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RECONFIGURABLE INTELLIGENT SURFACE AIDED NON-ORTHOGONAL MULTIPLE ACCESS COMMUNICATIONS: A REVIEW

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Abstract

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The exponential growth of the wireless data traffic and the rapid increase of linked devices have highlighted the limitations of conventional radio access technologies to respond to the needs of the next generation communication networks. Reconfigurable Intelligent Surface (RIS) technology has become an emerging transformative paradigm which can engineer smart wireless propagation environment through programmable meta-surfaces. At the same time, Non-Orthogonal Multiple Access (NOMA) has received massive interest due to the capability to increase spectral efficiency and provide a massive connectivity. This review work presents a comprehensive and structured analysis of the emerging integration of RIS and NOMA system, emphasizing the integration framework, system architectures, channel models, and signal processing methods. The proposed scope also discusses theoretical backgrounds as well as practical applications, viz., complex channel estimation schemes, power allocation mechanisms, and joint optimisation schemes. The review in addition defines trade-offs in performances of spectral efficiency, energy efficiency, and user fairness and critically reviews optimisation frameworks entailing machine learning and metaheuristics techniques. The present survey is unique in that it has summarised the latest developments as well as categorising RIS-NOMA strategies in terms of their system design and usage scenarios. Major open issues have been outlined, and the prospective areas of research have been suggested to guide the practical implementations of RIS-NOMA into 6G, and beyond networks. The piece of work can be utilised by scholars and engineers as their guiding text to leveraging RIS-NOMA in realising intelligent, scalable, and energy-efficient wireless transmission systems.

1. Introduction

The increasing demand for high transmission data rates due to the development of wireless devices and high-data-rate internet applications has necessitated the enhancement of wireless network capacity. The 3rd Generation Partnership Project (3GPP) has led to collaboration between academia and companies to achieve better data rates and other targets. Massive Multiple Input Multiple Output (MIMO) systems and other physical layer approaches have been proposed to improve spectral efficiency (Liang *et al*., 2014), but their deployment faces challenges due to hardware costs, energy usage, and signal processing complexity. Conventional orthogonal multiple access (OMA) techniques, such as FDMA, OFDM, CDMA, and TDMA, have limitations in enhancing wireless communication systems' performance, including latency, data rates, coverage, and spectral efficiency (Li *et al*., 2022; Wang *et al.,* 2022).

Innovative technology solutions for 5th generation (5G) and later cellular networks are expected to improve spectrum efficiency, increase system capacity, and offer better user experience. NOMA is considered an effective technique for multiple access in next-generation 5G networks (Ali, 2017; Ding *et al*. (2017), allowing users to concurrently share frequency and temporal resources within the same spatial region (Maraqa *et al*., 2020).

NOMA uses two fundamental techniques: At the transmitter, signals are combined using superposition coding, whereas at the receiver, interference is cancelled successively. Compared to OMA, NOMA exhibits advantages of greater connectivity, more efficient utilization of the spectrum, decreased end-to-end latency, and the ability to work with limited feedback control channels (Gurugopinath, 2019). NOMA is suitable for use in many fields, for example, cellular systems, wireless sensor networking, and drone networks (Ha, 2021).

However, the non-orthogonality of resources in NOMA introduces another challenge of inter-user interference, necessitating the development of a technique to minimise this interference (Ding *et al*., 2017). Furthermore, environmental barriers can degrade the needed channel condition, particularly for far NOMA users who are blocked by tall structures, resulting in unavoidable outage scenarios. To address the issues, reconfigurable intelligent surfaces (RISs) show promise in a variety of ways. Reflecting links through RISs can be used to improve the channel condition of blocked NOMA users via line-of-sight (LOS) propagation. RISs have emerged as highly promising technologies that is anticipated to be integrated into future wireless communications systems with the aim of achieving enhanced spectral efficiency across a wide range of frequencies. Integrating NOMA with RIS creates benefits in the areas of spectrum efficiency, energy efficiency, coverage, information security, latency, dependability, and extended connectivity, making it a fundamental part of 6G and newer networks (Di Renzo *et al*. 2020).

As a means of overcoming the peculiar drawbacks of each technology and gaining significant growth in terms of performance, RIS-NOMA combination offers a viable solution. But the extensive literature that is becoming available in the field is not unified and this creates a greater problem among the scholars and practitioners in order to access the state-of-the-art, perceive any crucial questions, or define upcoming research directions. Surveys of the current state of the situation usually either concern RIS or NOMA individually or represent only a partial picture of their joint application.

This gap in the literature is to be filled by an extensive and systematic survey, which considers the different research efforts, clarifies the basic concepts of RIS-aided NOMA, critically evaluates the different proposed schemes, and outlines a final platform concerning future studies. Here, this review paper can be considered to have made the following significant contributions:

- An general overview of extensive studies on RIS assisted NOMA communications.
- Suggests a classification of the current RIS-NOMA schemes based on the NOMA possibilities and RIS capabilities.
- Review of RIS-NOMA systems on the basis of technical elements and problems in RIS-NOMA systems.
- Critical evaluation of the performance of a number of RIS-NOMA schemes.
- Finding large open research problems, and exciting future opportunities regarding RIS-NOMA.

The review article will thus be useful to both the researchers and the academic as well as the industry players in facilitating future innovation and expeditious deployment of this breakthrough technology in future wireless networks.

The rest of this review article is organized in the following way: the second section provides an examination of the basic principles, types, benefits, and intrinsic difficulty in Non-Orthogonal Multiple Access (NOMA). Section 3 presents an elaborate discussion of reconfigurable intelligent surfaces (RIS) such as their functional aspects, constructions, channel representation, deployment, and personal benefits and limitations of RIS. The interaction between RIS and NOMA is discussed in Section 4 that deals with the combination of the technologies, different system structures, and an extensive examination of their performance along with all the important metrics. Section 5 addresses the most significant optimization algorithms that are used in RIS aided NOMA systems related to joint beamforming guidelines, resource allocation, and channel state information harvesting. In Section 6, key challenges and open research problems that have to be elaborated are outlined. Section 7 contains the new usages and potential future research trends of RIS-NOMA. Lastly, Section 8 completes the paper with a conclusion that covers the fundamental findings and once again highlights what this review brought.

2. Fundamentals of NOMA

2.1 Principle of NOMA

In contrast to orthogonal techniques like time division multiple access (TDMA) or frequency division multiple access (FDMA), which demonstrate a certain level of effectiveness, NOMA achieves a high spectrum efficiency with several users sharing similar time-frequency attributes (Choi, 2017). The major characteristic of NOMA is summarised as below:

i. Superposition coding

All user signals are combined into a single form after they have been modulated at the transmitter. (Choi, 2017; Ha, 2021). This enables concurrent transmission to several users utilising the same resource block.

ii. Successive interference cancellation

Successive interference cancellation (SIC) is employed at the receiver to distinguish the superimposed signals (Islam, *et al.,* 2016; Choi, 2017). In power domain NOMA, users with superior channel conditions receives the superimposed signals, decodes the signals of users with weaker conditions first by considering its own signal as interference. Subsequently, it extracts the decoded signal from the received composite signal, thus effectively removes interference from the weaker user. After cancellation, it then proceeds to decode its own signal with minimal interference (Li *et al*., 2023). This iterative process enables the differentiation of individual user signals.

iii. Power Allocation

Another important feature of NOMA, particularly in the downlink environment is the power allocation to users (Choi, 2017). The aggregation of channel conditions enables the determination of a user's overall channel condition and the corresponding power allocation. More power is given to users who are facing bad channel conditions compared to those with more robust channels (Li *et al*., 2023). The power difference enables SIC by prioritising the signal of the weaker user among the combined signals.

In order to illustrate the characteristics of SC and SIC, we will examine a downlink NOMA transmission scenario in which the BS assigns spectrum resources B to m users concurrently. Let s_k denote the k-th user's information signal, with the condition that the transmitted signal s_k is power-normalized, i.e., it has unit average power, and the transmit power is represented by p. The composite signal at the transmitting end can be articulated as expressed in equation (1) (Ali, 2017):

$$X = \sum_{k=1}^{m} \sqrt{p_k} s_k \tag{1}$$

where $\sum_{k=1}^{m} p_k \leq p_t$, given the base station's total transmit power budget of p_t. Conversely, the signal received at the k-th user terminal can be articulated as shown in equation (2):

$$y_k = h_k X + w_k \qquad \forall k \tag{2}$$

where h_k represents the BS – user k's channel gain. The variable w_k signifies the receiver Gauss se, which encompasses the inter-cell interference present at the k-th user's receiver (Ali, 2017).

2.2 Types of NOMA

There are two primary categories of NOMA, both utilising distinct methodologies. They are power-domain and code-domain.

In power-domain NOMA, a technique known as superposition coding is utilised by the transmitter, while receivers perform successive interference cancellation, with varying power levels allocated to users sharing the same resource (Sadia *et al*., 2018; Gurugopinath, 2019). Users experiencing suboptimal channel conditions, often referred to as far users, are assigned higher power levels. In contrast, users with more favourable channel conditions, known as near users, receive lower power levels (Ha, 2021). This allows far users to analyse and interpret their signal more easily, while near users employ successive interference cancellation to analyse and interpret their signal after removing the signals intended for far users (Maraqa *et al.,* 2021). The performance analysis of power-domain NOMA across different fading channels, modulation schemes, and coding rates provide insights into developing an adaptive modulation and coding schemes (Sadia *et al*., 2018).

In the code domain NOMA model, special spreading codes are assigned to the service of each user and, therefore, they can use one and the same frequency and time resources. Code-domain NOMA utilises low-density spreading sequences for user multiplexing, similar to CDMA (Gurugopinath, 2019). Liu *et al.* (2017) discuss various code-domain NOMA approaches, including trellis-coded multiple access (TCMA), Interleave Division Multiple Access (IDMA), and low-density signature (LDS) sequence-based CDMA. These methods are supplemented by the more recently proposed multiuser shared access (MUSA) technology, pattern-division multiple access (PDMA) (Chen *et al*., 2016), and sparse-code multiple access (SCMA) (Shukla *et al*., 2021; Sharma & Deka, 2023).

SCMA is a code domain NOMA technique that uses multiple orthogonal resources for communication, employing multidimensional codebooks for more shaping gain. It's an extended variant of the low density spreading (LDS) multiple access strategy and has gained interest in 5G and beyond wireless networks (Sharma & Deka, 2023). SCMA can improve spectral efficiency by assigning code domain layers without prior channel state information knowledge (Shukla *et al*., 2021).

Pattern division multiple access (PDMA) is a novel code domain nonorthogonal technique proposed for fifth-generation (5G) radio networks. It maps transmitted data to a resource group, including time, frequency, and spatial resources. Designed with disparate diversity order and sparsity, PDMA enhances system performance while maintaining detection complexity. It distinguishes signals from users sharing the same resources. System-level modelling studies show PDMA can enable six times more simultaneous connections and improve spectrum efficiency by at least 30% (Chen *et al*., 2016).

Other classification includes hybrid NOMA that encompasses both power and code domain, and channel-based where the channel characteristics determine the user grouping and resource allocation method (Ha, 2021). The integration of power-domain and code-domain NOMA approaches may facilitate a larger user capacity and enhance sum-rates relative to independent implementations (Balasubramanya *et al.,* 2018).

2.3 Advantages and Challenges of NOMA

The NOMA system brings several more effective benefits than traditional orthogonal multiple access (OMA) systems. Nevertheless, there are several obstacles associated with the implementation of the NOMA system. NOMA yields more efficient use of the spectrum when contrasted with OMA (Islam *et al*. 2016). It increases user equality according to Islam *et al*. (2016) and decreases latency for uplink communication as described by Makki *et al*. (2020). Users utilising same time-frequency resources gain superior performance compared to OMA. Decreased latency for uplink transmission is a significant benefit of NOMA if implementing IoT services (Makki *et al*. 2020). Challenges faced are increased receiver complexity (Makki *et al*., 2020), difficulty in handling error propagation (Islam *et al*. 2016), the optimisation of power allocation (Choi, 2017), user pairing difficulties, and security risks. Daunting receiver complexity may limit the effectiveness of interference cancellation, which in turn harms overall transmission quality. Power allocation optimization is crucial for NOMA's success (Choi, 2017), and user pairing should be efficient based on channel conditions. Concurrent usage of resources by multiple users can also raise security risks.

3. Reconfigurable Intelligent Surfaces (RIS)

3.1 Principle and Architecture of RIS

Reconfigurable intelligent surfaces refer to system of designs that comprise of nearly passive scattering elements that enable phase control of propagating electromagnetic waves (ElMossallamy *et al*., 2020). Every single element can change the phase and or amplitude of incident signal so as to control

reflected or transmitted wave in the case of RIS. These changes are software managed for dynamic beamforming or other wavefront shaping options as Zhang *et al*. (2021a) have noted.
A typical RIS architecture consists of three primary components and an intelligent controller as depicted in Figure 1 in order to enable the regulation of the propagation environment (Wu *et al*., 2021). The outer layer, having adjustable metallic patches, is a two-dimensional (2D) array of RIS components that will interact directly with the incident signals. The intermediate layer is a copper plate that can avert signal energy escape while the innermost layer is a printed circuit that connects to the RIS controller and controls the phase shifts of the RIS components (Wang *et al*., 2022).

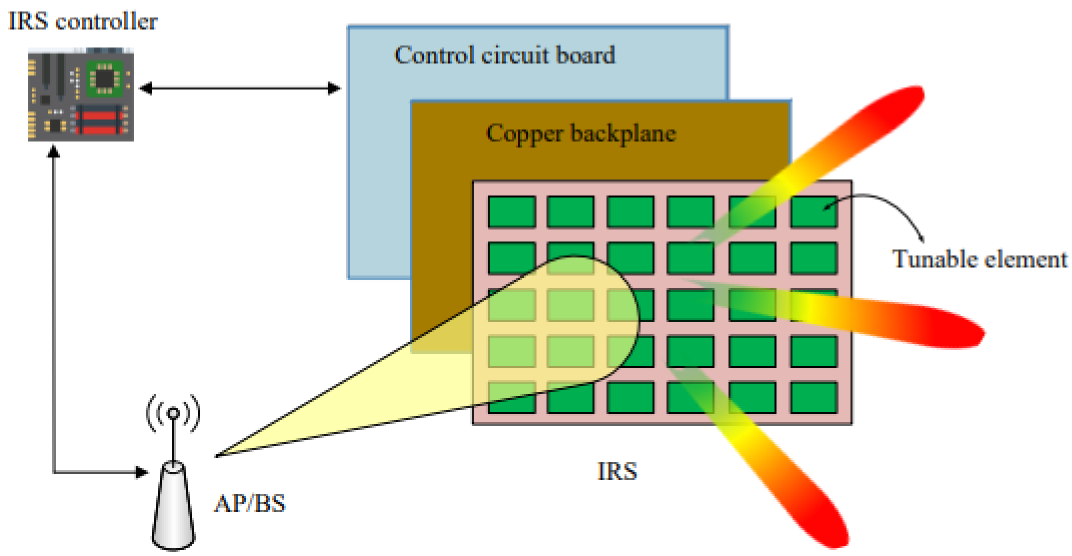

Figure 1: RIS structure and architecture (Wu *et al*., 2021).

The internal control circuit board energizes reflecting elements and controls reflection adaption. The meta-surface, made up of sub-wavelength scattering elements, governs the frequency response of the RIS (Wu *et al*., 2021). These surfaces have the potential to be strategically positioned within the radio channel connecting a transmitter and receiver, allowing for the manipulation of signal reflection along the propagation path.

Controlling the phase of each RIS element enables RIS to form a virtual line of sight to direct reflected signals towards a target destination and amplify the link power. This method enables RISs to provide better coverage and higher spectral efficiency to wireless networks (Zhang *et al*., 2021a).

3.2. RIS Channel Models

Proper modelling of the channels is vital when assessing the performance of the RIS-aided communications system. The striking property of RIS is that it adds a cascaded channel, which usually consists of two different linkages, transmitter-to-RIS link and RIS-to-receiver link (Liang *et al*., 2021). The overall channel in a RIS-aided system usually consists of three components:

i. Direct channel or path link between transmitter or base station (BS) and receiver (user), defined as h_{BU}.
ii. BS to RIS link, H_{BR} (usually, $M \times N$, M is the number of the BS antennas, N is the RIS elements).
iii. RIS-user channel, H_{RU} (usually $1 \times N$), which is modulated by reflection matrix of RIS (Φ).

The cascaded channel may be written as expressed (Liang *et al*., 2021) in equation (3):

$$H = H_{BR}\Phi H_{RU} \tag{3}$$

where $\Phi = diag\left(e^{j\emptyset_1},\ e^{j\emptyset_2}. \dots, e^{j\emptyset_N}\right)$ for an RIS with N elements and $\emptyset_n$ is the phase shift introduced by the n-th element.

With the inclusion of the direct link between the BS and the user, the effective channel H can be given as expressed (Zhang *et al*., 2021b) in equation (4).

$$H_{eff} = h_{BU} + H_{BR}\Phi H_{RU} \tag{4}$$

For the phase shift model, every RIS element provides a phase shift to the incident signal, so it is under control. There are however two means of modelling the phase shift of RIS namely; Continuous phase shift model and the discrete phase shift model. In the continuous phase shift model, the modelling theory is that each element can be used to provide continuous phase shift in the range $[0,\ 2\pi]$. This has the best performance, though perhaps, difficult to actualize. For a practical implementation, a discrete phase shift model is usually adopted. In practice, RIS elements are usually configured with limited number of phase shift bits (e.g., 1-bit, 2-bit, 3-bit). This causes quantization errors and lower possible performance compared to the continuous phase shifts but facilitates hardware implementation.

For the mathematical modelling of individual channel, the BS to RIS channel is typically modelled as Rician or LoS dominant as expressed by equation (5):

$$H_{BR} = \sqrt{\frac{\beta_{BR}K_{BR}}{K_{BR}+1}}\widehat{H}_{BR}^{LoS} + \sqrt{\frac{\beta_{BR}}{K_{BR}+1}}\ \widehat{H}_{BR}^{NLoS} \tag{5}$$

where β_{BR} is the BS-RIS link path loss, K_{BR} is the Rician factor for BS-RIS link, $\widehat{H}_{BR}^{LoS}$ represents the deterministic LoS components for the BS-RIS channel, and $\widehat{H}_{BR}^{NLoS}$ denoted the NLoS components of the BS-RIS channel. Similarly, the RIS-to-user channel is modelled using Rician fading model provided that the RIS is strategically positioned.

$$H_{RU} = \sqrt{\frac{\beta_{RU}K_{RU}}{K_{RU}+1}}\widehat{H}_{RU}^{LoS} + \sqrt{\frac{\beta_{RU}}{K_{RU}+1}}\ \widehat{H}_{RU}^{NLoS} \tag{6}$$

However, the BS-to-user direct link is often modelled as Rayleigh fading, and is thus expressed as given in equation (7), which may be ignored if there is blockage.

$$H_{BU} \sim \mathcal{CN}(0, \beta_{BU}I) \tag{7}$$

3.3 RIS Deployment Scenario

RISs can be applied in tasks such as safe communication and remote energy transfer (Zhang *et al*., 2021a). RIS technology may drastically enhance data transmission speeds, increasing area of cell coverage and improving the security of communication systems in future 6G wireless networks. The quality, range and reliability of wireless communications can be boosted by appropriately controlling the properties of electromagnetic waves using RIS (Figueiredo, 2023; Syed *et al*., 2023). RIS can conserve energy in wireless networks and improve the functionalities for sensing and imaging (Figueiredo, 2023; Sohal *et al*., 2024). Sohal, *et al.* (2024) emphasized that although the deployment and operation of RIS networks present hurdles such as high initial expenditures and intricate control needs, the technology has high promise for achieving responsive, efficient, and secure wireless signals. Widespread development and acceptance of RIS technology is likely to reinvent the way wireless communication is conducted in the years to come. RIS is not only applicable to wireless communication, but also for security using RF sensing (Saber *et al*., 2022), as well as in the development of smart space. This further research also suggests that RIS may significantly influence future development approaches in the field of wireless communication.

3.4 Advantages and Challenges of RIS

RISs as a passive antenna arrays have a number of benefits, such as energy efficiency, low price, ease of installation (DiRenzo, 2020), wireless environment programming, no amplification of noise, scalability (Wu & Zhang, 2020b). They are normally thin lightweight panels which can be readily installed into the infrastructures without the need of extensive cables or power supply networks (ElMossallamy *et al.,* 2020). The propagation environment can be dynamically manipulated by RISs which enable networks to become responsive to evolving channel conditions and user requirements in a real-time manner (Zhang *et al*., 2021a; Xiu *et al*., 2020).

Nonetheless passive channel state information (CSI) acquisition, complexity in beamforming optimization, multiplicative fading, discrete phase shifts (Liang *et al*., 2021), and imperfection are problems attached to RISs. RIS panels positioning is optimized according to the environment, distribution of the users and network topology, and it is important to plan to find optimal location where the RIS panels can work with the maximum effectiveness.

Being a developing technology, RIS has no standardized ways of controlling it, channel estimation, and integrating it within the available network frameworks. Poor power amplification is another problem since RISs are not able to amplify signals creating research of so-called active RIS (Long *et al.,* 2021). Although they pose a challenge, RISs provide economical access to large-scale installation and provide a scalable solution to improve coverage and capacity.

4. RIS-AIDED NOMA Systems

4.1 Integration of RIS with NOMA Network

Integrating Reconfigurable Intelligent Surfaces (RIS) with Non-Orthogonal Multiple Access (NOMA) is widely recognised as an encouraging alternative to the upcoming challenges in future wireless networks. This combination involves RIS and NOMA features that modify the wireless transmission environment and allow for more efficient allocation of user resources. The combination results in improvements in both spectral and energy efficiency (Goh *et al*., 2023). Recent studies suggest that the systems benefit from gains in both energy and overall performance (Ding *et al*., 2017; Huang *et al*., 2019; Fang *et al*., 2020). As a result, combining NOMA and RIS is known to upsurge the accuracy of signal-to-interference-plus-noise ratio (Dai *et al.*, 2018) and afford inexpensive coverage improvement (Goh *et al*., 2023; Huang *et al*., 2019; Fang *et al*., 2020) while supporting complex multi-access architectures including ultra-dense networks (uDNets) and Internet of Things (IoT) technologies (Ding *et al*., 2017; Huang *et al*., 2019).

In NOMA, the base station superimposes signals for the transmission to various users inside a specific network. Power-domain multiplexing ensures that individuals with poor signal quality receive increased transmission power (Ding *et al*., 2017). The RIS is strategically positioned to reflect the incoming signals to the intended users. In the same capacity, every RIS component changes the phase of the arriving wave such that it will reflect optimally, therefore supplementing the total amount of available channel gain for use by users (Wu & Zhang, 2020a). As observed, the users employ SIC, in order to demodulate the respective signal at the recipient. The effect of RIS is to improve the capability of channel condition, therefore increasing the effectiveness of SIC to eliminate remaining interference (Huang *et al.*, 2019).

4.2 RIS-aided NOMA System Architecture and Models

The system model of RIS-assisted NOMA network consists of a base station (BS), a reconfigurable intelligent surface, and multiple users that are classified into strong users and weak users. The RIS enhances transmission performance by facilitating optimal signal reflection to the users in order to increase the effective channel gain (Ding & Poor, 2020). The RIS comprises of N elements assumed to be passive reflectors. Each element integrates a controllable phase shift into the incident signal in order to enhance the conditions in the channel. Users are categorized into strong and weak users. Strong users are nearer to the base station, thus having better network conditions while weak users are further from the BS or in area where signal coverage is restricted as if blocked and hence, has to rely on RIS for signal enhancement. Figure 2 depicts a typical RIS-aided NOMA architecture where the straight route between the base station and the far user is obstructed.

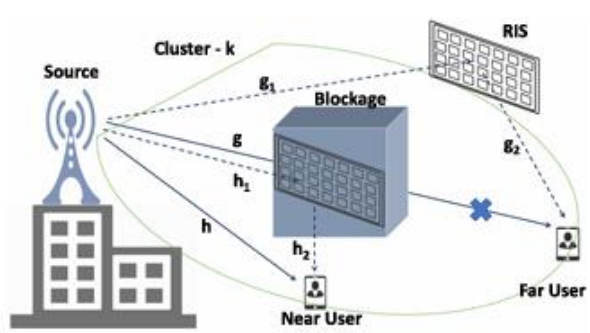

Figure 2: RIS-aided NOMA architecture (Shaikh *et al*., 2022)

Figure 3 illustrates the downlink of a MISO RIS-NOMA communication system where the base station with *N* antennas serves *2K* single-antenna users with the RISs. In order to achieve the goals of enhancing the efficiency of the spectrum and decreasing the load on the system, the users are organised into K clusters where the k-th cluster, $k \in K = \{1, \dots, K\}$, includes one cell-edge user $U_{k,c}$ and one central user $U_{k,e}$.

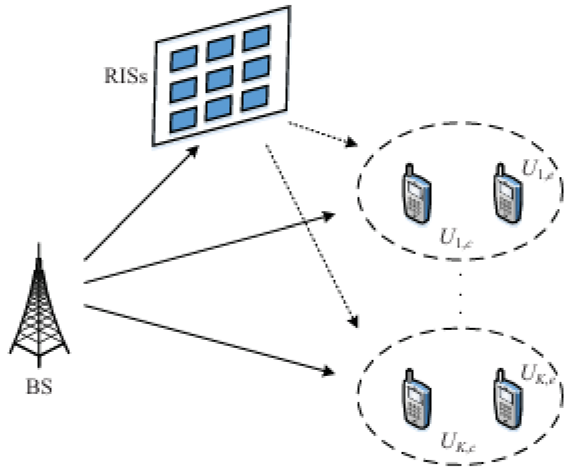

Figure 3: System model of a downlink RIS-NOMA communication networks (Li *et al.,* 2020)

For the system model in Figure 3, the complex baseband signal transmitted from the base station was formulated (Li *et al.,* 2020) as expressed by equation (8)

$$x = \sum_{k=1}^{K} \left(w_{k,c} s_{k,c} + w_{k,e} s_{k,e} \right) \tag{8}$$

where $s_{k,c}$ denotes the transmitted symbol for the central user, $s_{k,e}$ is the transmitted symbol for the cell edge user, while $w_{k,c}$ and $w_{k,e}$ represent the respective beamforming vectors intended for the central and the cell edge users in the *k*-th cluster.

The signal received by the users $U_{k,u}$was mathematically represented by equation (9);

$$y_{k,u} = \left(g_{k,u}^{H} \Phi \mathrm{H} + h_{k,u}^{H} \right) x + n_{k,u} \tag{9}$$

where Φ= diag(ϕ) symbolises the diagonal reflection coefficients matrix of the RIS; H, $g_{k,u}$ and $h_{k,u}$ denote the baseband equivalent channels from the base station to the reconfigurable intelligent surfaces, from the reconfigurable intelligent surfaces to user $U_{k,u}$, and from the base station to $U_{k,u}$, respectively.

4.3 Performance Analysis of RIS-aided NOMA

4.3.1 Capacity and throughput analysis

a. Effective capacity (EC)

EC is defined as the maximum constant arrival rate at the transmitter's queue under statistical QoS constraints. The concept of EC is introduced to quantify the accessibility of wireless systems under delay QoS constraints. Li *et al*. (2021) considers a RIS-aided NOMA network with a source (S), a RIS with N reflection elements, a near user (NU), and a far user (FU). The channels between the source, RIS, and users are modelled using independent Rayleigh fading. The work offers numerical analysis to confirm the accuracy of the generated equations, demonstrating that the far user's EC converges to a ceiling whereas the near user's EC rises linearly with SNR. Whereas, in the work of Liu *et al*. (2022), the EC for near users (Un) improves while that of far users (Um) remains the same at high SNR conditions.

According to Liu *et al*. (2022), the EC of near and far users are expressed by equations (10) and (11) respectively.

$$R_n = -\frac{1}{A} \log_2 \left(\int_0^{\infty} (1 + \gamma_n)^{-A} f(\gamma_n) d\gamma_n \right) \tag{10}$$

$$R_m = -\frac{1}{A}\log_2\left(\int_0^{\infty}(1+\gamma_m)^{-A} f(\gamma_m)d\gamma_m\right) \quad (11)$$

where A is the QoS exponent which characterizes the delay requirements of the user, γ is the SNR of user and $f(\gamma)$ is the probability density function of the user as the case may be.

These equations define the highest attainable data rate for near and far users respectively, subject to delay requirements when taking into account wireless channel statistical behavior. It is affirmed that the EC is strongly influenced by the amount of RIS elements, the more elements, the greater the EC. However, both authors assumed independent Rayleigh fading channels for simplicity and failed to investigate latency and QoS constraint.

b. Throughput analysis

In wireless communication, system throughput refers to the total amount of successful data transmission (often measured in bits per second, or bps) that a network or communication system can offer to all users or channels over a given period. It is a crucial performance indicator that shows how effective and large the wireless network is. In a RIS-aided NOMA system, system throughput is typically defined as the sum rate of all users served by the base station (BS), with the aid of the RIS and using power-domain multiplexing (Zuo *et al*., 2020).

The system throughput in a downlink RIS-aided NOMA system comprising of two users, strong user and weak user can then be given as in the equation (12):

$$R_{sum} = R_1 + R_2 \quad (12)$$

where R_1, symbolises the strong mobile user's rate that decodes and subtracts the weak mobile user's signal by using SIC before decoding its own, and R_2 represents the weak user's rate that decodes its signal by treating the strong user's signal as interference. Each rate is commonly represented by equation (13).

$$R_i = \log_2(1 + SINR_I) \quad (13)$$

The signal-to-interference-plus-noise ratio (SINR) for every signal is hence determined by the channel gains that the RIS strengthens, the NOMA power allocation, RIS phase shift settings and the noise power.

In delay-limited transmission mode, the RIS-NOMA networks yield system throughput which is governed by the outage behaviours of the non-orthogonal users that have constant data rate (Yue *et al*., 2018). In this regard, Liu *et al.* (2022) provide the same system throughput with hardware impairments as expressed by equation (14):

$$R_{dt,\Psi} = \left(1 - P_{n,\Psi}\right)R_n + (1 - P_m)R_m \quad (14)$$

where Ψ is a function of both perfect and imperfect SIC, P_n and P_m is the outage probability of users *n* and *m* respectively and R_n and R_m respectively denote the targeted data rates for users *n* and *m.*

4.3.2 Outage probability analysis

The likelihood that the SNR at the receiver will drop below a specific threshold is known as the outage probability (OP) (Kattekola *et al.,* (2023). Hou *et al*. (2020) described the OP as the probability that the achieved information rate falls below the specified target rate. The OP of a traditional NOMA and a RIS-assisted NOMA network are compared for performance analysis in Kattekola *et al.* (2023). The OPs of a near user (N) and far user (F) are provided by Cheng *et al*. (2021) respectively as expressed in equations (15) and (16).

$$\mathbb{P}_N^d = 1 - P_r\left(SINR_{N,F}^d \geq \tilde{\gamma}_F, SNR_N^d \geq \tilde{\gamma}_N\right) \quad (15)$$

$$\mathbb{P}_F^d = P_r\left(SINR_F^d < \tilde{\gamma}_F\right) \quad (16)$$

where $\tilde{\gamma}_N = 2^{\tilde{R}_N} - 1$ and $\tilde{\gamma}_F = 2^{\tilde{R}_F} - 1$ with $\tilde{R}_N$ and $\tilde{R}_F$ denoting the respective target rates of N and F. Cheng *et al*. (2021) pointed out that, for fixed-rate transmission systems, OP serves as a commonly utilised metric for measuring system performance.

5. Optimization Techniques for RIS-aided NOMA

Optimization is necessary to realise the full benefits of RIS-assisted NOMA systems. The power distribution to NOMA users, beamforming vectors at the BS, RIS phase shifts matrix and the SIC decoding order for every NOMA cluster are the variables that are frequently incorporated in the optimisation framework.

Improving the signal quality and user fairness of these networks is more challenging and can be achieved through the optimisation of phase shifts in RIS. Therefore, in the design of NOMA systems, possible data rates must be maximised depending on RIS phase shifts. Wu and Zhang (2020a) claimed that one can further improve the system metrics when beamforming is applied while the maximum phase shift is used. Although the reflection amplitude can also be changed, the authors observed that joint optimisation of both parameters offers significant difficulties. Zhang *et al*. (2020) also contend that appropriate phase shift design can reduce interference between users in Device-to- Device (D2D) communications, so improving data rates in heterogeneous networks.

Moreover, in the RIS aided NOMA systems, both phase shifts and power allocation are optimized jointly. Further implying a hybrid beamforming and phase shift optimisation to minimise mean squared error (MSE) in mmWave systems was suggested by Xiu *et al*. (2020). Given their revelations, it is shown that their system performance will also be much enhanced by better phase shift optimisation. Considering the downlink RIS-assisted NOMA system, Zuo *et al*. (2020) shows that jointly optimising phase shifts and resource allocation can raise the average sum rate and subsequently system efficiency.

5.1 Problem Formulation

The problem of joint optimisation is natively non-convex since the constraint of unit-modulus on phases shifts of RIS and the product of the reflection matrix element of channels and RIS are inherently non-convex. The objective function of RIS's optimisation framework can be any of the following depending on system goals:

1. Sum rate maximisation: The sum rate is the entire data rate among all the users, measured in bits per seconds (bits/s). Usually, its use is related to multiuser system performance. Generally, the maximisation problem is expressed as shown in equation (17).

$$\max_{\Theta, w_i, \rho_i} \sum_{k=1}^{K} R_k$$

where Θ is the RIS phase shift, w_i is the beamforming vector, ρ_i is the power allocated to user while R_k is the achievable rate for user *k.* (17)

2. Energy efficiency (EE) maximization: Identification of an optimal strategy to achieve maximal EE performance in intelligent reflecting surfaces (IRS) is of great relevance since energy efficiency (EE) is a fundamental performance metric for balancing throughput and power consumption. The optimisation problem is formulated as in equation (18).

$$\max \frac{\sum_{k=1}^{K} R_k}{P_{total} + P_{RIS}} \tag{18}$$

where P_{total} and P_{RIS} is the total transmit power and the power consumed by the RIS respectively.

3. Power optimisation: While making certain that the SNR at the receiver stays above a threshold, it is aimed to reduce power transmission at the base station by jointly optimising the transmit beamforming and reflect beamforming at the base station and the intelligent reflecting surface, respectively (Alghamdi *et al*., 2020). The model of this problem is presented in equation (14).

$$\min_{\Theta, p} \sum_{k=1}^{K} \|p\|^2 \tag{19}$$

where $\|p\|^2$ is the total transmit power.

4. Fairness-oriented rate: This is to ensure that the minimum achievable rate among all users in the system are maximised. The problem is formulated as expressed in equation (20).

$$\max_{\Theta, p, w} \min_{\mathrm{k}} \sum_{k=1}^{K} R_k \tag{20}$$

The problem is formulated to improve the minimum user rate, and commonly this is achieved through convex-concave methods or geometric programming (Mu *et al*., 2021). This goal will ensure that none of the users will be dropped below a specific rate.

5.2 Optimisation Techniques

There are several broad groups of main optimisation techniques employed in RIS-aided NOMA networks; the commonly used ones are:

5.2.1 Reflection coefficient-based optimization

Reflection coefficient-based optimization (RCO) focuses on enhancing the performance of the active beamformer in a transmitter by manipulating the effect of its companion passive beamformer. The method allows addressing a wider range of optimizations by focusing on the passive beamformer. The method has already been applied to minimising transmit power for a single user (Wu & Zhang. 2019) and reducing SINR for multiple users in MISO scenarios (Nadeem *et al.,* 2020). However, the RCO approach can be applied only when there is an explicit expression for the active beamformer, that frequently may not be available in more complicated wireless setups.

5.2.2 Alternating optimization

A complicated issue is often reduced into individual sub-problems through the use of the alternating optimisation (AO) approach. The technique proceeds by independently solving each component of the overall optimisation. Therefore, both the RIS phase shifts and the transmit beamforming and power allocation are optimised. Once the RIS has been configured, the method introduced by Wu and Zhang (2019) can be applied to improve the transmit settings. Most existing literature employs the AO algorithm to overcome the restrictions of conventional RCO methods. Approaches that optimise the active and passive beamformers in recursive steps are facilitated by the AO method.

The alternatives enable the separate optimisation of each problem section without requiring excessive computational resources. Many articles have utilised this method for enhancing either spectrum efficiency or energy efficiency in a multi-user MISO setting (Guo *et al.,* 2020; Huang *et al*., 2019). Another application is maximising the spectrum efficiency for a non-orthogonal multiple access (NOMA) system (Yang *et al*., 2020; Mu *et al*., 2020) and active RIS aided networks (Long *et al*., 2021). Though the AO method's implementation is simple, it alternately changes a set of variables on each iteration., so possibly requiring many iterations to reach convergence, especially in situations involving a significant number of RIS elements.

5.2.3 Project gradients

This iterative method maximises all variables over every iteration, thereby accelerating convergence and lowering computing complexity. This approach was proposed in Perovic *et al*. (2021a) and Perovic *et al*. (2021b) to solve the restrictions of AO methods in a RIS-assisted single-user MIMO system. In order to tackle the identified capacity maximisation challenge, the optimised active and passive beamformers consistently advance along the gradient of the objective, utilising a defined step size. The resulting solutions are then mapped onto the feasible region if they lie outside the feasible set before the subsequent iteration.

5.2.4 Semidefinite relaxation (SDR) optimization

This technique is applied to loosen rank restrictions and solve a semidefinite program (SDP) (Wu & Zhang, 2019), hence approximating non-convex quadratic optimisation problems (such as RIS phase design).

5.2.5 Successive Convex Approximation (SCA)

This procedure convexes the non-convex aspect by treating a chain of convex problems. Commonly used for cases, in which expressions containing the logarithmic, exponential, or fractional ones appear.

5.2.6 Fractional programming

Fractional Programming (FP) converts non-linear fractional objectives (i.e., those involving ratios of functions, e.g. signal-to-interference-plus-noise ratio (SINR)-based rate expressions or energy efficiency which is rate divided by power) into equivalent, more tractable subtractive or quadratic forms (Shen & Yu, 2018; Sharma *et al*., 2024).

5.2.7 Deep reinforcement learning

The online training of dynamic resource allocation methods, such as phase shifts and power tuning, is facilitated by deep reinforcement learning (DRL). It is efficient, as stated in research done by Zhang *et al.* (2019), under conditions that are continually changing in nature and uncertain data. In contrast to the AO method, which derives the active and passive beamformers in an alternating manner, the DRL approach enables the simultaneous design of both active and passive beamformers. This method optimises joint design by monitoring established rewards with ongoing states and behaviours via trial-and-error interactions with the environment. DRL-based approaches are employed in RIS-assisted multi-user systems to tackle optimization of spectrum efficiency as evidenced by Huang *et al.* (2020), secure capacity optimisation in Yang *et al.* (2020), energy-efficiency optimisation in Lee *et al.* (2020), and Terahertz communication beamforming optimisation in Huang *et al*. (2021).

5.2.8 Supervised learning for channel estimation

Because RIS is a passive device, estimating the channel in RIS-aided NOMA is highly complex. Methods based on learning can predict composite channels, which helps improve optimization in RIS deployments (Huang *et al*., 2019).

Table 1 presents a comparative analysis of typical optimization methods employed in RIS-aided NOMA systems so as to outline the peculiarities of their performance capabilities, the underlying effort of computational complexity, convergence, and practical considerations.

Table 1: Comparison of typical optimisation techniques used in RIS-aided NOMA

Technique **Features**	**Alternating Optimisation (AO)**	**Semidefinite Relaxation (SDR)**	**Successive Convex Approximation (SCA)**	**Fractional Programming (FP)**	**Deep Reinforcement Learning (DRL)**
Performance characteristics	Good local optimum. Sensitive to the initial solution selected.	Near-optimal/ Global optima of specific cases, provided the rank-one constraint is met naturally. Otherwise, gives a firm upper/ lower bound.	Near optimal performance, it can sometimes give better results than straight forward heuristic solutions. It is innately more robust to initial points than simple AO when the objective functions are highly non-convex	Good local optima. It serves especially well with problem related directly to SINR, energy efficiency or rate formulations. Can simplify non-convexity.	Achieves near-optimal solutions in complex, high-dimensional solutions, making real-time choices without specified channel models, making it better than model-oriented approaches in dynamic environments.

Computational complexity	Fairly low per iteration. It is easier to compute when compared to approaches such as Semidefinite Relaxation (SDR)	Very high. It is computationally expensive to solve, typically $O((MN)^3)$ or more, with M and N being the dimensions of the matrices.	High per iteration. A chain of convex optimization problems (e.g., SDPs or quadratically constrained quadratic programs, QCQPs) may be computationally demanding,	Moderate, High complexity varies based on transformation and iterative algorithms used to solve the equivalent non-fractional problem e.g. combining FP with AO or SCA.	Highly complex in training. Requires lots of computational power and time. Training can be done offline. Existence of Low Online Complexity. Once trained, inference application takes minimal time, requiring no iterative solution.
Scalability	relatively high scaling by adding more optimization variables	Poor for very large-scale problems as a result of high polynomial complexity.	Can be high when dealing with large-scale systems involving a large number of RIS elements and users	Can be scaled up more than SDR on some kinds of fractional computations	Extremely large state/ action spaces may be a problem with training.
Convergence	Guaranteed to converge to a stationary point (a local optimum) under mild conditions. Convergence speed: sometimes slow particularly when the sub-problems are highly coupled.	Guaranteed to reach global optimum of relaxed problem. The SDP itself is a convex problem that can efficiently be solved.	Guaranteed to converge to a stationary point (a local optimum) under suitable circumstances. Convergence speed: is faster and much more constant than simple AO of complex functions, but is itself an iterative method.	Certain to converge to a stationary point (a local optimum) when the conditions of the selected FP transformation and subsequent iterative solver are adopted. Convergence speed: depends on general algorithm setup	No convergence guarantee to optimal policy or stable policy. The processes that lead to learning might be unstable and hyper-parameters dependent. In practice, given enough training and thoughtful design, it is likely to go to a near-optimal policy

Practicality	Not too complex to implement, thus widely adopted	The algorithm is strong and localized, achieving rank-one solutions in tight-bound situations, but requires strong computing for real-time or massive-scale systems, necessitating rounding for optimality.	Extremely flexible, accommodating non-convex constraints. Needs mathematical reasoning for compact, efficient convex approximation. RIS phase shifts addressed through relaxation and quantization.	Naturally capable of maximizing performance metrics such as sum rate, energy efficiency and spectral efficiency which are typical targets of wireless communications.	Excellent for changing circumstances and on-the-fly work post-training. Does not require explicit channel model or complex mathematical proofs. Requires large data or long simulation runs for training. Faces issues like explainability, resistance to novel situations, and sim-to-real gap.
Appropriate Problem	Joint active/ passive beamforming design. Power allocation to RIS-NOMA problems where variables are logically split into smaller and solvable blocks.	Benchmarking RIS-NOMA Systems Performance. Joint active and passive beamforming problems.	Best suited for complex non-convex optimization problems with multiple variables and convex approximations, such as maximizing sum rate or energy efficiency.	Mainly applied in the optimization problems with the ratio of functions as an objective such as the sum rate maximization or the energy efficiency maximization in RIS-NOMA systems	Dynamic resource allocation and intelligent control. Adaptive beamformer. Channel estimation. User scheduling where the environment is highly dynamic or complex. Adaptive RIS deployment in mobile RIS-NOMA networks.

6. Challenges and Open Research Issues

The integration of RIS and NOMA networks holds great potential, but challenges must be addressed to fully exploit the performance gain. Channel estimation and feedback overhead are crucial for precise CSI in RIS-supported NOMA networks, but large-scale RIS and passive elements can be challenging due to their lack of active sensing capabilities (Almasi & Jafarkhani, 2023). Joint optimization becomes complex as the number of users and RIS reflecting elements increases, making current algorithms less applicable. Scalability and deployment strategy are also important, as the placement of RIS and number of elements for a particular context is not trivial (Gong *et al*., 2023). Base station and passive RIS control raise security and privacy issues, necessitating the development of straightforward and flexible security frameworks.

Hardware problems including phase noise and quantization errors must also be solved before the system can be used in practise. Standardization and interoperability are also key factors, given that there are no standardized models or frameworks for RIS-aided NOMA (Chen *et al*., 2022); and an accurate realistic channel modelling is handy for reliable protocol design and performance assessment on RIS-NOMA system.

7. Application and Future Direction

The use of RIS together with NOMA is expected to provide a revolutionary chance for modern wireless networks. RIS-assisted NOMA enhances spectrum efficiency and reduces connectivity issues such as dropped links and weak coverage while the dynamic control of the wireless channel becomes feasible. As a result, the adaptive technology can be utilised in a variety of sectors, such as ultra-dense networks, large-scale IoT, vehicular communications, and industrial automation. The capacity to modify the channel setting and dynamically organise resources encourages improved signal quality, energy optimization, and time delay minimization.

From the viewpoint of practical use, RIS-aided NOMA is anticipated to bring about robust coverage in difficult propagation settings including urban canyons and indoor settings, where transmission with a clear line of sight often fails. RIS can establish virtual line-of-sight paths and effectively mitigate interference in scenarios such as device-to-device communication, UAV connectivity, and integrated sensors and communications systems due to the tunable reflective elements. Besides, RIS's basic compatibility with advanced multiple access techniques indicates its suitability for enabling secure, energy-efficient, and simple solutions in 6G and post-6G networks.

On the research front, a number of important research directions must be thoroughly investigated. First, it is imperative to actively implement robust joint algorithms for concurrently designing RIS phase shifts, allocating transmit powers, optimising beamforming, and performing successive interference cancellation. Therefore, using artificial intelligence techniques, for example deep reinforcement learning and supervised learning frameworks, in conjunction with metaheuristic optimization show great promise for resolving the difficulties posed by the high-dimensional and highly dynamic nature of RIS-aided NOMA systems.

Second, it is important to handle practical problems including channel estimation under hardware impairments, quantization errors, and real-time reconfigurability to help close the gap between theory and practice. In addition, the development of hybrid systems that integrate both power-domain and code-domain NOMA for RIS-aided systems may bring about better performance and improved user fairness.

8. Conclusion

This review article has carefully surveyed the emerging direction of research in Reconfigurable Intelligent Surface (RIS)-aided Non-Orthogonal Multiple Access (NOMA) communications, which is a cornerstone paradigm, and as a result, wireless networks will experience a paradigm shift in the coming years. This paper started by explaining individual foundations of NOMA and RIS, discussing their positions as one of the ways to increase spectral efficiency and smartly utilize wireless environment, respectively. An in-depth evaluation of the effectiveness of the synergy between these two technologies that reveals that RIS is indeed a promising tool to overcome the inherent interferences and channel conditions of NOMA, which allows realising significant benefits in terms of achievable rates, energy efficiency and coverage, was highlighted.

Critical assessment of RIS-assisted networks architecture and performance of different important metrics demonstrated the great opportunity the current approach provides to other traditional NOMA and orthogonal multiple access (OMA) schemes. Nonetheless, it appears that despite the positive progress made, there are a number of challenges that can be considered formidable, such as hardware issues, mobility issues, security weaknesses, and the necessity to conduct experimental studies.

Summarily, RIS-aided NOMA could be viewed as a 6G and beyond breakthrough technology that might sustain the emerging needs of mass connectivity and data rates at unprecedented levels. As a part of this review, a unified, systematically organized picture of the present state-of-the-art was established, which might provide essential insights into the key design principles, performance potential and critical issues.

Our contribution consists of a synthesis of diverse efforts, a clear typology of known schemes, and a careful elucidation of the numerous technical factors. Although the current state of the research is quite positive, the named open research challenges, especially in the domain of AI-based solutions, interoperability with other advanced technologies such as millimetre wave, employing realistic channel models, as well as application-oriented issues of practical deployment testify to the potential area of future research. It is also hoped that these directions of research and development will be able to lead to the widespread implementation of RIS-NOMA, which will make a new era of intelligent and efficient wireless communications.

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