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SURVEY

Intelligent Reflecting Surfaces (IRS)-Enhanced Cooperative NOMA: A Contemporary Review

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ABSTRACT The integration of intelligent reflecting surfaces (IRS) into cooperative non-orthogonal multiple access (NOMA) systems revolutionizes wireless networks by enhancing signal strength, mitigating interference, and optimizing spectral efficiency. The cooperative NOMA (CNOMA) framework, empowered by IRS technology, further promises enhanced performance, robustness, and scalability for next-generation wireless networks as compared to NOMA only systems. This paper explores the synergy between IRS and NOMA to leverage cooperative techniques for superior wireless system design. Fundamental principles, technological advancements, and potential applications of IRS-assisted CNOMA systems are discussed, highlighting existing works. Both underlay and overlay NOMA principles are examined in conjunction with IRS in the paper. Spatial modulation-aided CNOMA is explored for multiple-input multiple-output (MIMO) systems, along with its advantages and practical challenges. Additionally, the paper discusses fundamental principles and technological advancements of IRS-assisted CNOMA systems, emphasizing solutions to potential challenges and the role of machine learning (ML)/deep learning (DL) in resource optimization like transmit power and IRS phase settings. Simulation results are presented to highlight the benefits of IRS-aided CNOMA system design. Finally, the paper outlines future directions and potential research topics in IRS-aided CNOMA.

INDEX TERMS Intelligent reflecting surfaces (IRS), cooperative-NOMA (CNOMA), bit error performance, 5G and beyond, machine learning, MIMO, spatial modulation.

I. INTRODUCTION

Non-orthogonal multiple access (NOMA) is emerged as a competitive technique for the next-generation wireless communication systems [1], [2], [3], [4]. With the unprecedented growth in wireless connectivity demands and the advent of technologies like fifth generation (5G) and beyond, NOMA offers a promising solution to address the challenges of spectral efficiency, massive connectivity, and diverse quality-of-service requirements. One of the compelling features of NOMA is its ability to unlock the full potential of multi-user diversity, ensuring that the resources are utilized efficiently, especially in scenarios with heterogeneous traffic requirements. This is particularly relevant for the internet-of-things (IoT), where a multitudinous of devices with different communication needs coexist. NOMA's flexibility extends to various application domains, having massive machine-type communication (mMTC), ultra-reliable low-latency communication (URLLC), and enhanced mobile broadband (eMBB) [5], [6], [7], [8].

As the communication technologies evolve towards sixth generation (6G) and beyond, NOMA continues to be a focus of intense research and standardization efforts. It holds the potential to revolutionize the design and operation of wireless networks, where connectivity is not only widespread but also customized to meet the specific needs of individual

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TABLE 1. List of abbreviations.

Abbreviation	Description	Abbreviation	Description
NOMA	Non-Orthogonal Multiple Access	CNOMA	Cooperative NOMA
IoT	Internet of Things	SNR	Signal-to-Noise Ratio
MIMO	Multiple-Input Multiple-Output	DL	Downlink
AI/ML	Artificial Intelligence/Machine Learning	UP	Uplink
IRS/RIS	Intelligent Reflecting Surface/Reflecting Intelligent Surface	D2D	Device-to-Device
BS	Base Station	SCMA	Sparse Code Multiple Access
UE	User Equipment	KPI	Key Performance Indicator
V2I	Vehicle-to-infrastructure	URLLC	Ultra-Reliable Low-Latency Communication
V2X	Vehicle-to-everything	mMTC	Massive Machine-type Communication
5G, 6G	Fifth Generation, Sixth Generation	eMBB	Enhanced Mobile Broadband
3GPPP	3rd Generation Partnership Project	*ProSe*	Proximity Services
F-RAN	Flexible Radio Access Networks	SWIPT	Simultaneous wireless information and power transfer
SIC	successive interference cancellation	ISIC	Imperfect SIC
MRC	maximum ratio combining	COMA	Cooperative Orthogonal Multiple Access
SM	Spatial Modulation	PSM	Precoded Spatial Modulation
QoS	Quality of Service	DCMA	Dense Code Multiple Access
MEC	Mobile Edge Computing	SDMA	Spatial Division Multiple Access
AP	Access Point	RSMA	Rate-Splitting Multiple Access

users and devices. In this context, NOMA stands as an innovation, poised to shape the next-generation communication systems [9]. Further, cooperative communication plays a pivotal role in shaping the landscape of 5G and beyond wireless networks. As we move into the era of advanced connectivity and ultra-high data rate, the concept of cooperation among network nodes becomes increasingly significant [6], [10], [11], [12]. Cooperative communication involves the collaboration of multiple devices or base stations (BSs) to transmit, receive, and process data collectively. This approach brings several advantages, including enhanced network reliability, reduced latency, improved coverage, and increased spectral efficiency of wireless networks. By intelligently sharing resources and information, cooperative communication technologies promise to unlock the full potential of 5G and future generations of wireless networks, enabling seamless connectivity, and low-latency applications [6], [9], [10], [11], [13], [14], [15].

In cooperative NOMA (CNOMA) multiple users simultaneously share the same time-frequency resources with distinct power levels and codebooks. The cooperation aspect comes into play as users with better channel conditions assist those with weaker signals by acting as relays [4], [15], [16], [17]. This enhances network coverage, improves reliability, and boosts overall system capacity. CNOMA paves the way for the seamless integration of massive connectivity, low latency, and high data rates, making it a promising technology for realizing the ambitious goals of next-generation wireless networks [8], [18], [19], including supporting diverse applications, from augmented reality (AR) to smart cities. CNOMA enables multiple users to simultaneously access the wireless channel by multiplexing them in the power domain over the same frequency resources. Further, by employing techniques such as power control, resource allocation, and user grouping, CNOMA can dynamically adjust transmission parameters to optimize quality-of-service (QoS) metrics such as throughput for each user.

Intelligent reflecting surfaces (IRS)[1] assisted communication is promising way in pioneering wireless technologies for 5G and beyond [8], [20], [21], [22]. IRS, which is also known as smart surfaces or meta-surfaces, comprises passive elements that can manipulate electromagnetic waves' propagation by reflecting or refracting them. These surfaces can be strategically deployed in the environment to enhance signal strength, mitigate interference, and optimize coverage in wireless communication systems. By dynamically adjusting the phase and amplitude of reflected signals, IRS can improve signal strength and enhance spectral efficiency. This technology holds high potential for revolutionizing wireless networks, enabling faster data rates, extended coverage, reduced energy consumption, and enhanced connectivity.

IRS integrated with NOMA communication represents an exciting frontier in the evolution of wireless networks [3], [9]. By combining NOMA with IRS, these benefits are further amplified. IRS elements can be strategically placed to reconfigure the wireless channel in NOMA [23], [24]. This synergy between IRS and NOMA promises to deliver unprecedented gains in network capacity, improved reliability, and enhanced performance for 5G and beyond. For example, in a dense urban environment where traditional BS deployments face challenges with coverage and capacity, integrating IRS with NOMA can significantly enhance both. By strategically placing IRS elements in areas with poor coverage or high user density, the signal reflection and manipulation capabilities of IRS can effectively extend coverage and increase capacity. Further, in indoor environments such as shopping malls or airports, integrating IRS with NOMA can improve

[1]IRS is also referred as reconfigurable intelligent surfaces (RIS) or metasurfaces in the literature.

localization accuracy by creating customized signal patterns that enhance the accuracy of indoor positioning systems.

In the literature [3], [20], and [22], both IRS and NOMA systems have been designed and analyzed either individually or in terms of their integration for next-generation wireless systems. Numerous survey articles have summarized the research conducted on IRS and NOMA, and some have focused on IRS-assisted NOMA systems. Additionally, CNOMA systems have been considered in certain survey articles. However, limited attention has been given to IRS-assisted CNOMA in the literature. Therefore, in this survey paper, we focus on IRS-aided CNOMA systems, exploring recent trends and their potential applications in next-generation wireless networks.

A. OBJECTIVES AND SCOPE OF THE SURVEY

This paper highlights the following aspects of the CNOMA:

- It provides an extensive review and analysis of existing literature, research, and advancements in CNOMA technologies, focusing on various aspects such as system architectures, resource allocation schemes, performance evaluations, and emerging trends.
- Paper outlines and compares different types of CNOMA systems, emphasizing their distinguishing features, advantages, limitations, and potential applications in next-generation wireless networks.
- The paper emphasizes the bit error rate (BER) and sum-rate performance of various NOMA schemes to illustrate the impact of system design.
- Paper explores and highlights the significance of IRS in the design and enhancement of CNOMA systems, specifically in optimizing spectral and energy efficiencies.
- It discusses and elucidates the role and impact of AI/ML techniques in optimizing and improving IRS-assisted CNOMA system design, potentially enhancing performance and adaptability.
- It describes and assesses the application of index modulation (IM)-based CNOMA systems in multiple-input multiple-output (MIMO) scenarios, elucidating the associated benefits and potential challenges in system design and implementation.

B. ORGANISATION OF THE PAPER

Related works on IRS-NOMA/CNOMA are summarized in Section II. Cooperative communication fundamentals are presented in Section III, while the fundamentals of IRS are detailed in Section IV. Section V illustrates cooperative communication system architectures for OMA and NOMA systems. Section V also highlights various CNOMA systems including the cooperative MIMO system. IRS-assisted CNOMA is discussed in Section VI with its possible advantages and practical challenges. The importance of resource allocation is emphasized in Section VII, and the role of AI/ML in IRS-aided cooperative NOMA is mentioned in Section VIII. Section IX presents simulation results of IRS-CNOMA to show various performance metrics. In Section X, some challenges and research directions in CNOMA are outlined with potential applications in Section XI, followed by conclusions drawn in Section XII. Furthermore, for readers' reference, Table 1 comprehensively lists the common abbreviations and terminologies used throughout this paper.

II. RELATED ARTICLES ON IRS-NOMA/CNOMA

Research has emerged in recent years regarding IRS in conjunction with NOMA and CNOMA systems. These articles delve into the innovative combination of IRS technology with NOMA and CNOMA schemes, exploring their potential for enhancing wireless networks. Researchers have investigated various aspects, including system design, performance analysis, optimization techniques, and practical implementations. These related articles provide valuable insights into harnessing the power of IRS to optimize resource allocation, improve spectral efficiency, and enable novel applications in the realm of next-generation wireless communication.

Device-to-device (D2D) communication in long-term evolution (LTE) and 5G networks involves cooperative principles. D2D communication is a communication paradigm that allows devices within close proximity to communicate directly with each other without the need for a BS or cellular network infrastructure. It can be used for various purposes, including offloading cellular traffic, proximity-based services, and public safety. In the context of 3rd Generation Partnership Project (3GPP) standards, D2D communication has been included in several releases, with a focus on enhancing cellular networks and enabling new services. Proximity Services (*ProSe*) is the 3GPP term for D2D communication. It is first introduced in 3GPP Release-12 and further enhanced in subsequent releases. *ProSe* allows direct communication between user equipment (UE) devices, allowing them to discover each other and establish direct links. *ProSe* can operate in both licensed spectrum (LTE-based) and unlicensed spectrum (e.g., Wi-Fi, LAN). Further, *ProSe* can be used for various use cases, including public safety, social networking, local discovery, and content sharing. In public safety applications, *ProSe* enables direct communication among devices even when the cellular network is congested or unavailable. The *ProSe* architecture includes *ProSe* function entities, which are responsible for managing *ProSe* services within the network. *ProSe* function entities assist in device discovery, group communication, and access control. *ProSe* supports several modes of operation, including D2D communication, network-assisted D2D (NA-D2D) communication, and device-to-network (D2N) communication. *ProSe* also has security mechanisms to ensure the confidentiality and integrity of D2D communication. 3GPP specifies interoperability between *ProSe*-capable devices from different network operators and vendors. IRS aided CNOMA principle is useful in D2D communication to boost its energy and spectral efficiencies, particularly in scenarios where traditional communication methods face challenges related to coverage, capacity, and reliability.

The integration of IRS with NOMA in satellite-terrestrial networks (STN) offers a promising solution to enhance spectral efficiency and connectivity. By strategically deploying IRS elements in these networks, it can mitigate signal attenuation and optimize resource allocation, improving communication performance for both satellite and terrestrial users. IRS-NOMA system for STN is analyzed in [25]. In [25], exploration of joint beamforming and power allocation techniques for uplink NOMA transmission is considered within an IRS-assisted cognitive STN that operates in the millimeter-wave frequency band. Impact of imperfect channel state information is also analyzed particularly concerning the angular characteristics of both primary users and secondary users of NOMA systems. Further, in [26] an uplink transmission scheme enhanced by IRS to extend wireless coverage and enhance spectral efficiency within an integrated satellite-terrestrial network (ISTN) is considered. In this context, several earth stations engage in communication with the satellite through NOMA technology. Meanwhile, multiple direct users and blockage users connect to the cellular network utilizing space division multiple access (SDMA), alongside IRS-assisted NOMA technology, respectively. Furthermore, cellular-connected unmanned aerial vehicle (UAV) is considered for cooperative communication [11]

Leveraging UAVs to implement an IRS-NOMA system introduces a dynamic and flexible approach to wireless communication. This combination allows UAVs to serve as mobile relays, strategically positioning themselves to enhance signal strength and network capacity, making it a compelling solution for various applications, including disaster recovery, surveillance, and remote connectivity [27]. Therefore, integrating NOMA into UAV communication networks, enhances spectrum efficiency and possesses inherent interference-mitigating capabilities [27]. A cooperative UAV NOMA network architecture is considered in [27], and it assesses the associated technical challenges. Moreover, with the aim of optimally utilizing limited resources in a distributed manner, whether through cooperation or competition, game theory emerges as a promising approach for addressing diverse technical challenges within cooperative wireless networks. Further, authors in [28] explore a design for an UAV-assisted multiple-input single-output (MISO) NOMA downlink network, incorporating a simple IRS panel.

A comprehensive examination of incorporating simultaneous wireless information and power transfer (SWIPT), a radio frequency-based energy harvesting method, into CNOMA networks has been introduced in the literature to improve device battery life [19], [29], [30]. In [17] an in-depth overview of the diverse research endeavors has focused on evaluating the performance of CNOMA networks with SWIPT assistance. A IRS is employed to improve the performance of CNOMA, and SWIPT technology at the cell-center user is considered to relay information to the cell-edge user [19], [29].

The fusion of NOMA with flexible radio access networks (F-RANs) has ushered in an emerging research domain known as NOMA-F-RANs [2]. Within NOMA-F-RANs, NOMA methodologies are employed both in content delivery from the BS to mobile users and in the process of task offloading when mobile users make computational task requests. Further, in [2], application of artificial intelligence (AI) techniques to address the challenges of the NOMA-F-RAN, is considered. In-depth examination of the NOMA-F-RANs architecture is examined to offer insights into its essential components, such as cooperative caching and cache-assisted mobile edge computing.

In [17], [18], and [31], integration of NOMA with cognitive radio (CR) is considered to form cognitive NOMA network, aimed at achieving more intelligent spectrum sharing. The design principles underpinning cognitive NOMA networks align harmoniously with the performance requirements of 5G wireless networks, encompassing objectives such as high spectrum efficiency, extensive connectivity, low latency, and enhanced fairness. The paper [18] presents three distinct cognitive NOMA architectures, including underlay NOMA networks, overlay NOMA networks, and CR-inspired NOMA networks, and their analysis. Further, IRS assisted CNOMA with mobile edge computing is analyzed in the literature [14]. When the direct connections between the BS and the user become obstructed, the offloading tasks are redirected towards the nearby user through the IRS.

To enhance rate performance and uphold fairness among NOMA users, authors in [32] focus on maximizing the minimum decoding signal-to-interference-plus-noise ratio (i.e., rate) for all users. This optimization involves the coordinated adjustment of both the active transmit beamforming at the BS and the phase shifts (passive beamforming) at the IRS. In the scenario with a single-antenna BS, the optimal power allocation at the BS is derived and obtain asymptotically optimal solutions for the phase shifts at the IRS, all in closed forms. However, in the case of a multi-antenna BS, it is demonstrated that the rank of the Semi-Definite Relaxation (SDR) solution for the transmit beamforming design is upper-bounded by two [32]. In [33], multiple IRSs are employed in NOMA system with discrete phase shifts. Article [22] introduced a novel concept called simultaneously transmitting/refracting and reflecting IRS (STAR-IRS) to ensure complete coverage across an area. Performance analysis of STAR-IRS-assisted NOMA networks operating over Rician fading channels is analyzed in [22]. In this setup, signals from the BS are directed toward the nearby user through reflection while simultaneously being transmitted to the distant user. In [34] power minimization challenge within an uplink multi-IRS assisted cooperative multi-cell NOMA network is investigated. In this network, IRSs are deployed with inter-RIS reflection capabilities near both the BSs and users. Additionally, a novel NOMA scheme based on inter-group interference cancellation (IGIC) is considered to effectively mitigate interference from central users to edge users.

In the literature [35] and [21], IRS in the context of NOMA is analyzed for outage probability and ergodic rate by considering: 1) imperfect successive interference cancellation (ISIC) and perfect successive interference cancellation (PSIC) methods at the receiver, 2) employing a 1-bit coding scheme. Further, cognitive non-terrestrial vehicle network empowered by STAR-IRS [21] is analyzed by considering Rician fading channels as well as both imperfect and perfect successive interference cancellation (SIC) techniques.

Role of IRS-NOMA is also highlighted for physical layer security in the literature [36], [37], and [38]. In an eavesdropping scenario, an IRS-NOMA system can play a crucial role in ensuring secure and private communication. By intelligently manipulating signal reflections, IRS elements can create intentional interference patterns that make it extremely challenging for eavesdroppers to decipher sensitive information, thereby enhancing the overall security of wireless transmissions. For example, two IRS-assisted schemes are designed to bolster the security of NOMA networks against both internal and external eavesdropping threats in [37] and [38]. To enhance the secrecy rate (SR) and perform a comprehensive analysis of IRS-based NOMA is analyzed in [36]. In this scenario, obstacles obstruct the direct links between the BS, users, and a potential eavesdropper. Despite the presence of these obstacles between the IRS and the second user, the first user serves as an Amplify-and-Forward (AF) relay for D2D communication. An eavesdropper attempts to intercept the transmission signals in two phases: from the IRS to the first user and from the first user to the second user. Consequently, the second user emits a cooperative jamming signal that is known to the first user.

Rate-splitting multiple access (RSMA) method operates by implementing rate-splitting (RS) at the BS and employing SIC at the users, offering a versatile multiple access framework for the next-generation networks. Application of IRS in RSMA is highlighted in [39] by considering a single-antenna BS and users with the assistance of an IRS. Further, in [8] and [40] resource allocation for mission-critical services within the smart grid context is considered for IRS scenario. System employs an IRS as part of the transmission strategy to mitigate the limitations of NOMA in URLLC. Furthermore, multiple antenna techniques are considered within NOMA networks [41]. It highlights resource management challenges within both single-carrier and multi-carrier MIMO-NOMA networks [41]. In [24], authors introduce a downlink MISO transmission scheme, enhanced by an IRS comprising a multitude of passive reflecting elements. Furthermore, paper [42] investigates the influence of two phase shifting approaches—coherent phase shifting and random discrete phase shifting—on the performance of IRS-assisted NOMA. Thus, in the literature, IRS-NOMA systems are analyzed, considering various aspects such as SWIFT, RSMA, ISIC/PSIC, AI/ML, MIMO, beamforming, and more. Summary of survey papers is summarized in Table 2. Most works in the literature have considered either NOMA or IRS or IRS-NOMA related works in detail. However, IRS-CNOMA is least discussed or not thoroughly considered in existing survey papers.

III. PRINCIPLE OF COOPERATIVE COMMUNICATION

Cooperative communication is a wireless communication technique where multiple nodes or devices collaborate to improve the overall performance of the network. In traditional point-to-point communication, a sender communicates directly with a receiver. However, in cooperative communication, intermediate nodes, often referred to as relays, assist in transmitting the data from the sender to the receiver [6], [10], [11], [13], [36], [48], [49]. A cooperative communication system model is depicted in Fig. 1, where a relay is employed to enhance the performance of the UE. In Fig. 1, communication occurs in two time phases: the first phase (broadcast phase) and the second phase (cooperative phase). In the first phase, the access point (AP) broadcasts a signal to both the relay and UE. In the second phase, the relay transmits a signal to the UE. The UE effectively combines the two signals from the AP and relay to decode the data symbols [16]. Key characteristics and concepts of cooperative communication are summarized as follows

- *Relaying:* Relay nodes receive the transmitted signal from the source and then forward it to the destination. This can extend the communication range and enhance signal quality, particularly in scenarios with obstacles or deep fading channels [18].
- *Diversity Gain:* Cooperative communication is used to provide diversity gain at the UE or receiver side, which helps combat wireless fading and improve the reliability of wireless network. By introducing multiple paths through relays, the system becomes more reliable to signal degradation.
- *Spatial Multiplexing:* In addition to relaying, MIMO cooperative systems can use spatial multiplexing techniques to transmit multiple streams of data simultaneously using multiple antennas at relay with BS and UE nodes. This can enhance the data rate and netwrok capacity [25].
- *Resource Allocation:* Efficient allocation of resources, such as transmit power and bandwidth, is essential in cooperative communication among the BS, UE and relay nodes to optimize system performance.
- *Relay Selection*: Selecting the most suitable relay nodes and determining when and how to relay data are critical aspects of cooperative communication protocols.
- *Cooperative Protocols*: Various cooperative protocols, such as AF, DF (decode and forward), and compress-and-forward (CF), dictate how relays process and transmit data to UE.
- *Applications:* Cooperative communication has applications in wireless sensor networks, ad-hoc networks, cellular networks, D2D, and beyond. It can improve

TABLE 2. A comprehensive list of existing survey papers on IRS-assisted cooperative NOMA and its comparison with our work.

References	Cooperative Communication	IRS	NOMA	MIMO	AI/ML	Main Contribution
[1]	✗	✗	✓	✓	✗	Paper provides a comprehensive survey of recent advancements in power domain NOMA mainly considering capacity analysis, power allocation strategies, user fairness, and user-pairing schemes in NOMA.
[3]	✗	✓	✓	✓	✗	Paper presents a survey of IRS-assisted NOMA networks by introducing the IRS and NOMA technologies. Additionally, a comparison between IRS-NOMA networks, MIMO-NOMA networks, and relay-aided NOMA networks is included.
[4]	✓	✗	✓	✓	✓	Paper provides an overview of various cooperative NOMA systems operating under both the decode-and-forward and amplify-and-forward protocols.
[5]	✓	⊠	✓	✓	✓	Paper examines different rate optimization scenarios explored in the literature when NOMA is combined with one or more candidate schemes and technologies for 5G networks including MIMO, massive MIMO, advanced antenna architectures, higher frequency millimeter-wave (mmWave) and terahertz communications, cooperative communications, cognitive radio (CR), and others.
[43]	✓	✗	✗	✗	✗	Paper presents a survey of resource allocation in cooperative cognitive radio networks (CRN). It discusses protocols utilized in the literature for resource allocation in cooperative CRN. Additionally, the paper highlights the utilization of power control, cooperation types, network configurations, and decision types in cooperative CRN.
[44]	✓	✗	✗	✗	✗	Paper considers an extensive examination of the current state-of-the-art spectrum sensing in CR communications including review existing spectrum sensing methodologies applied across various categories, including narrowband sensing, narrowband spectrum monitoring, wideband sensing, cooperative sensing, practical implementation considerations for different techniques.
[45]	✓	⊠	✓	✓	⊠	A comprehensive survey of NOMA and its variants is considered for the 5G technologies such as D2D communication, cooperative communication, MIMO, and heterogeneous networks (HetNets).
[46]	✗	✗	✓	✗	✗	An overview of physical layer security with finite-alphabet signaling for NOMA and other systems is considered.
[47]	✓	✗	✓	⊠	⊠	A comprehensive review and analysis of the current state-of-the-art in CR-based NOMA network architecture is considered. Additionally, it discusses the advancements made by integrating CR-based NOMA with recent multiple-access techniques.
Our paper	✓	✓	✓	✓	✓	Paper discusses fundamental principles, technological advancements, and potential applications of IRS-assisted CNOMA systems, emphasizing solutions to potential challenges and the role of machine learning (ML)/deep learning (DL) in resource optimization.

✗: not discussed, ⊠: partially discussed, ✓: discussed

coverage, reduce interference, and enhance the overall quality of service and various use cases depend on the specific communication scenarios [4].

AP transmits the signal x to the UE and relay, as shown in Fig. 1. h_d, h_r, and h_{ru} denote the channel response between AP-UE, AP-Relay, and Relay-UE links, respectively. Received signal at the UE and relay during first time phase is expressed as

$$y_1 = h_d x + n_1 \text{ and } y_r = h_r x + n_r, \tag{1}$$

respectively. n_1 and n_r denote the additive white Gaussian noise (AWGN) with zero mean and σ_n^2 variance at the UE and relay, respectively. During the second phase, relay decode successfully x using some traditional decoding techniques. Then relay transmits the symbols to the UE and received signals is

$$\tilde{y}_1 = h_{ru} x + n_2, \tag{2}$$

where n_2 is the noise. UE uses both the received signal in the first and second time phases to decode the information. The

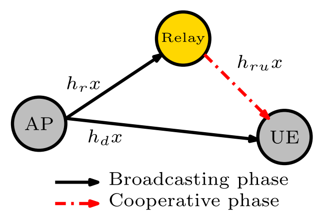

FIGURE 1. Cooperative communication system model.

maximum signal-to-noise ratio (SNR) signal or maximum ratio combining (MRC) can be used by UE as

$$\max\{\tilde{y}_1, y_1\} \quad \text{or} \quad h_{ru}^H \tilde{y}_1 + h_d^H y_1. \tag{3}$$

Hence, UE performance is enhanced by a cooperative scheme because diversity of the UE increased.

Relaying solutions has garnered significant interest among researchers and emerged as a vital strategy in cooperative systems to enhance coverage, reliability, as well as power and spectral efficiency. This promising strategy encompasses two widely recognized relaying protocols frequently employed in cooperative communication networks, specifically the DF and AF protocols [49], [50], [51], [52]. However, one significant disadvantage of cooperative communication is the increased complexity it introduces to the network. Cooperative systems often require additional coordination among multiple nodes, leading to more sophisticated signaling, synchronization, and resource allocation mechanisms.

IV. FUNDAMENTALS OF IRS

IRS represents an innovative advancement in wireless communication technology, poised to reshape the way signals are transmitted and received [20], [32]. These surfaces consist of an array of passive reflecting elements, strategically positioned in the environment where wireless communication is needed. These elements are often designed using metamaterials or specialized materials that allow for precise control of the reflected electromagnetic waves. The fundamental idea behind IRS is to intelligently manipulate the propagation of wireless signals by adjusting the phase and direction of reflection, resulting in improved signal quality and network performance [7], [14], [21], [53].

The architecture of an IRS typically comprises numerous small reflecting elements, often arranged in a two-dimensional or even three-dimensional array. These elements can be integrated into building structures, walls, ceilings, or other surfaces. Each element is equipped with the capability to independently control the phase of the incoming signal. This phase control is crucial because it enables the IRS to optimize signal strength and directionality according to the specific requirements of the wireless communication scenario [22], [38].

Each reflecting element within the IRS adjusts the phase of the incoming signal. By skillfully altering the phase of the reflected waves, the IRS can create constructive interference, effectively strengthening the signal at the intended receiver. One of the key functionalities of IRS is also beamforming. The IRS can concentrate the reflected signals into tightly focused beams directed toward the receiver. This beamforming capability significantly boosts the signal power and quality at the desired location. Further, IRS systems are designed to adapt dynamically to changing conditions [33], [36]. They can continuously optimize the phase shifts and beamforming based on real-time factors such as user mobility, channel characteristics, and network requirements. This adaptability ensures efficient signal enhancement in varying scenarios.

IRS mitigates signal loss, attenuation, and multipath fading, leading to higher data rates and improved connectivity of the wireless networks. By enhancing signal strength and quality, IRS reduces the need for high-power transmissions, resulting in lower energy consumption and reduced environmental impact [38]. The precise control over signal directionality by IRS enhances privacy and security

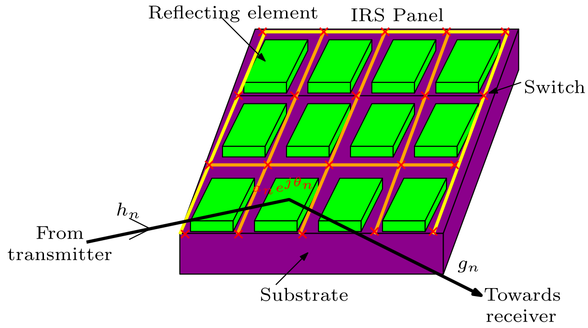

FIGURE 2. IRS panel with composed by an array of passive reflective elements.

by minimizing signal leakage and reducing interference in a wireless network [28], [36], [37].

IRS structure is shown in Fig. 2, consisting of an array of passive reflective elements. These elements are interconnected through switches, as illustrated in Fig. 2. The reflective elements are designed on the substrate. Each nth reflecting element can be modeled as $a_n e^{j\theta_n}$, where a_n represents the reflection amplitude, and θ_n is the phase of the nth element. The incoming and outgoing signal channels are denoted as h_n and g_n at the nth element, respectively. The cascaded response y_n between the transmitter and receiver via the IRS element is given as [42] and [36]

$$y_n = \left(h_n[a_n e^{j\theta_n}]g_n\right) x = [h_n g_n a_n e^{j\theta_n}]x, \tag{4}$$

where x denotes the transmitted signal. If IRS panel consists of total N reflecting elements, the received signal is expressed as

$$y = \sum_{n=1}^{N} y_n = \sum_{n=1}^{N} \left(h_n[a_n e^{j\theta_n}]g_n\right) x = \sum_{n=1}^{N} [h_n g_n a_n e^{j\theta_n}]x + w. \tag{5}$$

Here w represents AWGN. In the matrix form y is expressed as

$$y = \mathbf{g}^T \Theta \mathbf{h} x, \tag{6}$$

where $\mathbf{g} = [g_1, g_2, \ldots, g_N]^T$ and $\mathbf{h} = [h_1, h_2, \ldots, h_N]^T$ denote the channel response between IRS-UE and BS-IRS, respectively. The Θ is the IRS diagonal matrix and generated using vector $\theta = [a_1 e^{j\theta_1}, a_2 e^{j\theta_2}, \ldots, a_N e^{j\theta_N}]^T$ as $\Theta = \text{diag}[\theta]$, where vector elements are arranged in the diagonal of the matrix.

For perfect (optimized) phase setting, (6) can be written as

$$y = \left(\sum_{n=1}^{N} a_n |h_n||g_n|\right) x + w. \tag{7}$$

However, because of hardware constraints, the phases of the reflectors can only assume a finite number of discrete values, making perfect phase cancellation unattainable [54]. In such scenarios, the phase error $\tilde{\theta}_n$ for the nth reflector can be represented as the deviation of the optimal phase from its quantized counterpart. Consequently, in the presence of phase errors, (7) can be further refined as

$$y=\left(\sum_{n=1}^{N}a_n|h_n||g_n|e^{j\tilde{\theta}_n}\right)x+w.$$

Thus, in imperfect phase setting, IRS-aided system performance degrades due to reduced signal strength [54].

V. COOPERATIVE COMMUNICATION

In this section OMA, NOMA, and MIMO based cooperative communication is discussed.

A. COOPERATIVE OMA

Cooperative OMA (COMA) communication is a promising approach in wireless networking that combines the principles of cooperative communication with OMA techniques. In cooperative OMA, multiple users within a network collaborate to transmit their data efficiently, but they do so using orthogonal resource allocations [6], [18], [43], [44], [55].

One of the key advantages of cooperative OMA is its simplicity and compatibility with existing OMA methods like time division multiple access (TDMA) and frequency division multiple access (FDMA). Users in cooperative OMA networks can be assigned specific time slots or frequency bands, ensuring that they do not interfere with one another during transmission. This leads to straightforward signal separation at the receiver, simplifying the decoding process [44], [56], [57].

Cooperative techniques, such as relaying, can be seamlessly integrated into cooperative OMA networks, as shown in Fig. 1. Relay nodes assist in forwarding data from the source to the destination, extending coverage and mitigating fading effects. This collaborative aspect enhances the reliability and reach of the wireless network [58], [59].

Cooperative OMA is well-suited for scenarios where maintaining strict orthogonality between users is crucial, such as in scenarios with stringent QoS requirements or when interference management is a primary concern. However, it may not fully exploit the spectral efficiency gains achievable with non-orthogonal techniques like NOMA [48], [60]. Consequently, choosing between cooperative OMA and other multiple access strategies depends on the specific requirements and constraints of the wireless communication environment. Nonetheless, cooperative OMA continues to be an area of active research, offering valuable insights into optimizing the trade-offs between simplicity, orthogonality, and spectral efficiency in wireless networks [61], [62].

B. COOPERATIVE NOMA (CNOMA)

NOMA fundamentally departs from the traditional OMA by allowing multiple users to share the same time-frequency resources simultaneously [16], [53], [63], [64]. It achieves this by allocating distinct power levels or codebooks to individual users, enabling them to transmit and decode their signals with varying degrees of reliability [15]. The concept of SIC plays a pivotal role, as users with strong signals can decode and remove interference from weaker signals, thereby coexisting in the same resource block.

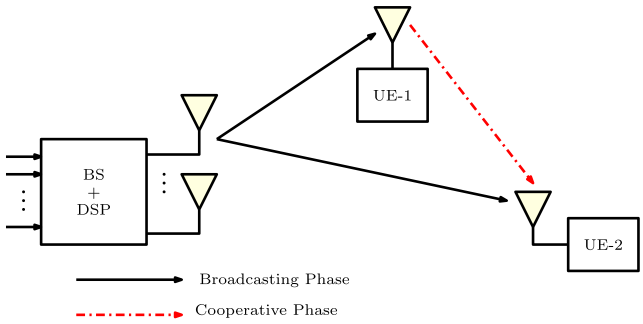

FIGURE 3. Cooperative NOMA communication system model.

In the literature [47], [65], [66], and [16], CNOMA systems have been analyzed in various scenarios. Additionally, MIMO-based CNOMA systems have been considered for analyzing multiple users [41]. Furthermore, IRS-assisted CNOMA has been studied to enhance system throughput, coverage, and power efficiency in the literature [3], [7], [37], and [29]. In [23] a double cooperative-IRS-assisted uplink NOMA system is investigated that incorporates inter-IRS reflections.

CNOMA communication system model is shown in Fig. 3, where UE-1 and UE-2 are communicating using NOMA and cooperative protocols. BS broadcast both users information with different power levels is $(\sqrt{P_1}x_1+\sqrt{P_2}x_2)$, where P_1 and P_2 are the power assigned to UE-1 and UE-2, respectively.

Furthermore, in the CNOMA system, UE-1 operates in half-duplex mode, decoding and forwarding signals. As a result, the received signals at UE-1 can be represented as,

$$y_1=h_1\sqrt{P_1}x_1+h_1\sqrt{P_2}x_2+n_1. \tag{8}$$

Initially, UE-1 decodes UE-2's information and transmits it to UE-2 through a cooperative channel h_c with power P_c. Further, UE-1 applies SIC based signal detection to decode own information symbol x_1. Moreover, UE-2 receives signals from both the BS and UE-1, contributing to an enhancement in UE-2's overall performance and UE-2 received signals are expressed as,

$$y_2=h_2\sqrt{P_1}x_1+h_2\sqrt{P_2}x_2+n_2,\ \tilde{y}_2=h_c\sqrt{P_c}\hat{x}_2+n_2. \tag{9}$$

Signals y_2 and $\tilde{y}_2$ are combined to decode the information symbol x_2 at the UE-2. Thus, it is evident that UE-2 diversity increases using the CNOMA concept unlike conventional NOMA system.

1) FUNDAMENTALS OF NOMA SYSTEM

NOMA is an innovative communication system that departs from the traditional orthogonal access methods. What sets NOMA apart is its ability to distinguish users based on

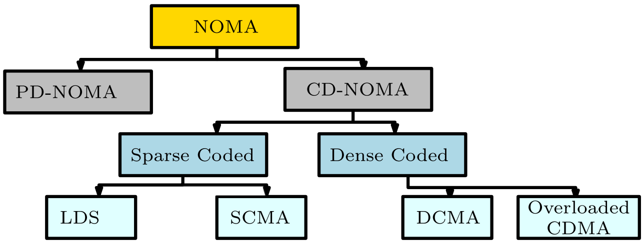

FIGURE 4. **Classification of NOMA schemes.**

power allocation and code-domain multiplexing, allowing for different power levels and code assignments for each user within the same resource block [67]. This diversity in resource allocation enables improved spectral efficiency, higher capacity, and enhanced connectivity in wireless networks, making NOMA a promising technology for next-generation communication systems like 5G and beyond. Different NOMA system's classification is shown in Fig. 4. NOMA mainly classified into two groups: power domain NOMA (PD-NOMA) and code domain NOMA (CD-NOMA). Further, CD-NOMA is divided into sparse (low density spreading (LDS) and sparse code multiple access (SCMA)-based CD-NOMA) and dense coded (dense coded multiple access (DCMA) and overloaded code division multiple access (CDMA)-based CD-NOMA systems, as shown in Fig. 4.

Downlink and uplink NOMA systems are shown in Fig. 5 and Fig. 6, respectively by considering two users: far user (FU) and near user (NU). However, multiple users can communicate in NOMA by using multiple resources and clusters. In downlink scenario, SIC is used at the NU since it has channel gain $|h_1|^2 \gg |h_2|^2$. FU information is decoded using maximum likelihood detector and subtracted from the received signal in SIC-based receiver, as shown in Fig. 5. However, FU directly decoded its information form the received signal $(h_2\sqrt{P_1}x_1 + h_2\sqrt{P_2}x_2)$ by considering NU signal as interference.

In an uplink NOMA system, users simultaneously transmit their signals with distinct transmit power levels within the same time and frequency allocation. The BS employs SIC to decode the stronger user or NU signals, and the information from the weaker user or FU is decoded after subtracting the detected NU symbols from the received signal $(y = \sqrt{P_1}h_1x_1 + \sqrt{P_2}h_2x_2)$, as sown in Fig. 6.

Next, we briefly discuss about Underlay, Overlay, and precoded spatial modulation (PSM)-aided CNOMA system in subsequent subsections.

2) UNDERLAY COOPERATIVE NOMA

An underlay communication system is a wireless communication approach that enables secondary users to operate in the presence of primary users while ensuring minimal interference to the primary users' transmissions. This technique is commonly used in CR networks, where secondary users take advantage of the available spectrum white spaces without causing harmful interference [60], [65]. Underlay systems employ advanced interference mitigation techniques and dynamic spectrum access policies to coexist with primary users gracefully. This approach allows for efficient spectrum utilization and improved overall network performance, making it particularly valuable for maximizing the utilization of scarce radio spectrum resources [60].

An illustration of underlay NOMA networks is presented in Fig. 7. In this configuration, a secondary transmitter (ST) serves multiple secondary receivers (SRs) through NOMA signaling, provided that the interference experienced by the primary receiver (PR) remains manageable. In contrast to underlay OMA networks, underlay NOMA networks offer more efficient spectrum utilization. This efficiency stems from the use of NOMA within the secondary network, enabling multiple SRs to simultaneously receive distinct signals within the same shared spectrum. This approach enhances SR connectivity and achieves high throughput for secondary access [65], [66]. Further, PR is getting signal form the direct link and reflecting links (from IRS and Relay), as shown in Fig. 7. IRS panel is optimized for the PU while relay amplify both PU and SUs signal in the system, as observed in Fig. 7.

Conversely, in underlay OMA networks, only one SR is permitted to transmit at a time, requiring other SRs to wait until the ongoing transmission concludes (essentially utilizing the spectrum in a sequential manner). When compared to traditional NOMA networks, underlay NOMA networks encounter the added challenge of stricter interference management [9], [66].

Underlay NOMA systems have their own set of advantages and disadvantages, which depend on the specific application and network conditions [65], [66]. Here are some key advantages and disadvantages of underlay NOMA:

Advantages of Underlay NOMA:

- Underlay NOMA allows multiple users to share the same spectrum resources simultaneously, which results in enhanced spectrum efficiency compared to conventional OMA systems, where users must take turns to transmit [65], [66].
- Underlay NOMA can support a larger number of users in a given bandwidth, making it suitable for higher user density and increased capacity requirements communication scenarios.
- The simultaneous transmission of multiple users in underlay NOMA can result in lower latency, which have some applications in IoT devices [66].
- Underlay NOMA can connect more users, including those at the cell-edge or in challenging signal environments, improving overall network coverage [65] of a system.

Disadvantages of Underlay NOMA:

- Underlay NOMA bring it inter-user interference, which can be challenging to mitigate. Users need to employ advanced signal processing techniques to decode signals effectively in the presence of interference.

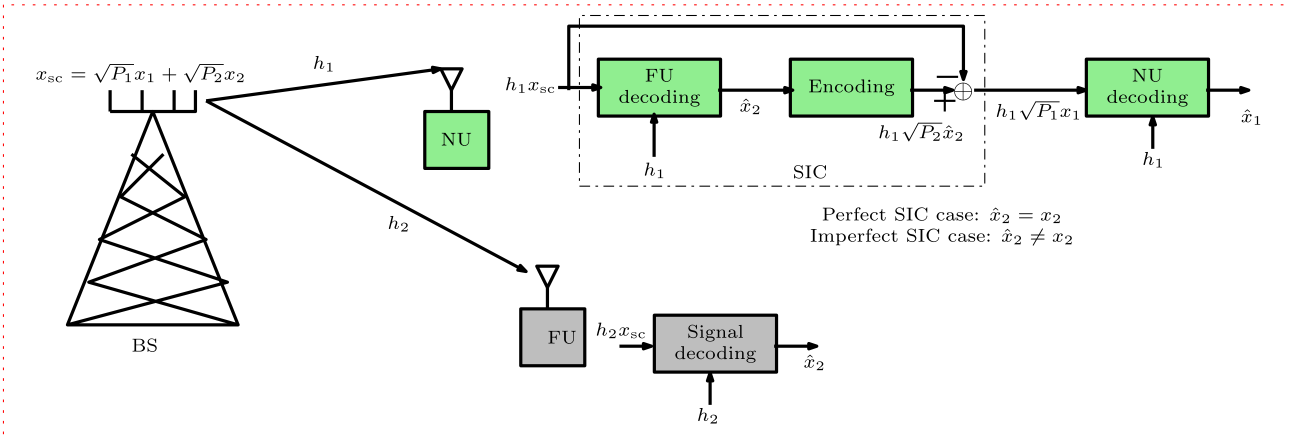

FIGURE 5. Downlink NOMA system.

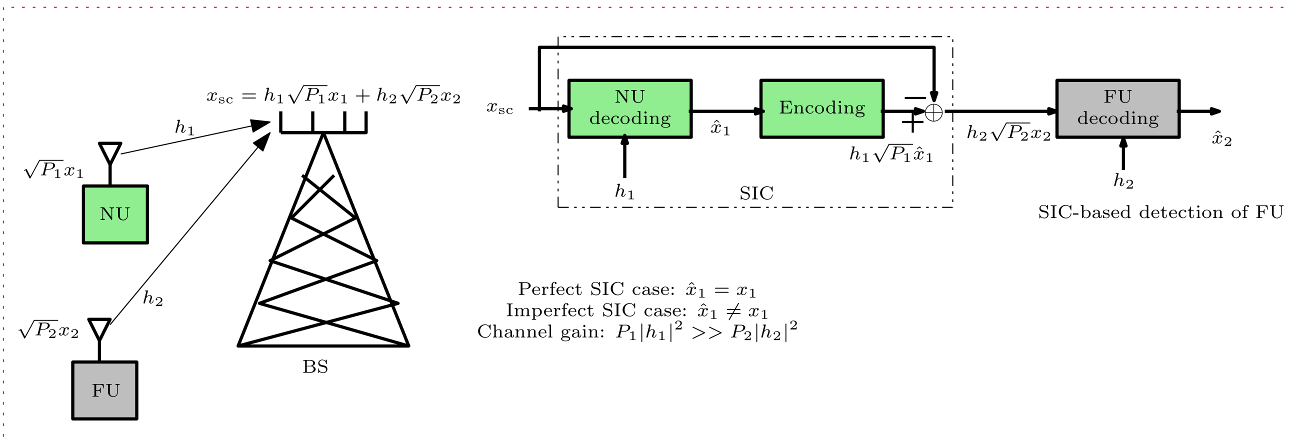

FIGURE 6. Uplink NOMA system.

- Implementing underlay NOMA can be more complex than traditional OMA systems, both in terms of hardware and signal processing. This complexity can increase the cost of network deployment and maintenance.
- Underlay NOMA performance is highly affected by channel conditions and user locations. Sub-optimal channel conditions may lead to reduced gains from NOMA, and careful power control and resource allocation are required in CNOMA.
- Efficient allocation of resources (power, bandwidth, etc.) is critical in underlay NOMA systems to maximize performance at relay, IRS, ST, and PT nodes. Improper resource allocation can lead to suboptimal results.

The choice to adopt underlay NOMA should consider the specific requirements and trade-offs of the intended application and network environment. Further, multiple IRS and relays can be considered in the underlay NOMA system to improve the overall system efficiency. Recently, many research article have focused on IRS assisted underlay NOMA system for the next-generation wireless networks.

3) OVERLAY COOPERATIVE NOMA

The depiction of overlay NOMA networks can be observed in Fig 8 and Fig 9. In this scenario, a ST assists in relaying a PT's signal to a PR while concurrently transmitting its signals to multiple SRs using NOMA principles. The NOMA-enabled spectrum sharing protocol is outlined as follows [68], [69]: In the initial time slot, the PT and ST transmit their signals to the PR and SRs, which are also received by relays. During the subsequent time slot, the relay regenerates the primary and secondary signals and combines them with its own signals using NOMA techniques. Subsequently, the relay transmits this amalgamated signal to both the PR and SRs. In Fig. 8, the PR also receives a signal via an IRS link. Therefore, the PR combines the links suitably to decode the primary transmitted signal. In overlay CNOMA, the relay uses SIC principle to re-transmit the PT and ST signals to their PR and SRs. Thus, system design and optimization are more challenging.

In comparison to traditional NOMA setups, overlay NOMA entails additional complexities in managing inter-network interference [68], [69]. Specifically, since the PR receives the primary signal in both time slots, it treats

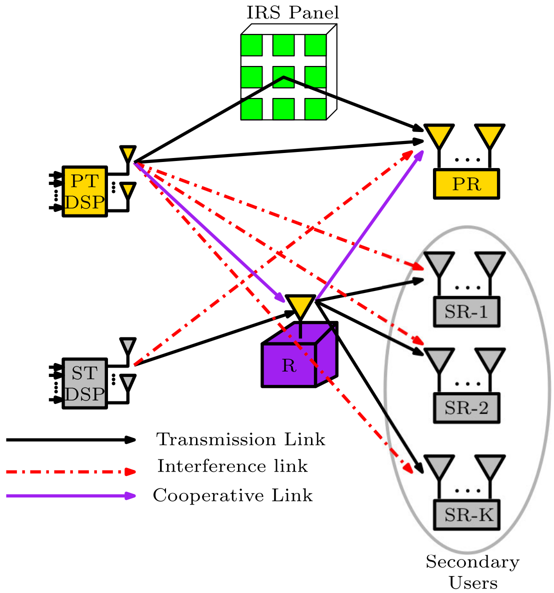

FIGURE 7. Underlay cooperative NOMA communication system model [65], [66].

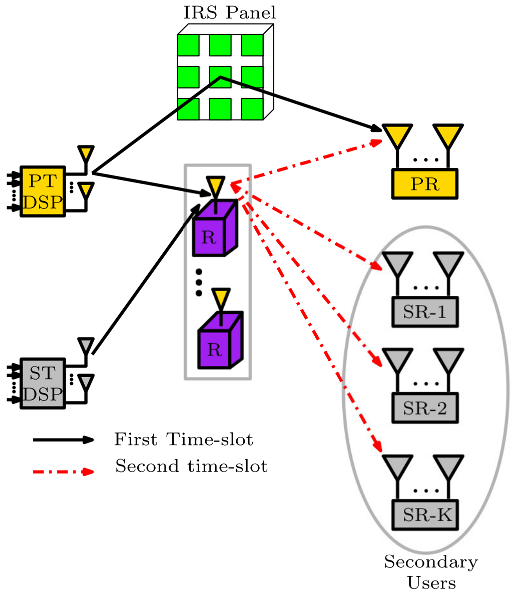

FIGURE 8. Overlay cooperative NOMA communication system model [68], [69].

secondary signals as noise and deciphers the primary signal through MRC. At an SR, the process involves initially decoding the primary signal through MRC and then utilizing SIC to sequentially decode secondary signals until its own signal is retrieved. Overlay NOMA systems offer unique advantages and disadvantages, which can vary depending on the specific application and network conditions [68], [69]. Here are some key advantages and disadvantages:

Advantages of Overlay NOMA:

- Overlay NOMA allows multiple users to share the same frequency resources by multiplexing them in the power domain. This enables more efficient utilization of the available spectrum, leading to higher spectral efficiency compared to traditional OMA schemes. [68], [69].
- Overlay NOMA enables multiple users to access the wireless channel simultaneously, even if they are experiencing different channel conditions. By assigning different power levels to users based on their channel conditions, overlay NOMA can accommodate multiple users within the same frequency band without requiring OMA.
- Users in overlay NOMA systems can achieve higher data rates due to concurrent transmission. This can lead to improved network performance and user experience [68], [69].

Disadvantages of Overlay NOMA:

- Overlay NOMA introduces inter-user interference, which must be carefully managed to avoid performance degradation. Decoding interference from other users can be complex and may require advanced signal processing techniques.
- Implementing overlay NOMA can be more complex than traditional OMA systems, both in terms of hardware and signal processing. This complexity can increase the cost of network deployment and maintenance.
- Overlay NOMA performance is highly dependent on channel conditions and user locations. Suboptimal channel conditions may lead to reduced gains from NOMA, and careful power control and resource allocation are required.
- IRS optimization is essential since it can significantly enhance both PR and SR signals. If IRS panel uses only for PR optimization, it is easy to manage IRS. However, it is complex if to use IRS for both PR and SR in the overlay CNOMA system design.

4) PRECODED SPATIAL MODULATION (PSM)-AIDED CNOMA

The PSM emerges as a technique offering substantial advantages in boosting spectral efficiency while upholding low costs and receiver complexity [48]. The core principle behind PSM involves transmitting information not solely through constellation points but also via the indices of the receiving antennas (RAs) or transmitting antennas (TAs) [10], [48]. PSM facilitates higher data transmission rates and can be seamlessly integrated with NOMA to enhance both total data rate and average symbol error rate (SER) performance [10], [48], and [10]. Moreover, ongoing research explores the amalgamation of spatial modulation with code-domain NOMA to further augment spectral efficiency.

SM provides spatial gain using a single RF chain with improved energy efficiency, reduced detection complexity with fewer receive antennas and simpler RF circuits; elimination of inter-channel interference; elimination of the need for inter-antenna synchronization; compatibility with

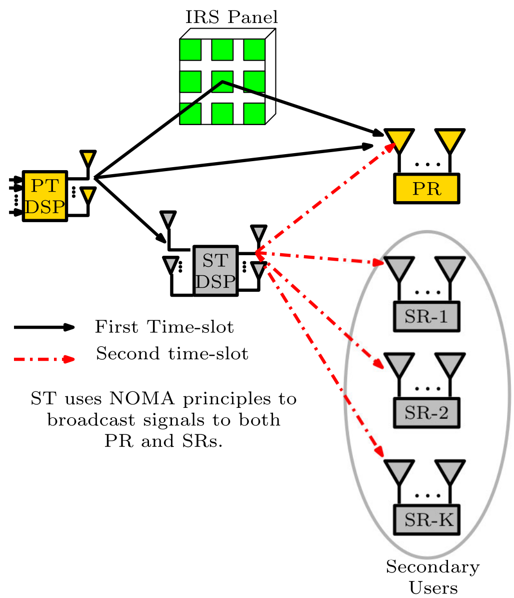

FIGURE 9. Overlay cooperative NOMA communication system model [68], [69].

massive MIMO configurations. For example, If BS has $N_t = 4$ antennas, PSM can use only one active antenna at a time to transmit the information symbol. Thus, data rate of system can be expressed as

$$\text{data rate} = \underbrace{\log_2(N_t)}_{\text{spatial bits}} + \log_2(M_d) \quad \text{bits per sec/channel}$$

Here, M_d is the modulation order. Thus, PSM transmits $\log_2(N_t)$ extra bits (2 bits for $N_t = 4$) using the antenna selection. System uses only single RF chain so power consumption or complexity will not increase. PSM-aided CNOMA uses both NOMA and PSM schemes thus having befits of both the systems. Thus, PSM-CNOMA increases data rate and reliability of the far user in the system [10], [48].

In PSM-aided CNOMA (PC-NOMA) is tailored for downlink MIMO transmissions in Fig. 10 [10], [48]. PC-NOMA involves two distinct time phases: the broadcast phase and the cooperative phase. Additionally, we assume that two users operate in close proximity to the BS in half-duplex mode, while the third user is positioned farther from the BS, leading to no direct link between them, as illustrated in in Fig. 10. During the "odd" time slot, the BS transmits precoded superposition symbols to user $\mathcal{U}_1$ as $\mathbf{x}_1 = [\underbrace{0,\ldots,0}_{(j-1)\text{zeros}}, \mathcal{S}_1, \underbrace{0,\ldots,0}_{(N_r-j)\text{zeros}}]^T \in \mathbb{C}^{N_r\times 1}$. Simultaneously, user $\mathcal{U}_2$ acts as a relay in cooperative mode, decoding signals from the previous time slot and relaying them to user $\mathcal{U}_3$.

User $\mathcal{U}_1$ transmits information by modulating the index and constellation points of receive antennas (RA). In this procedure, the initial segment of information bits selects the active RA index, while the remaining bits get assigned to modulated symbols. The signal $\mathcal{S}_1$ represents the composite signal of users $\mathcal{U}_1$ and $\mathcal{U}_3$ and comprises two elements: $\sqrt{\alpha_1 P_B}x_1$ from user $\mathcal{U}_1$, linked with constellation $\mathcal{X}_1$ and allocated power coefficient α_1, and $\sqrt{\alpha_3 P_B}x_3$ from user $\mathcal{U}_3$, linked with constellation $\mathcal{X}_3$ and assigned power coefficient α_2. These elements correspond to the modulated symbols transmitted by $\mathcal{U}_1$ and $\mathcal{U}_3$, respectively. The PB signifies the total power available at the BS. Similarly, during the "even" time slot, user $\mathcal{U}_2$ transmits $\mathbf{x}_2 = [\underbrace{0,\ldots,0}_{(j-1)\text{zeros}}, \mathcal{S}_2, \underbrace{0,\ldots,0}_{(N_r-j)\text{zeros}}]^T \in \mathbb{C}^{N_r\times 1}$, where $\mathcal{S}_2$ denotes the composite signal of users $\mathcal{U}_2$ and $\mathcal{U}_3$ [48].

Within the IM-aided NOMA (I-NOMA) framework [70], a BS utilizes the IRS to deliver information to three users. Among these users, the initial user is designated within the spatial domain, whereas the two others are multiplexed employing PD-NOMA, as shown in Fig. 11 [70].

User-1, identified as $\mathcal{U}_1$, transmits data at a rate of $\log_2(N\text{t})$ bits per symbol. The index of its TA is represented using the following equation [70]:

$$\mathbf{x}_1 = [\underbrace{0,\ldots,0}_{(t-1)}, 1, \underbrace{0,\ldots 0}_{(N_t-t)}]^T. \tag{10}$$

NOMA users $\mathcal{U}_2$ and $\mathcal{U}_3$ both transmit data at a rate of $\log_2(\text{M})$, where M represents the modulation order. These transmissions occur through the shared TA activated by $\mathcal{U}_1$. Consequently, the combined signal can be expressed as [70]:

$$\mathbf{x} = [\underbrace{0,\ldots,0}_{(t-1)}, \mathcal{S}, \underbrace{0,\ldots 0}_{(N_t-t)}]^T, \in \mathbb{C}^{N_t\times 1} \tag{11}$$

The expression for $\mathcal{S} = \sqrt{a_1 \text{P}_b}x_2 + \sqrt{a_2 \text{P}_b}x_3$ where x_2 belongs to the set $\mathcal{X}_2$ and x_3 belongs to the set $\mathcal{X}_3$. Furthermore, three users are decoded using the maximum likelihood function. One of the primary benefits of I-NOMA lies in its user detection simplicity, stemming from direct spatial index demodulation and receivers based on SIC [20].

Some practical advantages of IM-based CNOMA are summarized as 1) IM-based CNOMA can achieve higher spectral efficiency compared to traditional OMA schemes [71]. This is because multiple users can be served simultaneously on the same frequency resources, thereby increasing the overall system throughput. 2) The use of IM allows for additional redundancy in the transmission, which can enhance the reliability of the system, especially in challenging wireless environments with fading channels and interference. 3) IM-based CNOMA provides flexibility in resource allocation, allowing for adaptive adjustment of transmission parameters such as power allocation, user grouping, and modulation schemes based on channel conditions and system requirements.

Some practical challenges in IM-based CNOMA are higher complexity in decoding due to multiple users, modulation, and antenna index. Estimating the channel state information (CSI) for multiple users and antennas, especially in fast-fading channels, poses a significant challenge and requires efficient feedback mechanisms in IM-based NOMA. Further, the performance of a practical MIMO system may

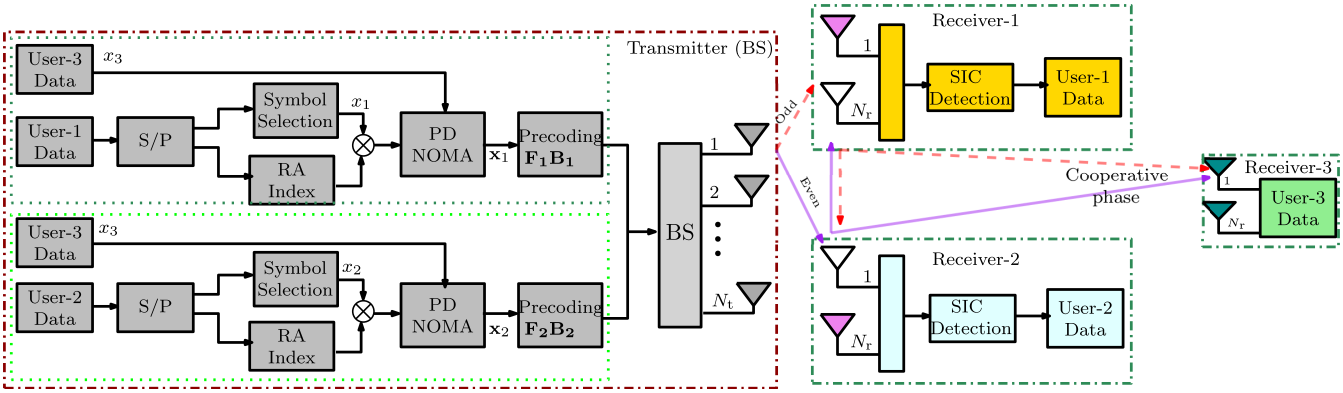

FIGURE 10. PC SM cooperative NOMA communication system model [48].

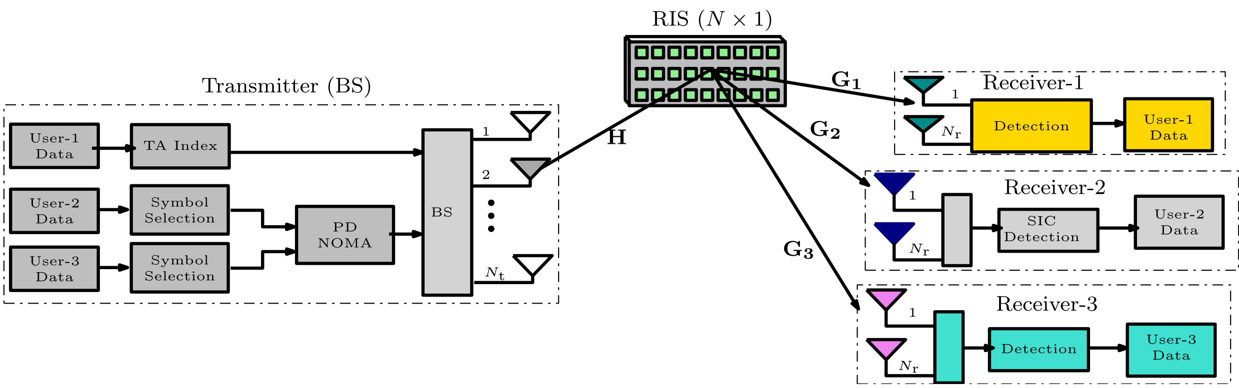

FIGURE 11. SM NOMA communication system model [20].

be limited by hardware constraints, such as antenna spacing, RF chain complexity, and power amplifier efficiency.

C. COOPERATIVE MIMO SYSTEMS

Cooperative MIMO communication represents a sophisticated and innovative approach to wireless networking. At its core, cooperative MIMO harnesses the power of multiple antennas, both at the transmitter and receiver sides [2], [45], to improve the performance and reliability of wireless communication systems.

In a cooperative MIMO system, multiple transmitters and receivers cooperate to create spatial diversity, where signals are transmitted simultaneously over different spatial dimensions [70]. This diversity enhances signal quality and reduces the effects of fading, resulting in improved coverage and robustness. Relay nodes, often strategically positioned to extend the communication range, play a crucial role in cooperative MIMO networks. These relay nodes assist in forwarding signals from the source to the destination, effectively acting as signal boosters and mitigating signal degradation over long distances or in challenging environments [70].

One of the fundamental advantages of cooperative MIMO is its ability to offer significant gains in spectral efficiency and data rate [48], [70]. By exploiting the spatial dimension, multiple data streams can be transmitted simultaneously without causing interference. This capability makes cooperative MIMO an ideal candidate for scenarios demanding high data rates, such as video streaming, augmented reality, and massive machine-type communications [72], [73]. Further, MIMO assisted cooperative systems can be extended as [70] and [48].

Hybrid MIMO-Relay Systems: Combining MIMO techniques with relaying offers a hybrid approach that can exploit both spatial diversity and cooperative gains.

Coordinated Multi-Point (CoMP) Transmission: CoMP is a technique that coordinates the transmission and reception across multiple BSs or APs, allowing for joint processing and interference management.

Collaborative Beamforming: Cooperative MIMO systems can employ beamforming techniques to enhance signal strength and reduce interference [10]. Beamforming aligns the transmitted signals in specific directions for optimal reception.

Space-Time Coding: Space-time coding techniques enable multiple antennas at both the transmitter and receiver to improve the diversity and coding gain of cooperative MIMO systems [74]. Alamouti coding is a well-known example. Finding the optimal number of users is essential in NOMA, CNOMA, and MIMO-based CNOMA systems due to the non-orthogonality among users.

Apart from the advantages of MIMO-CNOMA, it also faces some challenges in practical deployment due to multiple channel estimations, synchronization, MIMO-based signal detection algorithms, and complex SIC at multiple users.

The connection between IRS-aided CNOMA systems and MIMO technology lies in their combined potential to improve spectral efficiency, coverage, and reliability in wireless networks. MIMO and IRS-NOMA systems can employ spatial beamforming techniques to focus transmitted energy towards the intended receivers and suppress interference from other directions to enhance signal strength. Thus joint benefits of these technologies offer significant gains in next-generation wireless communications.

VI. IRS-ASSISTED COOPERATIVE COMMUNICATION

Cooperative communication, particularly when integrated with IRS, has the potential to revolutionize wireless networks. This synergy is apparent in both OMA and NOMA communication scenarios [3], [13].

In COMA, users within the network collaborate by sharing orthogonal time-frequency resources. These resources are optimally allocated to maximize the efficiency of data transmission. The addition of IRS further enhances the cooperative aspect. Dynamic beamforming capability augments the signal strength and mitigates interference, making COMA with IRS a promising solution for high-capacity and reliable communication systems [24], [36].

Similarly, in CNOMA, where users share the same time-frequency resources using power-domain multiplexing, the introduction of IRS offers intriguing possibilities. By leveraging NOMA's power allocation and SIC, users with distinct quality-of-service requirements can coexist harmoniously. IRS, with its beamforming and signal enhancement capabilities, plays a pivotal role in ensuring that signals reach their intended recipients with minimal interference. This cooperative synergy between NOMA and IRS holds the potential to meet the diverse communication needs of future networks [9], [24], [36].

In both cases, COMA and NOMA communication assisted by IRS promise to elevate the performance, capacity, and reliability of wireless networks. As these technologies continue to evolve, they hold the key to unlocking the full potential of next-generation communication systems, from 6G networks to the IoT and beyond.

Integrating IRS into CNOMA systems yields a multitude of benefits, revolutionizing the landscape of wireless communication. First and foremost, IRS dramatically enhances spectral efficiency. By intelligently manipulating signal paths, IRS enables simultaneous communication between multiple users over the same frequency resources, making more efficient use of the available spectrum. This optimization significantly increases the overall system capacity.

Secondly, IRS contributes to substantial improvements in signal quality and coverage. By actively shaping and

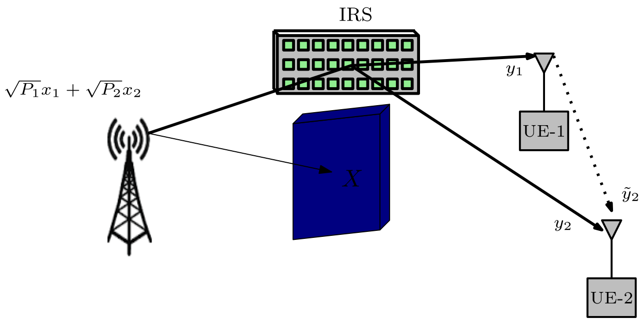

FIGURE 12. IRS-aided cooperative NOMA system.

redirecting electromagnetic waves, it mitigates signal blockages and shadowing, providing more robust and reliable connections, especially in challenging urban or indoor environments [9], [24], [36]..

Energy efficiency is another key advantage. IRS reduces the power consumption of user devices by optimizing signal strength, which not only extends the lifespan of battery-powered devices but also reduces the overall carbon footprint of wireless networks [42], [75]. Furthermore, IRS-assisted CNOMA enhances system security. By controlling signal propagation, it limits signal leakage and improves privacy, making it more challenging for eavesdroppers to intercept or decode sensitive information.

Additionally, IRS empowers resource allocation and interference management. It allows for precise control over resource allocation, dynamically adapting to changing channel conditions and user requirements. Moreover, IRS mitigates interference, resulting in fewer collisions and retransmissions, ultimately reducing network congestion and latency [28].

The Fig. 12 depicts the CNOMA system aided by the IRS, considering a blocked direct path between the BS and users. This blockage can result from large-scale fading or obstacles obstructing the transmission between the BS and users. Additionally, Fig. 13 illustrates the CNOMA system block diagram involving multiple IRS. In Fig. 13, the direct path between the BS and users is also accounted for, based on the specific application scenario of the communication system. The superimposed signal of two users is initially transmitted from the BS to users in the first phase. Subsequently, the decoded signal of UE-2, obtained after SIC, is retransmitted from UE-1 to UE-2 in the second phase (depicted by dotted lines) as shown in both Fig. 12 and Fig. 13.

Ir expects better performance in the scenario depicted in Fig. 13 compared to that in Fig. 12 due to multiple IRS and direct paths. However, the complexity in the scenario in Fig. 13 is higher due to complex signal processing and IRS phase optimization.

Recent research has explored the use of double-IRS or multiple IRS-assisted wireless communications. While deploying multiple IRSs in a wireless link may introduce multiplicative path loss, a large number of IRS reflection

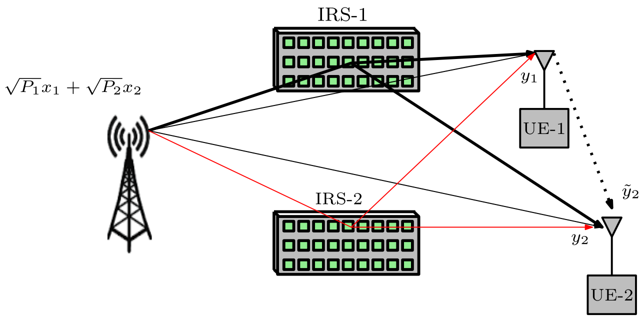

FIGURE 13. Multiple IRS-aided cooperative NOMA system.

elements can compensate for this loss by properly adjusting the reflection amplitudes and/or phases. Moreover, the deployment strategies of IRS are significant for minimizing the product-distance path loss over the multiple IRS-assisted links [76]. Contrast, the deployment of double/multiple-IRS systems is more flexible and can be tailored to various requirements, such as bypassing obstacles to expand coverage, improving channel rank conditions, suppressing interference, and enhancing physical layer security. Given the advantages of IRS technology, double-IRS or even multi-IRS configurations are more suitable for enhancing the cooperative communication environment.

By strategically deploying IRS elements, the CNOMA can mitigate interference, optimize resource allocation, and enable simultaneous access to the wireless channel by multiple users. This increases the overall throughput and spectral efficiency of the system, allowing it to accommodate more users and transmit more data within the available bandwidth. Further, a summary of IRS-CNOMA is given in Table 3.

Some practical limitations of IRS-aided CNOMA are 1) Limited hardware capabilities, such as the finite number of discrete values for reflector phases. This can hinder perfect phase cancellation and optimal signal manipulation by the IRS. 2) Accurate channel estimation becomes challenging or more complex due to the large number of reflecting elements in IRS. 3) Optimizing power allocation among users and relay nodes while considering the dynamic nature of the network and varying wireless channel conditions poses a significant challenge. 4) Joint optimization of active and passive beamforming strategies requires sophisticated algorithms to coordinate beamforming between transmitters, relays, and IRS elements effectively. Addressing these practical challenges requires innovative solutions in system design, algorithm development, and network optimization to realize the full potential of IRS-aided CNOMA systems in practical deployments [77], [78].

Managing the system design and optimization complexities of overlay NOMA requires innovative approaches in signal processing algorithms and hardware enhancements. Develop optimization algorithms for resource allocation, power control, user pairing, and interference management in overlay NOMA using artificial intelligence techniques based on dynamic channel conditions and user requirements. Further, the CoMP techniques can be used to mitigate interference and improve the performance of overlay NOMA systems. CoMP enables coordinated signal transmission and reception across multiple BSs or APs, enhancing system coverage, capacity, and reliability.

VII. RESOURCE ALLOCATION AND OPTIMIZATION

Resource allocation strategies play a pivotal role in the success of CNOMA. In CNOMA, several resource allocation approaches are employed to optimize system performance [28], [40]. Power allocation, where users receive different power levels based on their channel conditions, is a fundamental strategy. Additionally, code-domain allocation leverages superposition coding to enable multiple users to share the same resource, using distinct encoding schemes. User clustering groups users with similar channel conditions, allowing for tailored resource allocation within each cluster [8], [40], [43]. Cooperative relaying introduces the concept of strong users aiding weaker ones, thus enhancing overall system efficiency. SIC further refines resource allocation, enabling interference reduction. Dynamic allocation, coupled with optimization algorithms, adapts resources based on real-time conditions. QoS constraints ensure that user-specific requirements are met, while the availability of precise CSI is crucial. These strategies collectively empower CNOMA to enhance spectral efficiency, promote user fairness, and achieve superior performance in wireless communication systems.

Channel estimation in cooperative IRS-assisted NOMA is a critical component in enabling the seamless operation of this cutting-edge communication paradigm [52]. This process takes accurately assessing the dynamic channel conditions between users, reflecting surfaces, and BSs. With IRS elements strategically placed to manipulate signals, precise channel knowledge is predominant. Channel estimation in IRS-aided CNOMA presents unique challenges and opportunities. Traditional techniques for estimating users-to-BS channels may need to be adapted to account for the impact of IRS on signal propagation. Advanced algorithms, often based on ML/DL, are employed to capture the dynamic interactions of signals with IRS elements and users. Accurate channel estimation in IRS-assisted NOMA enhances the system's ability to optimize resource allocation, power control, and interference management among users [25]. It enables the IRS to intelligently reflect signals, mitigating interference and enhancing signal quality.

Efficient channel assignment involves allocating available frequency bands to users or clusters of users in a manner that minimizes interference and maximizes spectral efficiency. Thus, dynamic channel assignment algorithms should be utilized in IRS CNOMA based on changing network conditions and user requirements such as data rate and QoS. Further, by forming users' clusters, resources such as transmit power

TABLE 3. Summary of IRS-aided CNOMA systems.

Reference	Technology	BER	Sum-rate	OP	Channel model	Advantages
[13]	IRS-NOMA	–	✓	–	Rician and Rayleigh fading	Sum-rate of secondary users is maximized by optimizing phase shifts within an IRS-enabled co-operative NOMA framework with beamforming.
[23]	IRS-NOMA	–	✓	–	Rician fading	Double cooperative-IRS-assisted NOMA
[36]	IRS-NOMA	–	✓	–	Rayleigh fading	Cooperative jamming, Physical layer security
[51]	IRS-CNOMA	–	✓	–	Rician fading	Transmit power optimization
[14]	IRS-CNOMA	–	✓	✓	Rayleigh fading	Closed from OP analysis
[24]	IRS-NOMA	–	✓	–	Rayleigh fading	Optimize the beamforming vectors and the IRS phase shift matrix to minimize transmit power
[9]	IRS-CNOMA	–	✓	✓	Rician fading	Closed-form expressions of OP, Deep learning

and bandwidth can be allocated more effectively, enabling cooperative NOMA transmission within each cluster [20].

IRS phase optimization is crucial to enhance a system's performance. By adjusting the phase and magnitude of reflected signals, IRS elements can optimize signal coverage, mitigate interference, and maximize received signal strength at user terminals in the IRS-aided CNOMA system. Moreover, joint optimization of active and passive beamforming strategies allows for coordinated beamforming between the transmitter, relay nodes, and IRS elements. By jointly designing beamforming vectors, both active transmitters and passive reflecting elements can collaboratively focus energy toward desired receivers while suppressing interference.

Optimal time phase allocation ensures efficient utilization of available time resources, minimizes transmission delays, and maximizes system throughput. For time phase allocation, channel quality and user requirements can be considered in IRS-aided CNOMA systems.

VIII. AI/ML FOR IRS-ASSISTED COOPERATIVE NOMA

Designing and analysis of IRS-aided cooperative communication systems using AI and ML techniques is an exciting area of research and development [9]. AI/ML can enhance the performance, efficiency, and adaptability of IRS-aided systems. We have summarized an overview in Fig. 14 of how AI/ML can be applied in the design and analysis of CNOMA systems.

Some ML algorithms for resource optimization in IRS-aided CNOMA systems are:
Reinforcement learning (RL) algorithms, such as Q-learning or Deep Q-Networks (DQN) [79], can be used to optimize resource allocation in IRS-NOMA systems by learning decision-making policies that maximize system performance over time. RL agents can learn to adaptively adjust transmission parameters, such as power allocation and user grouping, based on environmental feedback and system objectives such as data rate and error performance.

Deep learning (DL) techniques, such as neural networks, can be employed for predicting channel states and optimizing resource allocation in IRS-NOMA systems. Convolutional neural networks (CNNs) or recurrent neural networks (RNNs) can learn complex patterns in channel data to predict optimal transmission parameters and adaptively adjust them in real-time.

Federated learning (FL) enables collaborative model training across multiple distributed edge devices without sharing raw data. In IRS-NOMA systems, FL can be used to train resource optimization models collaboratively across multiple BSs or users, leveraging local channel state information to improve system performance.

Evolutionary algorithms (EAs) such as genetic algorithms (GAs) or particle swarm optimization (PSO), can be applied to optimize resource allocation in IRS-NOMA systems by iteratively searching for optimal solutions in a large solution space. EAs can efficiently explore and exploit the search space to find near-optimal resource allocation strategies that maximize system performance.

Some AI/ML applications in CNOMA are:

Channel Estimation and Prediction: AI/ML algorithms can be applied to estimate and predict channel conditions between users, IRS elements, and relay nodes. This helps in optimizing IRS phase shifts and relay node selection. Deep Neural Networks (DNNs) or Long Short-Term Memory (LSTM) networks [80] can be trained offline to model time-varying channels and predict future channel states in real time applications. Further, AI/ML can also be used to fine-tune the channel parameters after the coarse estimation.

Resource Allocation: AI/ML can optimize resource allocation by considering dynamic factors such as user mobility and varying traffic loads of wireless network. Reinforcement learning algorithms (RLAs) may be used to adaptively allocate resources, such as power and bandwidth among nodes, to maximize system performance. In an IRS-aided

CNOMA system, AI/ML algorithms can be used to allocate resources in response to QoS variations.

Interference Management: ML-based interference management algorithms can help in identifying interference patterns and mitigating them. DL-based interference cancellation techniques is used to improve signal strength at the receiver. For example, in interference scenarios at the NU, ML can improve the SIC-based system performance by suitably training the DNN parameters.

Phase Control and Optimization: AI/ML-based algorithms can be employed to optimize IRS phase shifts dynamically. It can adapt IRS configurations in real-time based on the network's current state. Reinforcement learning can help find optimal phase shift strategies for IRS elements to maximize signal quality at the user node. For instance, finite phase shift values of IRS elements can be considered, and their optimal combination across all IRS elements can be optimized to enhance the sumrate or BER performance of IRS-aided CNOMA systems.

User Pairing: ML algorithms can assist in intelligent user pairing based on real-time channel conditions and QoS requirements in CNOMA system. Clustering algorithms can group users for CNOMA based on similarities and pathloss in their channel characteristics.

Energy Efficiency: AI/ML can optimize energy usage of wireless network by controlling the activation and operation of IRS elements based on traffic patterns and demand. ML-based algorithms can predict and manage energy harvesting and storage in mobile IRS units.

Security and Anomaly Detection: ML models can be used for detecting security threats and anomalies in IRS-aided communication systems, helping to safeguard the network. Anomaly detection algorithms can identify unauthorized access or malicious activities.

Performance Prediction: AI/ML algorithms are employed to predict system performance under different scenarios, enabling proactive adjustments and optimizations. Predictive analytics can estimate future traffic demands and user behaviors in the wireless network.

Network Optimization: AI/ML-based optimization algorithms are optimize the overall network architecture, including the placement of IRS elements, relay nodes, and user devices [80].

QoS Assurance: AI/ML can monitor and maintain QoS levels by adjusting network parameters in real-time. Dynamic QoS management ensures that users receive the desired service quality [80]. A summary of AI/ML applications in IRS-aided CNOMA system design is highlighted in Fig. 14.

Reinforcement learning (RL) and DNN approaches can facilitate cross-layer optimization by integrating information from multiple protocol layers. This enables joint optimization of physical layer parameters (e.g., beamforming, power control) with higher-layer functionalities (e.g., routing, scheduling) to achieve holistic performance improvements in IRS-aided NOMA systems. With the assistance of a DNN, optimal power allocation in IRS-aided CNOMA is achieved [81]. Users receive signals from the BS through relay nodes, and the framework determines the probability of each user's power requirement. The power coefficients denote the power of both users and relays in Figure 15. The DNN consists of various processing layers and predicts the optimal power of users by either maximizing the sum-rate or minimizing the decoded error probability [82].

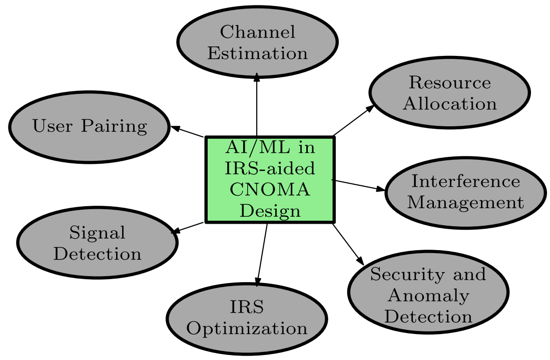

FIGURE 14. AI/ML applications in IRS-aided CNOMA system design and analysis.

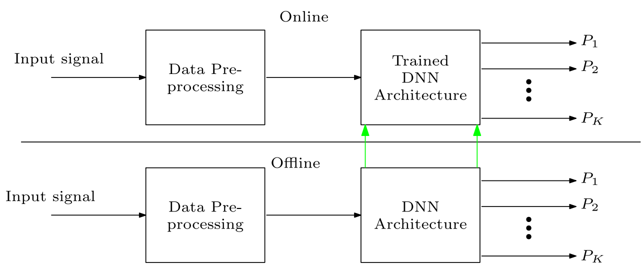

FIGURE 15. Structure of optimal power allocation using the DNN.

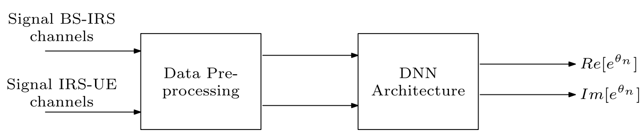

FIGURE 16. DNN for phase prediction at IRS.

For example, to optimize the SNR in IRS-aided NOMA, the neural network predicts the phase shifts of the IRS [83]. The architecture of the DNN is illustrated in Figure 16, comprising an input layer, hidden layers, and a regression layer at the output. The dataset used for training the DNN includes the channel coefficients as input and the corresponding phase shifts as output. Additionally, the DNN minimizes a loss function between the actual phase and the phase shift predicted by the network. DNN phase optimization can significantly enhance system performance, especially in multiple IRS scenarios [83].

IX. BER RESULTS IN CNOMA

We have assessed preliminary results of CNOMA with and without IRS. This section encompasses the simulation of

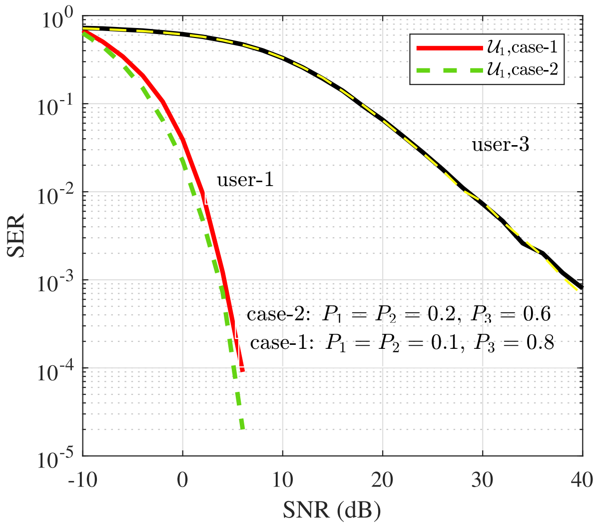

FIGURE 17. Numerical results of average SER of the PC-NOMA with QPSK transmission for NU $\mathcal{U}_1$ and FU $\mathcal{U}_3$ [48].

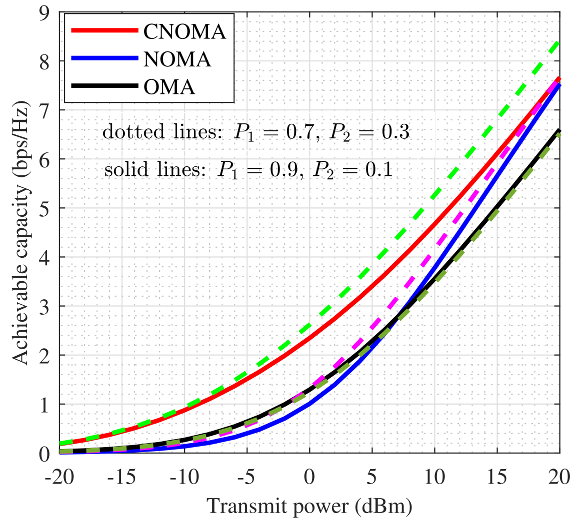

FIGURE 18. The sum rate vs SNR compassion of CNOMA, NOMA and OMA schemes.

BER and sum-rate performance within predefined CNOMA setups.

We present simulation results demonstrating the effectiveness of the CNOMA scheme in a three-user scenario, depicted in Fig. 10. Our assessment involves evaluating the system's symbol error rate (SER) and sum-rate performance metrics through simulations. These assessments consider power coefficients $\alpha_1 = 0.2$, $\alpha_2 = 0.2$, and $\alpha_3 = 0.8$ within a total power budget of $P_B = 1$ unit [48].

In Fig. 17, it is examined the average SER performance of the near user (NU) $\mathcal{U}_1$, which shows similarity in performance to User-2 due to symmetry, and the far user (FU) $\mathcal{U}_3$. The BS, $\mathcal{U}_1$, and $\mathcal{U}_3$ are equipped with $N_t = 32$ and $Nr = 4$ antennas, and $N_t = 1$ and $Nr = 4$ antennas, respectively, using quadrature phase-shift keying (QPSK) modulation. Fig. 17 illustrates that as N_t increases, $\mathcal{U}_1$ demonstrates improved SER performance due to more efficient mitigation of inter-user interference (IUI).[2] Further, smaller transmit antennas, IUI can be observed in $\mathcal{U}_1$ and $\mathcal{U}_2$ SER performance [48].

Fig. 18 illustrates the sum-rate performance of CNOMA, NOMA, and OMA schemes [48]. we have considered distances 800 m, and 500 m of NU and FU, respectively with Rayleigh fading channel and path loss exponent 4. It's noteworthy that CNOMA demonstrates superior performance over NOMA and OMA, attributed to its enhanced diversity of FU. The power splitting ratios of 0.3, 0.1 and 0.7, 0.9 are taken into account between Users NU and FU, as depicted in Fig. 18. Additionally, NOMA displays higher sum-rate performance compared to the conventional OMA system, as evident in the findings from Fig. 18.

The BER performance demonstrates improvement with an increase in the number of passive reflecting elements

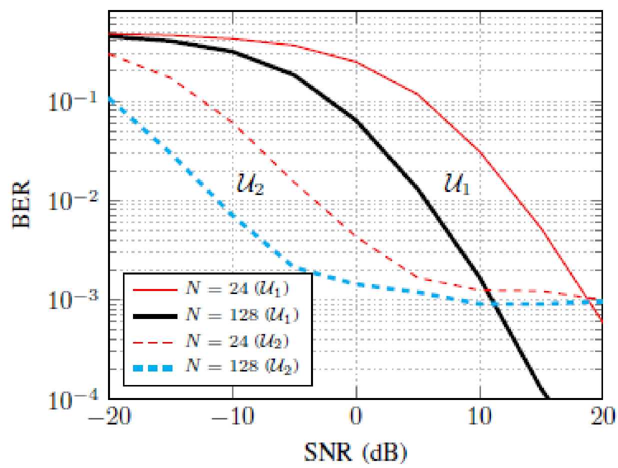

FIGURE 19. Average BER performance of R-INOMA with $N_t = N_r = 2$ for user-1 $\mathcal{U}_1$ and user-2 $\mathcal{U}_2$ [20].

denoted as N within the IRS, as depicted in Fig. 19 for both users with power allocation 0.2 and 0.8 unit for $\mathcal{U}_1$ and $\mathcal{U}_2$, respectability. This increase leads to an enhancement in the SNR, which notably benefits $\mathcal{U}_1$ and $\mathcal{U}_2$ [20]. A similar impact is noticed in the outcomes under low SNR conditions [20]. Consequently, there exists an inverse relationship between the error probability and the quantity of reflecting elements, N. Fig. 19 considers the phase setting due to all three users' channels at the IRS panel since the IRS is shared among all users in the R-INOMA [20]. User $\mathcal{U}_2$ experiences interference from $\mathcal{U}_1$, hence its performance saturates in the high SNR region, unlike $\mathcal{U}_1$, as observed in Fig. 19. Performance metrics evaluation summary of IRS-aided CNOMA is shown in Table 4 by considering possible NOMA configuration. Various resource allocation strategies in CNOMA and IRS optimization is essential to optimize the system performance.

[2] For more details kindly refer [48].

TABLE 4. Performance evaluation summary of IRS-assisted NOMA systems.

NOMA configuration	Performance Metrics	Resource allocation strategies and IRS optimization
IRS-aided NOMA	BER and sumrate performance analysis, impact of SIC	Yes, simpler
IRS-aided Coopeartive NOMA	BER and sumrate performance analysis, coverage analysis, impact of SIC	Yes, simple
IRS-aided PC-NOMA	BER and sumrate performance analysis, impact of number of users	Yes, simple
IRS-aided PSM-NOMA	BER and sumrate performance analysis, data throughput	Yes, simple
IRS-aided MIMO Cooperative NOMA	BER and sumrate performance analysis, detection complexity, beamforming analysis	Yes, complex

A summary of various NOMA systems' performance is given in Table 5. Specific performance improvements of NOMA/CNOMA over OMA depend on communication scenarios.

X. CHALLENGES AND FUTURE DIRECTIONS

In this section, we highlight some challenges and their related possible solution in the CNOMA system design with IRS and without IRS for the next-generation wireless network. Here are some possible challenges in CNOMA communication systems:

Power Allocation: CNOMA relies on power allocation between users to achieve better performance. Optimizing power allocation can be challenging, especially when there are multiple users with different channel conditions and QoS requirements. Further, properly pairing users for CNOMA can be complex. Finding the right combination of users with compatible channel conditions and power requirements is not always straightforward. Further, adaptive power allocation is essential since channels are time-varying.

Synchronization: Accurate synchronization among users and relay nodes is critical for CNOMA. Achieving precise synchronization in practical systems are challenging, especially in multipath fading environments. Moreover, choosing the appropriate relay nodes and deciding when and how to relay information is a non-trivial task in the CNOMA. Relay selection algorithms must consider factors like channel strength, interference, and power constraints in a system. Coordinating IRS elements and ensuring they work together harmoniously can be challenging, especially when there are multiple IRS units and their multiple links distributed across a wide area.

Interference Management: Managing interference between cooperative users and other users in the network can be challenging [69]. Interference from neighboring cells or other cooperative groups may affect the performance of CNOMA systems. Accurate channel estimation is essential for CNOMA. Estimating the channels between multiple users and relay nodes can be challenging, especially when dealing with fast-fading channels. Precise CSI is crucial for optimizing IRS configurations. Estimating and feeding back CSI for multiple IRS elements can be challenging, particularly in dynamic environments where channel conditions change rapidly. Further, efficiently allocating resources such as time, frequency, and bandwidth among users and relays is a complex optimization problem [69]. Dynamic resource allocation strategies are needed to adapt to changing network conditions. Furthermore, in multi-IRS systems, there can be interference between IRS elements when they are serving different users or reflecting signals in the same vicinity. Managing interference and optimizing IRS phase shifts to maximize the desired signal is complex.

Energy Efficiency and Security: CNOMA is required additional energy consumption for relaying. Designing energy-efficient protocols and relay strategies are important, especially in battery-powered devices. CNOMA systems must address security concerns related to information sharing among users and relay nodes. Ensuring data privacy and protection against eavesdropping is important. Further, as the number of users and relay nodes increases, the scalability of CNOMA systems becomes a matter of design. Scalable algorithms and architectures are needed to support larger networks. CNOMA needs coordination among multiple users and relay nodes, which can increase the overall system complexity. Managing this complexity efficiently is a challenge. IRS elements are typically static, which can limit their effectiveness in scenarios with mobile users. Adapting IRS configurations to accommodate user mobility is a challenge in IRS-aided CNOMA system.

Addressing these challenges requires a combination of advanced signal processing techniques, efficient algorithms, smart system design, and ongoing research and development efforts. Overcoming these challenges is essential to fully harness the potential benefits of multiple IRS-assisted communication CNOMA systems, such as increased capacity and coverage. Some possible challenges and future directions research in IRS-aided CNOMA system design and analysis are highlighted in Fig. 20.

A. EMERGING TRENDS AND FUTURE DIRECTIONS

The field of IRS-aided cooperative communication is evolving rapidly, driven by advances in wireless technology, increasing demand for higher data rates, and the need for more efficient use of the radio spectrum. The integration of AI/ML techniques for optimizing IRS operations and resource allocation is a promising trend. AI can help adapt IRS phase shifts, relay node selection, and power allocation in real-time based on changing network conditions.

TABLE 5. Performance summary of different systems.

Reference	System	BER	Sum-rate	Remark
[5], [24], [35]	OMA	Best performance	Lower	There may be suboptimal utilization of resources. Simpler
[5], [48], [55]	NOMA	User specific performance	Higher than OMA	Higher spectral efficiency, Simple
[49], [62], [66], [69]	CNOMA	User specific performance	Higher than OMA and NOMA	Higher spectral efficiency, Complex
[13], [20], [84]	IRS-OMA	Improved BER over OMA	Improved over conventional OMA	Improved over OMA, Improved energy efficiency,Simple
[13], [20], [35], [84]	IRS-NOMA	User specific performance, improved	Improved over conventional NOMA	Higher spectral efficiency and energy efficiency, Complex
[20], [24], [35], [56]	IRS-CNOMA	User specific performance, improved	Improved over conventional CNOMA	Higher spectral efficiency and energy efficiency, More complex

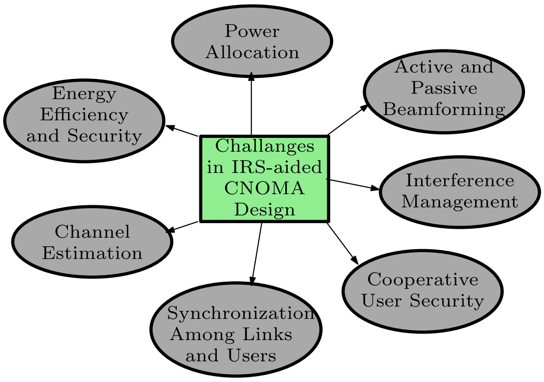

FIGURE 20. Challenges and future directions research in IRS-aided CNOMA system design and analysis.

Further, IRS technology can find applications in the terahertz frequency band [85], enabling ultra-high-speed wireless communication. THz frequencies can provide abundant bandwidth for IRS-aided systems, potentially revolutionizing data transmission. Future IRS-aided systems will need to address security and privacy concerns, especially in scenarios involving sensitive data. Developing robust security mechanisms, such as secure channel estimation and data encryption, is a priority.

IRS-aided cooperative communication will need to coexist with 5G and future generations of wireless networks. Interoperability and compatibility with these networks will be a key focus. Research into dynamic and mobile IRS elements is ongoing. Mobile IRS elements could be deployed on drones or autonomous vehicles to provide communication and reflect signals where needed, particularly in emergency or temporary scenarios. Further, combining IRS with MIMO technology is an emerging trend. This synergy can further enhance spectral efficiency and coverage. Standardization bodies like the Institute of Electrical and Electronics Engineers (IEEE), 3rd Generation Partnership Project (3GPP), and the International Electrotechnical Commission (IEC) develop technical standards for wireless communication systems. IRS-aided cooperative communication standards may need to be developed or integrated into existing standards.

Building real-world testbeds and prototypes for IRS-aided systems is essential for validating theoretical concepts and assessing their practical feasibility. Beyond consumer and mobile communication, IRS-aided cooperative communication is finding applications in various industries, including healthcare (e.g., remote surgery), transportation (e.g., connected vehicles), and smart cities (e.g., infrastructure optimization). The integration of quantum communication principles into IRS-aided systems could provide unprecedented levels of security for sensitive data transmission. The future of IRS-aided cooperative communication is promising, and these emerging trends and directions are expected to shape the development and deployment of IRS technology in diverse application scenarios, contributing to more efficient and reliable wireless communication networks.

Researchers are focusing on AI/ML-based resource allocation strategies in IRS-aided CNOMA/NOMA systems. They are also designing intelligent control mechanisms for efficient phase and amplitude adjustment of IRS elements. Additionally, multi-objective function optimization frameworks are being developed to simultaneously optimize different performance metrics such as spectral efficiency, energy efficiency, reliability, and fairness in cooperative NOMA systems assisted by IRS.

XI. POTENTIAL APPLICATIONS OF IRS-AIDED CNOMA

Next-generation wireless network is expected to introduce of innovative communication techniques to accommodate a multitude of new applications, including cloud-based applications, the IoT, machine-to-machine communications, D2D, V2I, etc. In pursuit of spectrum-efficient networks, NOMA has emerged as a preferred access technique for 5G and Beyond networks. Further, CNOMA is an extension of NOMA, where strong user helps to the weak user to improves its performance. Therefore, CNOMA can have the following possible advantages in the next-generation wireless network:

- CNOMA offers a key advantage by establishing dual links to transmit a message. This setup minimizes the impact of outages, as if one link fails, the likelihood of the second link remaining functional is higher. The probability of both links simultaneously failing is notably lower than the probability of any single link encountering an outage.

• This approach leads to a diminished outage probability and subsequent diversity gain without necessitating the use of extra antennas, such as those in MIMO systems.

• Moreover, relaying in cooperative NOMA communication can effectively expand the coverage area of the BS, enhancing the network's reach and connectivity with higher spectral efficiency.

Cooperative communication has been researched and considered as a potential enhancement for future wireless systems within the framework of 3GPP standards. Dynamic spectrum sharing (DSS) initially incorporated into the inaugural version of 5G. With 3GPP Release 18, advancements have been introduced to effectively manage substantial interference from adjacent 4G cells while augmenting downlink control channel capacity and extending coverage. IRSs have the potential to significantly enhance the performance of CNOMA systems across various applications. Some possible applications of IRS-aided CNOMA include:

Enhanced Coverage and Throughput: IRS can improve coverage and increase throughput in NOMA systems by suitably adjusting the signal paths, mitigating interference, and enhancing signal strength, especially in challenging environments. Especially, in terahertz frequency band NOMA systems, FU experiences outage due to molecular absorption. Therefore, CNOMA is suitable to enhance signal diversity in terahertz communication by adding a link from NU to FU.

Massive Connectivity for IoT: IRS can facilitate massive connectivity for the IoT devices by efficiently managing simultaneous connections and improving the reliability of communication links in NOMA-based IoT networks.

Energy-Efficient Communication: By optimizing signal paths and enhancing SNR, IRS can help reduce energy consumption in NOMA networks, thereby enabling more energy-efficient communication. In the literature, it is reported that IRS can enhance the energy efficiency of battery devices by 20 to 30% without decreasing performance.

Next-Generation Wireless Networks: Integration of IRS into NOMA setups could be crucial for future wireless networks, including 6G, as it can offer substantial improvements in spectral efficiency, coverage, and overall network performance.

Dynamic Resource Allocation: IRS-aided CNOMA enables dynamic resource allocation by intelligently allocating resources such as power and bandwidth based on the channel conditions and user requirements, optimizing the network performance. For example, if the IRS is optimized for the FU, system power allocation at the BS can be enhanced for the NU to achieve higher throughput.

Mobile Edge Computing (MEC): IRS can play a vital role in MEC environments by improving connectivity and offloading traffic from congested networks, thereby enhancing the overall QoS in NOMA-enabled MEC systems. A summary of applications of IRS-aided CNOMA system is highlighted in Fig. 21.

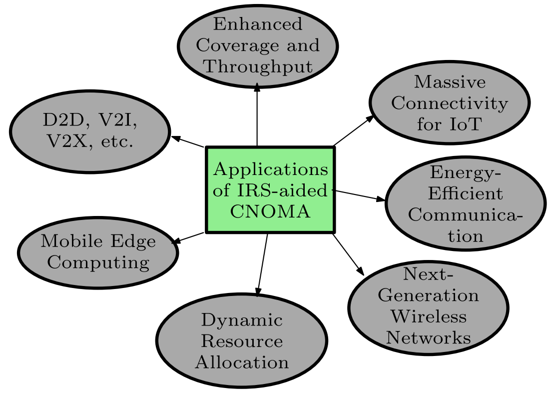

FIGURE 21. Potential applications of IRS-aided CNOMA system.

XII. CONCLUSION

This paper discussed an innovative framework for IRS-assisted cooperative NOMA systems, referred to as IRS-aided CNOMA system. The amalgamation of IRS technology with cooperative NOMA aims to enhance spectral and energy efficiencies, and mitigate interference in next-generation wireless networks. Various aspects of CNOMA, including underlay and overlay frameworks with and without IRS, were summarized. Various types of IRS-aided CNOMA systems were also discussed in the paper. Benefits of MIMO in the IRS-aided NOMA/CNOMA systems were discussed with some practical challenges. The cooperative transmission strategy, incorporating multiple users and relay nodes, was discussed in IRS-CNOMA. IRS-CNOMA exploits the benefits of NOMA's power domain multiplexing, while the IRS facilitates intelligent signal reflection and manipulation. The synergy between these two technologies was explored to achieve substantial gains in terms of throughput, coverage, and reliability. Furthermore, various challenges in CNOMA design, including resource allocation and interference management, were highlighted. Further, it was highlighted that AI/ML can play a pivotal role in resource allocation such as power and bandwidth and system optimization in cooperative NOMA, with potential applications.

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