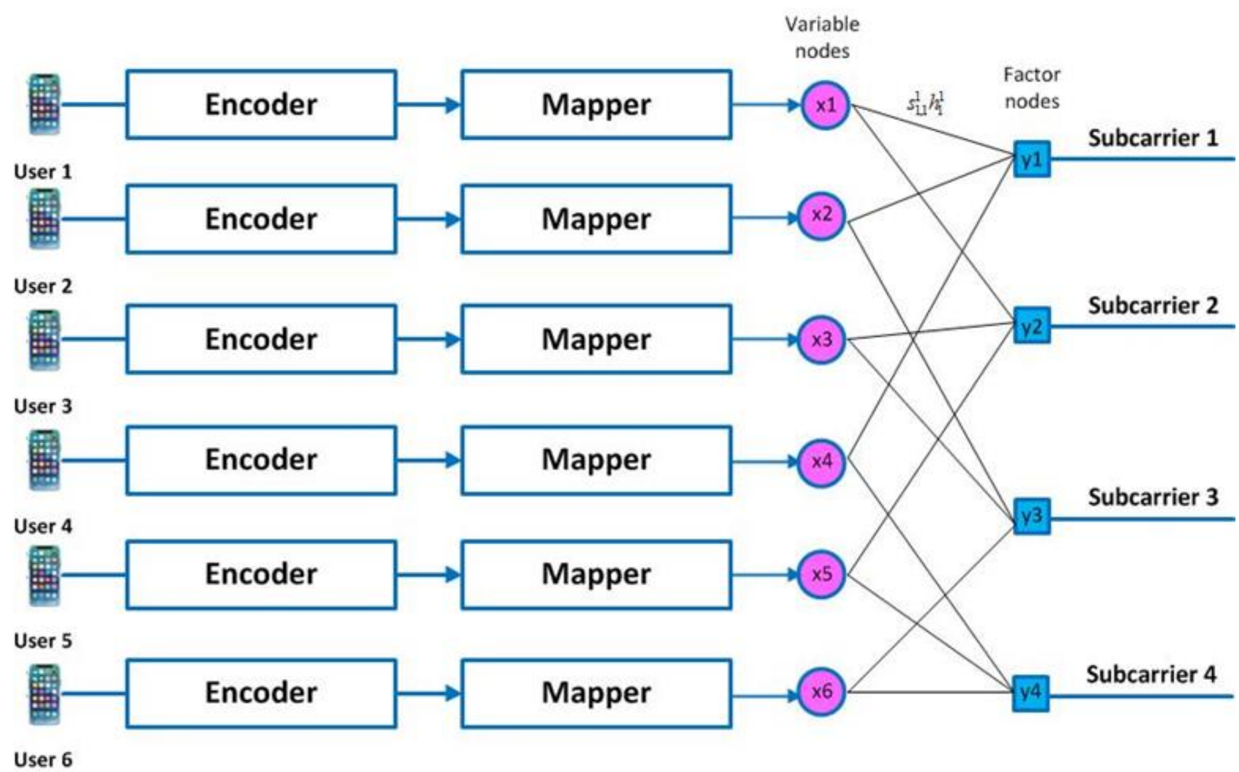

Figure 10: Illustration of LDS-CDMA with 6 Users but Only Employed 4 Chips for Transmission

2.5. Sparse-Code Multiple Access (SCMA)

This is a developed version of LDS. Its operating mechanism is based on [20], [21]. Unlike LDS, the mapping of the bit streams of the SCMA is direct to different sparse code words. The codebook is generated from a multi-dimensional constellation in which zeros in the same two dimensions appear in all code words from the same codebook. However, the more different the code books, the more distinct the positions of the zeros. As a result, the collision of any two users can be avoided. Figure 11 illustrates an example of a six-user and four-subcarrier SCMA system where a factor graph matrix is generated following [22].

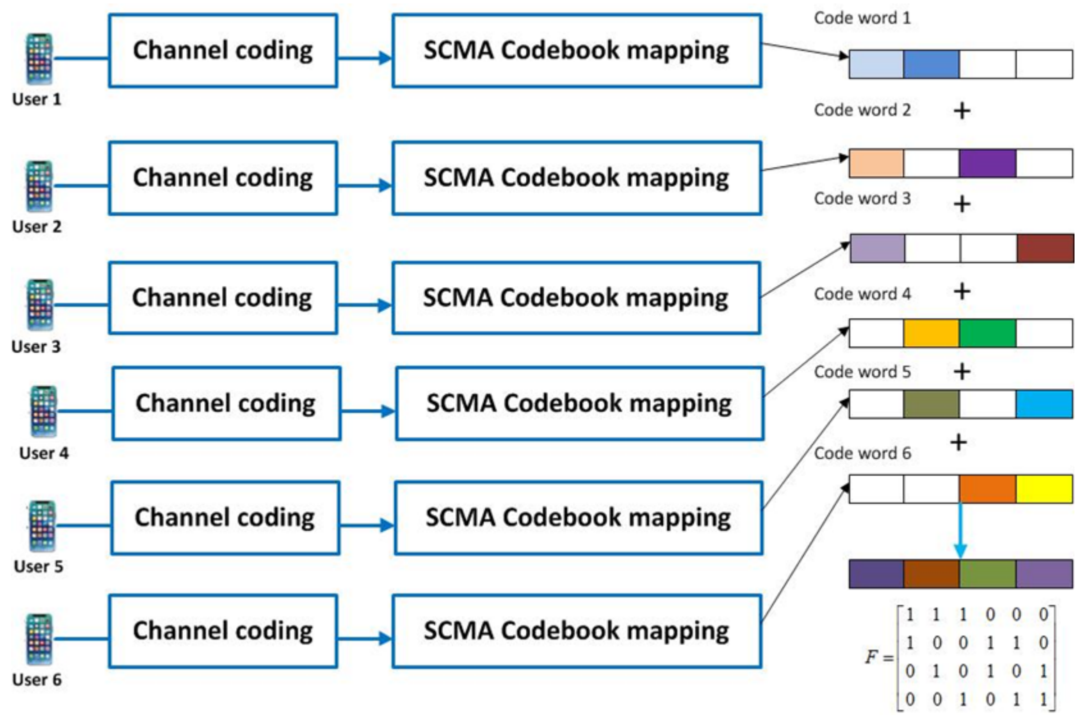

Figure 11: Illustration of an Six-User and Four-Subcarrier SCMA System

3. PERFORMANCE METRICS OF NOMA

The evaluation of the NOMA system performance can be based on several key parameters, such as the outage probability, through put, and energy efficiency.

3.1. Outage Probability

The outage probability is utilized to evaluate a NOMA network system and is the probability that the instantaneous achievable data rate is lower than the target rate. In NOMA, the outage probability expressions can be derived in closed-form expressions and verified using numerical simulations. The outage probability can be analyzed in both normal signal noise ratio (SNR) and high SNR regimes. The NOMA based system models investigated in the last decade almost achived a superior outage probability over the conventional OMA. This implies that the NOMA scheme outperforms OMA. SIC based decoding process in NOMA systems can occur imperfect SIC at which the received signal is not decoded fully. Therefore, the outage probability of the system is also affected.

3.2. Throughput

The throughput of a NOMA system is derived from a function of the outage probability variable. The throughput of a user is a crucial parameter which reflects the used throughput of a base station. The throughput derivation scenarios are exploited in the NOMA system models which operate in a delay-limitted transmission mode. The user throughput with successful SIC is higher than that with imperfect SIC. The optimization of throughput can be solved using several algorithms, such as [23], [24]. However, the tradeoff between the throughput and other parameters, e.g., fairness and sensing, also needs to be considered when designing the NOMA systems [25-27].

3.3. Energy efficiency

Superior energy efficiency is one of the key features which has demonstrated that NOMA technology outperforms the existing technologies. Energy efficiency is a crucial factor in the performance metric of emerging wireless technologies. [28]. The energy efficiency is calculated by the division between the summation of the achievable data rates and the summation of the consumed powers in the whole network. In cooperative NOMA, the relaying users usually harvest energy from RF signals for their operation, which are transmitted by base stations. The energy efficiency is utilized to evaluate the ability of energy harvesting and consuming under constraints such as time fraction and power spitting in energy harvesting protocols, hardward impairments (e.g. the nonlinearity of the rectifiers) and signal to noise ratio. In UAV based NOMA networks, the energy efficiency can be evaluated according to the user number per UAV, hovering power consumption [29]. Therefore, the energy efficiency maximization problem is a key target which needs to be achieved in energy harvesting enabled NOMA systems. The optimal problems of energy efficiency can be solved using several algorimths, such as [29-32]. In many reported research works, one can see that the NOMA system energy efficiency achieves a high value at a low SNR [33], [34]. In contrast, this energy efficiency decreases to 0 as the SNR is high.

4. APPLICATIONS OF NOMA

4.1. In Cellular Networks

In cellular networks, the NOMA deployment can be carried out on uplink and downlink communications. In the uplink transmission, NOMA is adopted at the BS in which the SC mechanism performs the summation of received signals from transmitted users with different power levels. Otherwise, in the downlink transmission, the source sends the combined signal to users with different power for each individual signal while the receiver applies the SIC technique to detect and decode their own signal. NOMA can provide enhanced spectral efficiency and fairness among users as compared to previous cellular network generations such as 1G to 4G. In addition, NOMA can be exploited in the case of multiple antennas, as known as MIMO NOMA. The multiple antenna technique is to obtain two purposes. The first one is to generate beamforming, resulting in a reduction in the signal-to-interference-plus-noise ratio (SINR) [3]. The other is to create spatial multiplex, resulting in an improvement in the throughput [35]. For the beamforming NOMA, the spectral efficiency is increased by improving the SINR. Figure 12 illustrates a NOMA system with beamforming consisting of four users and two antennas in which two antennas for beamforming are equipped for the BS and the antenna number for each user is one . In contrast, by using multiple antennas, NOMA with spatial multiplexing can enhance its gain. Because one independent data stream is sent by one transmit antenna, the achievable rate in this type of NOMA can be enhanced corresponding with the transmit antenna number. Another application of NOMA is communication among the BS and users with assistance of relaying user/dedicated relay as shown in Figure 12. In Figure 13, user 2 is hidden by the obstacle and thus cannot receive the transmitted signal from the BS. Therefore, user 1 assists the BS to forward the decoded signal to user 2.

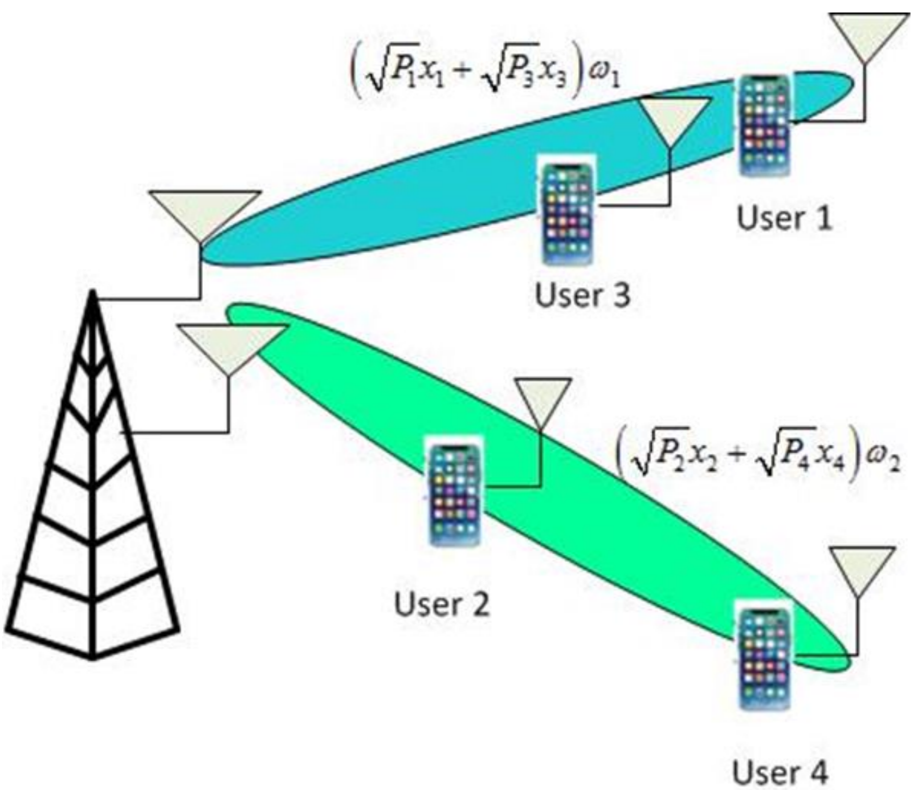

Figure 12: An Example of NOMA with Beamforming

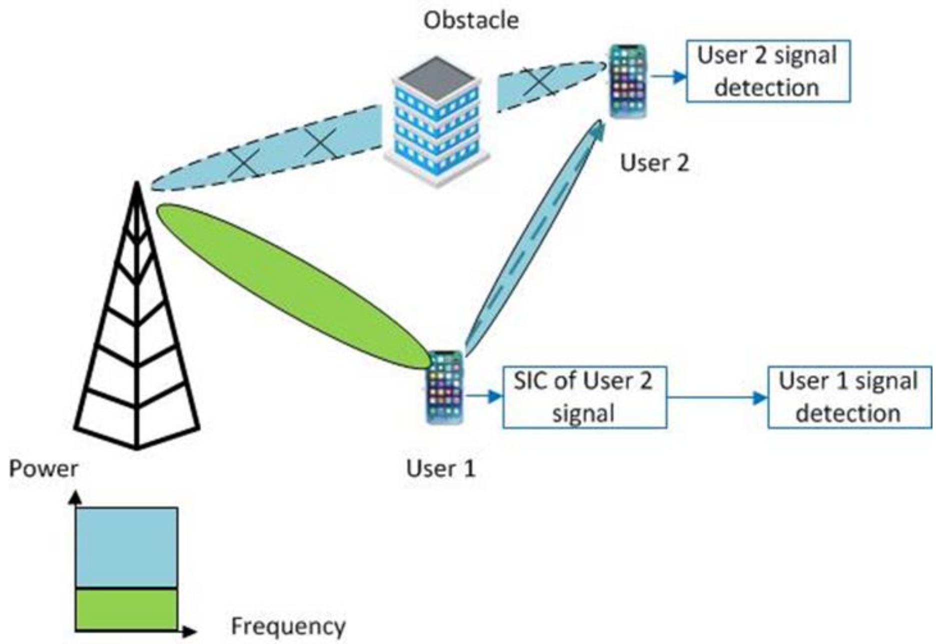

Figure 13: An Example of a Two-User and One-BS Cooperative NOMA System

The contributions of some current reports on NOMA in cellular networks are given in Table 1.

References	Type of NOMA networks	Technical Contributions
[36]	- Single-cell NOMA uplink network.	- The system sum rate is maximized. - The system capacity can be improved by using the proximity gain and interference relationship.
[37]	- A downlink NOMA based cellular network with single cell micro.	-Energy efficiency is maximized based on the joint time scheduling and resource allocation problem.
[38]	- A D2D MIMO-NOMA mmWave downlink cellular network.	- The outage probability and ergodic capacity are obtained in exact-form expressions. -The system performance can be boosted by enhancing the transmission power as well as the antenna array.
[39]	- Downlink/uplink NOMA cellular networks with D2D communications.	- The energy efficiency of the D2D pair is optimized using Karush–Kuhn–Tucker conditions.
[40]	- MIMO NOMA based downlink cellular network with randomly distributed users.	-The exact outage probabilities are based on the Wishart matrices.

Table 1: Applications of NOMA Scheme in Cellular Networks

4.2. In UAV Networks

Currently, unmaned aerial vehicles (UAVs) have gradually proven their potential in civil applications such as aerial photography, enhanced freight distribution, and wildfire management, disasters [41], [42]. UAV assisted communication has become a potential application in industry and academic areas. To integrate UAV into 5G and future networks, multiple access technique has become a critical component. NOMA is one of the important candidates in these networks due to its overwhelming characteristics, e.g. superior spectral efficiency, reduced latency and massive connectivity [43]. First, some key characteristics of UAV networks are described as follows.

- Mobility: the coverage areas of a UAV always change when it flies around. Thus, it can support many ground users.

- Path loss: the effect of shadowing and fading on UAV is not significant because the obstacle things do not appear in the air. Thus, the links between UAV and supported users are commonly modeled as line of sight.
- Agility: the deployment of UAVs can be quickly carried out. The locations of these UAVs may be dynamically managed within a 3D area depending on real-time user requirements. As a result, it offers ground users a more flexible and on-demand service at a lower cost than terrestrial BS [44].

NOMA can assist the massive connectivity in UAV based networks by adopting PD NOMA to aid users who share the same frequency/time resource. Due to LoS links, therefore, there are no evident channel gain variations between UAV and ground users. As a result, NOMA-assisted UAV networks must be redesigned to account for large-scale fading discrepancies among NOMA users, such as user pairing approaches (see Figure 14).

Let us consider an example including one UAV and two covered users 1 and 2 as shown in Figure 15. The UAV transmits a superimposed signal to two users. Because the distance between user 1 and UAV is shorter than that between user 2 and UAV, user 2 is allocated more power than user 1 for fairness according to the NOMA principle. Employing SIC at the receiver, user 2 is detected and decoded first by considering user 1 as noise. After that, subtraction between the signal component of user 2 and the received signal is carried out to facilitate the detection of user 1.

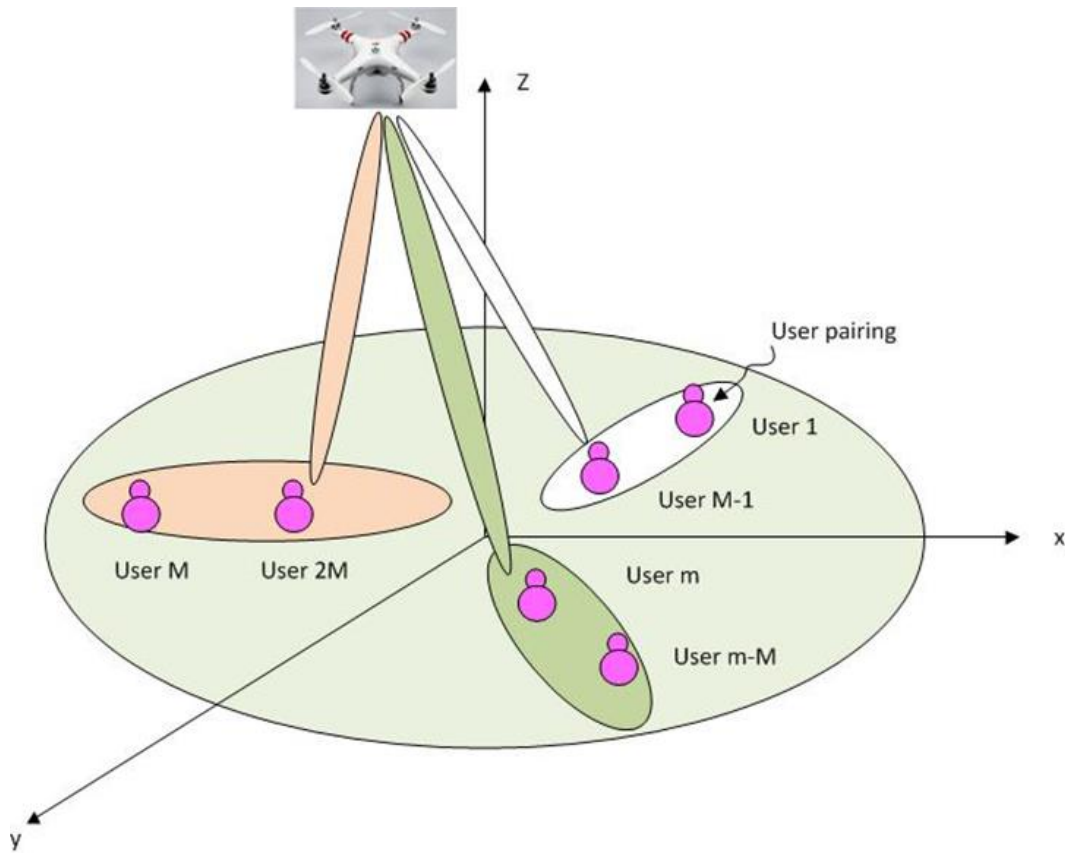

Figure 14: Illustration of User Pairing in NOMA Aided UAV Networks

Currently, several studies on UAV combined NOMA wireless communication have been reported. Specifically, in [45], a proposed resource allocation scheme in NOMA UAV communication was introduced to enhance the user transmission rate with worse channel state information (CSI). The UAVs in this model play a role as base stations to serve the ground users. In [46], NOMA networks with an enhanced intelligent reflecting surface using UAVs in their communications were investigated. With the assistance of intelligent reflecting surfaces, the UAVs act as flying BSs to serve multiple groups of ground users. In [47], a downlink NOMA network system aided by UAVs was investigated. One hovering UAV can serve one user cluster. In [48], UAV assisted NOMA multi-way cooperative networks were investigated. The UAVs operate as relays to assist the exchange of information among terrestrial users.

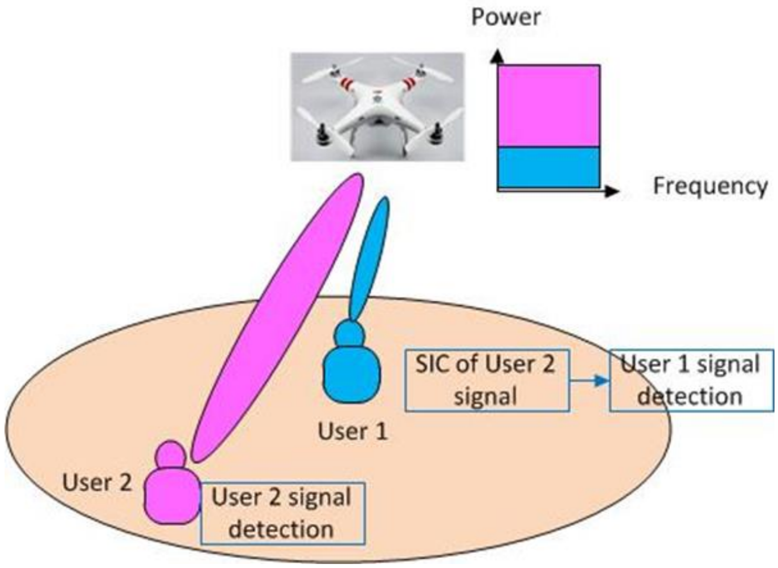

Figure 15: Illustration for NOMA Supported UAV Networks

Table 2 provides a summary of existing works exploiting UAV in NOMA networks.

References	The role of UAVs	Technical Contributions
[29]	-Being air base stations. -Serving UAV cells.	- Achieving a optimized energy efficiency of the UAV under the impacts of the limitations of transmit power, interference, imperfect CSI,
[49]	-Being mobile base station. -Acting as an agent for caching placement and resource allocation.	-Obtaining a balance between network performance and computation complexity. - Minimizing content delivery delays.
[50]	-Uplink communicating from a UAV to cellular base stations.	- The sum rate optimization problem for both ground user and UAV is analyzed. - The achievable rate balance between the UAV and ground users is improved by increasing the cancellation size.
[51]	-Being flying base stations -Serving a huge ground user number.	- The max-min rate is optimized under several constraints, such as total bandwidth, total power, antenna beam width, and UAV altitude.
[52-54]	-Being rotary-wing UAV to replace the malfunctioning terrestrial BS and serve ground users.	-Achieving the outage probability in closed form expressions. - The optimization problem of power control is solved to achieve a sub-optimal solution.

Table 2: Applications of NOMA Scheme in UAV based Networks

5. CHALLENGES AND FUTURE TRENDS

5.1. Imperfect SIC

In the perfect SIC process, the near user has a complete and perfect knowledge of the far user's signal information. In contrast, this information is not known perfectly in imperfect SIC cases. Thus, there is the appearance of residual inter-user interference in this imperfect SIC. The near user can not perfectly eliminate the interference from the far user [55]. The imperfect SIC can be caused by several parameters, such as channel estimation error, hardware limitation, and finit length code. The influences of the imperfect SIC on the performance of the NOMA systems as well as optimization problems are considerable. Specifically, with imperfect

SIC, the optimization problem of ideal power allocation (i.e. without power order constraints) in multiple-carrier NOMA systems is not easy to achieve reliable concavity conditions [56]. The imperfect SIC causes a higher outage probability and a lower regodic capacity than the perfect SIC [57]. For the NOMA systems with relays, the SIC process performed at these relays may error, and thus result in an outage. The imperfect SIC can happen at destination nodes as well as at relay nodes [58] and lead to an outage.

5.2. Imperfect CSI

Similarly, imperfect CSI is another key obstacle which affects the performance gain of NOMA based wireless communication systems in practice. The imperfect CSI can be categorized into partial CSI [59], [60], channel estimation errors [61], [62], and limited channel feedback [63-65]. Partial CSI is caused by small-scale fading path loss, whereas imperfect design of channel estimating algorithms and noisy observations are two causes leading to channel estimate errors. This yields user ordering ambiguities. The influences of the imperfect CSI on the NOMA system performance were studied in [29], [60], [66], [67].

5.3. Future trends

The trends of NOMA based wireless networks in the future will be broad frequency bands, extremely high data rates for immersive multimedia, closed zero latency, superior energy efficiency, and connectivity in three dimensional coverage.

6. CONCLUSION

This paper presented an overview of NOMA and its application in cellular networks as well as in NOMA aided UAV networks. The fundamentals of NOMA in terms of operation principles, detailed NOMA types and characteristics of each NOMA were discussed. Two key techniques in NOMA, including SC and SIC, were applied in our survey. Furthermore, we also discussed a one-BS and two-user NOMA system model as an illustration. Various NOMA such as power domain NOMA, LDS-CDMA, and CSMA were summarized in this overview. In addition, NOMA in cellular networks with beamforming and spatial multiplexing and NOMA aided UAV networks were provided as potential applications of NOMA. Besides, the performance metrics, including outage probability, throughput and energy efficiency, were presented. We also analyzed two challenges in NOMA networks, which include the imperfect SIC and imperfect CSI. The issues of future trends were also addressed in this paper. This overview can provide key issues for research on NOMA in 5G and beyond.

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