

Article

A Novel Design for Joint Collaborative NOMA Transmission with a Two-Hop Multi-Path UE Aggregation Mechanism

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Abstract: With the exponential growth of devices, particularly Internet of things (IoT) devices, connecting to wireless networks, existing networks face significant challenges. Spectral efficiency is crucial for uplink, which is the dominant form of asymmetrical network in today's communication landscape, in large-scale connectivity scenarios. In this paper, an uplink transmission scenario is considered and user equipment (UE) aggregation is employed, wherein some users act as cooperative nodes (CNs), and help to forward received data from other users requiring coverage extension, reliability improvement, and data-rate enhancement. Non-orthogonal multiple access (NOMA) technology is introduced to improve spectral efficiency. To reduce the interference impact to guarantee the data rate, one UE can be assisted by multiple CNs, and these CNs and corresponding assisted UEs are clustered into joint transmission pairs (JTPs). Interference-free transmission can be achieved within each JTP by utilizing different successive interference cancellation (SIC) decoding orders. To explore SIC gains and maximize data rates in NOMA-based UE aggregation, we propose a primary user CN-based channel-sorting algorithm for JTP construction and apply a whale optimization algorithm for JTP power allocation. Additionally, a conflict graph is established among feasible JTPs, and a greedy strategy is employed to find the maximum weighted independent set (MWIS) of the conflict graph for subchannel allocation. Simulation results demonstrate that our joint collaborative NOMA (JC-NOMA) design with two-hop multi-path UE aggregation significantly improves spectral efficiency and capacity under limited spectral resources.

Keywords: IoT; UE aggregation; NOMA; joint transmission; two-hop; multi-path; cooperative node; power allocation; subchannel allocation



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1. Introduction

With the rapid growth of wireless communication, the demand for networks for the 5th generation of mobile communication technology (5G) and 6G has become more stringent. With the increasing connectivity of smart devices, higher speeds and lower latency will become crucial considerations. In 6G networks, peak rates are expected to reach 1 Tbps with the support of technologies such as THz, equivalent to more than 50 times that of 5G. User experience rates are also anticipated to reach 10 Gbps [1]. Furthermore, to support new scenarios in the next generation of communication, such as smart factories and smart cities, the device's connection density will also significantly increase to 10^8 devices/km² [2]. Due to an unprecedented growth rate, 5G and B5G mobile communication systems face challenges in increased connection density, spectrum efficiency, mobility, seamless connectivity, energy efficiency, and user fairness [3]. In order to serve such massive and high-demand intelligent devices, the scarcity of wireless resources has become a problem that people have to confront. As a result, many technologies have been proposed, such as ultra-dense networks (UDN) and cognitive radio. With the increasing number of connected devices, managing scarce communication resources has become an important topic.

Three major application scenarios are proposed in the 5G wireless network, namely enhanced mobile broadband (eMBB), massive machine-type communication (mMTC), and ultra-reliable and low-latency communication (URLLC), aiming to achieve greater bandwidth, higher rates, increased connection density, greater reliability, and lower latency [4–7]. With the development of communication systems and people's speculation and discussion about the upcoming 6G communication system, 6G systems will support more scenarios and place higher demands on system performance. The upgrade to 6G will enhance and extend upon the three major scenarios of 5G, forming new integrated scenarios: further-eMBB (feMBB), ultra-mMTC (umMTC), and enhanced-uRLLC (euRLLC) [8–11]. In the next generation of mobile communication, key performance indicators (KPIs) of communication systems will expand beyond parameters, such as data rate, connection density, and latency to include new KPIs, such as imaging, positioning, sensing, security, and levels of intelligence. With the advancement of technology, 6G can support more KPIs and scenarios, and the range of applications it can support is greatly expanded. Cloud working/entertainment, 3D ultra high definition (UHD) video, extended reality (XR), and holographic communication applications can benefit from the high data rate of feMBB to be realized. UmMTC will also drive the development of applications, such as smart factories, smart agriculture, smart cities, and smart homes. Mission-critical applications, such as autonomous driving, vehicle-to-everything (V2X), and tactile networks, will also rapidly proliferate with the support of euRLLC. Additionally, these primary scenarios will further integrate into 6G, giving rise to emerging applications, such as dense scene communication, wireless data centers, wireless brain-machine interfaces, smart transportation, and smart factories.

In order to facilitate access for more users and handle increased traffic in UDN, a large number of small base stations are deployed. The reduction in path losses and subsequent enhancement in energy efficiency is achieved through the dense deployment of small base stations, which allow users to be closer to small cells [12]. However, as the density of small base stations increases, co-channel interference among users sharing spectrum resources becomes severe [13]. Therefore, resource allocation and interference coordination play a crucial role in enhancing system performance. Although some interference mitigation (IA) techniques [14–17] can enable multiple users to transmit data without interference in the same subchannel, relying solely on interference avoidance is not sufficient to effectively address interference issues in UDN due to its limited feasibility [18]. It becomes important to jointly consider IA and subchannel allocation in eliminating interference [19].

Similarly, cognitive radio technology has become an important solution to address the issue of resource scarcity in future networks. Cognitive radio allows secondary users (SU) to dynamically reuse the spectrum resources of primary users (PU), addressing the issue of spectrum scarcity. The dynamic spectrum access mode can be divided into underlay and overlay [20]. In underlay and overlay modes, PU and SU transmit data in the same frequency band. In overlay mode, SUs need to reuse the PU's frequency band based on prior knowledge of PU transmissions. In underlay mode, SUs can utilize their limited power and simultaneously share the same frequency band with PUs, ensuring that interference remains within a certain threshold.

Due to the combined advantages of cognitive radio, research on cognitive radio and cooperative relaying has become a hotspot in recent years. Cooperative relaying is considered to be an effective solution against multipath fading. Furthermore, cooperative relaying has significant effects on increasing network coverage, enhancing system capacity, utilizing diversity gain to improve reliability, and reducing transmission latency. Up to now, uplink (UL) [21–23] traffic has been the dominant form of asymmetrical network in today's communication landscape, which has been driven by the increasing demand for wireless service applications. Further, device capabilities and performance criteria are so diverse, from the perspective of coverage, power consumption, signal process capability, service type, and so on, that the network becomes more and more diverse and asymmetrical, especially for the industrial IoT scenarios, personal consumption, smart home, etc. In

response to the increasing demand for high-performance uplink services, 3GPP's Release 18 discusses many solutions for enhancing uplink system performance [24,25]. Among these solutions, UE aggregation technology has been frequently mentioned and continuously discussed in recent years [26–30]. In user equipment (UE) aggregation, edge users or users with limited transmission capacity can use other users with better channel conditions as relays for cooperative transmission. This significantly reduces the transmission delay for edge UEs, providing support for edge users to achieve URLLC. However, as the number of collaborating users increases, the number of edge relay links also significantly increases, posing a substantial challenge to the limited spectrum resources. This is similar to the resource allocation issue in device-to-device (D2D) relay scenarios. To increase the spectral efficiency of the system, it is necessary to consider allowing different relay links to share the spectrum.

To pursue higher spectrum efficiency, non-orthogonal multiple access (NOMA) technology is envisioned as a crucial multiple access scheme for 5G or next-generation communication networks. NOMA allows multiple users to transmit within the same frequency domain, enabling the same frequency resources to accommodate more traffic and enhancing spectrum efficiency. Typically, in the transmitter of NOMA, power domain multiplexing is employed to differentiate signals destined for various receiving UEs. Moreover, at the receiving end, different users can employ successive interference cancellation techniques to decode signals intended for themselves. This allows both distant NOMA users and nearby NOMA users to be served simultaneously.

The main contributions of this article are summarized as follows:

- Two-hop-based collaborative UE aggregation transmission with multiple cooperative nodes (CNs) is designed for multiple users in an uplink system. NOMA is considered for cooperative transmission among users to address the limitations of spectrum resources. UE aggregation means that users communicate with the base station by two-hop multipath transmission with the assistance of CNs, thereby enhancing system data rates and coverage, and addressing large-scale connectivity.
- A primary user CN-based channel-sorting search algorithm is proposed for constructing joint transmission pairs (JTPs) based on channel gains. This algorithm aims to group compatible CNs and NOMA users into appropriate JTPs. The constructed JTPs guarantee that each user's signal in the NOMA group is transmitted interference-free at different CNs due to the correct successive interference cancellation (SIC) order.
- A power-allocation algorithm based on the whale-optimization algorithm (WoA) for NOMA users is proposed to achieve the optimal decoding order at CNs and maximize the transmission rate of JTPs.
- A greedy strategy based on the maximum weighted independent set is designed to allocate limited subchannels among all feasible JTPs. The proposed approach prioritizes the allocation of subchannels to some optimal and non-overlapping JTPs when channel resources are limited, thereby maximizing spectral efficiency.

The remainder of this article is organized as follows. In Section 2, some related work is introduced. Section 3 describes the system model and explains the principles of our proposed spectrum-efficient NOMA cooperative transmission pair in the uplink two-hop transmission scenario. In Section 4, we formulate the problem as maximizing the system's spectral efficiency, the problem is broken down into three sub-problems—i.e., how to construct JTPs, optimize the transmit power of NOMA users, and allocate the subchannels—and corresponding algorithms are designed. The primary user CN-based channel-sorting search algorithm, WoA-based power-allocation algorithm, and maximum weighted independent set-based subchannel-allocation algorithm are proposed to solve these problems. Section 5 presents and discusses the simulation results. Section 6 summarizes the work of this paper.

2. Related Work

UE aggregation technology [4–7], which allows users to collaborate with each other and perform joint transmission, has become a research hotspot in recent years. With the explosive growth in the number of devices, performance degradation in network access often occurs due to resource limitations. Collaborative transmission with nearby users is considered an effective method to mitigate this issue and has become a trend for future networks to handle ultra-dense scenarios. Unlike traditional dedicated relays, UE aggregation technology allows users to perform uplink transmission to the base station with the collaboration of other users, offering greater flexibility. Additionally, UE aggregation can effectively improve the transmission rate, transmission delay, and coverage of the cooperating users. Sidelink, as an important solution for distributed transmission, has also been widely studied. UE aggregation shares many characteristics with sidelink relays, and there is extensive research on sidelink relays. In Rel-17, sidelink relay [31,32] technology was introduced to address the impact of various environmental factors such as high propagation loss and mutual interference on coverage and system performance. Sidelink relay includes two typical applications: UE-to-network and UE-to-UE [33]. The UE acts as a relay node, transmitting data between remote users and the infrastructure or between two remote users. Reference [34] demonstrates that the presence of relays can enhance system coverage and capacity, and mitigate interference. Sidelink relay is typically applied in V2X scenarios [35], and focuses on enhancing the vehicle-to-infrastructure (V2I) link through idle vehicular users to improve network performance. Idle users act as relays to boost the signal from the base station (BS) to users with poor-quality links. The analysis, conducted in a 2-dimensional Manhattan grid, uses stochastic geometry techniques to derive the coverage probability for direct and relay-assisted links, validated through Monte Carlo simulations. The paper [36] highlights the role of 5G and ultra-reliable low latency communication in V2X for automated driving. It shows that using V2X sidelink and cooperative retransmission of data packets can significantly enhance reliability. The analysis reveals that reliability improves with more cooperating users and additional retransmissions, though gains can be moderated by path-loss effects. Additionally, group communication, as a technology where one or more nodes send data to multiple receivers, has also been widely studied [37]. In systems supporting sidelink relays, communication between devices can effectively improve latency, data rate, spectrum, and energy efficiency through group communication, showing great promise [38].

NOMA technology was initially introduced into cellular communication systems to enhance spectral efficiency. With the continuous advancement of NOMA technology, it has also become an important multiple access technology in 6G [39–42] and even next-generation networks. In recent years, the research on NOMA for downlink systems has been extensive [43–45]. In [43], the authors introduce a novel multi-objective optimization technique for NOMA systems to maximize spectral and energy efficiency while minimizing transmit power. Jointly addressing spectrum and energy optimization with user quality of service (QoS) constraints, the proposed method significantly outperforms traditional NOMA and orthogonal multiple access (OMA) schemes in terms of efficiency. The paper [44] analyzes a multi-antenna two-user downlink NOMA system in an underlay spectrum-sharing framework, and it derives expressions for average sum rate and outage probability, showing that NOMA outperforms OMA in terms of efficiency. The paper [45] optimizes power control and user clustering in a coordinated multipoint (CoMP) assisted full-duplex cooperative non-orthogonal multiple access (C-NOMA) system to maximize network sum rate. The approach decomposes the problem into power allocation and user clustering, using a low-complexity algorithm.

Additionally, NOMA technology is also used in relay-assisted communication scenarios. In [46], the authors address user pairing, subchannel assignment, and power allocation in downlink cooperative NOMA networks. This paper proposes pairing strong and weak channel users on the same subchannel, with strong users relaying for weak users. A Stackelberg game optimizes power allocation. Simulations show the scheme outperforms

cooperative OMA and existing NOMA schemes in average sum rate. In [47], the authors examined how hardware impairments (HIs) affect NOMA-based energy harvesting relaying networks over Weibull channels with imperfect channel state information, focusing on outage probability and throughput. However, many studies are based on downlink relay-assisted scenarios. In recent years, with the development of AR/VR technology and the emergence of many large-scale connected scenarios, the need for research on uplink systems is increasing. In some works, uplink systems have been studied. The paper [48] presents a relay-assisted uplink system using a hybrid NOMA/OMA strategy to improve EE and access rate. The A-CFSFDP algorithm efficiently clusters Internet of things (IoT) devices, and a hypergraph-based model optimizes EE through channel assignment, power allocation, and relay selection. In [49], the authors focus on enhancing physical layer security in NOMA-based uplink mMTC networks by maximizing system secrecy capacity against eavesdroppers. It introduces a joint power and sub-channel allocation (JPSASC) algorithm. The power allocation problem is treated as a non-cooperative game, with MTC devices optimizing their own secrecy capacity.

In uplink systems, compared to single-relay networks, multi-relay cooperative systems can enhance diversity gain and have significant potential for improving spectral efficiency. The paper [50] proposes a spectrally efficient uplink cooperative relaying protocol for IoT networks using multiple half-duplex relays and NOMA. Two IoT devices transmit simultaneously, with one relay forwarding packets while others receive new ones, achieving N packets in $N + 1$ slots without duty-cycle loss. In [51], the authors propose a virtual full-duplex cooperative NOMA framework for downlink two-hop networks with half-duplex relay stations. It addresses inter-relay interference using an adaptive RS selection algorithm and derives the closed-form outage probability. Simulation results show its superiority over conventional cooperative NOMA in both outage probability and diversity-multiplexing trade-off performance.

3. Scenario Description and System Model

In this work, an uplink wireless network scenario is considered. As shown in Figure 1, it is assumed that a macro base station (BS) is located at the center of the cell, and some cooperation nodes (CNs) and wireless users are deployed in this cell. The users would play UE aggregation [26,27] with the CNs in which users upload messages by the assisting of CNs to the macro BS. A CN can be a relay node but, different from a traditional relay, a CN is also a special type of UE, for example, it could be a UAV or robot in a smart factory, or a normal UE with higher signal-processing capability, and a better channel condition. To better support the uplink service, users can reuse the same subchannel to communicate with the CN by NOMA technology, and the CN performs SIC decoding for the superimposed signals on the same subchannel. Let $\mathcal{S} = \{1, 2, \dots, S\}$ denote the set of CN nodes, and users $\mathcal{J} = \{1, 2, \dots, J\}$ are distributed within the cell. The total bandwidth of the system is B , and the bandwidth can be divided into K subchannels with a subchannel bandwidth $B_k = B/K$ into a resource set. Considering the practical scenario where resources are limited, $J \gg K$ is assumed. The maximum transmit power of users and CNs is P_{UE} and P_{CN} , respectively. Users with poor channel conditions could first broadcast their messages to CNs, and the CNs that receive the signal will forward these messages to the BS through the channel between the CNs and BS.

For easy reading, the notation and operation descriptions are summarized in Table 1 first.

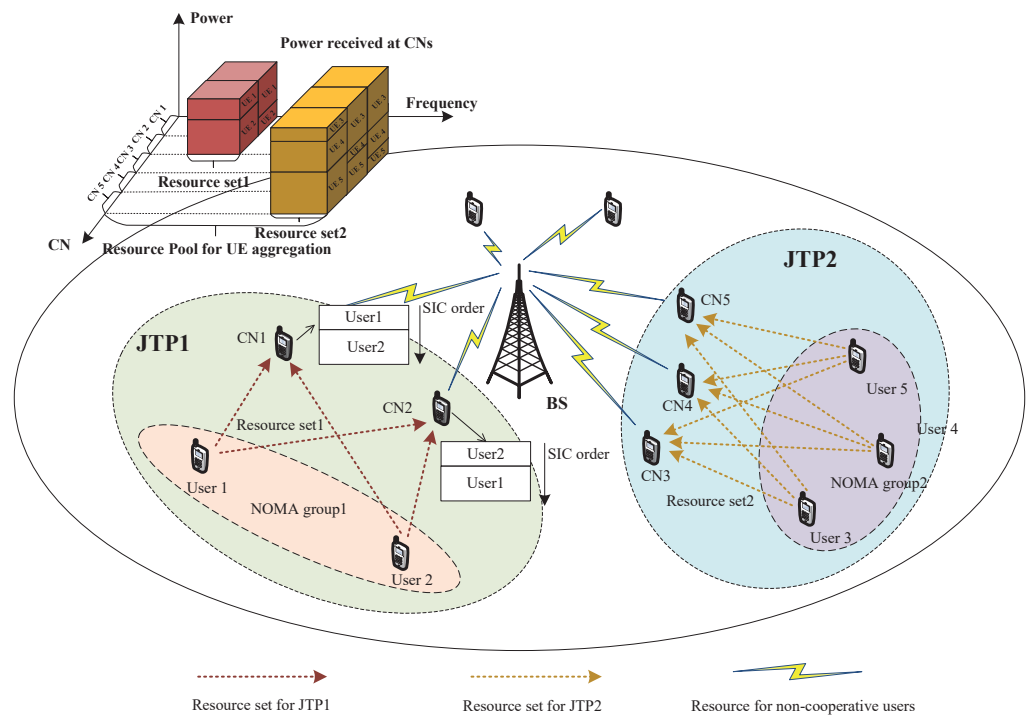


Figure 1. System model.

Table 1. Notation and operation descriptions.

Notation	Explanation
$\mathcal{S}$	The set of CNs within the cell
$\mathcal{J}$	The set of users requiring coordination
B	The total bandwidth of the system
K	Number of subchannels
B_k	The bandwidth of each subchannel
P_{UE}	The maximum transmit power of the user
P_{CN}	The maximum transmit power of the CN
$x_{j,k}$	Signal of the j th user on the k th subchannel
$y_{j,s}$	Received signal at the s th CN from the j th user
$h_{j,s}$	Channel coefficient of the link between the j th UE and the s th CN
$\gamma_{j,s}$	SINR between the j th user and the s th CN
$R_{j,s}$	Data rate between the j th user to the s th CN
R_{th}	Threshold of minimum decoding rate
$\theta_{j,k}$	Subchannel reuse indicator of the j th user on the k th subchannel
Q_i	The set of users in the i th NOMA group
q_i	User in the NOMA group
$R_{q_i,s}^i$	Data rate between NOMA group user q_i and the s th CN
s_{min}	The CN with the minimum channel gain for the NOMA group i
s_{max}	The CN with the maximum channel gain for the NOMA group i
I	Number of NOMA groups
$\mathcal{A}_{Q_i}$	Power allocation of the NOMA users in NOMA group Q_i
a_q	Power allocation factor for the q th user in NOMA
$\max(\cdot)$	The maximum value of the function
η	Spectral efficiency of the system
C_j	Feasible CNs set of user j
γ_{th}	SINR threshold

3.1. Two-Hop Cooperative Transmission with UE Aggregation

UE aggregation is a technology of cooperative transmission between users, and it is a two-hop transmission mechanism. In the first hop, users transmit the messages directly to the BS. For users being assisted, the performance of the direct link in terms of transmission rate and reliability is limited under high-channel fading.

The CN can detect and decode signals from users when the users send signals to the base station firstly. Let $x_{j,BS}^k$ be the signal from the j th user to the BS on the k th subchannel. The detectable signal at the s th CN can be described as

$$y_{j,s} = h_{j,s} \sqrt{P_j} x_{j,BS}^k + \sum_{j', j' \neq j}^J \theta_{j',k} \sqrt{P_{j'}} h_{j',s} x_{j',BS}^k + n, \quad (1)$$

where $h_{j,s}$ denotes the channel coefficient of the link between the j th UE and the s th CN, which includes path loss, shadowing, and fast fading [52]. The j' th UE is the user reusing the subchannel k . P_j represents the transmit power of the j th user. $n \sim \mathcal{CN}(0, \sigma^2)$ represents zero-mean additive white Gaussian noise (AWGN) and $\theta_{j,k}$ represents a binary variable indicating whether a user reuses the subchannel k ; if $\theta_{j,k} = 1$, this means the j th user is reusing the k th subchannel, otherwise $\theta_{j,k} = 0$. The SINR of the j th UE signal at the s th CN can be expressed as

$$\gamma_{j,s} = \frac{P_j |h_{j,s}|^2}{\sum_{j', j' \neq j}^J \theta_{j',k} P_{j'} |h_{j',s}|^2 + \sigma^2}. \quad (2)$$

So, the data rate from the j th users to the s th CN is $R_{j,s} = B_k \log_2(1 + \gamma_{j,s})$. To decode the signal of the j th user, the data rate should meet the constraint $R_{j,s} \geq R_{th}$, where R_{th} denotes the minimum decoding rate threshold.

After detecting and receiving signals from the j th user, the CNs decode and forward these signals to the BS. This process can be considered as the second hop transmission. Assume the CN set $C_j \in \{1, 2, \dots, |C_j|\}$ have successfully decoded the message of the j th user, and the total number of these CNs is $|C_j|$. So, the SINR of the signal received by the BS can be given as

$$\gamma_{C_j,BS}^{joint} = \sum_{l=1}^{|C_j|} \frac{P_l |h_{l,BS}|^2}{I_{l,k} + \sigma^2}. \quad (3)$$

where $I_{l,k}$ represents the interference on the l th CN transmission within C_j caused by other users within the cell or users from neighboring cells occupying channel k . All signals from the CNs are received at the base station and combined. Since the base station receives the same information, its reception rate is determined by the path with the highest rate. At the same time, assuming that the error probability of each path is ε_s , the reliability of the data received at the base station can be denoted by $1 - \prod_{l=1}^{|C_j|} \varepsilon_l$. For simplicity, we assume that central and edge users utilize different spectral resources, and we suppose that interference occurs only in the first hop of UE aggregation, namely the CN listening phase for UEs. Moreover, since in cooperative transmission, the rate from the user to the base station depends on the poorest link either from the user to the CN or from the CN to the base station, we assume that the phase where the CN listens to the UE is the weaker link.

3.2. Design of NOMA-Based Joint Transmission Pair

To support the access of a large number of devices, we consider that users communicate with CNs and BS by the NOMA scheme. Unlike traditional orthogonal multiple access (OMA) schemes, where a subchannel can only be used by one user at a time, in the NOMA scheme, a subchannel can be shared by multiple users. Therefore, systems that consider NOMA are expected to achieve higher spectral efficiency, which can reduce the waste

of spectral resources associated with OMA schemes. Considering the above aspects, we assume each user can be allocated at most one subchannel, and all the users share the k th subchannel in a NOMA group to upload data. To eliminate co-channel interference, the receiver can perform SIC technique decoding to separate the superimposed signals coming from the same channel. The optimal decoding order is the descending order in terms of channel power gain.

Assuming the s th CN forwards the signals of the users, the i th paired NOMA group users are denoted as $Q_i = \{1, 2, \dots, |Q_i|\}$. Additionally, unlike a traditional C-NOMA relay, we perform SIC decoding at the CN. The paired NOMA users can transmit messages to the CN or the BS on the same subchannel. Paired NOMA users can be categorized into strong and weak users based on channel gains. For the same CN node s , the channel gain typically satisfies $|h_{1,s}^i| > |h_{2,s}^i| > \dots > |h_{|Q_i|,s}^i|$, where $|h_{1,s}^i|$ denotes the channel gain parameter between the first user of the i th NOMA group and the s th CN. This also means that at the receiving end, the decoding order of SIC is executed such that the message of the user with the highest channel gain is decoded first.

Power-domain NOMA relies on differentiating users' signals based on their power levels. Let $\mathcal{A}_{Q_i} = \{a_{q_i}\}, q_i \in \{1, 2, \dots, |Q_i|\}$ denote the power allocation of the users in group Q_i . Specifically, a_{q_i} represents the power allocation factor for the q_i th user in the Q_i NOMA group. The transmit power of the q th user can be expressed as $a_{q_i} P_{UE}$, and a_{q_i} satisfies $0 \leq a_{q_i} \leq 1$. Therefore, solving for the optimal $\mathcal{A}_{Q_i}$ determines the optimal power allocation for the NOMA group. To ensure the successful execution of SIC, the transmission power of users must be carefully allocated. Additionally, when the i th NOMA group is assisted by the s th CN, the following equation must be satisfied at the receiver.

$$a_{q_i} P_{UE} |h_{q_i,s}|^2 - \sum_{l=q_i+1}^{|Q_i|} a_l P_{UE} |h_{l,s}|^2 \geq P_{th}, \quad (4)$$

where P_{th} denotes the minimum received power gap required to enable SIC. In the same NOMA group, the SIC decoding order for the signals of each user is in descending order of their respective channel gains. If $q < q'$, then $|h_{q,s}|^2 > |h_{q',s}|^2$. The SINR of the signal of the q_i th user from the i th NOMA group at the s th CN can be given as

$$\gamma_{q_i,s}^i = \frac{a_{q_i} P_{UE} |h_{q_i,s}|^2}{\sum_{l=q_i+1}^{|Q_i|} a_l P_{UE} |h_{l,s}|^2 + \sigma^2}. \quad (5)$$

Obviously, in a NOMA group, the signal of the q_i th user will only be interfered with by users with higher indices after performing SIC. Thus the received data rate of the q_i th user in the NOMA group i is $R_{q_i,s}^i = B_k \log_2(1 + \gamma_{q_i,s}^i)$.

It can be observed that in each NOMA group, the user decoded last can enjoy interference-free transmission. Moreover, we find that for the i th NOMA group Q_i , the feasible CNs are not unique, which means that different interference-free users in Q_i can be observed at different CNs. This implies that when NOMA users reuse the same subchannel, an interference-free signal can be obtained at different suboptimal CNs, which mitigates the impact of interference on the rate. For simplicity, we assume that SIC is perfect when the aforementioned conditions Equation (4) are met.

Therefore, we allow more CNs to detect the data transmitted by the NOMA group. Let $S_i = \{1, 2, \dots, s_i, \dots, |S_i|\}$ be the set of CNs the i th NOMA group could choose; to ensure the rationality of this choice, the rate of the CNs should follow

$$\begin{aligned} R_{q,s_{\min}}^i, R_{1,s_{\max}}^i &\geq R_{th} \\ s_{\min} &= \arg \max_{s \in S_i} (|h_{q,s}|^2), \forall q \in Q_i \\ s_{\max} &= \arg \min_{s \in S_i} (|h_{q,s}|^2), \forall q \in Q_i, \end{aligned} \quad (6)$$

This ensures that users in the NOMA group have the opportunity to be successfully decoded by the CNs in the selected set of CNs.

For each user, having their broadcast signals monitored by more CNs is beneficial, as when NOMA groups can transmit via multiple CNs, the achievable rates of these NOMA users are determined solely by the best CN of a particular user, which means that for the NOMA user q , the optimal CN s_i^* within S_i satisfies that $|h_{q,s_i^*}|^2 > |h_{q,s_i}|^2, s_i^* \neq s_i$, which can achieve the maximum rate for q at this CN. Relative to the best CN $s_{q_n}^*$ for user q_n , q_n can be considered as a near user in the NOMA group, and within the NOMA group, the user q_m is the far user of this CN. Similarly, for the best CN $s_{q_m}^*$ of user q_m , q_m is the near user, and q_n is the far user. Therefore, we refer to this combination of a NOMA group and its multiple optimal CNs as a joint transmission pair (JTP). A JTP consists of a NOMA group and a set of CNs and can be represented as $\psi_i = (Q_i, S_i)$.

For example, as shown in Figure 1, JTP1 is a joint transmission pair, wherein two CNs assist in the transmission of two users, namely CN1 and CN2, and user 1 and user 2. For user 1, CN1 is the best CN, where user 1 is the near user of CN1, and user 2 is the far user of CN1. Thus, at the receiving end CN1, SIC is executed by first decoding the signal from the near user, user 1, and then subtracting this decoded signal from the original signal to obtain the signal for the far user of user 2. For simplicity, we operate under the assumption of perfect SIC, the SINR at CN1 from user 1 and user 2 can be represented, respectively, as

$$\begin{cases} \gamma_{1,1} = \frac{P_1 |h_{1,1}|^2}{P_2 |h_{2,1}|^2 + \sigma^2} \\ \gamma_{2,1} = \frac{P_2 |h_{2,1}|^2}{\sigma^2} \end{cases} \quad (7)$$

It can be observed that, as the far user, user 2 is able to send a signal to CN1 without interference. At this point, by connecting to CN1, the data rates of user 1 and user 2 are $R_{1,1} = B_k \log(1 + \gamma_{1,1})$ and $R_{2,1} = B_k \log(1 + \gamma_{2,1})$. Similarly, when there exists another optimal CN in the NOMA group, specifically the best CN for user 2, which is CN2, user 1 then becomes the far user. As a result, user 1 is able to send data to CN2 on subchannel k without interference. The data rates of user 1 and user 2 received at CN2 are, respectively, $R_{1,2} = B_k \log(1 + \gamma_{1,2})$ and $R_{2,2} = B_k \log(1 + \gamma_{2,2})$.

In an uplink scenario with CN collaboration, the data rate of a NOMA user is determined by the maximum rate it can achieve. In the example above, the data rate of user 1 is $R_1 = \max(R_{1,1}, R_{1,2})$ and similarly for user 2. In a NOMA system with multiple CNs, all users within the NOMA group have the opportunity to transmit without interference. Therefore, the maximum achievable uplink rate for the q th NOMA user can be represented as

$$R_q = \max_{q, S_i \in \psi_i} (R_{q, S_i}). \quad (8)$$

In a system with multiple CNs, the order of NOMA users in each NOMA group determines the level of interference each user experiences. Particularly in the scenario with two users and two CNs, it is possible to find two users who can access the CN on the same sub-channel without interfering with each other. After receiving the messages, these CNs then forward them to the base station.

4. Problem Formulation and Problem Solving

According to the described scenario, the presence of CNs can help users combat fading to enhance the performance of delay and energy consumption. However, in the first hop of UE aggregation, when users transmit data to the CN, they are subjected to interference from other users reusing the same channel, which thus reduces the overall delay performance of the system. To coordinate interference among users and ensure the rate of users sharing the same channel, pairing users into NOMA groups and using SIC technology to eliminate interference is considered. However, in traditional uplink NOMA systems, users with lower

priority still experience significant interference. We introduce multiple CNs to enhance the performance of NOMA, allowing two-user NOMA to achieve improved rate performance.

Optimizing the rate of users connected to the CNs on each subchannel, thereby enhancing the overall spectral efficiency of the system, is considered. The definition of the spectral efficiency of the system can be denoted by

$$\eta = \frac{\sum_{k=1}^K \sum_{i=1}^I \sum_{q=1}^{|Q_i|} R_q^k}{B}, q \in Q_i. \quad (9)$$

For a link between the j th user and the BS, the spectral efficiency can be given as $\eta_{j,BS} = R_{j,BS}/B_k$. So, the main optimization goal is

$$\begin{aligned} (\mathcal{P}_1) : & \max_{\theta, Q, A} \eta \\ \text{s.t. } & C_1 : \sum_{k \in K} \theta_{j,k} \leq 1, \forall j \in J \\ & C_2 : \sum_{q \in Q_i} a_q \leq 1, \forall q \\ & C_3 : |Q_i| \leq Q_{\max}, \forall i \in I \\ & C_4 : R_{j,s} \geq R_{\text{th}}, \forall j \in J \\ & C_5 : \gamma_{q, S_{Q_i}} > \gamma_{\text{th}}, \forall i \in I \\ & C_6 : |C_j| \leq C_{\max}, \forall j \in J \end{aligned} \quad (10)$$

where C_1 means that each user can only be allocated no more than one subchannel; C_2 means the power allocation coefficient in a NOMA group is no more than 1; C_3 is that the number of users in a NOMA group can not exceed $Q_{\max}$; C_4 is that if a user assists by a CN node, the received rate at this CN must be more than R_{th} ; C_5 indicates that for all CNs in S_{Q_i} , the SINR for all users in the Q_i must be greater than the SINR threshold γ_{th} to ensure that SIC can be correctly performed; C_6 indicates that the j th user can be connected to at most $C_{\max}$ CNs, with $C_{\max}$ being at least 1. For simplicity, we focus only on users requiring CN assistance for transmission, without considering central cellular users with better channel conditions.

The problem is formulated as maximizing the system's spectral efficiency, and the problem can be broken down into three sub-problems as how to construct JTPs, optimize the transmit power of NOMA users, and allocate the subchannels, and corresponding algorithms are designed. The primary user CN-based channel sorting search Algorithm, WoA-based power-allocation algorithm, and maximum independent set-based subchannel-allocation algorithm are proposed to solve these problems.

4.1. Design of Primary User CN-Based Channel-Sorting Search Algorithm

Based on the JTP proposed in the previous section, an algorithm for JTP construction that combines CNs and user channel gains is proposed. In traditional uplink NOMA, if SIC is performed in descending order of channel gains, the strong user close to the CN experiences higher interference, limiting the capacity of the NOMA group and reducing user access. Then, spectrum efficiency and the number of users reusing the same subchannel are also limited. However, when multiple CNs are introduced to receive signals from the same NOMA group simultaneously, under certain conditions of satisfactory channel gains, each user can obtain an interference-free link at the suboptimal CN. In summary, a primary user CN-based channel-sorting search algorithm is proposed to search and match JTPs through the primary user. The details of the JTP constructing process are shown in Algorithm 1.

- (1) First, for each user j , which is considered the primary user of the current JTP, we obtain its feasible CN set C_j and add user j to NOMA group Q_j . Feasible CN implies that these CNs possess better channel conditions relative to the base station compared to user j , and their cooperative communication is advantageous for j .

- (2) Since we aim to increase the spectrum efficiency for users needing assistance and are more focused on the access rate of the first hop, we sort C_j in descending order based on the channel gain C_j' for user j .
- (3) After obtaining C_j' , pair the eligible NOMA group users based on their channel conditions. Users that satisfy (12) can be paired with user j to form a feasible NOMA group and update the NOMA group Q_j .
- (4) After all feasible JTPs have been paired, output the conflict graph $\mathcal{G}$ and the JTP groups ψ .

Algorithm 1 Primary user CN-based channel-sorting search algorithm (PCCSSA).

```

1: initialization:  $\mathcal{G}(\mathcal{V}, \mathcal{E}, \mathcal{W}) = \emptyset, \mathcal{C}_J, \psi = \emptyset$ 
2: for  $j = 1 : J$  do
3:    $Q_j = Q_j \cup \{j\}$ .
4:   Get the feasible CNs set of user  $j$ ,  $C_j$ .
5:   Update the  $\psi$ ,  $\psi_i = \psi_i \cup \{C_j\}$ .
6:   Sort the  $C_j$  into  $C_j'$  by  $h_{j,C_j}$  in decent order.
7:   for  $z = 2 : |C_j'|$  do
8:     for  $j' = 1 : J, j' \neq j$  do
9:       Get the channel gain  $h_{j',C_j'(z)}$ .
10:      if  $h_{j',C_j(z)}$  satisfies (12) then
11:        Update the  $S$  in  $\psi$ ,  $Q_j' = Q_j \cup \{j'\}$ .
12:        Form a feasible JTP,  $\psi_i' = \psi_i' \cup \{Q_j\}$ .
13:      end if
14:    end for
15:  end for
16:  Update the graph  $\mathcal{G}$  with all feasible JTPs.
17: end for
18: return  $\mathcal{G}, \psi$ ;

```

JTPs can be regarded as a set of virtual multiple-input multiple-output (MIMO) transmitters and receivers. During the first-hop transmission in the user's uplink, users can be seen as multiple transmitting antennas of a virtual MIMO system. Meanwhile, the process where multiple CNs receive signals from these users can be seen as the receiving end of the virtual MIMO system. Combining these CNs and users into a joint transmission point for overlaid NOMA signals provides more decoding sequences, enhancing the diversity gain of virtual MIMO. Then, unlike the model shown in Equation (1), where only one CN receives the signal from users, the transmission model of JTPs can be given by the following formula

$$\begin{aligned}
 Y &= XH + N \\
 &= \begin{bmatrix} x_1 & x_2 & \dots & x_{|Q_j|} \end{bmatrix} \begin{bmatrix} h_{1,1} & \dots & h_{1,|C_j|} \\ \vdots & \ddots & \vdots \\ h_{|Q_j|,1} & \dots & h_{|Q_j|,|C_j|} \end{bmatrix} + N.
 \end{aligned} \tag{11}$$

The above equation describes the relationship between the received and transmitted signal, where H is a $|Q_j| \times |C_j|$ matrix that represents the channel gain matrix between the user and CNs and N represents noise matrix.

In the i th JTP, to achieve interference-free transmission for the NOMA group users, H needs to meet certain requirements. From (8), it can be observed that the conditions that the H matrix needs to satisfy

$$\begin{aligned} \text{row}(\min\{H_i\}) &\neq \text{row}(\min\{H_j\}), \\ i &\neq j, \forall i, j \in (1, 2, \dots, m), \end{aligned} \quad (12)$$

where $\text{row}(\cdot)$ represents the row index value and m denotes the maximum dimension of H , and H_i and H_j represent the i th and j th columns of matrix H , respectively. This Equation (12) means that each row of matrix H contains a column minimum, and the row indices of the column minimums in each column are distinct. Once the JTP channel matrix meets the above conditions, each paired user can be decoded by the CNs in the correct order, since the interference impact is removed.

The computation complexity of Algorithm 1 is analyzed as follows. Lines 8 to 14 check whether the candidate user meets the requirements, with a complexity of $O(J)$. Lines 7 to 15 iterate through all candidate CNs, so the complexity is $O(C \cdot J)$, where C represents the number of candidate CNs. Lines 3 to 6 retrieve the candidate CNs for the primary user, with a complexity of $O(C \log C)$. Therefore, the total complexity of Algorithm 1 can be expressed as $O(JC \log C + J^2C)$.

4.2. WoA-Based Power Allocation of NOMA Group for Each JTP

In this section, we design a power-allocation strategy based on the whale-optimization algorithm [53] for allocating reasonable power to each NOMA user in a multi-CN enhanced NOMA system. In this model, users belonging to the same NOMA group share the same subchannel for transmission, which means there is co-channel interference between each user. Furthermore, within the NOMA group, while transmitting over identical frequencies, distinct users may employ varying levels of transmission power for uplink transmission. A specific user can utilize higher transmission power to increase the data rate, but it means greater interference to another device in the NOMA group. Therefore, to maximize the overall data rate of users in the NOMA group, the power of each user within the NOMA group needs to be carefully selected. The WoA is employed to optimize power allocation.

WoA is a naturally inspired meta-heuristic optimization algorithm that simulates the hunting behavior of humpback whales. Humpback whales utilize the bubble-net feeding method. This algorithm emulates the whales' processes of searching, encircling, chasing, and attacking prey by using random or best search agents and spiral operators to explore the solution space. Below, we will introduce the basic concepts of WoA, and apply the WoA algorithm to solve for the optimal power allocation among users in the NOMA group. The algorithm flow for power optimization based on WoA is illustrated in Algorithm 2.

4.2.1. Encircling Prey

Humpback whale pods can locate and encircle their prey. Since the location of the optimal solution in the search space is unknown, the WoA algorithm can only assume the current position of the whale with the best fitness as the target prey or close to the optimal solution. Once the optimal whale in the pod is determined, the other whales will attempt to approach the best search whale and update their positions. This behavior can be described as

$$\vec{R} = \left| \vec{Z} \cdot \overrightarrow{X^{best}}(t) - \vec{X}(t) \right|, \quad (13)$$

$$\vec{X}(t+1) = \vec{X}^*(t) - \vec{A} \cdot \vec{R}, \quad (14)$$

where $\vec{X}(t)$ denotes the position vector of whales. In this paper's assumption, the value of the power allocation factor vector $\mathcal{A}_i$ represents the position of the whale in the algorithm, that is,

$$\vec{X}(t) = \mathcal{A}_i = \{a_{q_i}\}, q_i \in Q_i, \quad (15)$$

$\overrightarrow{X^{best}}(t)$ represents the position of the whale with the highest current fitness, which is the current optimal solution, and t is the current iteration.

Algorithm 2 WoA-based power-allocation algorithm (WBPA).

```

1: initialization: Population size  $N_g$ , Maximum number of iterations  $M_i$ , whales position  $X_i (i = 1, 2, \dots, N_g)$ .
2:  $X^{best}$  = the best whale's position
3: while  $t < M_i$  do
4:   for  $n = 1 : N_g$  do
5:     Update  $a, A, R, l$  and  $\delta$ 
6:     if  $\delta < 0.5$  then
7:       if  $|A| < 1$  then
8:         Update the position of this whale by Equation (14).
9:       else if  $|A| \geq 1$  then
10:        Randomly select a whale's position  $X_{rand}$ .
11:        Update the position of this whale by Equation (22).
12:      end if
13:    else if  $\delta \geq 0.5$  then
14:      Update the position of this whale by Equation (19).
15:    end if
16:  end for
17:  Check if any whale's position goes beyond the search space and amend it.
18:  Calculate the fitness of each whale.
19:  Update  $X^{best}$  if there is a better solution.
20:   $t = t + 1$ 
21: end while
22: return  $X^{best}$ 

```

Furthermore, $\vec{A}$ and $\vec{Z}$ represent coefficient vectors, and their values are given by the following equation

$$\vec{A} = 2 \vec{a} \cdot \vec{r} - \vec{a}, \quad (16)$$

$$\vec{Z} = 2 \cdot \vec{r}, \quad (17)$$

During the iteration process, the value of $\vec{a}$ linearly decreases from 2 to 0, and the value of $\vec{r}$ ranges from $[0, 1]$.

4.2.2. Bubble-Net Attacking Method

The bubble-net attacking behavior of humpback whales can be modeled as two strategies: the spiral position updating strategy and the shrinking encircling strategy.

- Shrinking encircling strategy: The shrinking encircling strategy is achieved by reducing the value of $\vec{a}$, resulting in a decreased search range $\vec{A}$. Since the value of a linearly decreases from 2 to 0, the value of the search range $\vec{A}$ is constrained to $[-a, a]$ and when the value of $\vec{A}$ is between $[-1, 1]$, the updated position of the current whale can fall between its original position and the position of the optimal whale.
- Spiral position updating strategy: Under this strategy, the update of the current whale's position towards the optimal whale's position is modeled as a spiral equation to mimic the humpback whale's helical movement. This behavior can be expressed as

$$\vec{R}^j = \left| \vec{X}^{best}(t) - \vec{X}(t) \right|, \quad (18)$$

$$\vec{X}(t+1) = \vec{R}^j \cdot e^{bl} \cdot \cos(2\pi l) + \vec{X}^{best}(t), \quad (19)$$

where $\vec{R}^j$ denotes the distance of the current whale to the prey or the optimal whale, b is a constant, and l is a random value in the range $[-1, 1]$.

When approaching prey, humpback whales not only swim around the prey in a shrinking circle but also move along a spiral path. To simulate this behavior, the WoA algorithm assumes that whales will update their position with a 50% probability of adopting

either the shrinking encircling strategy or the spiral strategy, where δ is a random value between 0 and 1, used to determine the position update mechanism of the whales during the optimization process.

$$\vec{X}(t+1) = \begin{cases} \vec{X}^{best}(t) - \vec{A} \cdot \vec{R} & \text{if } \delta < 0.5 \\ \vec{R}' \cdot e^{bl} \cdot \cos(2\pi l) + \vec{X}^{best}(t) & \text{if } \delta \geq 0.5 \end{cases} \quad (20)$$

where δ is a random value of $[0, 1]$.

4.2.3. Search for Prey

Humpback whale pods can utilize the variation in the $\vec{A}$ vector to search for prey. Humpback whales can conduct random searches based on each other's positions. This means that when $|A| > 1$ holds, we can force the current whale's position to move away from the reference whale. Unlike the previous phase, in this phase, we will randomly select a reference whale instead of using the current optimal whale as the reference target to update the position. This behavior can be described as

$$\vec{R}'' = |\vec{Z} \cdot \vec{X}_{rand}(t) - \vec{X}(t)|, \quad (21)$$

$$\vec{X}(t+1) = \vec{X}_{rand}(t) - \vec{A} \cdot \vec{R}'', \quad (22)$$

where $\vec{X}_{rand}(t)$ is a random whale's position.

Meta-heuristic algorithms comprise two phases: the exploration phase and the exploitation phase. These correspond to the prey search and the bubble-net attacking strategies in the WoA, respectively. In the prey search phase, whales are forced to move away from each other to explore more potential solutions, avoiding being trapped in local optima. In the bubble-net attacking phase, whales move closer to the current optimal solution in search of the global optimal solution.

4.2.4. WoA-Based Power Allocation

According to the system model description in Section 3, users within one NOMA group forward their signals to the base station with the assistance of one or more CN nodes. The base station can obtain the channel gains of all NOMA users within its coverage area; therefore, the power allocation is completed on the base station side. Due to the uncertainty of the positions of users and CNs, finding the optimal solution is an NP-hard problem, making it difficult to directly determine the optimal power allocation. Therefore, we employ the WOA algorithm to allocate power to users within the same NOMA group, aiming to maximize the sum rate of the entire NOMA group. The following pseudocode illustrates the process of the power-allocation algorithm for NOMA group users within a JTP based on WoA. We assume that the power allocation factors assigned to each user in the NOMA group constitute the whale's positions in the WoA algorithm. Through multiple iterations, we search for a set of solutions that maximizes the data rate of the NOMA group.

The process of Algorithm 2 can be described as follows:

- (1) First, initialize the population size as N_g , the maximum number of iterations as M_i , and the whale position information $\mathcal{A}_i$, which represents the power allocation factor vector for NOMA users in the i th JTP and also serves as the input vector for this algorithm, along with the optimal whale position $\mathcal{A}^{best}$.
- (2) Start the iteration process. When the current iteration count t is less than the maximum iteration count M_i , update the parameters a, A, R , and l for each whale in the population, and randomly select a value for δ .
- (3) If the value of δ is less than 0.5, evaluate the value of $|A|$. If $|A|$ is less than 1, update the current whale position according to Equation (14). If A is greater than or equal to

- 1, randomly select the position of a whale in the population as the target and update the current whale position according to Equation (22).
- (4) If the value of δ is greater than or equal to 0.5, update the current whale position according to Equation (19).
- (5) After completing this iteration of updating the whale population's positions, calculate the population fitness, which is the sum rate of the JTP under the power allocation factors corresponding to each whale's position. If the fitness of a whale's position exceeds the current optimal position $\mathcal{A}^{\text{best}}$, update that position to be the new optimal position.
- (6) Proceed to the next iteration until the iteration count t reaches the maximum number of iterations M_i , obtaining the power allocation factors corresponding to the optimal whale position. Output these power allocation factors to complete the power allocation for NOMA users in this JTP.

The computation complexity of Algorithm 2 is analyzed as follows. Lines 1 to 2 represent the initialization process, with a complexity that can be expressed as $O(N_g \cdot f(D))$, where $O(D)$ denotes the computational complexity of the population fitness evaluation, and D represents the number of NOMA users in the JTP. Lines 4 to 16 perform position updates, so the complexity is $O(N_g \cdot D)$. Lines 17 to 19 calculate the population fitness after updating the positions, with a complexity of $O(N \cdot D)$. So the overall complexity of Algorithm 2 can be expressed as $O(M_i \cdot N_g \cdot (f(D) + D))$.

4.3. Resource Set Allocation among JTPs

To solve $\mathcal{P}_1$ in (10), it is necessary to address the issues of user pairing and subchannel allocation. Considering that the number of users far exceeds the number of subchannels, and they are randomly distributed within the cell, this constitutes an NP-hard problem, making it very difficult to directly find the optimal solution. Assuming that an exhaustive search is employed, the computational complexity of the system will increase dramatically with the number of subchannels and users. Therefore, we transform the problem into a maximum weight independent set (MWIS) problem in graph theory, attempting to use a low-complexity algorithm to achieve suboptimal user pairing and subchannel allocation.

In our assumption, users within the same NOMA group communicate with the CN through the same subchannel and a user cannot appear in two or more NOMA groups, meaning there is no overlap between different NOMA groups. This is similar to the MWIS problem where there are no edges between independent vertices. Moreover, maximizing the spectral efficiency in $\mathcal{P}_1$ is equivalent to finding the maximum sum of the weights of independent vertices in the graph.

Assume $\mathcal{G} = (\mathcal{V}, \mathcal{E}, \mathcal{W})$ is a weighted undirected graph, $\mathcal{V}$ represents the vertices in the graph, $\mathcal{E}$ represents the edges between vertices, and $\mathcal{W}$ is the weight of the vertices. In our assumption, the vertices are composed of users from the NOMA group Q_i in a feasible JTP, as well as the subchannel k that this NOMA group of users can reuse, that is

$$v = (q_1, q_2, \dots, q_{|Q_i|}, k). \quad (23)$$

The weight of the vertex is determined by the sum rate generated by the current NOMA users and subchannel combination according to (8) and Algorithm 2, and this can be expressed as

$$w = R_{q_1}^k + R_{q_2}^k + \dots + R_{|Q_i|}^k. \quad (24)$$

Whether there is an edge between two fixed points is determined by whether there is an intersection between the two vertices. When two vertices contain the same elements, there is an edge between these two vertices. After forming edges between vertices, this graph becomes a conflict graph. The main goal is to resolve the conflicts between vertices as much as possible so that we can find the largest independent set in the graph, and ultimately maximize the system's utility.

After Algorithm 1 completes the construction of all feasible JTPs, the vertices composed of NOMA users from all feasible JTPs form the current conflict graph. The conflict graph contains information about conflicts between various user combinations. Since the main goal is to maximize the system's spectral efficiency, this is equivalent to matching each subchannel with the NOMA group that offers the highest rate. Therefore, the objective is to find the maximum independent set in $\mathcal{G}$ by identifying the NOMA groups with the highest rates on each subchannel that are mutually non-intersecting, in order to maximize the system's spectral efficiency. The MWIS problem is an NP-complete problem, making it challenging to solve. Consequently, a method based on a greedy strategy is proposed to suboptimally find the maximum independent set of the conflict graph to allocate the subchannels. The algorithmic process for subchannel allocation is as described in Algorithm 3.

The process of Algorithm 3 can be described as follows:

- (1) First, initialize the conflict graph $\mathcal{G}$, where the vertices are composed of NOMA group users constructed by Algorithm 1, and the set of subchannels to be allocated $\mathcal{K}$.
- (2) Select the vertex v_i from the graph and determine if subchannels k can be used by the current NOMA group. If subchannel k can be used, add k to the current vertex. The weight of the vertex is calculated by Algorithm 2.
- (3) When the graph $\mathcal{G}$ is not empty, find the vertex v^* with the highest weight in the graph $\mathcal{G}$, and add v^* to the independent set $\mathcal{U}$.
- (4) After adding v^* to $\mathcal{U}$, remove the node v^* and its neighbor nodes $\mathcal{N}_{\mathcal{G}_i}^+(v^*)$ from the original graph $\mathcal{G}_i$, resulting in the updated graph $\mathcal{G}_{i+1}$.
- (5) Repeat the above steps until the graph $\mathcal{G}$ becomes an empty set. Finally, output the WMIS $\mathcal{U}$, where the vertices in the independent set include the NOMA groups that need to be allocated subchannels and the subchannels allocated to them.

Algorithm 3 MWIS-based greedy subchannel-allocation algorithm (MGSBA).

```

1: initialization:  $\mathcal{G}(\mathcal{V}, \mathcal{E}, \mathcal{W}), \mathcal{K}$ 
2: for  $v_i$  in  $\mathcal{G}$  do
3:   Gets the vertex  $v_i = (q_1, q_2, \dots, q_{|Q_i|})$ 
4:   for  $k$  in  $\mathcal{K}$  do
5:     If the subchannel can be used by  $Q_i$ , then update  $v_i' = v_i \cup \{k\}$ 
6:     Update the weight of the vertex by Algorithm 2.
7:   end for
8: end for
9: while  $\mathcal{V}(\mathcal{G}) \neq \emptyset$  do
10:  Find the vertex  $v$  in graph  $\mathcal{G}$  that satisfies :
11:   $v_i = \arg \max_{i \in |\mathcal{V}|} (\mathcal{V}(\mathcal{W}))$ 
12:  choose the vertex  $v^* = v_i$ 
13:  Set  $\mathcal{U} = \mathcal{U} \cup \{v^*\}$ 
14:  Let  $\mathcal{G}_{i+1} = \mathcal{G}_i(\mathcal{V}(\mathcal{G}) - \mathcal{N}_{\mathcal{G}_i}^+(v^*) - v^*)$ 
15:   $i = i + 1$ 
16: end while
17: return the WMIS  $\mathcal{U}$  which represents the user and subchannel allocation;

```

The complexity analysis for Algorithm 3 is as follows. Lines 2 to 8 combine the known JTP with different channels k , with a computational complexity of $O(|V| \cdot |\mathcal{K}|)$. Lines 9 to 16 represent the stage of finding the maximum weighted independent set, with a complexity of $O(|V| \cdot (|V| + |E|))$, where E represents the number of edges. Therefore, the complexity of Algorithm 3 is $O(|V| \cdot (|\mathcal{K}| + |V| + |E|))$.

5. Simulation Result

The simulation results and detailed analysis are provided in this section, according to the proposed algorithm. Further, some performance comparison is discussed. The specific simulation settings are shown in Table 2. The system's carrier frequency spectrum is set to 3.6 GHz, with a subcarrier spacing of 30 kHz according to TS38.101 [54], and one subchannel contains 4 PRBs. Additionally, the path loss model is also provided in Table 2. Considering that the system model simulates an outdoor environment, we set the shadow fading value to be log-normal as $\mathcal{N}(0, 8^2)$, with fast fading modeled as Rayleigh [22,26,48].

Table 2. Simulation parameters.

Parameters	Value
Carrier frequency	3.6 GHz
Pathloss	$131.5 + 20 \cdot \log(d[\text{km}])$
Shadowing	Log normal as $\mathcal{N}(0, 8^2)$
Fast fading	Rayleigh fading
Bandwidth per subchannel B_k	1440 KHz
Number of subchannel	12
Number of CNs	9
Minimum distance between UE and CNs	20 m
Maximum transmitted power of user	23 dBm
Maximum transmitted power of the CN	33 dBm
Cell radius of macro cell	500 m
Collaborative radius of the CN	200 m
Thermal noise	−174 dBm/Hz

Figure 2 shows the SINR cumulative distribution function (CDF) curves under different resource allocation strategies. The red curve represents random subchannel allocation to users, with each device assigned only one subchannel. The yellow curve represents subchannel allocation to paired two-user NOMA, with one subchannel allocated per NOMA pair. The purple curve represents subchannel allocation for paired JTPs using the MWIS-based strategy, and the blue curve represents the scenario without interference.

It can be observed that the scarcity of spectral resources, and randomly allocating subchannels to users causes interference among devices, significantly degrading SINR performance. Therefore, UE aggregation transmission is constrained by resource availability and signal interference. Using the NOMA scheme, 50% of users have an SINR below 15 dB, while under the random scheme, this value is only 4 dB. When NOMA is introduced, thanks to the implementation of SIC, some of the interference affecting users' transmission can be decoded and eliminated, resulting in improved SINR performance compared to random allocation. Compared to traditional NOMA, JC-NOMA transmission based on JTPs can further enhance SINR. It can be observed that JC-NOMA allows 50% of users to have an SINR below 20 dB, which is a 33% improvement compared to traditional NOMA. This improvement utilizes the two users in the JTP, both of whom can transmit without interference with the help of multiple CNs. However, compared to the interference-free scenario, the interference-free transmission for NOMA users is not obtained at their optimal CN. Therefore, the JC-NOMA curve does not completely coincide with the SNR curve.

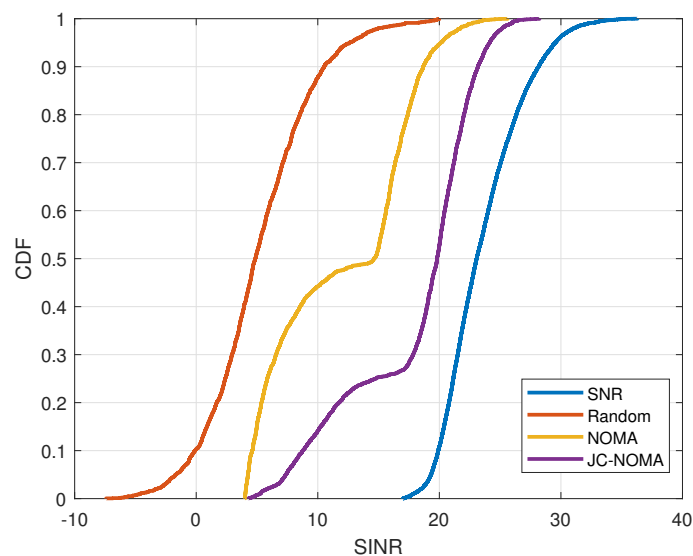


Figure 2. SINR CDF curve of users under different resource allocations.

The performance of spectral efficiency varies with changes in the transmission power of users, as illustrated in Figure 3. The scenario contains 35 users and 20 subchannels. It can be observed that since JTPs ensure interference-free transmission, they offer better spectral efficiency compared to traditional NOMA, where strong users are affected by interference from weak users. In the transmission power range shown in the figure, JC-NOMA can achieve approximately a 10% improvement in spectral efficiency compared to traditional NOMA. Additionally, compared to the OMA transmission scheme, JC-NOMA supports more users for interference-free transmission, resulting in a 30% increase in spectral efficiency. Compared to random resource allocation, it can be observed that as device transmission power increases, the system's interference becomes more complex, leading to an insignificant change in spectral efficiency with increasing transmission power.

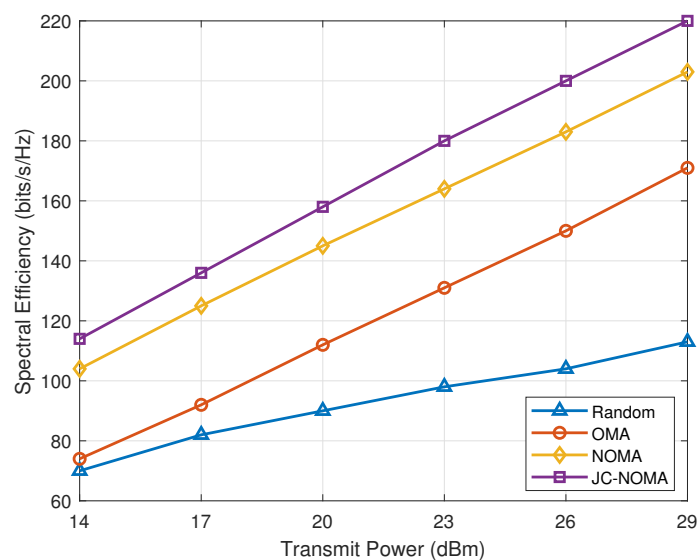


Figure 3. Collaboration spectral efficiency vs. transmit power of collaborative users.

The curve of how the collaboration capacity varies with the number of subchannels is shown in Figure 4. As shown in the figure, when the number of users is fixed at 30, the collaboration capacity under all four strategies increases with the number of subchannels. The advantage of JC-NOMA lies in its ability to support a certain number of users reusing

the same subchannel for interference-free transmission, which is especially important when channel resources are limited. Therefore, when the number of available subchannels in the system is 5, JC-NOMA's cooperative capacity can achieve gains of 33%, 80%, and 125% compared to traditional NOMA, OMA, and random resource allocation, respectively. However, as channel resources become less scarce compared to the number of users, the performance of JC-NOMA will reach a bottleneck because its interference-free transmission is not at the optimal CN.

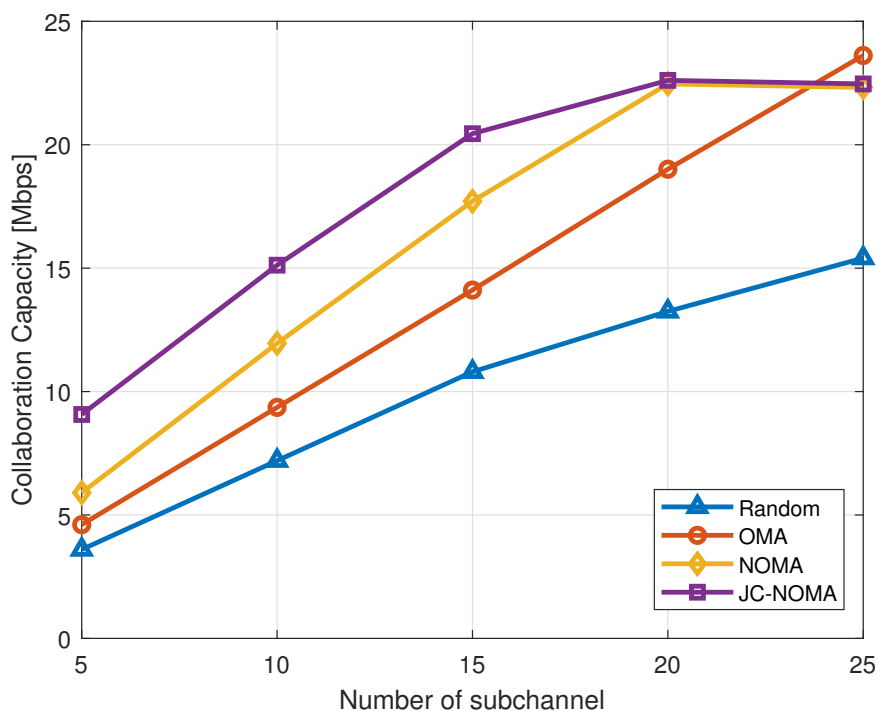


Figure 4. Sum rate vs. number of subchannels.

The variation in collaboration capacity as the number of cell users increases, while keeping the number of subchannels constant, is illustrated in Figure 5. Furthermore, each JTP contains two CNs and two NOMA users. With a fixed number of 20 subchannels, as the number of users gradually increases, the capacity of OMA reaches saturation once the number of users exceeds the number of available subchannels. As the number of users continues to increase, thanks to NOMA's capacity advantage, it can accommodate more users. Therefore, when the number of users exceeds 25, the strategies based on NOMA gain a capacity advantage. After the number exceeds 35, the capacity of NOMA also begins to saturate. At this point, JTPs, with their interference-free transmission, can support more users, thus offering greater advantages when a large number of users are connected. Furthermore, when the number of users exceeds 50, there is no significant improvement in the system's total sum rate. Under the current assumptions, 50 is the optimal number of collaborative users for the system.

Figure 6 shows the variation in JTPs and data rate with the number of users in the same NOMA group. It also illustrates the number of NOMA users successfully accessing under different conditions. In this figure, the performance of {1, 2, 3} CNs per JTP is compared. It becomes the traditional NOMA uplink scenario when the JTP contains only one CN. It can be observed that the increase in NOMA groups and rates is not significant if only one CN receives messages from different users. However, this approach allows more users to access it simultaneously. When the number of users in a NOMA group exceeds five, not using power optimization methods will result in excessive NOMA interference, making SIC unable to function properly. When a JTP contains 2 CNs, the rate reaches its maximum when the number of users in the NOMA group is 2 or 4. The conclusion can be drawn that

the formation of a JTP effectively improves the capacity of the NOMA group. When a JTP contains 3 CNs, as the number of users increases, the rate reaches its maximum when the number of users is 3. However, when the number of users is 2, the rate is slightly lower compared to when there are 2 CNs. This is because the distance to achieve interference-free transmission for the CNs becomes greater. However, although having 3 CNs can achieve the highest total rate, such a JTP can accommodate fewer users. When the number of users exceeds 3, the total rate begins to decrease due to the increased interference. Despite the reduction in total rate, it ensures that more users can access it simultaneously.

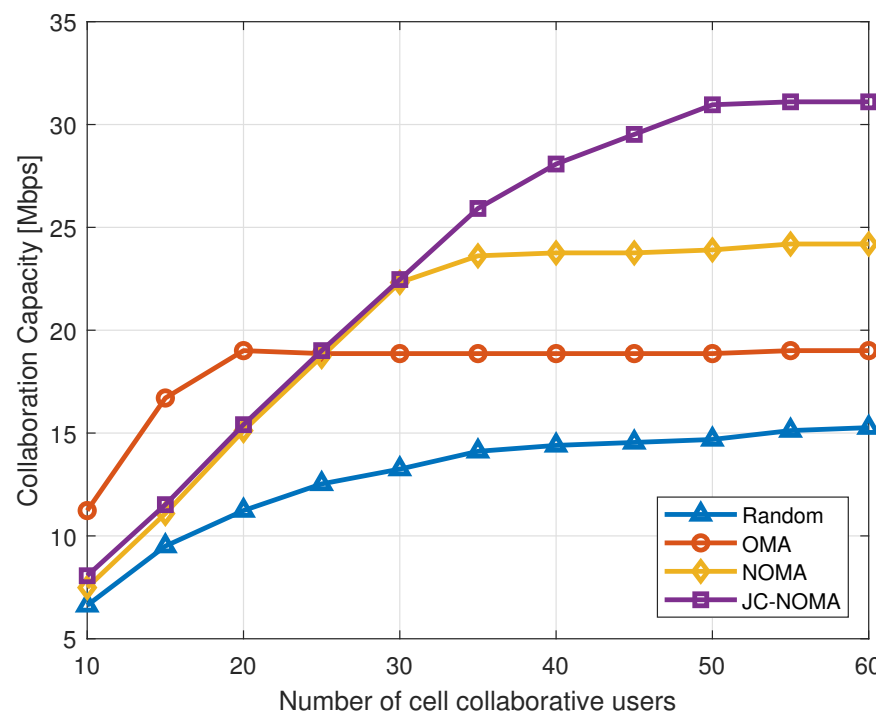


Figure 5. Number of collaborative users vs. collaboration capacity.

The performance of the system's total rate as the number of available subchannels varies is illustrated in Figure 7. JTP = (2,2) means that each JTP in the scenario can be configured with 2 CNs and 2 NOMA users. The number of users distributed in the scenario is 50. For the power allocation schemes, FPA represents the fixed power allocation scheme, which allocates the same power to each user in the JTP, while WBPA denotes the WoA-based power allocation scheme. For subchannel allocation, RSBA indicates the random subchannel allocation and MWIS-based subchannel allocation schemes. It can be observed that, compared to the case with 2 CNs, when the subchannels are allocated using the MGSBA, the total system rate is higher than with random allocation. Our design proves that the MGSBA can find a more optimal JTP combination. This indicates when the CN number is 3, that is, the yellow curve and the green curve in the graph. A conclusion similar to that in Figure 6 can be drawn: when more CNs are configured for JTPs, a higher system sum rate can be achieved, which also means higher system spectral efficiency. Another important conclusion is that when JTPs use WBPA for power optimization, a higher sum rate can be achieved compared to the fixed power allocation strategy. WBPA guarantees that SIC can be properly executed at each CN in a JTP, and maximizes the JTP rate under this premise, resulting in the highest system sum rate. This means that with a fixed number of subchannels, the system sum rate is maximized to achieve the highest spectral efficiency.

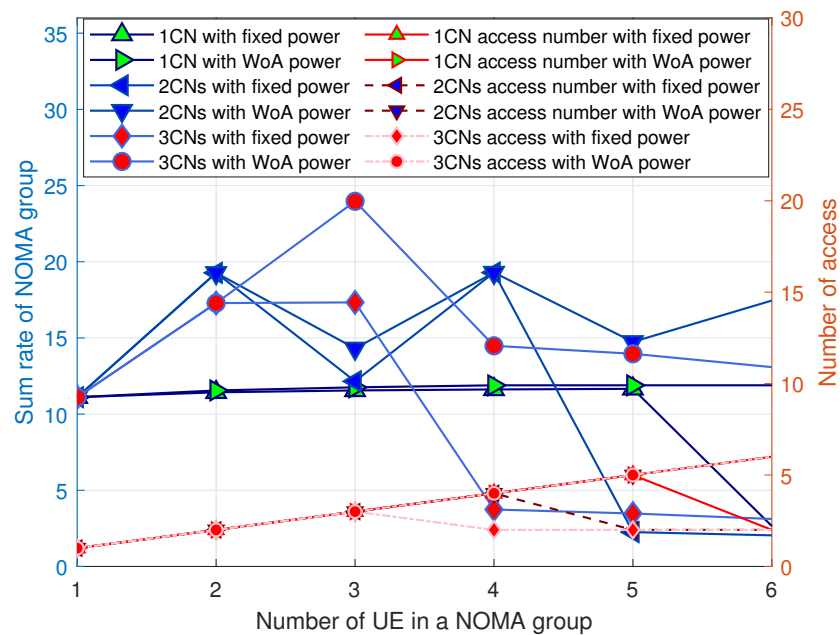


Figure 6. Sum rate and access number of a NOMA group with different user numbers.

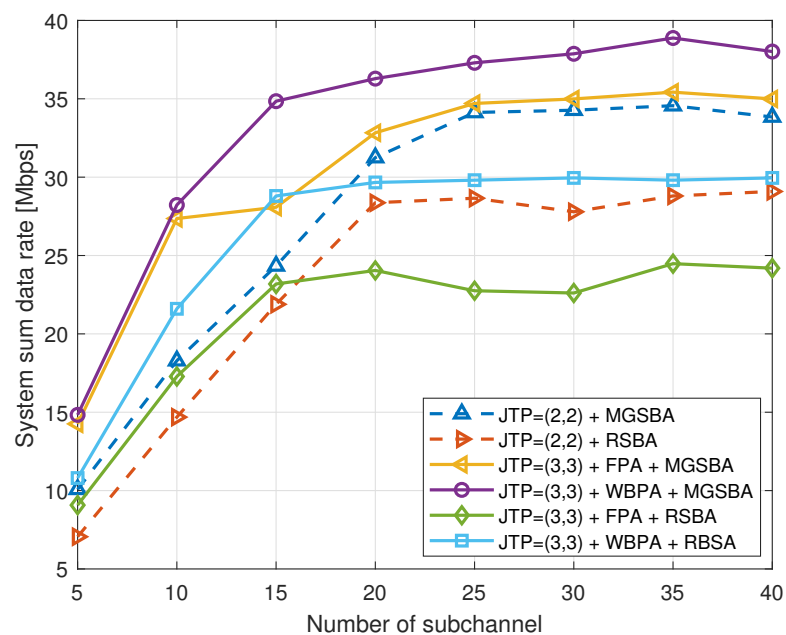


Figure 7. Relationship between rate and number of subchannels under different resource allocation strategies.

6. Conclusions

In this paper, an uplink transmission scenario with multi-node cooperation of UE aggregation is introduced, in which users can perform uplink transmissions with the assistance of CNs. How to improve system spectral efficiency during the first hop transmission of UE aggregation is studied. NOMA technology is introduced to UE aggregation to mitigate co-channel interference while allowing more users to reuse the same subchannel. Furthermore, based on the discovered multi-CN gain, we propose the concept of joint transmission pairs and JC-NOMA, aiming to achieve interference-free transmission for different users at different CNs when multiple CNs and users collaborate. Moreover, a primary user CN-based channel-sorting search algorithm (Section 4.1) is proposed to

construct these CNs and users into JTPs. After successfully obtaining feasible JTPs, WBPA (Section 4.2) is designed to allocate the power for NOMA users in the JTP to ensure the maximum sum rate of the feasible JTP. Additionally, due to the limited spectrum resources, a subchannel-allocation algorithm based on the maximum independent set (Section 4.3) is used to allocate subchannels to the feasible JTPs. The final simulation results show that our proposed JTP-based JC-NOMA optimization strategy can significantly improve the sum rate of collaborating users accessing CNs, greatly enhancing the overall system spectral efficiency.

For future research, we plan to explore several key directions. Firstly, we intend to investigate the integration of machine-learning techniques to further optimize resource allocation and power control in JC-NOMA systems. Secondly, we will examine the potential of incorporating advanced antenna technologies, such as massive MIMO and beamforming, to enhance spatial multiplexing gain and further mitigate interference. Finally, we aim to study the energy efficiency of users accessing the network in uplink scenarios, which is crucial for sustainable and efficient network operations. These future directions will not only enhance the current research but also pave the way for broader and more impactful applications of JC-NOMA in next-generation wireless networks.

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Abbreviations

The following abbreviations are used in this manuscript:

IoT	Internet of things
CN	Cooperative nodes
NOMA	Non-orthogonal multiple access
JTP	Joint transmission pair
SIC	Successive interference cancellation
MWIS	Maximum weighted independent set
UDN	Ultra-dense network
eMBB	Enhanced mobile broadband
mMTC	Machine type communication
URLLC	Ultra-reliable and low latency communication
feMBB	Further-eMBB
umMTC	Ultra-mMTC
euRLLC	Enhanced-uRLLC
KPI	Key performance indicators
IA	Interference mitigation
SU	Secondary user
D2D	Device-to-device
PU	Primary user
UE	User equipment
QoS	User quality of service
OMA	Orthogonal multiple access
CoMP	Coordinated multipoint

C-NOMA	Cooperative non-orthogonal multiple access
HI	Hardware impairment
BS	Base station
MIMO	Multiple-input multiple-output
WoA	Whale-optimization algorithm
CDF	Cumulative distribution function

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