

RIS-Assisted Physical Layer Security in Emerging RF and Optical Wireless Communication Systems: A Comprehensive Survey

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Abstract—Security and latency are crucial aspects in the design of future wireless networks. Physical layer security (PLS) has received a growing interest from the research community in recent years for its ability to safeguard data confidentiality without relying on key distribution or encryption/decryption, and for its latency advantage over bit-level cryptographic techniques. However, the evolution towards the fifth generation (5G) technology and beyond poses new security challenges that must be addressed in order to fulfill the unprecedented performance requirements of future wireless communication networks. Among the potential key-enabling technologies, reconfigurable intelligent surface (RIS) has attracted extensive attention due to its ability to proactively and intelligently reconfigure the wireless propagation environment to combat dynamic wireless channel impairments. Consequently, the RIS technology can be adopted to improve the information-theoretic security of both radio frequency (RF) and optical wireless communications (OWC) systems. It is worth noting that the configuration of RIS in RF communications is different from the one in optical systems at many levels (e.g., RIS materials, signal characteristics, and functionalities). This survey

paper provides a comprehensive overview of the information-theoretic security of RIS-based RF and optical systems. The article first discusses the fundamental concepts of PLS and RIS technologies, followed by their combination in both RF and OWC systems. Subsequently, some optimization techniques are presented in the context of the underlying system model, followed by an assessment of the impact of RIS-assisted PLS through a comprehensive performance analysis. Given that the computational complexity of future communication systems that adopt RIS-assisted PLS is likely to increase rapidly as the number of interactions between the users and infrastructure grows, machine learning (ML) is seen as a promising approach to address this complexity issue while sustaining or improving the network performance. A discussion of recent research studies on RIS-assisted PLS-based systems embedded with ML is presented. Furthermore, some important open research challenges are proposed and discussed to provide insightful future research directions, with the aim of moving a step closer towards the development and implementation of the forthcoming sixth-generation (6G) wireless technology.

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Index Terms—Physical layer security (PLS), reconfigurable intelligent surface (RIS), smart radio environment, beyond 5G (B5G) networks, multiple-input multiple-output (MIMO), millimeter wave (mmWave), terahertz (THz), unmanned aerial vehicle (UAV), device-to-device (D2D) communication, cognitive radio networks (CRNs), simultaneous wireless information and power transfer (SWIPT), energy harvesting (EH), mobile edge computing (MEC), satellite communications, multicast communications, cell-free networks, relay-aided networks, vehicular communications, wireless body area network (WBAN), integrated sensing and communications (ISAC), internet-of-everything (IoT), industrial internet of thing (IIoT), internet of medical things (IoMT), backscatter communications, wireless sensor networks (WSNs), optical wireless communications (OWC), visible light communications (VLC), free space optical (FSO), high-altitude platform systems (HAPs), coordinated multipoint (CoMP) communications, blockchain technology, Ad-hoc networks, underwater communications, mixed reality, optimization, performance analysis, machine learning (ML), non-orthogonal multiple access (NOMA).

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LIST OF ABBREVIATIONS

2D	Two-dimensional
5G	Fifth generation
6G	Sixth generation
AANET	Aeronautical ad-hoc networks
AI	Artificial intelligence
AN	Artificial noise
AO	Alternating optimization
AP	Access point
AR	Augmented reality
ARIS	Aerial RIS
ASR	Average secrecy rate
BackCom	Backscatter communication
BCD	Block coordinate descent
BER	Bit error rate
BF	Beamforming
BS	Base station
CCP	Convex-concave procedure
CoMP	Coordinate multi-point
CRN	Cognitive radio network
CSI	Channel state information
D2D	Device-to-Device
DDPG	Deep deterministic policy gradient
DNN	Deep neural network
SWIPT	Simultaneous wireless information and power transfer
SymR	Symbiotic radio
TDD	Time division duplexing
THz	Terahertz
UAV	Unmanned aerial vehicle
V2X	Vehicle-to-everything
VLC	Visible light communications
VR	Virtual reality

WBAN	Wireless body area network
WPAN	Wireless personal area network
WPC	Wireless power communication
WPT	Wireless power transfer
WSNs	Wireless sensor networks
WSSCE	Weighted sum secrecy computation efficiency

I. INTRODUCTION

Despite the enormous potential of the fifth generation (5G) technology as a key enabler for the internet-of-everything (IoE), it is anticipated that the rapid emergence of fully intelligent and automated systems such as tactile internet, industrial automation, augmented reality (AR), mixed reality (MR), virtual reality (VR), telemedicine, haptics, flying vehicles, brain-computer interfaces, and connected autonomous systems, will overburden the capacity and limit the performance of 5G mobile networks in supporting the stringent requirements of next-generation networks such as extremely high-spectrum- and energy-efficiency, ultra-low latency, ultra-massive, and ubiquitous wireless connectivity, full dimensional network coverage, as well as connected intelligence [1]–[3]. As a result, there have been intensive research efforts from both industry and academia devoted to the sixth generation (6G) technology to meet such technical requirements and demands as it is expected to provide much improved key performance indicators (KPIs) [4], [5]. Fig. 1 shows a comparison between the 5G and 6G technologies in terms of some important KPIs.

Although the key requirements of the above-mentioned future wireless technologies are mainly characterized by low latency and high reliability, the leakage of critical and confidential information remains a challenge that must be addressed to fulfill its full potential. These security loopholes are due to the broadcast nature of the wireless environment, which makes it difficult to prevent information leakage by unauthorized receivers (e.g., an eavesdropper). To deal with security threats or attacks, cryptography-based tools have traditionally been adopted. However, such techniques may not be suitable for next-generation technologies for the following reasons: (a) cryptography algorithms cannot be adopted in resource-limited networks because they require a high computational complexity yielding a large amount of energy consumption [6]; (b) encryption-based techniques may not be able to sufficiently protect against information leakage due to the unlimited computing resources of the adversaries [7]; (c) processes involving key distribution and management in distributed networks (e.g., internet of things (IoT) and vehicular networks) are challenging. To overcome these limitations, physical layer security (PLS) has emerged as a promising solution to achieve secrecy by exploiting the inherent randomness of wireless channels [8]–[12]. Unlike encryption-based techniques, PLS does not require key distribution/sharing that may violate the low-latency requirements of future wireless systems and is therefore, an attractive approach to provide security and privacy for such systems. Several studies reported in the literature have investigated the PLS enhancement of wireless networks through artificial noise (AN) [13], cooperative jamming [14]–[16], beamforming [17], directional modulation [18], multiple-input multiple-output (MIMO) [19], etc. However, these techniques cannot always guarantee secure communication under

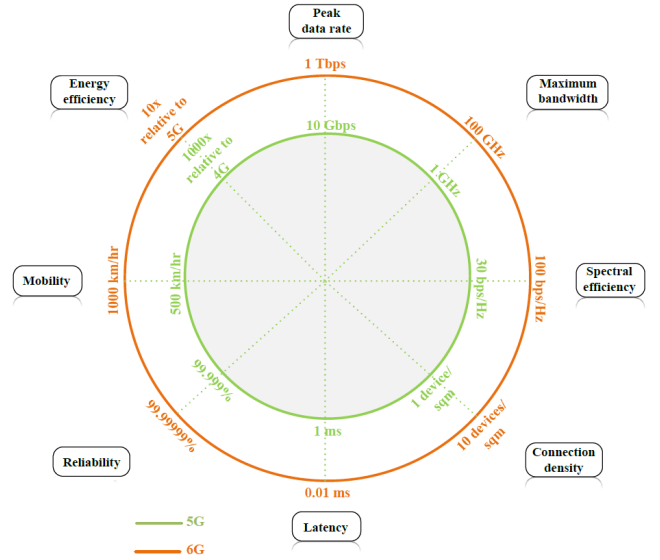


Fig. 1. Comparison of some KPIs between 5G and 6G communication systems.

certain system configurations. Additionally, they do require extra power and/or hardware costs for their practical implementation.

The advancement of metamaterial techniques has led to the emergence of a low-cost and energy-efficient wireless device termed reconfigurable intelligent surface (RIS) that can control the phase shift of the reflecting units via a programmable surface [20]–[22]. These features enable the RIS technology to intelligently reconfigure the wireless propagation environment. Unlike conventional techniques that only adapt to or with no limited control over dynamic wireless channels, RIS provides a new and cost-effective approach to combat channel impairments by guiding the reflected signal in a desirable direction for better reception reliability while suppressing the interference at unintended or unauthorized receivers [23]. These appealing features have motivated the integration of RIS into next-generation wireless networks for performance improvement. More specifically, RIS has been adopted into future wireless networks since it has the potential to offer an effective way for PLS improvements. In light of the above, RIS has emerged as a viable solution to tackle wireless security concerns from an information-theoretic perspective. By incorporating the RIS technology into PLS, a new paradigm that mitigates eavesdropping threats is introduced, leading to more secure and reliable communications for future wireless networks [24]–[27].

To fully implement the IoE concept, next-generation wireless networks will require large bandwidths due to their real-time demands. To this end, the exploration of high-frequency bands for radio frequency (RF) communications (e.g., millimeter wave (mmWave) and terahertz (THz)) and optical communications (e.g., free space optical (FSO), visible light communications (VLC), infrared (IR)) is imperative. However, communications occurring at these frequency bands suffer from severe atmospheric attenuations - owing to the absorption by water vapor and oxygen molecules - yield-

ing short transmission distances. Consequently, a dead-zone problem may arise in many scenarios (e.g., a long distance between the transmitter and the receiver or a blocked received signal due to an obstacle between the transmitter and the receiver). Recent efforts have adopted the RIS technology as an effective approach to solve skip-zone situations as opposed to the cooperative relaying technology (see [28]–[33] and the references therein) where the propagation of radio waves cannot be altered and/or controlled. Hence, RIS can be deployed in RF and optical communications in the high-frequency bands to mitigate privacy and security threats (e.g., jamming, eavesdropping, and pilot contamination attacks).

A. Related Work and Existing Surveys

Many works have reported the progress made on the integration of RIS in RF and/or optical systems for the development of future wireless communications to provide a plethora of services to the users (see [34]–[36] and references therein). In [34], a contemporary overview of the RIS architecture and deployment strategies in the future 6G was presented. On the latter, the authors particularly focused on the integration of the RIS technology with other 6G-enabling applications such as non-orthogonal multiple access (NOMA), THz/mmWave, unmanned aerial vehicle (UAV), mobile edge computing (MEC) and PLS for the system performance improvement. The research work of [35] provided an in-depth survey on the integration of RIS and UAV in the context of emerging communications, deep reinforcement learning (DRL), optimization, secrecy performance, and IoT. The authors of [36] presented a comprehensive tutorial on the design and application of indoor VLC systems utilizing the RIS technology. Moreover, an overview on optical RISs was provided and the differences with RF-RIS in terms of functionalities were highlighted. However, the security aspect of these systems was not investigated.

Only a handful of research works has considered the integration of RIS-assisted PLS for future wireless systems [26], [37]–[39]. In [26], the authors conducted a literature review on the information-theoretic security of RIS-assisted wireless networks focusing on the classification of the RIS-assisted PLS applications, on multi-antenna configurations, and on optimization problems for the maximization of some performance metrics (e.g., secrecy rate (SR), secrecy capacity (SC)). In [37], the authors reviewed the security challenges impacting the integration of RIS in future wireless networks. To this end, the authors outlined the security and privacy threats associated with the adoption of RIS and mmWave, THz, Device-to-Device (D2D), IoT networks, MEC, simultaneous wireless information and power transfer (SWIPT), integrated sensing and communications (ISAC), and UAVs. In [38], the authors discussed the designs of RIS-assisted PLS for 6G-IoT networks against security and privacy attacks. Moreover, simulation results are provided to illustrate the effectiveness of RIS from an information-theoretic viewpoint. The authors in [39] discussed the various secrecy performance metrics for wireless networks and presented an overview of RIS-assisted PLS for various multi-antenna technologies including

single-input single-output (SISO), multiple-input single-output (MISO) and MIMO. Some common points of existing research works are: (a) the reported studies of RIS-assisted PLS are mainly investigated in RF systems; (b) the issue of security from an information-theoretic perspective is partially investigated except for [39]. However, the work of [39] is limited to multi-antenna architectures in RF systems. To the best of the authors' knowledge, there is no comprehensive and up-to-date survey in the open literature that discusses information-theoretic aspects of RIS-assisted RF and optical wireless communication (OWC) systems. To this end, our motivation is to close this knowledge gap by specifically focusing on the following aspects:

- *Integration of RIS technology with PLS in RF communication systems:* We first introduce some PLS techniques such as AN, beamforming (BF) and cooperative jamming to mitigate the security threats in different scenarios for future wireless communication systems. Subsequently, we provide valuable insights into the adaptability and optimization of RIS for various communication scenarios. We also highlight the scalability and adaptability of the RIS-assisted PLS techniques when the network complexity increases. Moreover, we outline the integration of RIS in emerging RF communication systems, namely with multi-antenna communications, mmWave communications, THz communications, UAV communications, D2D communications, cognitive radio networks (CRNs), wireless power communication (WPC)/SWIPT, MEC, satellite-enabled networks, multicast communications, cell-free networks, relay-aided networks, vehicular communications, wireless body area network (WBAN), ad-hoc networks, ISAC, radar communications, IoT networks, backscatter communications, wireless sensor networks, and high-altitude platform systems (HAPS).
- *Integration of RIS technology with PLS in OWC systems:* We review the integration of RIS-assisted PLS in VLC systems by discussing its evolution from single-user scenarios for static or mobile user to multi-user scenarios. Furthermore, an extension of the RIS-assisted PLS in hybrid VLC-RF and FSO-RF systems is discussed with emphasis on the motivation for such mixed systems and some useful secrecy performance measures.
- *Optimization techniques:* We first review state-of-the-art optimization techniques for PLS and then summarize existing optimization strategies for the SR maximization and various secrecy metrics associated with RIS-assisted PLS systems such as: (a) alternating optimization (AO) and block coordinate descent (BCD) to decouple joint optimization variables into sub-problems; (b) semidefinite relaxation (SDR) to relax non-convex RIS phase constraints; (c) majorization-minimization (MM), successive convex approximation (SCA), and quadratic transform for non-convex and nonlinear objective functions and constraint; (d) convex-concave procedure (CCP) to solve the base station (BS) beamforming sub-optimization problem. A discussion on the optimization of the SR and various secrecy metrics (e.g. signal-to-noise ratio (SNR), power consumption, computation and energy efficiencies,

ergodic secrecy rate, channel gain, secrecy key rate, utility function and outage probability) ensue.

- *Machine learning techniques:* Machine learning (ML) has become popular in wireless communications due to its ability to solve complex optimization problems in wireless networks. We explore state-of-the-art ML techniques for optimizing RIS-assisted PLS in RF and OWC systems, such as DRL and unsupervised learning. Besides addressing the issues associated with the stringent requirements of future wireless communication networks, the adoption of ML algorithms in improving the security of wireless networks results in some advantages, such as proactive detection and preventive threats.
- *Performance analysis:* We explore the improvement of some performance metrics (SNR, SC and secrecy outage probability (SOP)) via the integration of the RIS technology within the context of PLS in RF and OWC systems. Furthermore, we highlight the important role of RIS to mitigate the noise and increase the signal strength on one hand and to improve the SC and reduce the SOP on the other hand.
- *Applications and challenges:* We give a general review of applications of RIS-assisted PLS towards future wireless networks including all the aforementioned technologies mentioned in the first two bullets. Moreover, we discuss how the integration of RIS and cutting-edge technologies can improve the security of future wireless networks. Finally, we highlight some key research challenges and future directions for RIS-assisted PLS in upcoming wireless networks.

B. Paper Organization

The remainder of this survey paper is organized as follows. Section II presents the basic concepts of PLS followed by a description of the type of attacks and performance metrics in PLS. Section III introduces the RIS technology and its fundamental principles that enable its basic operation. A description of the RIS architectures and the integration of this emerging technology in optical systems is subsequently provided. Section IV discusses PLS techniques associated with RIS-aided systems, and further explores the efficacy of integrating RIS with RF-based emerging technologies for security and privacy improvements of future wireless communication systems. Section V elaborates on PLS in wireless systems that integrate RIS with OWC. Some optimization techniques tailored for RIS-assisted PLS are comprehensively reviewed in Section VI. Section VII explores various ML techniques adopted for the optimization of RIS-assisted PLS for both RF and optical systems. Section VIII highlights the impact of RIS-assisted PLS from a performance analysis viewpoint. Section IX highlights the key challenges and future research directions associated with the adoption of RIS-assisted PLS in future wireless networks. Further discussions on the integration of PLS and cutting-edge technologies to improve wireless network security are presented. Concluding remarks are given in Section X.

II. PLS FUNDAMENTALS

A. Introduction to PLS

Wireless communication is crucial in connecting individuals globally, regardless of location or time. While wireless technologies offer numerous advantages, it is essential to acknowledge the significant risk users face from potential attacks due to the broadcast nature of wireless signals. As a result, the attention to communication security has increased. The conventional approach to enhancing communication security involves employing encryption techniques in the upper layers of the communication stack to protect user data [8]. However, these methods have limitations regarding adaptability and flexibility owing to computational tasks and system complexity. Additionally, the unique characteristics of wireless channels enable signals to be transmitted securely between transmitters and receivers at the physical layer. This concept has proven effective in improving communication security. Consequently, PLS has emerged as a prominent topic of interest, given the advancements in wireless communication techniques [9], [40]. In this section, we will provide the fundamentals of PLS, covering its concepts, technical evolution, and applications in wireless networks.

In 1949, Shannon established the information-theoretic principles that form the basis of modern cryptography [41]. Shannon's model encompassed the assumption that a non-reusable private key, denoted as \mathcal{K} , is employed to encrypt a confidential message, referred to as \mathcal{M} , generating a cryptogram, denoted as \mathcal{C} . This cryptogram is subsequently transmitted across a channel that is assumed to be noise-free. The eavesdropper, characterized by unlimited computational power, knowledge of the transmission coding scheme, and access to an identical copy of the signal intended for the receiver, is considered. The concept of perfect secrecy was introduced, which necessitates that the *a posteriori* probability of the eavesdropper correctly deducing the secret message based on the received signal is equal to the *a priori* probability of that message. In essence, perfect secrecy implies that the eavesdropper gains no additional knowledge about the secret message beyond what was already known before intercepting the signal. From the information-theoretic perspective, perfect secrecy can be expressed as

$$I(\mathcal{M}; \mathcal{C}) = 0, \quad (1)$$

where $I(\cdot; \cdot)$ represent mutual information. Equation (1) states that the mutual information between the message \mathcal{M} and the cryptogram \mathcal{C} is zero, indicating their statistical independence. This absence of correlation implies that there exists no means for the adversary to obtain information about the original message. Thus, perfect secrecy can only be assured if and only if the secret key \mathcal{K} possesses entropy that is equal to or greater than that of the message \mathcal{M} , i.e., $H(\mathcal{K}) \geq H(\mathcal{M})$, where $H(\cdot)$ is the entropy.

In 1975, Wyner introduced a significant advancement in the area of information-theoretic security with the proposal of the wiretap channel [42]. Wyner's system, in contrast to Shannon's original secrecy system, incorporated a random noise channel, which is considered an inherent element of

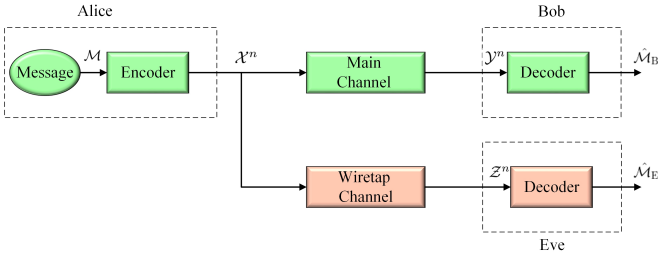


Fig. 2. Wireless wiretap system model.

physical communications. As illustrated in Fig. 2, comprising the system consists of a legitimate transmitter and receiver, which are commonly designated as Alice and Bob, respectively, the general wiretap model of PLS endeavors to establish communication while contending with the existence of an eavesdropper, commonly referred to as Eve. Both the legitimate channel and the wiretap channel are modeled as discrete memoryless channels. The transmitter encodes the message \mathcal{M} into a codeword \mathcal{X}^n comprising n symbols, where $\mathcal{X}^n = [\mathcal{X}_1, \dots, \mathcal{X}_n]$, and transmits it to the intended receiver as a degraded message \mathcal{Y}^n , where $\mathcal{Y}^n = [\mathcal{Y}_1, \dots, \mathcal{Y}_n]$, while simultaneously sending it via a wiretap channel to the adversary as \mathcal{Z}^n , where $\mathcal{Z}^n = [\mathcal{Z}_1, \dots, \mathcal{Z}_n]$, as illustrated in Fig. 2. Moreover, Wyner proposed an alternative definition for perfect secrecy instead of (1). A new secrecy condition was introduced, according to which the equivocation rate $\mathcal{R}_e = \frac{1}{n}H(\mathcal{M}/\mathcal{Z}^n)$ should approach the entropy rate \mathcal{R} of the message $\mathcal{R} = \frac{1}{n}H(\mathcal{M})$ as n tends to infinity. Consequently, as the value of $\mathcal{R} - \mathcal{R}_e = \frac{1}{n}I(\mathcal{M}; \mathcal{Z}^n)$ suggests, the message \mathcal{M} gradually achieves perfect security against the adversary if $\frac{1}{n}I(\mathcal{M}; \mathcal{Z}^n) \leq \varepsilon$, where ε is arbitrarily small, positive number [43]. Furthermore, Wyner defined the secrecy capacity as the highest achievable transmission rate to the legitimate receiver that guarantees reliability and information-theoretic security against eavesdroppers.

B. Categorization of Attacks in PLS

In PLS, attacks can be classified into two categories based on the capabilities of the illegitimate nodes: passive attacks and active attacks [10]. Passive attacks involve illegitimate nodes assuming the role of eavesdroppers, discreetly intercepting transmitted information from legitimate wireless channels without actively transmitting any signals. By concealing their presence, these nodes do not disrupt network operations. Their primary objective is to clandestinely intercept and potentially analyze the information received from the legitimate source, Alice. Consequently, it becomes imperative to prevent eavesdroppers from successfully intercepting information by employing carefully designed signaling techniques [44].

On the other hand, active attacks involve illegitimate nodes with the capacity to withstand the risk of detection by legitimate nodes, enabling them to engage in powerful active attacks. These nodes transmit deceptive signals to confuse the intended recipient, Bob. They can intercept and forge messages, thus compromising the security performance of the communication system. Such attacks are also known as

masquerade attacks [10]. Also, malicious nodes can act as jammers, transmitting noisy signals intending to interrupt communication [45]. When Bob receives both the desired and jamming signals simultaneously, the legitimacy of the intended signal becomes less trustworthy. Consequently, the legitimate signal may fail to be decoded. Active attacks can significantly impact normal network operations since adversaries seek to manipulate network data. In the event of an attack, legitimate users must identify the presence of such attacks and subsequently implement appropriate protective measures to safeguard the transmitted signal accordingly.

C. Secrecy Performance Metrics

1) *Secrecy Rate*: The SR of the Gaussian noise wiretap channel is determined by calculating the difference between the achievable rates of the main channel and the wiretap channel when utilizing a Gaussian codebook [45]. Mathematically, the secrecy rate, \mathcal{R}_s , can be represented as

$$\mathcal{R}_s = [\mathcal{R}_b - \mathcal{R}_e]^+, \quad (2)$$

where \mathcal{R}_b is the achievable rate of the legitimate link, \mathcal{R}_e is the achievable rate of the eavesdropping link, and $[x, 0]^+ = \max(x, 0)$.

2) *Secrecy Capacity*: The SC, \mathcal{C}_s , can be defined as the highest achievable rate \mathcal{R}_s that ensures perfect secrecy rate, i.e., the maximum rate at which secure information can be transmitted over a wireless channel while maintaining confidentiality [46]. Secrecy capacity indicates the amount of secure communication that can be achieved in the presence of eavesdroppers. In this regard, \mathcal{C}_s can be obtained by

$$\mathcal{C}_s = [\mathcal{C}_b - \mathcal{C}_e, 0]^+, \quad (3)$$

where \mathcal{C}_b and \mathcal{C}_e are the legitimate link and the eavesdropping link capacities, respectively. The primary requirement in this context is that \mathcal{C}_b should be greater than \mathcal{C}_e , highlighting the crucial aspect that the quality of the main channel must surpass that of the wiretap channel, regardless of the computational capabilities possessed by the eavesdropper.

3) *Secrecy Outage Probability*: In specific scenarios, Alice may not possess perfect channel state information (CSI) regarding Bob and Eve. Consequently, the SOP is employed as a performance metric. The secrecy outage occurs when the current secrecy rate \mathcal{R}_s falls below a predefined threshold, indicating an inability to meet the security requirement. The secrecy outage probability corresponds to the likelihood of observing a secrecy outage given a specific fading distribution [47]. Mathematically, it is represented as:

$$\text{SOP} = \Pr(\mathcal{C}_s < \mathcal{R}_s). \quad (4)$$

4) *Probability of Non-Zero Secrecy Capacity*: The probability of non-zero secrecy capacity (PNSC), which can be called the probability of positive secrecy capacity (PPSC) or strictly positive secrecy capacity (SPSC), is a performance metric used in PLS to evaluate the probability that a secure communication link can be established, i.e., the probability that the secrecy capacity is greater than zero. It indicates the likelihood of achieving positive, secure communication

rates and provides insights into the effectiveness of PLS mechanisms [48], [49], which is given as

$$\text{PNSC} = \Pr(\mathcal{C}_s > 0). \quad (5)$$

5) *Intercept Probability*: The intercept probability (IP), P_{int} , is a performance metric used to assess the vulnerability of wireless communication systems to eavesdropping attacks. The intercept probability is the likelihood that \mathcal{C}_s of a wireless communication system is below zero, indicating a situation where the system fails to achieve secure communication [50], [51], which is given as

$$P_{\text{int}} = \Pr(\mathcal{C}_s < 0). \quad (6)$$

This probability quantifies the vulnerability of the system to unauthorized interception and provides insight into the probability of unsuccessful secrecy establishment. A lower intercept probability indicates a more secure system, while a higher intercept probability indicates a higher vulnerability to eavesdropping. It serves as a crucial metric for evaluating system security and guiding the implementation of PLS techniques to mitigate interception risks and enhance the confidentiality of communication.

6) *Ergodic Secrecy Capacity*: The ergodic secrecy capacity (ESC) refers to the statistical mean of the secrecy rate across fading channels. This metric provides insights into the system's ability to maintain confidentiality over time. Mathematically, the ESC, \mathcal{R}_s , can be represented as

$$\mathcal{R}_s = \mathbb{E}[\mathcal{C}_b - \mathcal{C}_e, 0]^+. \quad (7)$$

7) *Effective Secrecy Throughput*: the effective secrecy throughput (EST) is a metric introduced in [52] to explicitly account for the reliability and secrecy constraints inherent in wiretap channels. This metric quantifies the average rate at which confidential information is transmitted from the transmitter to the receiver without being wiretapped. In this regard, EST can be obtained by [52]

$$\text{EST} = (\mathcal{R}_b - \mathcal{R}_e) [1 - \mathcal{O}_r(\mathcal{R}_b)] [1 - \mathcal{O}_s(\mathcal{R}_e)], \quad (8)$$

where $\mathcal{O}_r(\mathcal{R}_b) = \Pr(\mathcal{R}_b > \mathcal{C}_b)$ and $\mathcal{O}_s(\mathcal{R}_e) = \Pr(\mathcal{R}_e < \mathcal{C}_e)$ are the reliability outage probability and the SOP, respectively.

D. Techniques for Achieving PLS

PLS techniques have been extensively studied and developed to enhance the security of wireless communications at the physical layer. These techniques exploit the unique characteristics of the wireless channel to protect the confidentiality and integrity of transmitted data. One well-known technique is artificial noise generation [53], which involves deliberately introducing carefully designed random noise to confuse eavesdroppers and make it difficult for them to decode the desired signal accurately. Beamforming is another effective technique [54] that focuses the transmitted signal toward the intended receiver while minimizing signal leakage to unintended eavesdroppers, thereby improving communication security. Secure coding schemes, incorporating error correction and channel coding techniques, add redundancy and error correction capabilities to thwart eavesdroppers' decoding

attempts [55]. Physical layer key generation leverages the channel's randomness to establish shared secret keys between communicating parties [56]. Interference alignment aligns interference caused by eavesdroppers to minimize its impact on the desired signal [57]. Cooperative jamming involves the coordinated transmission of jamming signals to disrupt eavesdroppers' reception [58], [59]. These techniques, among others, have demonstrated their effectiveness in enhancing the security of wireless communications at the physical layer (see [60] and the references therein). Their selection and adaptation depend on system requirements, channel conditions, and potential eavesdropper capabilities, and combining multiple techniques can further bolster communication security. The significance of PLS approaches within relay networks is highlighted by the heightened susceptibility of intermediate relay nodes to potential wiretapping compared to other network terminals [61], [62].

III. RIS: ARCHITECTURE AND CAPABILITIES

This section first introduces the RIS technology before delving into the fundamental working principles that enable their operation. Subsequently, a discussion on the RIS architecture is presented, followed by the integration of such a technology into RF and OWC systems.

A. Introduction to RISs

RISs are man-made sheets of electromagnetic (EM) material with programmable macroscopic physical characteristics that intelligently reconfigure the wireless propagation environment by guiding or modifying the impinged radio waves in a desirable direction (e.g., through reflection, refraction, diffraction properties) to boost the signal power at intended receivers and/or to suppress interference at unintended receivers [22], [23], [63]–[65]. Furthermore, they consist of a large number of low-cost and low-power scattering elements that can individually adjust the wireless channel by digitally tuning the amplitude and/or phase shift of the incident signal. This tuning mechanism does not require power amplifiers or modulation/demodulation, making the RIS technology attractive to fulfill one of the requirements for future wireless communication systems. In general, RISs can be considered as nearly-passive devices as they require power only for ensuring their reconfigurability. Recently, hybrid RISs have been proposed where some elements may be active [66]. Unlike similar key-enabling technologies for 5G and beyond (e.g., active relays, massive MIMO, ultra-dense networks and mmWave communications [67]) that can compensate or adapt to no or with limited control over dynamic wireless channels, RISs provide an innovative and cost-effective approach to achieve the KPIs of 5G and beyond (see Fig. 1) without the need for power amplifiers, RF chains, and information encoding/decoding algorithms [2].

In light of the potential benefits, the RIS technology has emerged as a promising solution to mitigate a range of practical challenges inherent to future wireless systems such as the ever-increasing energy consumption, hardware cost, and intra-/inter-system interference. Besides controlling the wireless

environment to a certain extent, RISs are economical and environmental friendly due to their low-power consumption and carbon footprint. Moreover, they yield improvement of key performance metrics such as network coverage, spectral efficiency, throughput, and energy efficiency, especially in deep-fade and non-line-of-sight (NLoS) environments wherein the transmitted signal cannot reach the end user with enough power. Moreover, they can readily and seamlessly be integrated into existing wireless networks by mounting them on various structures such as building facades, walls, ceilings, roadside billboards, clothes as well as mobile vehicles due to their flexibility [68]. Fig. 8 illustrates examples of some RISs deployments that have been widely investigated in the existing literature.

B. Working Principles and Basic Architecture

In what follows, we provide an overview of the working principles of the RIS technology as well as its architecture from a hardware architecture and operating principles viewpoint.

1) *Working Principles*: An RIS is a two-dimensional (2D) planar metasurface consisting of a very large number of nearly-passive elements that reflect the impinging EM in a desired manner by adjusting the phase and the amplitude of the incident signals. In practice, an RIS can be implemented by using different technologies, such as liquid crystals, microelectromechanical systems, doped semiconductors, and electromechanical switches [69]. Broadly speaking, to operate an RIS needs a smart controller, and it often consists of three layers:

- A meta-atom layer that consists of a large number of passive scattering elements interacting directly with the incident signals.
- A control layer that aims at adjusting the reflection amplitude and phase shift of each meta-atom element, triggered by the smart controller.
- A communication layer that serves as a gateway to communicate between the control layer and other network components (e.g. BSs, access points (APs), etc.).

As mentioned, the most studied implementation for RIS assumes that the RIS elements are nearly passive, i.e., they do not amplify the incident signals (see [20], [22], [23], [63], [70]–[72] and references therein). Due to the absence of power amplifiers, a nearly-passive RIS needs to be sufficiently large in size in order to achieve the desired beamforming gain in the far field, since in this regime the path-loss scales with the product of the transmitter-RIS and RIS-receiver links [73], [74]. To increase the coverage of an RIS-aided link while keeping the size of the RIS small, a possible solution is to use active or hybrid RISs [75]–[78]. The reflecting elements of an active RIS consist of active RF components, which are capable of amplifying the incident signals. Although the basic operation principle is the same in both the passive and active RIS, the latter necessitates additional power consumption during the amplification process to support the active elements.

2) *RIS Architecture*: Each RIS reflecting element is conventionally controlled by a tunable circuit, which can be

modeled as a tunable impedance connected to the ground [79]. In [80], two new circuit topologies have been proposed, wherein all or a subset of the RIS reflecting elements are connected via a reconfigurable impedance network. Based on the connection configuration of the reflecting elements, an RIS can be classified into three types of architecture (see Fig. 3):

- **Single connected RIS**: This is the conventional architecture widely adopted in the literature in which each RIS reflecting element is independently controlled by a reconfigurable impedance connected to the ground. It is the simplest of all the RIS architectures with limited performance.
- **Fully connected RIS**: In this setup, each RIS element is connected to all the other reflecting elements through a reconfigurable impedance network. This architecture enables an improvement of the RIS received signal power due to the additional degrees of freedom [80]. However, this performance gain comes at the cost of a complex circuit topology.
- **Group or partially connected RIS**: As the number of reconfigurable impedance components in the network becomes increasingly large, the practical use of the fully connected RIS is limited. Consequently, the group/partially RIS architecture represents a good trade-off between complexity and performance as it combines both the single and fully connected RIS architectures.

Recent results have shown that RISs with inter-element circuit connections, which are often referred to as beyond diagonal RISs, are especially useful in the presence of mutual coupling among the RIS elements, as they enable to better control the electromagnetic coupling among the elements [81].

C. Reflection Modes and Deployment Techniques

1) *Reflection Modes*: Fig. 4 depicts the reflected and refracted signals from the incident signal of a generic RIS element. With an appropriate design of the geometric parameters and arrangement of the meta-atoms, the incident signal on the meta-surface can be controlled in three possible modes [82], [83]: reflective, refractive, and reflective-refractive.

- In the reflective-refractive mode, the surface can simultaneously reflect and refract the incident signal to serve users on either side of the surface. This surface is also called intelligent omni-surface (IOS) [84] or simultaneous transmitting and reflecting (STAR)-RIS [85], [86], and has been proposed to address the half-space limitation of reflecting-only RISs [22], [87], [88]. Here, the amplitude response of both the reflection and transmission coefficients, denoted by Γ_l and Γ_r , respectively, are non-negligible.
- In the reflective mode, the surface fully reflects the incident signal in the direction of the users located on the same side of the transmitter. This is possible through an RIS [89] whose transmission coefficient is close to zero to ensure that the energy of the incident signal can be optimally reflected by the surface.
- In the refractive mode, the surface also known as reconfigurable refractive surface (RRS) (see [90]) fully refracts

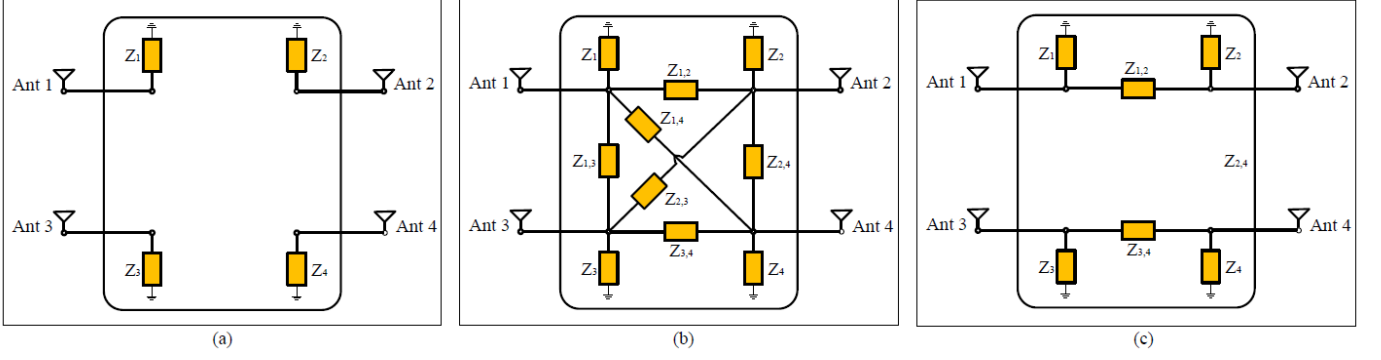


Fig. 3. 4-element RIS with (a) single connected reconfigurable impedance network, (b) fully connected reconfigurable impedance network, and (c) group connected (2 groups and group size of 2) reconfigurable impedance network. RE X stands for RIS element X with $X \in \{1, 2, 3, 4\}$.

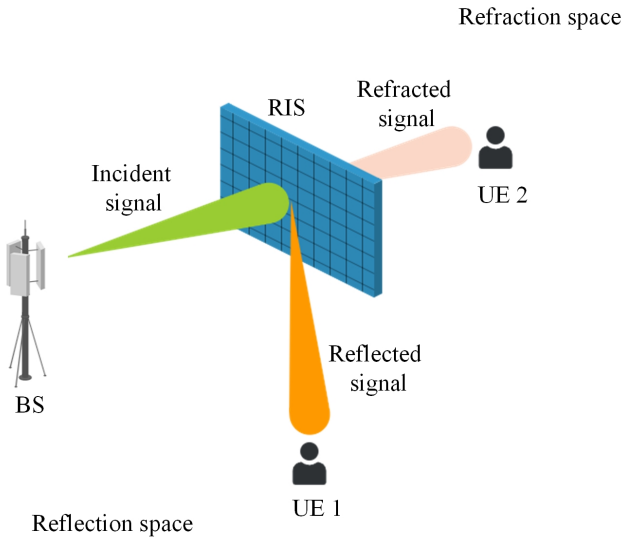


Fig. 4. Illustration of signal propagation on an RIS, where Tx denotes the transmitter, UE1 and UE2 denote User 1 and User 2, respectively.

the incident EM wave to serve users located on the opposite side of the transmitter with respect to the surface. To ensure that the incident signal fully penetrates the surface, it is required that the transmission coefficient is much larger than the reflection coefficient, which should be ideally equal to zero.

As illustrated in Table I, an IOS encompasses reflecting and refracting RISs, provided that the reflection and transmission coefficients can be appropriately optimized.

TABLE I
VARIOUS RIS MODES

RIS Modes	IOS	
	Reflective-Refractive	
	IRS Reflective	RRS Refractive

2) *Deployment Techniques*: To further improve the performance gains of RIS-assisted wireless networks, it is crucial to appropriately design the reflection pattern of the RIS and optimize its deployment in various system setups (i.e.,

single/multi-antenna, single/multi-user [20], [91], [92]). However, the design of the reflection coefficients is an intricate task since the location of the RIS, which is dependent on the path-loss function, is different from that of a relay. To this end, the pioneer work of [93] has devoted great effort to address this issue for a single-user scenario. For a more general multi-user cluster scenario, [94] reviews two RIS deployment architectures in an effort to reduce the resultant double path loss of the RIS-enabled link. From the perspective of RIS deployment, there are two main strategies [95]–[98]: distributed RIS and centralized RIS. Fig. 5 illustrates a downlink communication between a BS and a single and multiple user clusters in a centralized and distributed manner, respectively.

- **Centralized RIS**: For the centralized RIS setup, multiple RIS elements are co-located to form or are grouped as a single large RIS and placed in the vicinity of an AP as shown in Fig. 5 (on the left-hand side).
- **Distributed RIS**: For the distributed RIS strategy as illustrated in Fig. 5 (on the right-hand side), all the RIS elements can be partitioned into multiple RISs, each of them placed near a user cluster to serve the latter. Due to the multiple RISs, there is a greater probability of establishing line-of-sight (LoS) between the AP or BS and the RISs than the one in the centralized RIS scenario. However, the communication between the AP or BS and the RISs requires some level of coordination leading to an increase in the signaling overhead.

From a system performance viewpoint, both strategies yield different user achievable rates. This is because their respective effective channels between the user and AP are different from one another. Although the users or user clusters in a central deployment scenario enjoy strong passive beamforming (due to the large a RIS size), they suffer from a reduction in the gain (as a result of sharing the resulting gain among all the users). However, the users in the distributed deployment strategy enjoy a better gain (since the gain is not shared among users or user clusters from different RISs) albeit a weaker beamforming gain. This weak gain is due to the fact that the reflected signals by other RISs placed far apart from the RIS of interest, are very weak as a result of the significant path loss.

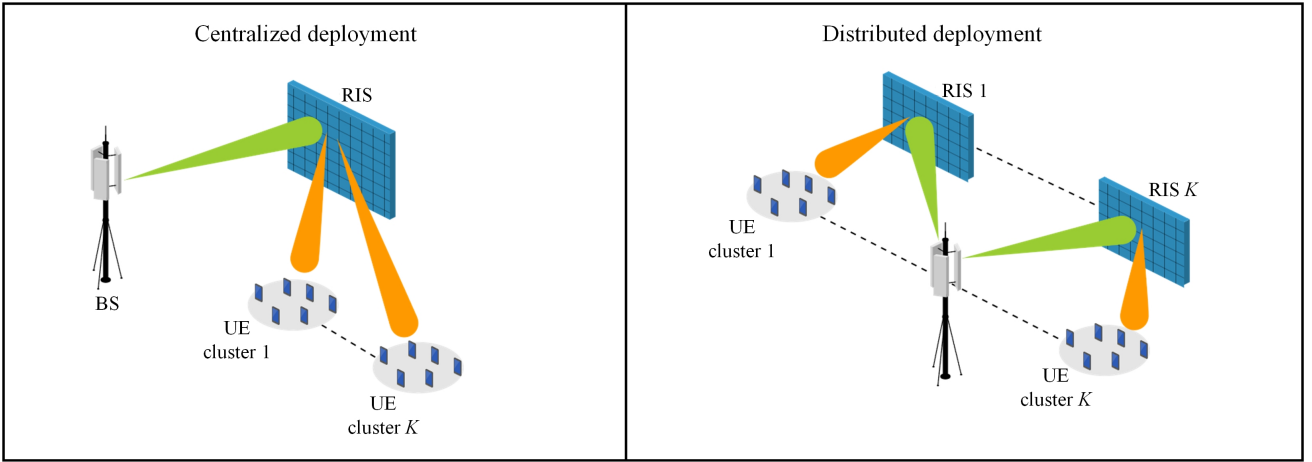


Fig. 5. An RIS-aided multi-user downlink communication system with different RIS deployment strategies.

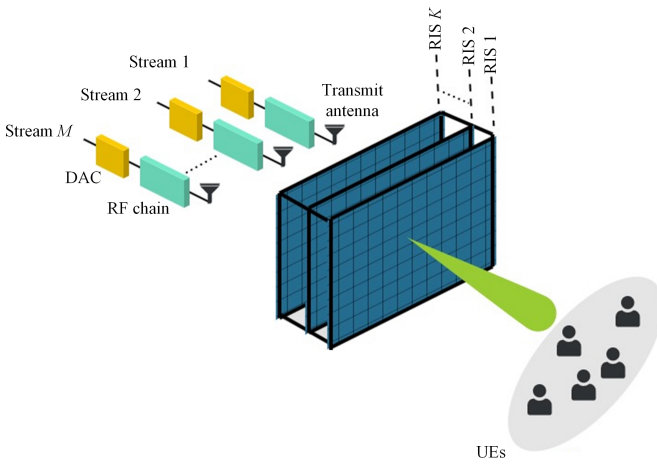


Fig. 6. A stacked intelligent metasurface-assisted multi-user MISO downlink system.

3) *Multi-layer RIS (or Stacked Intelligent Meta-surface)*: Beyond-diagonal RISs offer more degree of freedom for optimization in the presence of mutual coupling; however, they increase the complexity and power consumption. An alternative way to realize a non-diagonal scattering matrix is to leverage the multi-layer RIS architecture that is presented in [99] and [100], and it is illustrated in Fig. 6. A multi-layer RIS is constituted by closely spaced refracting metasurfaces: The incident signal illuminates the first layer, which then refracts the signal towards the second layer, etc., until the signal reaches the last layer, where it is finally radiated towards the receiver. As the wave propagates through the layers, it is appropriately shaped by the tunable meta-atoms in each of the layers, resulting in an end-to-end scattering matrix that is not diagonal anymore thanks to the broadcast nature of wireless signals when propagating from one layer to another [100, eq. 7 and Fig. 2]. In other words, a non-diagonal scattering matrix is obtained by utilizing dynamic refracting metasurfaces each equipped with single-connected electronics.

D. Optical RIS

The RIS technology discussed thus far in this section is based on its integration for RF communications. Unlike RF systems where RISs can manipulate the phase of the reflected signal, the integration of RIS in optical wireless systems¹ is possible using either a mirror arrays-based RISs or a meta-surface based RISs designed to steer the light [104]–[106].

In RIS-aided VLC systems, phase control is not directly applicable, as these systems operate with intensity modulation and direct detection (IM/DD), focusing solely on the non-negative and real part of the signal [107]. There are three primary approaches to incorporating RIS into VLC systems, namely, mirror array-based RIS [107]–[111], meta-surface-based RIS [112]–[116], and liquid crystal (LC)-based RIS [117]–[120]. Both the mirror array-based and meta-surface-based optical RISs consist of nearly-passive elements in the form of mirror arrays or intelligent metasurfaces used to control incident lights based on the light reflection or refraction principle and the manipulation of the EM waves, while the latter uses LCs as front-row materials embedded in a layered structure to control light reflection and/or refraction.

1) *Mirror Array-based RIS*: The mirror array-based RIS is typically made of glass with a flat or curvy surface covered by a reflective coat. Moreover, it relies on geometric optics principles such as the generalized Snell's law of reflection and refraction. Each mirror within the array is controlled by a mechanical unit which enables independent rotation around two axes that are both orthogonal.

2) *Meta-surface-based RIS*: In contrast, the meta-surface-based RIS relies on a range of meta-materials to control the light propagation behavior [121]. These materials are metallic nanospheres in a dielectric structure, thin metallic rods isotropically distributed in a dielectric medium, splitting metallic elements in a dielectric structure, negative index meta-materials, and hyperbolic metamaterials among others. Unlike its mirror-array counterpart, which does not operate

¹Optical wireless communications have gained significant interest in recent years due to (a) their ability to offer large bandwidth required for the next generation of wireless applications and beyond [101]–[103] and (b) their low cost and ease of implementation with cheap transceivers.

in refractive mode (as it only reflects the incident light), the meta-surface-based RIS can yield all light phenomena related to the impact of photon on the unit surface, i.e., reflection, refraction, scattering, and absorption. However, this versatility comes at the expense of cost and complexity. Furthermore, a mirror array-based RIS exhibits better performance gains than its meta-surface-based RIS counterpart both in VLC systems according to the findings in [122].

3) *Liquid Crystal-based RIS*: This type of RIS primarily consists of LC materials due to their duplex transparency which can be used as reflectors and/or refractors [117], [118], since an RIS element can smoothly steer and amplify the light signal owing to its electrically controllable birefringence property. Furthermore, RIS-based LC materials can be placed (a) in front of the light emitting diode (LED) arrays of the VLC transmitter for high data rates and adequate illumination performance [119]; (b) in the VLC receiver for light amplification and beam steering [120]. The integration of LC in RIS-aided systems can greatly contribute to satisfying the joint illumination and communication needs of indoor VLC technology.

IV. RIS-ASSISTED PLS IN RF COMMUNICATION SYSTEMS

RIS-assisted PLS has emerged as a promising strategy for enhancing the security of RF communication systems. By incorporating the RIS, this approach introduces a new paradigm for mitigating eavesdropping risks and achieving secure wireless communication. RIS elements act as passive reflecting surfaces that can intelligently modify the wireless channel characteristics. Through careful adjustment of the reflection coefficients, transmitted signals can be manipulated to optimize signal strength at legitimate receivers while simultaneously degrading signal quality at potential eavesdroppers. Achieving this dual optimization involves joint consideration of beamforming, power allocation, and RIS phase shifts. RIS-assisted PLS not only enhances SC but also enhances the performance of RF communication systems against eavesdropping attacks. Various aspects of RIS design and deployment have been explored, including RIS placement, channel estimation, resource allocation, and signal processing algorithms, to optimize the efficacy of RIS-assisted PLS techniques. Integration of RIS technology with PLS in RF communication systems holds substantial potential for addressing security challenges in wireless networks and enabling secure and reliable communication in applications such as IoE, 5G/6G, and future wireless systems.

A. RIS-Assisted PLS Techniques

RIS offers a unique opportunity to enhance physical layer security in wireless communication systems through their ability to manipulate the wireless channel characteristics intelligently. Here are some PLS techniques on how RIS can be used to improve PLS.

1) *Artificial Noise*: To enhance the security of communication, AN is deliberately injected into the transmitted signal with the purpose of confounding potential eavesdroppers [53]. A critical aspect of AN design lies in its ability to avoid

causing interference to the intended receiver while simultaneously degrading the intercepted signal quality for the eavesdropper. To achieve this objective, AN is integrated with multiple-antenna techniques. By leveraging the spatial degrees of freedom provided by multiple transmit antennas, spatial beamforming allows for the joint adjustment of AN and the transmit signal's directions, thereby optimizing the secrecy performance [123], [124]. The effectiveness of AN depends on the transmitter's CSI accuracy. When the transmitter possesses perfect CSI, it gains access to the maximum spatial degrees of freedom for designing the beamformer. However, in practical scenarios, the CSI at the eavesdropper's end is often imperfect or entirely unavailable, introducing challenges and limitations to the AN's overall performance.

Integrating AN into RIS presents a promising avenue to enhance PLS in wireless communication systems. By strategically incorporating AN during transmission, RIS can introduce controlled random noise alongside the primary signal, confounding potential eavesdroppers and enhancing the confidentiality of transmitted information. This approach benefits from RIS's unique channel manipulation capabilities, enabling it to create constructive interference at the intended receiver and destructive interference at unauthorized recipients. Combining AN and RIS can strengthen security measures, reducing the risk of unauthorized data interception and providing additional protection beyond conventional encryption techniques. The potential benefits of integrating AN to enhance the SR in a wireless communication system assisted by RIS were investigated in [125]. To optimize the achievable SR, a joint design problem was formulated for optimizing transmit beamforming with AN or jamming alongside RIS reflect beamforming. The complexity of the problem arises from its non-convex nature and coupled variables, leading to the proposal of an efficient alternating optimization algorithm as a suboptimal solution. The simulation results demonstrate the benefits of incorporating AN in transmit beamforming, particularly in the context of RIS reflect beamforming. Notably, the findings reveal that the RIS-aided design without AN performs worse than the AN-aided design without RIS, particularly when a higher number of eavesdroppers are in proximity to the RIS. The authors in [126] proposed an approach based on the virtual division of RIS into two distinct segments. This division aims to strategically configure the phase shifts for each partition, enhance the achievable rate for legitimate users, and strengthen the impact of AN on illegitimate users. Two optimization problems were formulated, one focusing on maximizing SC and the other on minimizing power consumption. Closed-form solutions were derived by jointly optimizing the partitioning ratio and signal or noise power levels while considering rate constraints for both legitimate and illegitimate users' effectiveness of the proposed RIS-partitioning strategy in significantly improving SC. In [127], the PLS for a RIS-aided NOMA was investigated, considering scenarios involving both internal and external eavesdropping. A sub-optimal scheme, combining joint beamforming and power allocation, was proposed to enhance the system's PLS against internal eavesdropping, while AN scheme was introduced to counter external eavesdropping effectively.

Using AN for a STAR-RIS-assisted NOMA transmission system was investigated in [128] to maximize the sum secrecy rate (SSR). To address the inherent non-convexity of the optimization problem, a decoupling strategy was proposed, wherein the optimization of active and passive beamforming vectors at the BS and STAR-RIS, respectively, were separated. It is found that the proposed algorithm provides better secrecy performance with less AN power compared with the other schemes by using more RIS elements to reduce the AN power. Increasing the number of transmit antennas at the BS reduces the AN power if the eavesdropper is quite close to the transmitter while improving it when the eavesdropper is far away. The authors in [126] utilized the AN and RIS-partitioning to optimize secure communication. The proposed technique maximizes the legitimate SC while constraining Eve's achievable rate by simultaneously reflecting the signal towards the legitimate user and jamming Eve with AN. The proposed scheme showed improved SC performance compared to traditional AN-only and RIS-only scenarios. An AN-aided secure MIMO wireless communication system was investigated in [129], where an advanced RIS technology was employed, and multiple antennas were deployed at the BS, legitimate receiver, and Eve. The main objective is to maximize the SR while considering transmit power constraints and unit modulus conditions on RIS phase shifts. The efficacy of the proposed approach was demonstrated through simulation results, affirming the effectiveness of the RIS in enhancing system security.

The authors in [130] proposed a secure aerial-ground communication system integrated with RIS to counter potential eavesdropping threats via AN. The proposed system involves confidential data transmission from a UAV operating at a fixed altitude to a legitimate user, while a strategically placed RIS enhances secrecy communication performance on a building's facade. The focus is jointly optimizing the phase shifts, trajectory, and transmit power of the UAV to improve the secrecy performance of the downlink communication. A prototype of the aerial-ground communication system was implemented, revealing the superiority of the proposed scheme and showing significant performance improvement. Given the imperfect CSI possessed by potential eavesdroppers, the authors in [25] introduced a strategy for optimizing the system sum rate while ensuring that information leakage to eavesdroppers remains within acceptable bounds. However, acquiring the CSI of potential eavesdroppers is challenging, particularly in scenarios where a passive eavesdropper aims to remain inconspicuous within the network. Furthermore, increasing the transmitted power corresponds to an increased susceptibility of the eavesdropper to extract valuable information, thereby decreasing the secrecy performance. The utilization of the RIS characterized by multiplicative randomness to enhance security against passive eavesdropping in wireless communication systems was investigated in [131]. Enhanced security was achieved without prior knowledge of specific wiretap channels by applying the dynamic adjustment of reflection coefficients during data transmission while maintaining the reliability of the main channel. Performance assessment employs degree of freedom (DoF), spectral efficiency, and bit error rate (BER). The inves-

tigation highlighted the potential of RIS-enabled multiplicative randomness to enhance wireless network security substantially.

2) *Beamforming*: Employing beamforming techniques together with RIS presents a significant advancement in enhancing PLS within wireless communication systems [132]. Beamforming, a signal processing method, holds the potential to profoundly influence the signal propagation characteristics by focusing the radiated energy in a specific direction or spatial region, thereby shaping the wireless channel for improved communication quality and performance [133]. When integrated with RISs, beamforming confers several substantial benefits that enhance PLS. Firstly, strategically manipulating the reflecting elements' phase shifts through beamforming enables precise control over signal propagation paths [134]. This control extends to actively steering the transmitted signal towards intended legitimate users while simultaneously attenuating or redirecting signals intended for potential eavesdroppers. Such targeted control over signal distribution significantly mitigates eavesdropping, thereby improving the security of transmitted information. Secondly, the adaptability of RISs in real-time facilitates dynamic adjustments to the reflecting elements' configurations, responding to changing communication scenarios [135]. Integrating beamforming with RISs allows for real-time adjustments in signal directionality and spatial focus, thereby aiding in establishing secure communication links amidst dynamic and potentially insecure environments. This adaptability also empowers the system to counteract eavesdropping attempts through instantaneous reconfiguration of the reflecting elements, making identifying secure transmission paths challenging for potential adversaries [136]. Moreover, the integration of beamforming with RISs augments the overall link quality by mitigating signal fading and shadowing effects. By intelligently redistributing and focusing energy, the combined approach enhances SNRs and minimizes the impact of interference, thereby contributing to improved communication reliability and strength against unauthorized access.

In [137], a self-sustainable RIS was employed to enhance the security at the PLS within a MISO broadcast configuration featuring multiple eavesdroppers. The unique characteristic of the RISs is their ability to manage the activation status of their reflecting elements, directing them either for signal reflection or energy-harvesting purposes. The authors in [138] proposed a secure communication system between UAVs and ground stations, where the operation of an RIS was incorporated. A joint optimization endeavor concerning the optimal trajectory of the UAV and the passive beamforming configuration of the RIS, where imperfect CSI on the RIS-eavesdropper and UAV-eavesdropper connections were considered. In addition, enhancing the ergodic SR within a secure communication paradigm employing MIMO architectures was investigated in [139], where direct links between the BS and authorized users, and potential eavesdroppers were blocked, with statistical CSI for the RIS. A deterministic approximation for this scenario was derived using random matrix theory. The resource allocation in multi-user communication networks was investigated in [140], focusing on a scenario where a RIS enhances a wireless transmitter. The aim was to minimize the total network transmit power by optimizing RIS phase

beamforming and BS transmit power, subject to user signal-to-interference-plus-noise ratio (SINR) constraints. A dual technique was proposed, transforming the problem into a semidefinite programming form. A closed-form RIS phase beamforming was provided, and an optimal transmit power was obtained based on standard interference functions. Simulation results highlighted the proposed method's effectiveness, achieving substantial reductions in total transmit power compared to maximal ratio transmission and zero-forcing beamforming techniques.

In [141], the RIS was used to reduce power consumption and enhance information security in a multi-user cellular network, particularly with imperfect angular CSI. The main objective was to maximize worst-case sum rates by designing the system to optimize the receive decoders, digital precoding, and AN at the transmitter and analog precoders at the RIS. The optimization was done while meeting the constraints, including minimum achievable rate, maximum wiretap rate, and maximum power allocation. The author in [142] investigated enhancing PLS in a multi-antenna communication system using an RIS by jointly optimizing the active and passive beamforming to maximize SRs and minimize power consumption. An algorithm was proposed to utilize the mathematical structure of optimal active beamforming vectors, in which the iterative updates between transmit and RIS-reflecting beamformers were not required. Robust and secure beamforming in a RIS-assisted mmWave MISO system was investigated in [143] in the presence of multiple single-antenna eavesdroppers near the legitimate receiver, and the CSI of cascaded wiretap channels was imperfectly known to the legitimate transmitter. The target was formulating optimization design problems to maximize worst-case achievable SR while considering constraints on total transmission power and unit modulus. Maximizing SRs in a mmWave network containing a BS, multiple RISs, multiple users, and a single eavesdropper was introduced in [144]. The objective was to ensure fairness in SRs among users, which gives rise to a mixed integer problem under a maximum fairness criterion. The proposed algorithm converges to a Karush-Kuhn-Tucker point for the original problem, and its overall convergence and computational complexity were analyzed.

The authors in [145] investigated integrating secure directional modulation in RIS-assisted communication networks. The technique involves selecting specific antenna subsets to generate randomized signals, enhancing PLS. However, introducing RIS poses the challenge of aligning an additional beam, which can lead to high sidelobe effects due to discrete optimization in antenna subset selection. To address this, a cross-entropy iterative method was proposed to achieve low-sidelobe hybrid beamforming for secure directional modulation in RIS-aided networks. The approach minimizes maximum sidelobe energy and employs the Kullback-Leibler divergence to select suitable antenna subsets. The RIS-assisted single-input multiple-output (SIMO) system was utilized in [146] to improve the PLS, considering the presence of a multi-antenna eavesdropper. To do so, the legitimate receiver employs active full-duplex jamming while simultaneously coordinating the passive beamforming capabilities of the RIS with legitimate

reception and jamming. This coordination leads to a joint optimization approach encompassing receive beamforming, active jamming, and passive beamforming. The complexity of this optimization was managed through a block coordinate descent framework, utilizing techniques such as the generalized eigenvalue decomposition and the semidefinite programming. In [147], using an RIS from the standpoint of wireless attackers to degrade communication performance in a time-division duplex system was examined, considering a time division duplexing (TDD) massive MIMO system. The RIS was strategically employed to disrupt channel estimates obtained by the BS during the training phase and distort signals received by users during the transmission phase. The performance assessment utilized mean square error (MSE) of users, and an efficient method for optimizing the RIS's reflection pattern was proposed based on theoretical findings. In [148], considering active and passive eavesdroppers investigated a multi-antenna secure transmission system with RIS enhancement. A zero-forcing beamforming strategy was proposed to nullify the transmit beam towards active eavesdroppers' channels and simultaneously enhance SNRs for legitimate users and passive eavesdroppers, even without perfect CSI. The goal was to optimize the user's SNR while respecting constraints on transmit power, SNRs of passive eavesdroppers, and RIS reflection.

3) *Cooperative Jamming*: In wireless communication systems, ensuring robust security while maintaining efficient data transmission has become an increasingly critical challenge. The emergence of the RIS technology has introduced a novel dimension to enhancing the PLS. This subsection investigates the promising avenue of employing cooperative jamming methods to increase the security of systems featuring RIS integration. As an advanced signal processing strategy, cooperative jamming offers the potential to prevent eavesdropping attempts and optimizes the use of RIS-enabled beamforming to enhance the confidentiality of information transmission, as summarized in Fig. 7.

Enhancing secure communications through a RIS-assisted MISO wireless communication network with independently cooperative jamming was investigated in [149]. The main objective was maximizing energy efficiency, achieved through the joint optimization of beamforming, jamming precode vectors, and the RIS phase shift matrix under perfect and imperfect CSI conditions. Additionally, a trade-off between SR and energy efficiency was observed, highlighting the capacity of the RIS to enhance energy efficiency, even when faced with cases of imperfect CSI. The authors in [150] investigated the potential of utilizing the RIS, focusing on aerial RIS (ARIS), for anti-jamming communications. A joint ARIS deployment and passive beamforming optimization through an alternating optimization framework was explored, effectively mitigating jamming attacks and ensuring the security of legitimate data transmissions. In [151], the RIS was utilized to suppress interference and jamming in radio wireless communication systems. The goal was to enhance the quality of service (QoS); the results demonstrated the significance of employing RIS, yielding significant anti-interference and jamming benefits. An approach to enhance the resistance of wireless communication

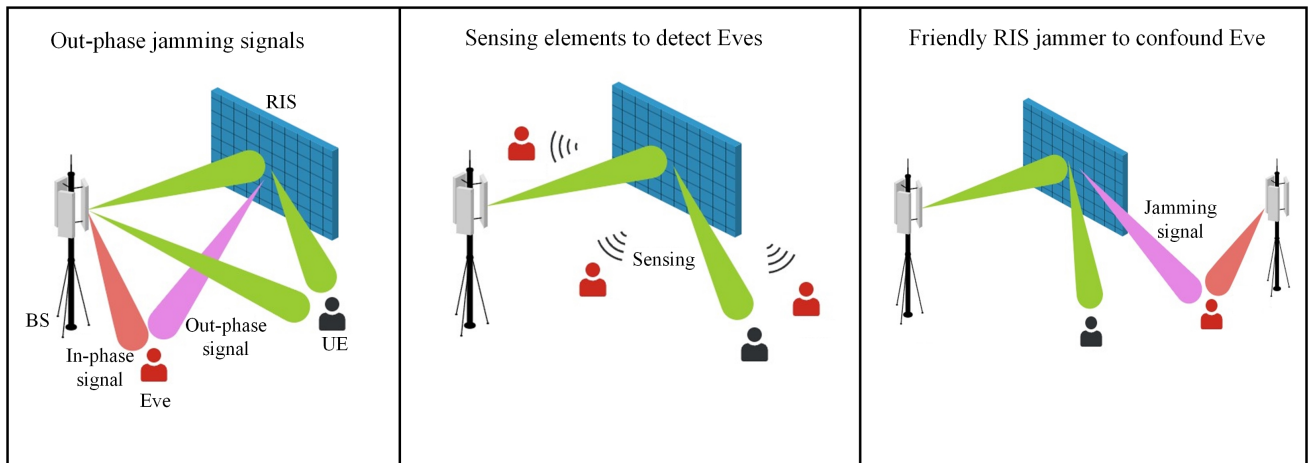


Fig. 7. RIS-assisted PLS scenarios.

systems against jamming interference using RIS was presented in [152] by improving signal reception for legitimate users while mitigating jamming signals. An optimization problem was formulated to jointly optimize transmit power allocation at the BS and reflecting beamforming at the RIS, resulting in anti-jamming performance enhancement. A passive secure communication scheme using an RIS was investigated in [153], where the RIS allocated power from incoming signals to transmit confidential information and generate passive jamming signals simultaneously. Each RIS's reflection coefficient served communication and jamming functions, and their joint optimization aimed to maximize the SR. The authors of [154] investigated the secure communication techniques utilizing a fixed RIS in conjunction with an aerial platform equipped with another RIS and a friendly jamming device to enhance security. The ARIS improved the legitimate signal, and the fixed RIS reinforced cooperative jamming, considering imperfect CSI. The problem of configuring RISs to counter jamming attacks in a multi-user OFDMA system was discussed in [155], with the uncertainties posed by an uncooperative jammer and limited CSI availability. To tackle this problem, a DRL-based approach was proposed. The DRL framework efficiently learned the RIS configuration, expedited learning through this strategy, and achieved rapid convergence in simulations.

B. Integrating RIS with Enabling Technologies for Secure Communications

Current research contributions have demonstrated that RIS plays a pivotal role in increasing the levels of security and confidentiality within wireless networks. This notable secrecy performance enhancement holds considerable potential for application across diverse wireless communication networks. This subsection dives into the integration of RIS with emerging and cutting-edge technologies, which encompass mmWave, THz, UAVs, NOMA, CRN, D2D communications, and other pertinent technologies. In this subsection, we explore the efficacy of integrating the RIS with emerging technologies to heighten wireless networks' security and confidentiality, offering tangible benefits for various wireless communication

networks. In the following, we delve into integrating RIS with current technologies, clarifying these integrations' contributions to wireless communication security. The integration of RIS in PLS-aided systems with RF-enabling technologies for secure communications is summarized in Fig. 8.

1) *RIS-Assisted Secure mmWave Communications*: Integrating RIS into mmWave communications represents a significant advancement in enhancing security. RIS's adaptability enables dynamic adjustments to the propagation environment, establishing secure communication channels in mmWave contexts. Its role in optimizing beamforming and channel characteristics addresses the directional communication requirements of mmWave, minimizing the risk of unauthorized interception. The RIS further contributes to security by employing dynamic signal jamming and controlled reflections to deter potential eavesdropping. Additionally, its collaboration with PLS techniques ensures secure communication between legitimate users. Incorporating RIS and mmWave technologies addresses security concerns and holds promise for developing efficient and adaptive communication networks in future wireless systems. The authors of [274] investigated the secrecy rate of a mmWave system improved by an RIS with low-resolution digital-to-analog converters, focusing on mitigating hardware losses and improving secrecy rates by integrating with RIS. The obtained results demonstrated the effectiveness of RIS in reducing hardware losses. Secure beamforming in the mmWave MISO system, aided by an RIS, was explored in [143]. The presence of multiple single-antenna eavesdroppers near the legitimate receiver was addressed, taking into account imperfect knowledge of cascaded wiretap CSI at the transmitter and the colluding and non-colluding eavesdropping scenarios. Simulation results showed the superior performance of the proposed scheme in terms of average secrecy rate (ASR).

2) *RIS-Assisted Secure THz Communications*: RIS is a promising technology, significantly advancing security measures across cutting-edge technologies. In the THz communications domain, incorporating RIS signifies a noteworthy advancement, elevating security within this frequency band. Leveraging the adaptability of RIS, the propagation envi-

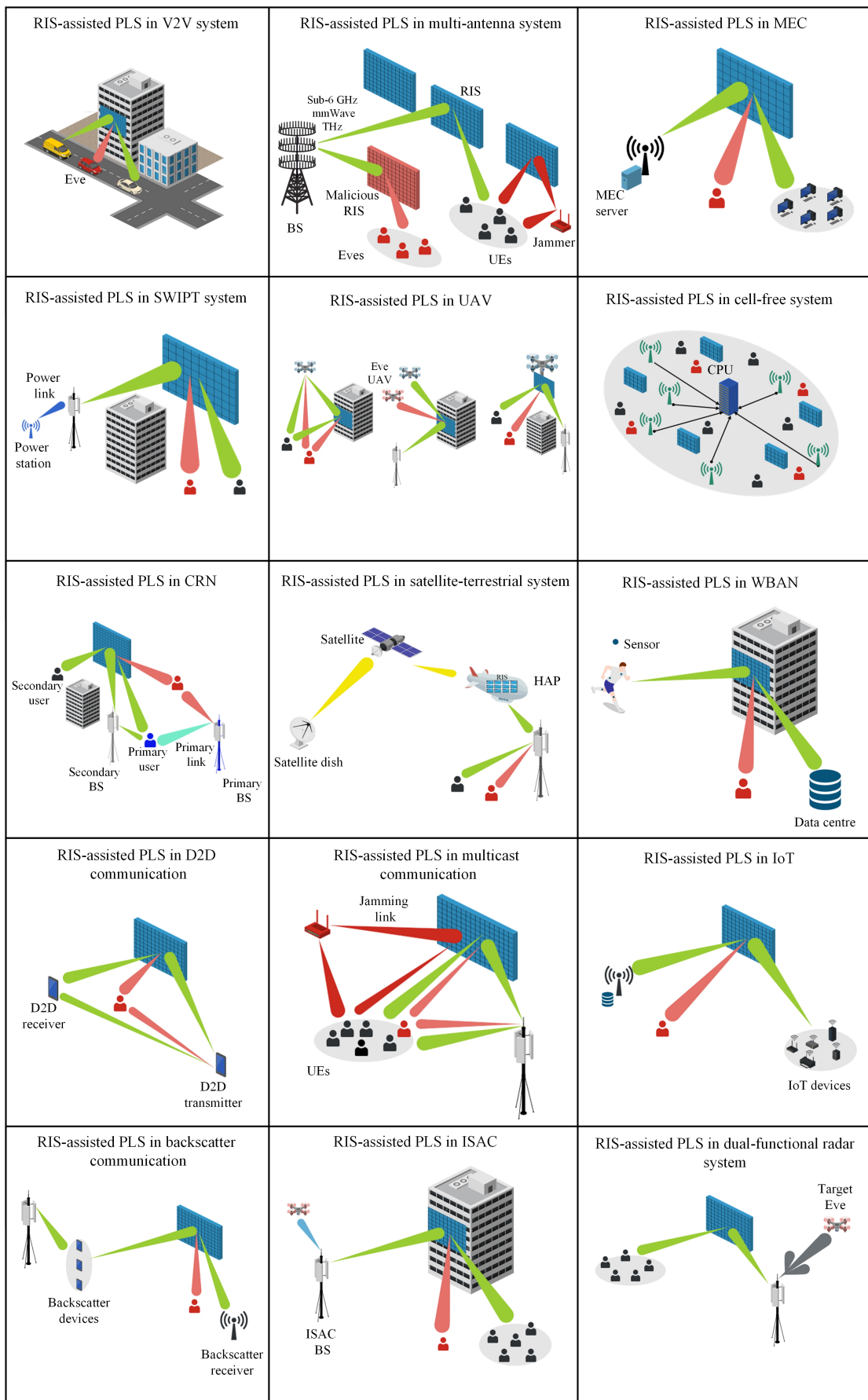


Fig. 8. The integration of RIS in PLS-aided systems with RF enabling technologies for secure communications.

TABLE II(a)
SUMMARY OF RIS-ASSISTED PLS ADOPTED SYSTEM MODELS IN RF COMMUNICATION SYSTEMS

[#]	System related content			RIS related content		Security related content		Performance Metric(s)	
	Technology	System Model	CSI Condition	Channel Model	RIS Type	RIS(s)	PLS Technique		Eve(s)
[149]	Multi-antenna commun.	SU-MISO-DL	Perfect/Imperfect	Rayleigh	Passive	Single	Jamming	Multiple	EE
[156]		SU-MISO-DL	Perfect	Rician	Passive	Single	BF	Single	ASR
[157]		MU-MISO-DL	Statistical	Rician	Passive	Single	BF	Single	SSR
[158]		MU-MISO-DL	Perfect	Rayleigh	Passive	Multiple	BF	Single	SR
[159]		SU-MISO-DL	Perfect	Rayleigh	Passive	Single	AN	Single	SR
[160]		MU-MISO-DL	Perfect	Rayleigh	Passive	Multiple	BF	Multiple	SR
[161]		SU-MISO-DL	Perfect	Rayleigh	Passive	Single	BF	Single	SR
[162]		SU-MISO-DL	Perfect	Rician	Passive	Single	BF	Single	SR
[163]		SU-MISO-DL	Perfect	Rayleigh	Passive	Single	BF	Single	SR
[164]		MU-MISO-DL	Perfect	Rician	Passive	Single	BF	Multiple	SR
[165]		MU-MISO-DL	Perfect	Rayleigh	Passive	Single	BF	Single	Transmit power
[166]		MU-MIMO-DL	Perfect	Rayleigh	Passive	Single	AN	Single	SR
[167]		MU-MIMO-DL	Perfect	Rayleigh	Passive	Multiple	Jamming	Single	Sum rate
[168]		MU-MISO-DL	Perfect	Rayleigh	Active	Single	BF	Multiple	SSR
[169]		MU-MISO-DL	Perfect	Nakagami- m	Passive	Single	BF	Single	SOP, PNISC, and ASR
[170]		SU-MIMO-DL	Perfect	Rayleigh/Rician	Passive	Single	BF	Single	ASR
[171]		MU-MIMO-DL	Imperfect	Rayleigh	Passive	Single	-	Multiple	Secrecy EE, SR
[172]		SU-MISO-DL	Perfect	Rician	Passive	Single	BF	Multiple	SOP and ESC
[173]		SU-MISO-DL	Statistical	Rayleigh	Passive	Single	BF	Single	SOP
[174]		MU-MIMO-DL	Perfect/Imperfect	Rayleigh/Rician	Passive	Single	Jamming	Single	Sum rate
[175]		SU-MIMO-DL	Perfect	Rayleigh/Rician	Passive	Single	BF	Single	SR
[176]		MU-MIMO-DL	Statistical	Correlated Rayleigh	Passive	Single	AN	Single	Ergodic SR
[177]		SU-MISO-DL	Perfect	Rayleigh/Rician	Passive	Multiple	BF	Multiple	Secrecy EE
[178]		SU-MISO-FD	Imperfect	Rayleigh/Rician	Passive	Single	BF	Single	Worst-case SSR
[179]		SU-MISO-DL	Statistical	Rician	Passive	Single	BF	Single	Ergodic SR
[180]		SU-MIMO-DL	Perfect	Rayleigh/Rician	Passive	Single	BF	Single	SSR
[181]		SU-MIMO-DL	Perfect	Rayleigh/Rician	Passive	Single	AN	Single	SR
[182]		SU-MIMO-DL	Perfect/No CSI	Rayleigh/Rician	Passive	Single	AN	Single	SR
[183]	mmWave commun.	SU-MISO-DL	Perfect	-	Passive	Single	AN	Single	ASR
[184]		SU-MISO-DL	Perfect	Rayleigh	Passive	Single	BF	Single	SR
[185]		MU-MISO-DL	Imperfect	Rayleigh	Passive	Single	BF	Multiple	SSR
[143]		SU-MISO-DL	Imperfect	Rayleigh/Rician	Passive	Single	BF	Multiple	SR
[144]		MU-MISO-DL	Perfect	Rayleigh	Passive	Multiple	BF	Single	SR
[186]		SU-MIMO-DL	Perfect	Rayleigh/Rician	Passive	Single	BF	Single	SC
[187]		SU-MISO-DL	Perfect	-	Passive	Single	AN	Single	Ergodic SR
[188]		MU-MISO-DL	Perfect	-	Passive	Single	BF	Single	SSR
[189]	THz commun.	SU-SISO-DL	Perfect/Statistical	-	Passive	Single	-	Single	Ergodic SR
[190]		SU-MISO-DL	Imperfect	-	Passive	Multiple	BF	Single	Worst-case SR
[191]		SU-MISO-DL	Perfect	-	Passive	Single	BF	Single	SR
[192]		SU-SISO-DL	Statistical	-	Passive	Single	-	Multiple	SC

ronment undergoes dynamic modulation to optimize beamforming and channel characteristics, particularly salient in the distinctive context of THz communications. The authors in [188] investigated a secure THz-empowered network, which involved transmitting confidential information from a low earth orbit satellite to a UAV via RIS-mounted HAPS in the presence of an untrustworthy UAV. The RIS phase shifts were optimized to enhance the secrecy performance. In [189], a THz MIMO-NOMA system with the assistance of a RIS was investigated, considering the presence of an eavesdropper. Results demonstrated that deploying RIS led to substantial beamforming gains, effectively mitigating eavesdropping threats.

3) *RIS-Assisted Secure UAV Communications*: Integrating RIS with UAVs offers significant potential for increasing security measures within wireless communication networks. This convergence between RIS and UAV technologies represents a pivotal advancement, as it harnesses the unique capabilities of both systems to address security challenges across various operational scenarios. With its adaptive electromagnetic surface ability, RIS can effectively manipulate electromagnetic wave propagation, facilitating secure communication by altering signal characteristics. The integrated RIS-UAV system becomes proficient in delivering secure communication links and surveillance capabilities in dynamic and demanding

TABLE II(b)
SUMMARY OF RIS-ASSISTED PLS ADOPTED SYSTEM MODELS IN RF COMMUNICATION SYSTEMS

[#]	System related content			RIS related content		Security related content		Performance Metric(s)	
	Technology	System Model	CSI Condition	Channel Model	RIS Type	RIS(s)	PLS Technique		Eve(s)
[193]	UAV commun.	SU-SISO-DL	Perfect	Rayleigh	Passive	Single	BF	Single	SR
[130]		SU-SISO-DL	Perfect	Rician	Passive	Single	AN	Single	ASR
[194]		MU-SISO-DL	Perfect	Rician	Passive	Single	AN	Single	ASR
[195]		SU-SISO-DL	Perfect	Rayleigh	Passive	Multiple	BF	Multiple	ASR
[138]		SU-SISO-UL/DL	Perfect	Rician	Passive	Single	BF	Single	ASR
[154]		SU-SISO-DL	Perfect	Rician	Passive	Multiple	Jamming	Multiple	SR
[196]		SU-SISO-DL	Perfect	Rayleigh	Passive	Single	BF	Multiple	SC
[197]		SU-MISO-DL	Perfect	Rician	Passive	Single	BF	Multiple	SR
[198]		SU-SISO-DL	Perfect	Rician	Passive	Single	BF	Single	ASR
[199]		MU-MISO-DL	Perfect	Rayleigh	Passive	Single	BF	Multiple	SSR
[200]		MU-SISO-DL	Perfect	Rician	Passive	Single	-	Single	SSR
[201]		SU-MISO-DL	Perfect	Rayleigh	Passive	Single	-	Single	ASR
[202]		SU-SISO-DL	Perfect	Nakagami- m	Passive	Single	-	Multiple	Number of RIS elements
[203]		MU-SISO-UL	Perfect	Rician	Passive	Single	-	Multiple	Secrecy EE
[204]		SU-MISO-DL	Perfect	Rician	Passive	Single	BF	Multiple	ASR
[205]		SU-SISO-UL	Perfect	Rayleigh	Passive	Single	BF	Multiple	Energy consumption
[206]		SU-SISO-DL	Outdated	Rayleigh/Rician	Passive	Single	BF	Single	ASR
[207]		MU-MISO-DL	Imperfect	Rician	Active	Single	BF	Single	Transmit power
[208]		SU-SIMO	Perfect	Rayleigh	Passive	Multiple	AN/BF	Single	Ergodic capacity
[209]		SU-SISO	Perfect	Rayleigh	Passive	Single	Jamming	Single	SOP and PNSC
[210]	SU-SISO	Perfect	Rayleigh	Passive	Single	BF	Single	Data rate and SR	
[211]	SU-SISO-DL	Perfect	Rayleigh	Passive	Single	Jamming	Single	SOP and PNSC	
[212]	SU-MISO-DL	Perfect	Rayleigh	Passive	Single	BF	Multiple	SR	
[213]	SU-MISO-DL	Perfect	Rayleigh	Passive	Single	AN	Single	SR	
[214]	SU-MISO-DL	Perfect	Rayleigh	Active	Single	AN	Single	SR	
[215]	SU-MISO-DL	Perfect	Rayleigh	Passive	Single	BF	Multiple	Secrecy EE	
[216]	SU-MISO-DL	Imperfect	Quasi-static	Passive	Single	BF	Multiple	Worst-case SR	
[217]	MU-SISO-DL	Perfect	Rayleigh	Passive	single	BF	Multiple	Consumed energy	
[218]	SU-SISO-DL	Perfect	Rayleigh/Rician	Passive	Single	-	Single	ASR	
[219]	MU-MISO-DL/UL	Perfect	Rayleigh	Passive	Single	BF	Single	Secrecy throughput	
[220]	SU-SISO-DL	Perfect	Rayleigh/Rician	Passive	Single	BF	Single	SOP, and EST	
[221]	SU-SISO-DL	Perfect	Rayleigh/Rician	Passive	Single	BF	Single	ESC	
[222]	SU-MISO-DL	Statistical	Rician	Passive	Single	BF	Multiple	ASR	
[223]	SU-MISO-DL	Perfect	Rician	Passive	Single	BF	Single	SR	
[224]	MU-MISO-DL	Statistical	Rician	Passive	Multiple	AN	Multiple	Power consumption	
[225]	MU-MISO-DL	Perfect	Rayleigh/Rician	Passive	Single	Jamming	Multiple	Transmit power	
[226]	MU-MISO-DL	Imperfect	Rayleigh/Rician	Passive	Single	AN	Multiple	Outage rate	
[227]	SU-SISO-UL	Perfect	Rayleigh/Rician	Passive	Single	Jamming	Single	SR	
[228]	SU-MIMO-DL	Perfect	Rayleigh/Rician	Passive	Single	AN	Single	SR	
[229]	MU-FD-UL/DL	Perfect	Rayleigh	Passive	Single	AN	Multiple	Secure energy consumption	
[230]	MU-SISO-UL	Perfect	Rayleigh	Passive	Single	-	Multiple	Sum secrecy computation efficiency	
[231]	MU-MISO-UL	Perfect	Rayleigh/Rician	Passive	Single	BF	single	SR, secure EE	
[232]	MU-FD-UL/DL	Perfect	Rayleigh	Passive	Single	BF	Single	Secure computational bits	

settings when combined with UAVs, which provide mobility and adaptability in deployment. This integration introduces a multifaceted approach to security, encompassing surveillance, communication, and the ability to establish secure connections in scenarios where traditional infrastructure may be deficient or compromised. In this context, we explore the complexities, potential application scenarios, and security implications of

RIS-UAV integration, shedding light on its significance in contemporary models of wireless communication security.

Utilizing a swarm of UAVs with ARIS presents an effective avenue for increasing ground users' PLS through control of phase shifts, spatial placement, and strategic movement. Additionally, a traceable PLS mechanism conducive to secure vehicle-to-everything (V2X) communications was

TABLE II(c)
SUMMARY OF RIS-ASSISTED PLS ADOPTED SYSTEM MODELS IN RF COMMUNICATION SYSTEMS (CONTINUED)

[#]	System related content				RIS related content		Security related content		Performance Metric(s)
	Technology	System Model	CSI Condition	Channel Model	RIS Type	RIS(s)	PLS Technique	Eve(s)	
[233]	Satellite commun.	SU-SISO-DL	Statistical	Rayleigh/Rician	Passive	Single	-	Single	Secure transmission probability
[234]		SU-MISO-DL	Imperfect	Rayleigh/Rician	Active	Single	BF	Single	Transmit power
[235]		SU-MISO-DL	Imperfect	Rician	Passive	Single	BF	Multiple	SR
[236]		SU-SISO-DL	Perfect	Rayleigh/Rician	Passive	Single	-	Multiple	SOP
[237]		MU-MISO-DL	Imperfect	Rayleigh	Passive	Single	Unintended interference	Multiple	Sum rate
[238]		SU-MISO-DL	Perfect	Rayleigh/Rician	Passive	Single	Jamming	Single	Eve SINR
[239]	Multicast commun.	MU-MISO-DL	Perfect	Rician	Passive	Single	-	Single	SC
[240]		MU-MISO-DL	Imperfect	Rayleigh	Passive	Single	BF	Single	SR
[241]		SU-MISO-DL	Bounded/Statistical	Rayleigh/Rician	Active	Single	BF	Multiple	Power consumption
[242]		MU-MISO-DL	Imperfect	Rayleigh	Passive	Single	Jamming	Multiple	Secure EE
[243]		MU-MISO-DL	Imperfect	Rayleigh/Rician	Passive	Single	BF	Multiple	worst Bob SNR
[244]	Cell-free networks	MU-MISO-DL	Perfect/Imperfect	Rayleigh/Rician	Passive	Multiple	BF	Multiple	Weighted SSR
[245]		MU-MIMO-DL	Perfect	Rician	Passive	Multiple	BF	Single	ASR
[246]	Relay networks	SU-SISO-DL	Perfect	Rayleigh	Passive	Single	Jamming	Single	SR
[247]		SU-SISO-DL	Perfect	Rayleigh/Rician	Passive	Single	BF	Single	ASR and throughput
[248]		SU-MISO-DL	Perfect	Rayleigh	Passive	Single	BF	Single	ASR
[249]		SU-MISO-DL	Perfect	Rayleigh	Semi-active	Single	-	Single	Secrecy EE
[250]		SU-SISO-DL	Perfect	Rayleigh	Passive	Single	-	Single	SOP
[251]	Vehicular commun.	SU-SISO-DL	Imperfect	Rayleigh	Passive	Single	BF	Single	ASR
[252]		SU-SISO-DL	Perfect	Rayleigh	Passive	Single	BF	Multiple	SOP and SC
[253]	WBAN	SU-SISO-D2D	Estimated	Rayleigh	Semi-passive	Single	Anti-jamming	Single	Eve rate, energy, latency, SC
[254]	Ad-hoc Networks	SU-MISO-DL	Perfect	Rician	Passive	Single	BF	Single	ASR
[255]	ISAC	MU-MISO-DL	Perfect	Rician	Active	Single	BF	Single	ASR
[256]		MU-MISO-DL	Perfect	Rayleigh/Rician	Passive	Single	BF	Single	SNR
[257]		SU-MISO-DL	Perfect	Rayleigh	Passive	Single	BF	Single	Ergodic SR
[258]		MU-MISO-DL	Perfect	Rayleigh	Passive	Single	BF	Single	SR
[259]		MU-MISO-DL	Perfect	Rayleigh	Passive	Single	BF	Single	SSR
[260]	Radar commun.	MU-MISO-DL	Perfect	Rayleigh/Rician	Passive	Single	BF	Multiple	Radar sensing power
[261]		MU-MIMO-DL	Perfect	Rayleigh/Rician	Passive	Single	AN	Single	SR
[262]	IoT Networks	MU-SISO-UL	Perfect	Rayleigh/Rician	Passive	Single	BF	Multiple	Computation EE
[263]		SU-SISO-DL	Perfect	Rayleigh	Passive	Single	Jamming	Single	ASR
[264]		MU-MISO-DL	Perfect	Rayleigh	Passive	Single	BF	Multiple	SSR
[265]		SU-SISO-DL	Perfect	Nakagami- m	Passive	Single	-	Single	SOP, PNSC, and ASR
[266]		MU-MISO-DL	Perfect	Rician	Passive/Active	Multiple	BF	Multiple	SSR and Secrecy EE
[267]	Backscatter Commun.	MU-MISO-DL	Perfect	Rician	BackCom	Single	BF	Multiple	ASR
[268]		SU-MISO-DL	Unknown	Nakagami- m	BackCom	Single	AN	Single	SR
[269]		MU-MISO-DL	Perfect	Rayleigh	BackCom	Single	BF	Multiple	SR
[270]		SU-MISO-DL	Perfect	Rician	BackCom	Single	BF	Multiple	Transmit power
[271]		SU-SIMO-UL	Perfect	Rician	BackCom	Single	BF	Single	Destination SINR
[272]	WSNs	MU-SISO-UL	Perfect	Rayleigh	Passive	Single	BF	Single	SNR
[273]	HAPs	MU-MIMO-DL	Perfect	Rayleigh	Passive	Single	BF	Multiple	EE
[115]		MU-SISO-UL	Perfect	Nakagami- m	Passive	Single	-	Single	SOP and PPSC
[189]		SU-SISO-DL	Perfect/Statistical	Gamma-Gamma	Passive	Single	-	Single	Ergodic SR

introduced [275]. Utilizing a RIS in the presence of UAVs acting as potential eavesdroppers was analyzed in [196], where enhanced security was achieved through RIS deployment. The authors of [154] proposed a strategy for enhancing wireless security by employing aerial reflection and jamming techniques

to address channel uncertainties effectively. ARIS mounted on a UAV was introduced to improve the wireless secrecy of fixed-deployed RISs and optimize the ARIS trajectory to maximize average secrecy rates [195]. The authors of [200] investigated a secure multi-user UAV communication system

supported by a RIS and considered hardware impairments in the transceiver and the RIS. In [202], the minimum number of reflecting elements required for secure and energy-efficient RIS-assisted UAV systems was investigated, considering the phase estimation errors. Robust optimization methods were utilized, and aerial deployment was accomplished through DRL. Additionally, the superiority of flexible deployment of ARIS over fixed RIS was highlighted, and significant security improvements were achieved through the collaboration between fixed RIS and ARIS.

4) *RIS-Assisted Secure D2D Communications*: RIS presents a compelling avenue for strengthening the security infrastructure of D2D communications. The capacity of RIS to dynamically modulate surface properties affords the selective manipulation of wireless signals, establishing secure communication channels by redirecting signals away from potential eavesdroppers or unauthorized users. Through careful manipulation of the propagation environment, RIS engenders the dynamic reconfiguration of wireless communication channels, confusing interception and interference by unauthorized devices, thereby adding an additional level of security. Furthermore, the precision of RIS in producing highly directional communication links heightens privacy and security by constricting signal exposure to unintended recipients, thereby attenuating the susceptibility to signal interception. These diverse capabilities, encompassing the mitigation of jamming, interference, and dynamic signal beamforming, collectively form a robust security framework for D2D communications [209], [210].

5) *RIS-Assisted Secure Cognitive Radio Networks*: Regarding the CRN, the utilization of RIS aims to enhance the PLS of the network. Leveraging the numerous reflecting elements in the RIS facilitates establishing a highly directional and manipulable wireless transmission environment. This capability enables selective enhancement or nullation of the signal strength of legitimate or malicious signals, thereby improving the network's overall security. Furthermore, integrating RIS allows for generating multiple virtual channels, which can effectively separate legitimate and malicious signals, providing an additional layer of protection against eavesdropping and jamming attacks. The authors in [211] proposed a novel system model that utilized the RIS technology to enhance simultaneous wireless communication and security in CRN environments. It aimed to improve the transmission of the secondary network and enhance the secrecy performance of the primary network concurrently. In [213], utilizing an RIS in CRN was explored, focusing on improving secrecy rates under various scenarios, including perfect/imperfect Eve's CSI. Additionally, an AN-aided approach was proposed for scenarios without Eve's CSI to enhance the secrecy rate. The authors in [214] focused on employing an active RIS in a secure cognitive satellite-terrestrial network to optimize the secrecy rate. This involved concurrently optimizing the design of the BF, AN, and reflection coefficients. The results revealed the superior performance of the active RIS scheme in enhancing secrecy within the network.

6) *RIS-Assisted Secure WPT and SWIPT*: RIS's utility extends further to secure wireless power transfer (WPT) and

SWIPT communications, optimizing energy transfer efficiency while ensuring secure communication channels. Integrating RIS into a secure WPCN multicast setup was proposed in [217] to enhance energy transfer efficiency and ensure secure communication. Specifically, the energy was initially harvested from a power station and subsequently utilized to transmit data to multiple IoT devices in the presence of multiple eavesdroppers. The beamforming optimization challenge within a RIS-enhanced SWIPT framework was investigated in [222], with energy users accounted for as potential eavesdroppers. The purpose was to maximize the average worst-case SR while adhering to power and energy harvesting constraints. The authors of [220], [221] explored the PLS of a WPC system with enhancements provided by an RIS in the presence of a passive eavesdropper. Three secure modes for RIS-WPC systems were introduced and examined. In [218], RIS was utilized to maximize secure SWIPT systems with a power splitting scheme. The objective was to optimize the system's SR by choosing the optimal transmitter power and RIS phase shifts while ensuring user energy-harvesting requirements and adhering to transmit power constraints at the transmitter.

7) *RIS-Assisted Secure MEC*: The integration of RIS into MEC enhances the security of edge networks. Through the dynamic configuration of the wireless environment, RIS contributes to securing data transmission and computation processes in MEC systems. The authors of [262] presented an approach for ensuring secure task offloading and efficient wireless resource management in MEC networks increased with RIS, considering IoT devices' secure computation rate constraints. The secure computation performance in an RIS-assisted WPT and MEC system with a passive eavesdropper was investigated in [232]. A harvest-then-offload protocol was focused on, where users were charged by the AP in the first slot, and harvested energy was used to offload computation tasks in the second slot, assuming concurrent local computation during energy harvesting. Strategies to enhance the security of MEC systems by leveraging RIS technology and AN in the IoT were explored in [229], aiming to strengthen users' signals while simultaneously attenuating eavesdroppers' signals by manipulating RIS phase configurations.

8) *RIS-Assisted Secure Satellite Networks*: The sophisticated integration of RIS into satellite networks provides insights into applications for enhancing communication security in space-based systems. The authors of [233] introduced a two-hop content delivery strategy within a cache-enabled satellite-terrestrial network supported by an RIS. The system incorporated probabilistic caching policies at both the satellite and ground station. The analysis evaluated the system's connection and secrecy probability, utilizing asymptotic and closed-form expressions. In [234], a secure beamforming design for cognitive satellite-terrestrial networks with active RIS was introduced, considering CSI. The objective was to minimize transmission power at the BS while ensuring an acceptable SR for primary users and an acceptable rate for secondary users. Two configurations of RIS-aided space-ground networks, double-RIS and single-RIS schemes, were explored in [235] to maximize the SR. The superiority of the double-RIS scheme in terms of security performance compared to the

single-RIS method was demonstrated.

9) *RIS-Assisted Secure ISAC*: Integrating an RIS with ISACs systems enhances secrecy performance by dynamically controlling signal propagation. The RIS enables precise communication through dynamic beamforming, directing signals to intended recipients and reducing interception threats. The combined optimization of transmit and reflection beamforming for secure RIS-ISAC systems was analyzed in [256]. The results validated that the proposed design enhances radar SNR performance, confirming the benefits of incorporating RIS in secure ISAC systems. The authors of [257] introduced a beamforming design assisted by RIS in an ISAC system to enhance PLS. The objective was to maximize secrecy performance while meeting the minimum requirements for communication and sensing performance. RIS-assisted secure ISAC system was examined in [258] wherein the objective was to maximize the SR by concurrently optimizing the transmit beamforming, AN matrix, and RIS phase-shift matrix. The results confirmed the significance of the proposed DRL algorithm compared to benchmark techniques.

10) *RIS-Assisted Secure IoT*: Incorporating RIS into IoT networks optimizes security through dynamic signal reflection control, interference mitigation, secure zone establishment, adaptability to changes, jamming prevention, and enhanced privacy measures. This collaborative integration strengthens the overall security resilience of IoT networks, providing robust protection against a spectrum of potential threats [262]–[265], [276].

11) *RIS-Assisted Secure Other Cutting-Edge Technologies*: The exploration extends to RIS-assisted secure multicast communications, strategically deploying RIS to reinforce security in the face of the unique challenges posed by one-to-many communication paradigms [239]–[242]. RIS-assisted secure cell-free networks utilize RIS to optimize signal coverage and mitigate interference in distributed antenna systems [244], [245]. Transitioning to relay networks, RIS dynamically configures relay paths and signal reflections, enhancing the security and reliability of relayed communications [246], [247]. Vehicular networks, a critical domain for secure communication, the strategic deployment of RIS to optimize communication links in vehicular environments, addressing security concerns and improving overall network performance [250]. WBANs find RIS enhancing communication security and reliability in healthcare and wearable technologies, especially in wearable health monitoring devices [253].

Integrating RIS with a radar system enhances security by dynamically controlling electromagnetic wave propagation. This integration improves signal directionality, supports stealth and camouflage, facilitates adaptive radar sensing, and mitigates interference [260], [261]. Moreover, backscatter communications can be integrated with RIS to improve security performance by dynamically optimizing signal reflection, establishing secure signal directionality, adapting security configurations, and creating secure zones [267]–[269]. Furthermore, the benefits of using RIS to improve the secrecy performance of wireless sensor networks (WSNs) were investigated in [272]. As summarized in Tables II(a), II(b), and II(c), the attractive advantages of RIS-assisted PLS have generated enor-

mous studies investigating its applicability to 5G/6G cutting-edge wireless technologies such as multi-antenna communications, mmWave communications, THz communications, UAV communications, D2D communications, CRNs, WPC/SWIPT, MEC, satellite-enabled networks, multicast communications, cell-free networks, relay-aided networks, vehicular communications, WBAN, ad-hoc networks, ISAC, radar communications, IoT networks, backscatter communications, wireless sensor networks, and HAPS.

C. Lessons Learnt

The lessons learnt from this section can be summarized as follows.

- Lessons can be drawn from the effectiveness of RIS-assisted PLS techniques, such as AN, BF, and cooperative strategies, in mitigating specific security threats in different communication scenarios. Understanding how these techniques address challenges like eavesdropping and jamming provides valuable insights. Moreover, understanding how cooperative strategies, possibly involving multiple RIS elements, impact the overall security of the communication system can provide valuable insights into the potential for collaborative security tools against potential threats.
- The integration of RIS with enabling communications technologies, including mmWave [274], UAV [265], D2D [209], THz [188], CRNs [211], SWIPT [222], MEC [262], satellite networks [233], ISAC [256], and IoT [264] clarifies the considerable significance of RIS in strengthening security across multiple domains. This section provides insights into the adaptability and optimization of RIS for varied communication environments. Concurrently, it unveils potential challenges associated with the seamless integration of RIS with these advanced technologies.
- Insights are gained regarding the real-world applicability of RIS-assisted PLS techniques. Considerations related to implementation challenges, scalability, and adaptability to diverse communication scenarios can provide practical applications for deploying such technologies in communication networks. In addition, the scalability and adaptability of RIS-assisted PLS techniques have been highlighted to understand how well RIS scales with increasing network complexity, and its adaptability to dynamic communication scenarios contributes to practical system deployment. Furthermore, using active RIS to address the dual-fading issue arising in RIS-supported links within wireless communication systems and improve PLS has been highlighted as a possible approach at the expenses of higher complexity and power consumption. Each active element within the RIS amplifies the incident signal it reflects, in contrast to the sole reflection characteristic of nearly passive RIS modules [75].

V. RIS-ASSISTED PLS IN OWC SYSTEMS

This section discusses the potential of the adoption of the RIS technology to secure OWC networks. Specifically,

the integration with VLC, VLC-RF, and FSO-RF, which are summarized in both Fig. 9 and Table III.

A. Integrating RIS with OWC Enabling Technologies for Secure Communications

1) *RIS-Assisted Secure VLC*: when it comes to the integration of RIS-aided PLS in VLC systems, the research started with single user scenarios for a static user [107], [110], [111] or a mobile user [109], then evolved to multi-user scenarios [108]. These works employed different PLS techniques to improve the secrecy rate performance. Specifically, in [107], [110], the mirror-array-based RIS elements are optimized to increase the channel gain difference between the trusted user and the un-trusted user (i.e., performing channel gain manipulation, as stated in Table III). In [108], the closest LED to the eavesdropper is employed to send an unintended interference to the eavesdropper in an attempt to degrade its SINR. In [109], the transmit BF of the VLC AP is optimized to maximize the system's secrecy capacity. Lastly, in [111], an RIS is deployed close to a jamming receiver, which transmits a jamming interference toward the eavesdropper.

2) *RIS-Assisted Secure VLC-RF*: The high data rates of VLC and the extended coverage of RF communications have motivated the research of VLC-RF hybrid systems. In [113], [114], a two-hop scenario is considered, where in the first hop, VLC is used for data transmission in an electromagnetic-sensitive environment, and in the second hop, a relay that can perform an optical-to-electrical conversion is deployed next to an RIS to extend the communication coverage. Additionally, there exists an eavesdropper in the second hop trying to wiretap the RF link. The aforementioned works evaluated both the SOP and the SPSC of the proposed systems without employing a specific PLS technique. Rather, the introduction of the RIS is shown to increase the SOP to a certain extent.

3) *RIS-Assisted Secure FSO-RF*: The motivation for RF/FSO networks arises from the need for high-speed, reliable, and flexible communication solutions in various scenarios, ranging from urban environments with high data demands to remote areas with limited infrastructure. The security of the FSO links is inherently assured by the laser beam's narrow and imperceptible nature, while the inherent broadcast nature of wireless RF communication implies the likelihood of information leakage to eavesdroppers [115]. However, the propagation characteristics of the FSO link need to be taken into account, such as the pointing errors, the path loss due to random atmospheric radio medium, and the atmospheric turbulence. In [116], a secure mixed RF/FSO RIS-aided system is proposed, where a secure message is conveyed from an RF transmitter to an FSO receiver with the assistance of a decode-and-forward intermediary relay. This work deploys one RIS between the RF transmitter and the relay and another one between the relay and the FSO receiver, such deployment is suitable in urban environments. In [115], a secure mixed RF/FSO RIS-aided HAPS-UAV collaborative system is proposed, which is suitable to serve remote areas users. A wiretap RF link is assumed from the users to an eavesdropper.

B. Lessons Learnt

The lessons learnt from this section can be summarized as follows.

- There is consensus in the provided RIS-aided PLS VLC literature that increasing the number of RIS elements attributes in enhancing the overall secrecy performance of VLC systems. Specifically, the additional RIS elements enable spatial beamforming and nulling, allowing for precise directionality of transmitted light and constructive interference patterns towards intended receivers while creating interference for potential eavesdroppers. The dynamic adaptability of a larger number of RIS elements facilitates continuous optimization in response to changing environmental conditions, contributing to improved security against eavesdropping attempts. This increased spatial diversity and improved SNR at the legitimate receiver enhance the reliability of communication links, making it more challenging for unauthorized entities to intercept the communication.
- The core characteristics of VLC and the potential of employing red-green-blue (RGB) LEDs as VLC transmitters facilitate the adoption of advanced PLS techniques in VLC systems. For example, the Watermark Blind PLS algorithm [278] that utilizes a combination of spread-spectrum watermarking and a jamming receiver to provide confidentiality and protect the transmitted information from eavesdroppers has been adopted in VLC in [279]. In [111], leveraging the RIS technology with such advanced PLS technique attain further improvement in the security properties of VLC systems. Overall, utilizing the capabilities of the RIS technology facilitates the effective adoption of new PLS techniques in VLC systems.

VI. OPTIMIZATION TECHNIQUES FOR RIS-ASSISTED PLS

A general mathematical optimization problem typically has the form

$$\begin{aligned} & \min_{\mathbf{x}} f(\mathbf{x}) \\ & \text{s.t.} \\ & g_i(\mathbf{x}) \leq b_i, \quad i = 1, 2, \dots, m, \\ & h_i(\mathbf{x}) = c_j, \quad i = 1, 2, \dots, n, \end{aligned} \quad (9)$$

where the function $f(\mathbf{x})$ is the objective function that needs to be minimized, \mathbf{x} is the set of optimization variables, $g_i(\mathbf{x}) \leq b_i$ and $h_i(\mathbf{x}) = c_j$, are the inequality and equality constraints that restrict the feasible region, respectively, m denotes the number of inequality constraints, and n is the number of equality constraints. The optimization problem in (9) is a constrained optimization problem. If there are no constraints on the optimization variables, the problem then becomes an unconstrained optimization problem. Depending on the nature of the objective function and constraint sets, optimization problems can be broadly categorized into two types: convex and non-convex problems. Problem (9) is convex if $f(\mathbf{x})$ and $g_i(\mathbf{x})$ are convex functions and $h_i(\mathbf{x}) - c_j$ is affine [286]. Else, (9) is a non-convex optimization problem. Convex functions have a specific property known as convexity, which implies that any line segment connecting two points on the graph of

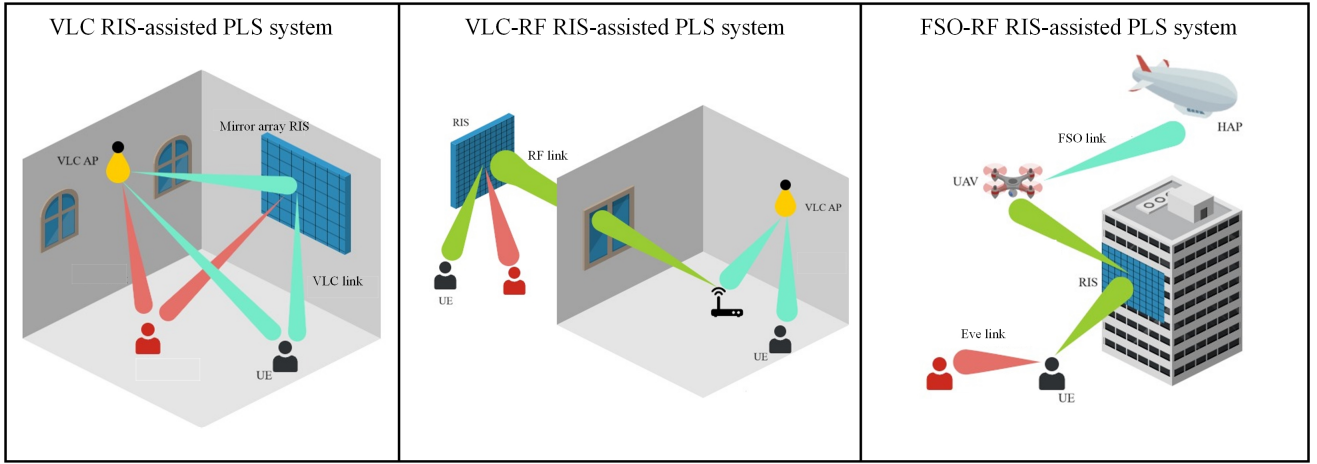


Fig. 9. The integration of RIS in PLS-aided systems with OWC enabling technologies for secure communications.

TABLE III
SUMMARY OF RIS-ASSISTED PLS ADOPTED SYSTEM MODELS IN OWC SYSTEMS

[#]	System related content			RIS related content			Security related content		Performance Metric(s)	
	Technology	System Model	CSI Condition	RIS Type	RIS(s)	RIS Arch.	PLS Technique	Eve(s)		
[107]	VLC	SU-SISO-DL	Perfect	Passive	Single	Mirror array	Channel gain manipulation	Single	SC	
[108]		MU-SISO-DL	Perfect	Passive	Single	Mirror array	Unintended interference	Single	SR	
[109]		SU-SISO-DL	Perfect	Passive	Single	Mirror array	BF	Single	SC	
[110]		SU-SISO-DL	Perfect	Passive	Single	Single	Mirror array	Channel gain manipulation	Single	SR
[111]		SU-SISO-DL	Perfect	Passive	Single	Single	Mirror array	Jamming	Single	SC
[113]	VLC-RF	SU-SISO-DL	Perfect	Passive	Single	Meta-surface	-	Single	SOP and SPSC	
[114]		SU-SISO-DL	Perfect	Passive	Single	Meta-surface	-	Single	SOP and SPSC	
[116]	FSO-RF	SU-SISO-DL	Perfect	Passive	Multiple	Meta-surface	-	Multiple	SOP, SPSC, IP, ASC, and EST	
[115]		MU-SISO-UL	Perfect	Passive	Single	Meta-surface	-	Single	SOP and PPSC	
[277]		SU-SISO-DL	Perfect	Passive	Single	Single	Meta-surface	-	Single	SOP, ASC, SPSC, and EST

the function lies above the graph itself [286]. This class of optimization problems is particularly desirable because convex problems have a single global optimum that can be found using many efficient algorithms, such as interior-point methods. Non-convex optimization problems on the other hand can have multiple local optima, are more challenging to solve in a reasonable amount of time (i.e., intractable), and often require specialized algorithms. Typical optimization approaches to tackling non-convex problems include approximating non-convex functions as convex ones and solving the resulting approximated convex problem or using heuristic techniques to provide reasonably good solutions in a reasonable amount of time.

In the context of optimizing RIS-assisted PLS, typical objective functions include SR, SC, SOP, PNCS, IP, secure

energy efficiency (EE), and transmit power. The decision variables include resource allocation (e.g., power and bandwidth), RIS phase shifts and placement, beamformer/precoder design, and antenna selection. This section reviews state-of-the-art optimization techniques for RIS-assisted PLS and summarizes existing optimization schemes for SR maximization and other secrecy metric optimization in Tables IV (a and b) and V (a and b), respectively.

A. Secrecy Rate Optimization

In [130], the authors investigated SR maximization by optimizing the phase shifts of the RIS, the trajectory of a drone BS, and its transmit power. In this paper, the authors first used BCD approach to decompose the joint problem into three subproblems. A closed-form expression of the optimal

TABLE IV(a)
SUMMARY OF SECRECY RATE OPTIMIZATION RELATED LITERATURE FOR RIS-ASSISTED PLS SYSTEMS

[#]	Phase-shift resolution	Optimization variables	Optimization techniques	Constraints
[130]	Continuous	RIS phase shifts, Drones' trajectory, Transmit power	BCD, AO, SCA, One-dimension search	Drone mobility, Power, and RIS phase constraints
[280]	Continuous	RIS location, RIS phase shifts	Heuristic search, Charnes-Cooper transformation, Sequential rank-one constraint relaxation	RIS location and RIS phase constraints
[244]	Continuous	BS beamforming vector, RIS phase shifts	AO, SDR, SCA, Linear conic relaxation	Min. SNR and RIS phase constraints
[146]	Continuous	BS beamforming vector, RIS phase shifts	AO, SDR, BCD	Power and RIS phase constraints
[213]	Continuous	BS beamforming vector, RIS phase shifts	AO, Dinkelbach Method, SCA, CCP	Interference threshold, Power, and RIS phase constraints
[170]	Continuous/Discrete	Transmit covariance matrix, RIS phase shifts	AO, SCA, Dinkelbach Method	Power, Transmit covariance matrix, and RIS phase constraints
[219]	Continuous	Time allocation, Energy transmit covariance matrix, Information transmit beamforming matrix, and RIS phase shifts	Mean-square error method, AO, Dual subgradient method, MM, SCA, Second-order cone programming	Energy and information transmit power constraints, RIS phase constraints
[167]	Continuous	BS beamforming vector, Phase shifts for transmitting and reflecting RISs, Users' digital decoder	Akaike information criterion based diagonalization method, BCD, AO, Double Deterministic Transformation, Lagrange multiplier method, Penalty method	SR, power, and RIS phase shifts constraints
[166]	Continuous	BS precoding matrix, Number of data streams, AN covariance matrix, Combining matrix, RIS phase shifts	AO, MM, Manifold optimization	Power, Thermal noise, and RIS phase shifts constraints
[163]	Continuous	BS covariance matrix, RIS phase shifts	AO, Bisection search	Power and RIS phase shifts constraints
[156]	Continuous	BS beamforming matrix, RIS phase shifts	AO, SDR	Power and RIS phase shifts constraints
[281]	Continuous	BS beamforming vector, RIS phase shifts	AO, Manifold optimization, Fractional programming	Power and RIS phase shifts constraints
[161]	Continuous	BS beamforming vector, RIS phase shifts	AO, SCA, SDR	Power and RIS phase shifts constraints
[239]	Continuous	Transmit covariance matrix, RIS phase shifts	Logarithmic barrier method	Power and RIS phase shifts constraints
[282]	Continuous	BS beamforming vector, RIS amplification and phase shifts matrix	AO, Dual-SCA, SDR	BS and RIS reflecting power budget, Max. amplification coefficient and SOP constraints
[283]	Continuous	BS beamforming vector, RIS reflective and transmissive coefficients	AO, SOCP, SCA	BS power budget, min. SNR requirement, Transmissive and reflective phase shifts and SIC order constraint
[284]	Continuous	BS beamforming vector, RIS phase shifts	AO, SCA, SDR, multi-dimensional quadratic transform	BS power budget, min. SINR requirement, RIS phase shift, and SIC order constraint
[285]	Continuous	BS beamforming vector, RIS phase shifts	AO, SDR, SCA, Dual ascent, Quadratic transform method	Power and RIS phase shifts constraints
[108]	N/A	RIS-LED association matrix	Bipartite graph, Kuhn-Munkres algorithm	RIS-LED association and fairness constraints

phase shifts given the drone's trajectory and transmit power was proposed. Then, an SCA method was developed to obtain an approximate solution for the drone trajectory subproblem. Finally, a one-dimension search method was designed for the transmit power allocation subproblem. Under the criteria of

maximizing the SR, the authors in [142] proposed a low-complexity technique based on the Riemannian conjugate gradient approach to optimize the BS beamforming vector and the RIS phase shift under transmit power budget and RIS phase constraint. In [280], the RIS phase shift and

TABLE IV(b)
SUMMARY OF SECRECY RATE OPTIMIZATION RELATED LITERATURE FOR RIS-ASSISTED PLS SYSTEMS (CONTINUED)

[#]	Phase-shift resolution	Optimization variables	Optimization techniques	Constraints
[197]	Continuous	BS beamforming vector, RIS phase shifts, UAV-mounted RIS location	SCA, Sequential rank-one constraint relaxation, Penalty method	UAV and BS power budgets, RIS phase shifts constraint
[198]	Continuous	UAV trajectory, BS beamforming vector, RIS phase shifts	Dinkelbach method, SCA	RIS phase shifts constraints, UAV power budget, UAV mobility constraints
[255]	Continuous	Radar receive beamforming, RIS phase shifts, BS transmit beamforming	Quadratic transformation, MM	Radar detection QoS, Power budgets of BS and RIS
[200]	Continuous	BS transmit precoding matrix, RIS phase shifts, UAV trajectory	AO, SDR, SCA, Riemannian Manifold gradient	UAV trajectory constraints, constraints, UAV power budget, RIS phase shifts constraint
[263]	Continuous	AP and UAV transmit power, UAV trajectory, RIS transmit and reflective phase shifts, Power splitting factor	SCA, SDR	UAV trajectory constraints, Jamming and transmit power budget, Power splitting ratio constraint, Harvested energy and RIS phase shifts
[240]	Continuous	BS beamforming vector, RIS phase shifts	AO, SCA	BS transmit power budget, RIS phase shift constraint
[257]	Continuous	BS transmit and receive beamforming vectors, AN covariance matrix, RIS phase shifts	AO, SCA, SDR	BS transmit power budget, RIS phase shift constraint, Min. data rate and sensing SNR requirements.
[267]	Continuous	UAV BS beamforming, UAV's trajectory, RIS phase shifts	BCD, SDP, SCA, Reinforcement learning	BS transmit power budget, RIS phase shift constraint, UAV trajectory constraints.
[269]	Continuous	BS beamforming vector, RIS phase shifts	AO, SDP	BS transmit power budget, RIS phase shifts constraint.
[107]	Continuous	BS transmit power, RIS allocation matrix	Heuristics, Adaptive restart genetic algorithm	BS transmit power budget, Minimum rate requirement, RIS allocation constraints.
[210]	Continuous	User transmit power, RIS phase shifts	AO, MM, Difference of concave programming	User transmit power budget, RIS phase shifts constraints.
[188]	Continuous	BS transmit power, RIS phase shifts	AO, SDR	BS transmit power budget, RIS phase shifts constraints Min. data rate requirement
[189]	Continuous	RIS phase shifts	SDR	RIS phase shifts constraints
[214]	Continuous	BS beamforming vector, BS AN, RIS phase shifts	AO, QCQP	BS transmit power budget, Interference threshold constraint, RIS phase shifts constraints
[235]	Continuous	Ground BS beamforming vector, Ground and satellite RIS phase shifts	Dinkelbach's method, AO	BS transmit power budget, RIS phase shifts constraints
[246]	Continuous	BS transmit power, RIS phase shifts	AO, SDR	BS transmit power budget, RIS phase shifts constraints
[162]	Continuous	BS beamforming vector, RIS phase shifts	Fractional programming Manifold optimization	BS transmit power budget, RIS phase shifts constraints
[110]	Continuous	RIS orientation angles	Particle swarm optimization	RIS orientation angle constraints
[184]	Continuous	UAV BS beamforming vector, RIS phase shifts, UAV BS and RIS positions	AO, Exhaustive search, SDR	Power, Minimum rate, RIS phase shifts, and UAV position constraints

location were optimized to maximize the SR by exploiting the Charnes-Cooper transformation and sequential rank-one constraint relaxation methods while considering constraints on the RIS phase shifts and the RIS location. In [141], the authors examined a worst-case sum rate maximization

problem under minimum achievable rate, maximum wiretap rate, and maximum transmit power constraints. An algorithm to design the receive decoder at the users, both the digital precoder and the AN at the BS, and the analog precoder at the RIS was developed by leveraging on AO, the MM method,

quadratically constrained quadratic programming (QCQP), and the Riemannian manifold optimization technique. In [222], the authors investigated a stochastic SCA-based algorithm to optimize the beamforming vectors at the BS and the phase shifts of an RIS to maximize the average worst-case SR subject to both the power constraint at the BS and energy harvesting constraints at the energy harvesting users.

A SR maximization problem to optimize the BS beamforming vector and RIS phase shifts was explored and solved using AO, SDR, SCA, and the linear conic relaxation method in [244]. The authors in [146] developed an algorithm based on SDR and the BCD framework to optimize BS beamforming vector and RIS phase shifts while considering constraints on the BS transmit power and RIS phase shifts. In [213], the authors proposed an algorithm to optimize the beamforming vector of the BS and the RIS phase shift subject to total power constraint at the secondary transmitter, interference power constraint at the primary receiver as well as unit modulus constraint at RIS. Under the assumption of both continuous and discrete RIS phase shift resolution, the joint optimization of transmit covariance matrix at the BS and RIS phase shifts to maximize the SR under power budget, the positive semi-definite constraint on transmit covariance matrix, and RIS phase constraints was investigated in [170]. In that paper, the authors proposed an AO-based algorithm in which, given the reflecting coefficients at the IRS and by leveraging the SCA, a convex approach was used to solve the transmit covariance matrix optimization at the AP, while given the transmit covariance matrix at the AP, AO was explored to find the RIS phase shifts. In [219], the authors maximized sum SR by optimizing the downlink/uplink time allocation, the energy transmit covariance matrix of a BS, the information transmit beamforming matrix of users and the RIS phase shift matrix subject to constraints on energy/information transmit power at the hybrid BS/users and the RIS phase shifts. The proposed AO algorithm involved the MSE method to reformulate the original problem, an AO algorithm and the dual subgradient method to optimize the energy covariance and information beamforming matrices, a one-dimensional search to obtain the optimal time allocation, and second order cone programming (SOCP), SCA, and the MM algorithm to find the RIS phase shifts.

A worst-case rate maximization problem to optimize the joint transmissive and reflective phase shifts, cascaded angular uncertainties, and the unknown jamming and BSs beamforming vectors, under power budgets, secure QoS requirements, and RISs' phase shift constraints was explored in [167]. The authors proposed several optimization techniques for the individual subproblems. First, an Akaike information criterion-based diagonalization method was designed to estimate the unknown jamming covariance matrix. Second, a double deterministic transformation method was proposed to tackle the cascaded angular uncertainties. Third, a two-layer iterative Lagrange multiplier algorithm was developed to obtain the globally optimal solution of the digital precoder. Finally, a polyblock-based multiple penalty method was designed to obtain the solutions to RISs' phase shifts. Focusing on SR maximization, the authors in [166] proposed an algorithm to

optimize the BS precoding matrix, the number of data streams, the AN covariance matrix, the receive combining matrices for the legitimate user and eavesdropper, and the RIS phase shifts for the legitimate and malicious RISs under constraints on undesired amplification of thermal noise, power budget, and RIS phase shifts constraint. The designed algorithm was based on AO, MM, and manifold optimization. In [143], the authors proposed a scheme based on AO and SDR techniques to optimize the BS beamforming matrix and the RIS phase shifts under power and unit-modulus constraints to maximize worst-case SR.

In [164], the authors explored a minimum SR maximization problem to optimize BS beamforming vector and RIS phase shifts under power budget and RIS phase shifts constraint. The proposed solution involved AO to deal with the coupled optimization variables and the path-following algorithm to handle the non-cavity of the objective function. A SR maximization algorithm that optimizes the covariance matrix of the BS and the RIS phase shifts subject to transmit power and RIS phase shifts constraint was explored in [163]. By exploiting AO and the bisection search method, the authors developed closed-form and semi-closed-form solutions for the BS transmit covariance and the RIS phase shift matrix, respectively. An algorithm based on AO and SDR techniques to maximize SR by optimizing the BS beamforming vector and RIS phase shifts under the RIS unit modulus constraints and BS power budget was proposed in [156]. In [281], the authors developed a SR maximization algorithm based on fractional programming and manifold optimization to optimize the BS beamforming vector and RIS phase shifts under BS power budget and RIS phase shifts constraint. In [161], the authors investigated SR maximization while ensuring the transmit power constraint on the BS beamforming vector and the unit modulus constraint on the RIS phase shifts. An AO-based minimum SR maximization algorithm that exploits the SCA and SDR techniques to optimize BS beamforming vector and RIS phase shifts under power budget and RIS phase shifts constraint was proposed in [160].

In [158], the authors investigated a max-min problem regarding SR by optimizing the BS beamforming matrix, RIS phase shifts, AN matrix, and the RIS-user association matrix under constraints on BS power budget and RIS phase shifts, and that each user should be served by one RIS. A SR maximization algorithm based on the difference of convex programming, SCA, and manifold optimization to optimize BS beamforming vector and RIS phase shifts under power and RIS phase shifts constraint was explored in [183]. Aiming to maximize SR in a UAV and RIS assisted mmWave wireless network, the optimization of UAV BS and RIS positions, the UAV BS beamforming vector, and the RIS phase shift was investigated in [184]. To tackle this non-convex problem, the AO approach, SDR technique, and the exhaustive search method were exploited to propose a solution method. A logarithmic barrier method-based SR maximization algorithm was proposed to optimize the transmit covariance matrix and RIS phase shift under power budget and RIS phase shifts constraints in [239]. Focusing on maximizing the worst-case SR and weighted sum SR by optimizing BS beamforming

vector, RIS phase shifts and amplification coefficients under BS and RIS power budgets, maximum RIS amplification coefficient, and SOP constraints, two AO-based algorithms were proposed in [282]. In [287], the authors maximized minimum SR by designing BS beamforming vector and RIS phase shifts subject to transmit power constraint at the BS, phase shifts constraints of the RIS, the successive interference cancellation (SIC) decoding constraints and the SOP constraints for single-antenna and multi-antenna BS scenarios. For the single-antenna BS scenario, the authors derived the exact SOP in closed-form expressions and proposed a ring-penalty-based SCA algorithm. In addition, a Bernstein-type inequality approximation based AO algorithm that uses the Dinkelbach method and the ring-penalty based SCA algorithm was proposed for the multi-antenna BS case. The study in [283] considered a maximum SR problem and proposed an SCA-based AO algorithm to design the BS beamforming vector and the reflective and transmissive phase shift vectors of STAR-RIS under constraints on the minimum SINR of legitimate users, BS maximum transmit power, SIC decoding order, and the reflective and transmissive coefficients of the RIS.

In [284], the authors investigated sum SR maximization by optimizing the BS transmit beamforming vector and the RIS phase shifts under constraints on minimum SINR requirements for legitimate users, maximum transmit power, SIC decoding condition, and the RIS phase shifts. An AO-based solution was proposed that uses the multi-dimensional quadratic transform method and the SDR technique to transform the non-convex objective functions into convex forms and the SCA algorithm to deal with the non-convex constraints. Optimization techniques to maximize the average SR by adjusting the BS beamforming vector and the RIS phase shift under transmit power budget and RIS phase shifts constraints were studied in [285]. An iterative Khun-Munkres algorithm was proposed in [108] to maximize the sum secrecy rate in an RIS-aided VLC system by optimizing the association of LEDs to RIS elements. In [199], the authors optimized the hovering position of UAV, the transmit beamforming of AP, and the phase shift matrix of RIS to maximize the worst-case sum secrecy rate. An AO-based algorithm whereby the non-convex hovering position optimization sub-problem is transformed into a convex problem by the SCA and the beamforming and RIS phase shift optimization sub-problems are converted into rank-constrained problems by the SCA and tackled by SDR is developed. A secrecy rate maximization problem was formulated in a UAV-mounted multi-functional-RIS assisted secure communication system by optimizing BS beamforming, RIS phase shifts, and the 3D location of the UAV-enabled RIS in [197]. Under the consideration of BS and UAV power budgets and RIS phase shift constraints, an AO algorithm that exploits SCA and the sequential rank-one constraint relaxation method was proposed. In [154], the authors proposed a two-layer worst-case secrecy rate maximization algorithm for a UAV-enabled RIS and fixed RIS and secured communication system. The inner layer optimizes RIS phase shifts and jamming by the aerial RIS via the BCD framework while the outer layer solves the UAV deployment problem using DRL technique.

An AO algorithm based on fractional programming and SCA was developed in [198] to maximize secrecy rate via the optimization of BS beamforming vector, trajectory of UAV, and RIS phase shifts. In [144], the authors proposed an algorithm that exploits continuous relaxation, BCD approach, SCA, and penalizing methods to maximize the minimum secrecy rate by optimizing BS beamforming vector and RIS phase shifts matrix under BS power budget and RIS phase constraints. The optimization problem to maximize the worst-case secrecy rate by designing UAV's trajectory, RIS phase shifts, and UAV and BS transmit power under constraints on UAV trajectory, RIS phase shifts and transmit power budgets was considered and a solution based on SCA and SDR was proposed in [138]. To achieve the maximum worst-case secrecy rate via optimizing power allocation, RIS phase shifts, and UAV trajectory, an AO-based algorithm that leverages SDR and SCA was investigated in [251].

A particle swarm optimization-based algorithm was proposed in [110] to optimize the orientation of RIS mirrors and maximize the secrecy rate. An algorithm that exploits fractional programming and manifold optimization to optimize BS beamforming and RIS phase shifts for secrecy rate maximization was proposed in [162]. An iterative algorithm based on SDR for optimizing RIS phase shift and BS power allocation to maximize secrecy rate under the constraints of unit modulus and total power in [246]. In [235], the authors proposed two AO-based algorithms to maximize secrecy rate by optimizing the beamforming vector of a ground BS and phase shifts of a pair of RIS under power budget and RIS phase constraints. In [214], the authors focused on maximizing the secrecy rate subject to the transmit power constraint and interference threshold by proposing an AO scheme to optimize the beamformer and AN at the BS and the RIS phase shifts. In [189], the authors developed an algorithm to optimize RIS phase shifts by using SDR method. A secrecy rate maximization problem via the optimization of radar receive beamformers, RIS phase shifts, and radar transmit beamformers under minimum radar detection SNR and total system power budget constraints was studied in [255]. The authors tackled this problem by exploiting MM and fractional programming techniques to achieve a solution. In [200], the authors focused on maximizing the secrecy rate by optimizing BS transmit precoding matrices, RIS phase shifts matrices, and UAV trajectory under constraints on UAV flying distance, maximum transmit power, and RIS phase shifts. For this design problem, an AO-based procedure where semidefinite programming (SDP) is used to solve the transmit precoding and RIS phase shift matrices while SCA is used to obtain the UAV trajectory was proposed.

An SCA-based procedure to maximize secrecy rate by optimizing BS and UAV transmit powers, UAV trajectory, transmit and reflect phase shifts of RIS, and power splitting factor at the legitimate receiver under UAV trajectory constraints, power budgets, power splitting and energy harvesting constraints, and RIS phase constraints was examined in [263]. The study in [189] focused on maximizing the secrecy rate by optimizing BS beamforming vector and RIS phase shifts under transmit power budget and RIS phase shift constraint. An optimization

problem to maximize ergodic secrecy rate by optimizing BS transmit and receive beamformer, the covariance matrix of the AN, and RIS phase shift matrix was considered and solved by exploiting SCA and Rayleigh-quotient techniques in [257]. In [267], the authors investigated secrecy rate maximization by optimizing UAV BS beamforming vector, UAV trajectory, and the RIS phase shifts with constraints on power budgets, UAV trajectory, and RIS phase shifts. The proposed AO-based algorithm involved SDP and SCA techniques for beamformer and RIS phase optimization and a deep reinforcement learning (RL) scheme for the trajectory optimization. An alternating algorithm to optimize RIS phase shifts and beamforming vector at the BS under constraints on total transmit power and RIS phase shifts was developed in [269]. In [107], the authors proposed an algorithm to maximize secrecy rate of the trusted user under minimum rate requirements for the untrusted user and transmit power budget by optimizing NOMA power allocation and RIS allocation matrix. In [210], the authors studied the optimization of D2D transmit power and RIS phase shifts to maximize secrecy rate while guaranteeing transmit power budgets and RIS phase constraints. An optimization problem to maximize secrecy rate by optimizing BS power allocation and RIS phase shifts subject to the total transmit power budget, minimal achievable rate requirements, and RIS phase shifts was examined and solved in [188].

B. Other Secrecy Metrics for Optimization

1) *Signal-to-Interference-Noise/ Signal-to-Noise Ratio Optimization*: In [288], the authors studied SINR maximization problem via RIS phase shift and BS precoding vector optimization. By utilizing the BCD technique, a brute force-maximum likelihood detection method was proposed to obtain the BS precoding vector while a penalty method-based solution was developed for the RIS phase shift optimization. Focusing on maximizing SNR of the legitimate user, the authors in [148] considered the joint optimization of BS beamforming vector and RIS phase shifts while considering constraints on the SNR of the eavesdropper, the RIS phase shifts, and the maximum transmit power. An AO solution method that uses SDR technique to solve the RIS phase shift optimization subproblem and the SCA and CCP to solve the BS beamforming optimization subproblem was developed. In [245], the authors proposed Dinkelbach-style algorithms to optimize the transmit power of BSs and the RIS phase shifts to minimize the SINR of the eavesdroppers subject to constraints on the legitimate users' SINR, BS power, and RIS phase shifts. In [272], the authors studied the optimization of RIS phase shifts and sensor nodes precoding vector to maximize the SNR at the fusion center under constraints on transmit power budgets for sensor nodes, RIS phase shifts, and the SNR at the eavesdropper.

2) *Power Consumption Optimization*: In [142], the authors proposed a BS beamforming vector and RIS phase optimization scheme based on the Riemannian conjugate gradient method to minimize the total power consumed while considering the minimum SR requirement. An alternating algorithm to optimize the beamforming vectors for cognitive

and primary BSs and the phase shifts of an RIS while considering rate requirements of primary and secondary users, interference thresholds, and power budgets of the BS was designed in [212]. In [292], the authors proposed an alternating algorithm to optimize the beamformer vector at the BS and the RIS phase shift under SR constraints and power budget in order to minimize the total power consumption. A transmit power minimization algorithm based on AO and SDR techniques to optimize BS beamforming vector and RIS phase shifts subject to the SR and RIS phase shifts constraints was investigated in [165]. In [159], the authors proposed an alternating direction algorithm to optimize the BS beamforming vector and RIS phase shifts under QoS, transmit power, and RIS phase shifts constraints. In [183], an SCA-based algorithm was proposed to maximize the AN power by optimizing the BS beamforming vector, the RIS phase shifts, and AN power under transmit power and minimum user rate constraint. Focusing on minimizing the transmit power at the ground BS while guaranteeing the achievable secrecy rate of the satellite user and the achievable rate of the terrestrial user, an AO-based algorithm for optimizing BS precoding matrix and RIS phase matrix was proposed in [234].

3) *Computation Efficiency Optimization*: In [262], the authors studied the optimization of time-slot assignment, RIS phase shifts, local computing frequencies, and the transmit power of IoT devices, with the objective of max-min computation efficiency, while guaranteeing the IoT devices' secure computation rate and minimum computation requirements. A secure energy consumption minimization problem that optimizes the BS receive beamforming vectors, AN covariance matrix, RIS phase shifts, users' offloading time, transmit power, and local computation tasks was examined in [229]. To efficiently solve this non-convex problem, the authors decomposed the joint problem and adopted a SDR algorithm to optimize the BS receive beamforming vectors, AN covariance matrix, and RIS phase shifts, and the Dinkelbach method to optimize the power and local computation tasks. The design constraints included task offloading time, users' maximum power constraint, maximum delay constraint, maximum local computation tasks constraint, BS receive beamforming vectors constraint, maximum power constraint for BS transmitting AN, and the phase shifts constraint of the RIS. In [232], the design problem of maximizing the secure computation task bits of users by optimizing the AP energy transmit beamforming, the RIS phase shifts, users' uplink transmit power, users' offloading time, and the local computation frequency of users under energy harvesting, energy beamforming, and RIS phase constraints and users' transmit power budget was examined. The authors proposed an alternating solution method in which SDP and SDR algorithms were used to optimize the energy transmit beamforming of the AP and the RIS phase shifts, and the Lagrange duality method and Karush-Kuhn-Tucker condition were utilized to obtain the users' transmit power and computation time.

4) *Energy Efficiency Optimization*: An energy efficiency maximization problem to optimize BS beamforming vector, jamming beamforming vector, and RIS phase shifts under minimum SR requirement, power budgets, and RIS phase shift

TABLE V(a)
SUMMARY OF SECRECY METRICS OPTIMIZATION (OTHER THAN SECRECY RATE) RELATED LITERATURE FOR RIS-ASSISTED PLS SYSTEMS

[#]	Phase-shift resolution	Optimization variables	Objective	Optimization techniques	Constraints
[222]	Continuous	BS beamforming vector, RIS phase shifts	Maxmin secrecy rate	Stochastic SCA	Energy harvesting and Power constraints
[164]	Continuous/Discrete	BS beamforming vector, RIS phase shifts		AO, Path-following algorithm	Power and RIS phase shifts constraints
[143]	Continuous	BS beamforming vector, RIS phase shifts		AO, SDR	Power and RIS phase shifts constraints
[158]	Continuous	BS beamforming matrix, RIS phase shifts, AN matrix, RIS assignment matrix		AO, SDR, SCA	RIS-user single connectivity, Power, and RIS phase shifts constraints
[160]	Continuous	BS beamforming vector, RIS phase shifts		AO, SCA, SDR	Power and RIS phase shifts constraints
[282]	Continuous	BS beamforming vector, RIS amplification and phase shifts matrix		AO, Dual-SCA, SDR, Dinkelbach method, Bisection search	BS and RIS reflecting power budget, Maximum amplification coefficient and SOP constraints
[199]	Continuous	UAV position, AP transmit beamforming phase shifts matrix		AO, SCA, SDR	Min. rate requirement of legitimate users, LoS connection requirement, Power budget, RIS phase constraints, UAV position constraints
[154]	Continuous	UAV position, Covariance of jamming signal by UAV RIS, Fixed RIS and UAV RIS phase shifts matrix		AO, BCD, SDP, SCA, DRL	Jamming Power budget, RIS phase constraints, UAV position constraints
[251]	Continuous	BS Power allocation, RIS phase shifts, RIS-UAV trajectory		AO, SCA, SDR	BS Power budget, RIS phase constraints, UAV position constraints
[138]	Continuous	UAV BS transmit power, RIS phase shifts, UAV trajectory		AO, SCA, SDR	BS and legitimate user power budget, RIS phase constraints, UAV position constraints
[144]	Continuous	BS beamforming vector, RIS phase shifts	BCD, SCA, SDP	BS power budget, RIS phase constraints	
[287]	Continuous	BS beamforming vector, RIS phase shifts	AO, Ring-penalty based SCA, Dinkelbach method	BS power budget, RIS phase shifts, users' SIC decoding, and SOP constraints	
[141]	Continuous	Receive decoder, Digital precoder, Analog precoder, Artificial noise	Maxmin rate	AO, MM, QCQP, Riemannian manifold optimization	Minimum rate requirements for user and eavesdropper, Transmit power budget and RIS phase constraint
[288]	Continuous	RIS phase shifts, BS precoding vector	Max. SINR	BCD, Brute force, Penalty method	Interference constraints, Power and RIS phase constraints
[245]	Continuous	BS transmit power, RIS phase shifts	Min. SINR	AO, SDR, Dinkelbach method	Minimum SINR, power, and RIS phase constraints
[148]	Continuous	BS beamforming vector, RIS phase shifts	Max. SNR	AO, CCP, SDR	Power, SNR, and RIS phase constraints
[272]	Discrete	BS precoding vector, RIS phase shifts		AO, SDR	Power budget, eavesdropper SNR constraint
[256]	Continuous	BS beamforming vector, RIS phase shifts, Radar receive filter	Max. radar SNR	BCD,SDR, MM, Quadratic transformation	Communication QoS, Secure transmission rate, Power budget and RIS phase shifts constraint
[289]	Continuous	BS beamforming vector, RIS phase shifts	Maxmin approximate ergodic SR	AO, CCP, SDR, MM, Quadratic transform, BCD, SOCP	Power and RIS phase constraints
[290]	Continuous	RIS phase shifts	Max. variance of Eve-RIS generated channel	SDR	RIS phase shifts constraints
[291]	Continuous	BS precoding matrix, RIS phase shifts	Max. secret key rate	Water-filling algorithm, Bisection search, Grassmann manifold optimization	RIS unit-module constraint, Channel measurement constraints, Power budget

TABLE V(b)

SUMMARY OF SECRECY METRICS OPTIMIZATION (OTHER THAN SECRECY RATE) RELATED LITERATURE FOR RIS-ASSISTED PLS SYSTEMS (CONTINUED)

[#]	Phase-shift resolution	Optimization variables	Objective	Optimization techniques	Constraints
[165]	Continuous	BS beamforming vector, RIS phase shifts	Min. power	AO, SDR	Minimum rate requirement, and RIS phase shifts constraints
[212]	Continuous	BS beamforming vector, RIS phase shifts		SOCP	Minimum rate requirements, Interference threshold, and RIS phase constraints
[292]	Continuous	BS beamforming vector, RIS phase shifts		AO, SCA	SR and Power constraints
[142]	Continuous	BS beamforming vector, RIS phase shifts	Min. power, Max. SR	Riemannian gradient-based method	Power budget, Minimum secrecy rate and RIS phase constraints
[159]	Continuous	BS beamforming vector, RIS phase shifts	Max. power	Alternating direction algorithm	Power, minimum SNR, and RIS phase shifts constraints
[183]	Continuous	BS beamforming vector, RIS phase shifts	Max. AN power Max. SR	difference of convex programming, SCA Manifold optimization	Power, RIS phase shifts and minimum rate constraints
[262]	Continuous	IoT device transmit power, RIS phase shifts, Computing frequencies, Time-slot assignment	Maxmin computation efficiency	AO, SCA, BCD, Dinkelbach method	SR, Minimum computation requirements, Power, Time-slot, Computing frequencies, and RIS phase constraints
[229]	Continuous	BS receive beamforming vector, AN covariance matrix, RIS phase shifts, Users' offloading time Transmit power, Local computation tasks	Min. secure energy	AO, SDR, Dinkelbach Method	Task offloading, BS and users' Power, Delay, Computation, Beamforming, and RIS phase constraints
[149]	Continuous	BS beamforming vector, Jamming beamforming vector, RIS phase shifts	Max. secure EE	AO, SDR, Dinkelbach method	Minimum rate requirement, Power and RIS phase shifts constraints
[171]	continuous	Transmit covariance matrix, RIS phase shifts, and redundancy rate		AO, concave-convex procedure	SOP, Power and RIS phase shifts constraints
[242]	Continuous/Discrete	BS beamforming vector, RIS phase shifts, and Transmission rate		AO, Path-following procedure, Quadratic transformation	SOP, Power and RIS phase shifts constraints
[260]	Continuous	Transmission waveform signal, BS beamforming vector, RIS transmit and reflective phase shifts	Max. received radar sensing power	Distance-majorization based algorithm, AO	Signal waveform and peak-to-average-power ratio constraints, Amplitude constraints on transmit and reflective RIS, Constructive interference constraints for communication users, Security constraints for malicious radar targets
[261]	Continuous	BS beamforming vector, BS AN covariance matrix, RIS phase shift matrix,	Min. eavesdropper data rate, Maxmin communication SINR, Max. communication sum rate	Quadratic transformation, Lagrangian dual transform., AO, Penalty-based method, Riemannian gradient-based method, SDP	Radar similarity constraint, RIS phase shifts constraint
[241]	Continuous	BS beamforming vector, RIS phase shift	Min. BS transmit power	AO, SDR, Sequential rank-one constraint relaxation	Eve's worst-case SNR and SNR OP constraints
[268]	Continuous	BS beamforming vector, RIS phase shift		BCD, SDP	Minimum SINR requirements for legitimate user, RIS phase shifts constraints
[217]	Continuous	Energy price, Wireless energy transfer time, energy and information phases matrices, Beamforming vector	Max. utility function	Stackelberg game, AO, SDR, BCD, Golden search method, SCA	Scheduling and RIS phase shifts constraints and Power budget
[232]	Continuous	BS beamforming vector, RIS phase shifts, Users' offloading time, Users' transmit power, Users' local computation frequency	Max. Secure computation performance	SDR, Lagrange duality theory	Energy harvesting constraint, RIS phase shifts constraints, Constraint on energy harvesting and computation time.
[233]	Continuous	Redundant rate, Caching probability	Max. secure transmission probability	AO, Bisection search, Exhaustive search	Caching probability and Cache storage capacity constraints
[234]	Continuous	Transmit power, RIS phase shifts	Min. ground BS transmit power	AO, S-procedure	Min. secrecy rate requirements
[173]	Continuous	BS beamforming vector, RIS phase shifts	Min. secrecy outage probability	AO, SDR, Manifold optimization	BS transmit power budget, RIS phase shifts constraints

constraints was investigated in [149]. The authors proposed an AO-based algorithm that leverages the SDR technique and

Dinkelbach method. In [242], the authors proposed an AO algorithm that exploits a path-following procedure and quadratic transformation to maximize energy efficiency by optimizing BS beamforming vector, RIS phase shift, and transmission rate under SOP, BS power and RIS phase shifts constraint. In [171], the authors studied secure EE maximization by optimizing the BS transmit covariance matrix, RIS phase shifts, and the redundancy rate subject to SOP constraint, RIS phase shifts constraints, and transmit power constraint.

5) *Ergodic Secrecy Rate*: In [289], the authors investigated the optimization of the BS beamforming vector and the phase shifts of the reflecting elements at the RIS so as to maximize the weighted minimum approximate ergodic SR subject to BS transmit power constraint and RIS phase shifts constraint. To solve this problem, the joint problem was first decoupled into two tractable subproblems, which were tackled alternatively via the BCD method. Two different methods were proposed to solve the two subproblems. The first method exploited SOCP, CCP, and the quadratic transform while the second method was based on the MM algorithm.

6) *Channel Gain*: A SDR approach to maximize the variance of the Eve-RIS generated deceiving channel by optimizing RIS phase shift was investigated in [290].

7) *Secret Key Rate*: In [291], the authors investigated an RIS-assisted key generation system by focusing on the design of precoding and phase shift matrices to fully exploit the randomness from the direct and cascaded channels. First, a water-filling algorithm was proposed to find the upper bound on the key rate of the system. In addition, the authors developed an algorithm by exploring the bisection search method and Grassmann manifold optimization to obtain the phase shift and precoding matrices such that the key rate approaches the upper bound. The authors in [293] proposed a multi-user secret key generation system that utilized RISs within the given environment. The channel model induced by RISs was characterized as the sum of products involving the channel from the transmitter to the RIS, the phase shifts introduced by the RIS, and the subsequent channel from the RIS to the receiver. A closed-form expression for the secret key rate was derived, providing a general analytical representation of the key generation process.

8) *Utility Function*: The study in [217] explored the integration of RIS in a wireless-powered communication network, focusing on energy harvesting from a power station and secure information transmission to IoT devices in the presence of eavesdroppers. In that paper, the authors proposed a RIS-aided energy trading and secure communication scheme that employs a Stackelberg game model between the transmitter and power station where the transmitter optimizes the energy price, wireless energy transfer time, RIS phase shift, and beamforming vector to maximize its utility function. On the other hand, the power station adjusts the transmit power based on the energy price of the transmitter.

9) *Outage Probability*: In [173], the authors first developed an expression of secrecy outage probability as a metric for RIS-assisted PLS system and then formulated a secrecy outage probability minimization problem that optimizes BS beamforming vectors and RIS phase shift matrices under RIS

phase constraints and BS transmit power budget. An AO-based procedure that involves a closed-form solution for the optimal beamforming vector and two techniques for phase shifter matrix optimization (i.e., SDR-based and manifold-based methods) were proposed. An iterative scheme to maximize the secure transmission probability of an IRS-assisted cache-enabled space-terrestrial network by optimizing the transmission rates and caching probability under cache storage capacity limitations was explored in [233].

C. Lessons Learnt

This section has investigated various optimization frameworks for RIS-assisted PLS systems. A summary and the key points are presented below.

- Most of the objective functions and sets of constraints of RIS-assisted PLS systems are typically non-convex, non-linear, and involve highly coupled decision variables since RIS phase shift optimization is often combined with other techniques such as BS beamforming optimization, UAV trajectory optimization, and RIS location design. To address these challenges, various transformation and convexifying techniques are often employed. As an example, AO and BCD are used to decouple joint optimization variables into subproblems, SDR is used to relax non-convex RIS phase constraints, MM, SCA, and quadratic transform are used for non-convex and non-linear objective functions and constraints. However, such techniques can lead to suboptimal solutions. It is therefore important to investigate global optimization techniques that can better handle the coupled variables (i.e., without decomposing into subproblems), non-convexity, and efficiently explore the resulting large solution spaces.
- Most studies in the literature focused on SR optimization. However, 6G and beyond networks seek significant improvements in EE, connection density, mobility management, transmission latency, and the support for sensing services. It is therefore important to consider novel objective functions and multi-objective optimization problems that jointly capture the impact of user mobility, energy consumption, connection density, transmission latency, and sensing QoS. This will help align the optimization strategies with the multifaceted goals of next-generation networks.
- It can be observed from Tables IV and V that most works assume continuous phase shifts (i.e., infinite resolution phase shifts), which are difficult to implement in practical systems. Consequently, there is a compelling need to investigate the impact of the limited phase shifts on the secrecy rate and also consider optimizing discrete (i.e., finite-level) phase shifters.

VII. MACHINE LEARNING TECHNIQUES FOR RIS-ASSISTED PLS

ML has proven highly successful across diverse domains, including solving involved optimization problems of wireless communication systems. Integrating machine learning techniques into enhancing PLS within wireless communications

TABLE VI
SUMMARY OF ML RELATED LITERATURE FOR RIS-ASSISTED PLS SYSTEMS

[#]	Phase-shift resolution	Optimization variables	Objective	ML technique(s)	Constraints
[152]	Continuous	BS transmit power, RIS phase shifts	Max. SR	Fast-policy hill-climbing RL algorithm	Minimum SINR, transmit power constraints
[294]	Continuous	BS beamforming vector, RIS phase shifts		Deep Q-learning algorithm	BS transmit power constraint
[295]	Continuous	BS beamforming matrix, RIS phase shifts		Deep deterministic policy gradient RL algorithm	BS transmit power, RIS phase constraints
[264]	Continuous	BS beamforming matrix, RIS phase shifts		Deep deterministic policy gradient RL algorithm	Minimum SINR, BS transmit power, RIS phase constraints
[258]	Continuous	BS transmit beamforming, BS AN vector, RIS phase shifts		Soft actor-critic DRL algorithm	BS transmit power, maximum error constraints
[185]	Continuous	UAV beamforming matrix, RIS phase shifts, UAV trajectory		Twin-deep deterministic policy gradient RL algorithm	Secrecy outage probability constraint
[193]	Continuous	Aerial RIS deployment, Aerial RIS phase shifts		Two layer-based solution, inner layer: semidefinite programming and outer layer: deep Q-learning algorithm	Aerial RIS location, Aerial RIS phase constraints
[195]	Continuous	RIS phase shifts, UAV trajectory		Two layer-based solution, inner layer: manifold optimization and outer layer: DRL algorithm	UAV flying waypoints and velocities, RIS phase constraints
[254]	Continuous	BS beamforming vector, RIS phase shifts		Unsupervised projection-based deep neural network algorithm	BS transmit power, RIS phase constraints
[109]	N/A	AP beamforming vector, RIS mirror orientations		Deep deterministic policy gradient RL algorithm	BF weights, orientation angles limits constraints
[296]	Continuous	BS beamforming matrix, RIS phase shifts	Maxmin SR	Post-decision state and prioritized experience replay DRL algorithm	Minimum SR, minimum data rate, power, RIS phase constraints
[247]	Discrete	Relay selection, RIS phase shifts	Max. SR, Max. throughput	Distributed multi-agent RL algorithm	delay, secrecy, RIS phase constraints
[231]	Continuous	BS beamforming matrix, Cooperative jammer beamforming matrix, RIS phase shifts	Max. SR, Max. secure energy efficiency	Deep deterministic policy gradient RL algorithm	BS transmit power, user minimum SR, RIS phase constraints
[297]	Discrete	RIS phase shifts	Max. Eve rate	Double deep Q-Learning network algorithm	RIS phase, proactive eavesdropping-related constraint
[253]	Continuous	Sensor encryption key, sensor transmit power, RIS phase shifts	Max. long-term utility that consists: the data protection level, the Eve rate, the SINR, the sensor energy consumption, the transmission latency	Actor-critic-based DRL algorithm	RIS phase constraint
[201]	Continuous	RIS phase shifts, UAV trajectory	Max. achievable rate	Q-learning and Deep Q-network algorithms	UAV horizontal coordinate, RIS phase constraints
[230]	Continuous	RIS phase shift, device power control, device computation rate, device time-slot allocation	Weighted sum secrecy computation efficiency	Deep deterministic policy gradient RL algorithm	Device transmit power, RIS phase constraints

shows significant potential across diverse characteristics. A notable advantage lies in the capability for proactive detection and prevention of threats. By using supervised learning algorithms trained on datasets, patterns indicative of malicious activities can be identified in real time, enabling the prompt recognition of eavesdropping attempts. On the other hand, unsupervised learning methods offer adaptability in revealing emerging threats without predefined training datasets. The applications of machine learning in fortifying PLS contain the mitigation of eavesdropping, jamming attacks, and unauthorized access. Advanced techniques demonstrate effectiveness in extracting complicated features from wireless signals, enhancing the precision of threat detection. Additionally, RL can be utilized to optimize adaptive strategies for securing communication channels over time, establishing a responsive defense mechanism. The presented work in the literature that solve optimization problems resulting from the integration of RIS technology in secure RF and OWC systems mainly adopted DRL techniques and unsupervised learning. Data-intensive requirements of supervised learning, coupled with the potential unavailability of detailed datasets in real-world scenarios and the challenges associated with labeling, hinder the adoption of supervised learning algorithms. Hence, this segment explores many ML techniques (involving DRL and unsupervised learning techniques) that help in solving optimization problems resulting from the integration of RIS technology in secure RF and OWC systems. This section reviews state-of-the-art ML techniques for RIS-assisted PLS and summarizes existing ML schemes for SR maximization and other secrecy metric optimization in Table VI.

A. Deep Reinforcement Learning

RL is a potent machine learning technique with significant implications for advancing artificial intelligence (AI). In RL, an autonomous agent undergoes a learning process, consistently making decisions by observing environmental states and autonomously adjusting its approach to attain an optimal policy [298]. However, the time-intensive nature of this learning process renders RL less suitable for large-scale networks, given the dynamic nature of wireless channels over time. Consequently, RL applications face substantial limitations in real-world scenarios [299]. Recently, the emergence of deep learning [300] has been identified as a transformative approach capable of addressing RL's constraints. In light of these considerations, DRL is proposed, representing a revolutionary development in AI and a promising avenue for autonomous systems. Presently, deep learning facilitates the scalability of RL to previously intractable problems. DRL algorithms find application in robotics, enabling real-time learning from inputs, such as camera data, by leveraging the advantages of deep neural networks to enhance the learning speed in the DRL [300], [301]. In [295], a secure communication system utilizing RIS in a full-duplex setting was investigated, considering the impact of hardware impairment. An optimization problem was formulated to maximize the SSR through joint optimization of transmit beamforming at the BS and phase shifts at the RIS. Due to the mathematical intractability, a

DRL-based algorithm was proposed to obtain a solution. The efficacy of the developed DRL-based algorithm in enhancing SSR was validated through extensive simulation results. A RIS-assisted secure ISAC system was investigated in [258]. The technique aimed to maximize the SR through the joint optimization of transmit beamforming, AN matrix, and RIS phase-shift matrix. An algorithm based on DRL was introduced to tackle the optimization problem. The effectiveness of the proposed technique revealed higher secrecy performance. An energy-efficient and secure wireless personal area network (WPAN) transmission system, enhanced by RIS and RL, was introduced in [253]. The sensor encryption key, transmit power, and optimized RIS phase shifts were coordinated to minimize eavesdropping rates. Secrecy performance improvement was achieved through a DRL approach. ARIS-assisted secure communications were explored in [195] to enhance security. The proposed approach involved trajectory design based on RL and reflection optimization. The PLS enhancement was validated through simulation results. The RL was utilized to maximize the eavesdropping rate in [297] in the presence of legitimate RIS to assess the eavesdropping performance. The authors in [247] utilized the multi-agent DRL-based technique to design RIS reflection coefficients and relay selection to secure buffer-aided cooperative networks. To enhance the anti-jamming strategy of wireless communication systems, the RIS was used in [152], where the fast RL technique was presented to achieve the optimal anti-jamming design.

1) *Deep Deterministic Policy Gradient*: deep deterministic policy gradient (DDPG) is a specialized reinforcement learning algorithm for addressing challenges associated with continuous action spaces. Extending the foundations of the deterministic policy gradient (DPG), DDPG incorporates deep neural networks for both the policy and value function [302]. Noteworthy is its adoption of a deterministic policy, directly mapping states to specific actions, offering a streamlined approach for learning in continuous action domains. The algorithm employs an actor-critic architecture, where the actor-network formulates the optimal action policy, and the critic assesses the selected actions. Integration of experience replay involves storing past experiences in a buffer, mitigating temporal correlations in training sequences [303].

Utilizing DDPG in PLS introduces an innovative approach to addressing security challenges within wireless communication networks. DDPG's ability to handle continuous action spaces makes it a strategic choice for optimizing decision-making processes about PLS. The deterministic policy inherent in DDPG facilitates precise and strategic decision-making for secure wireless communication systems. DDPG provides a sophisticated framework capable of adapting security strategies in response to the dynamic nature of wireless channels by integrating deep neural networks for policy formulation and value function evaluation. The advantages of implementing RIS in MEC to secure the industrial internet of things (IIoT) networks were investigated in [230]. The optimization of RIS phase shift, power control, local computation rate, and time slot was collectively undertaken to maximize the weighted sum secrecy computation efficiency, in which a DDPG-based algorithm was developed to address this intricate optimization problem.

Simulation results demonstrated that deploying RIS in MEC-enabled IIoT networks enhanced task offloading security, and the proposed DDPG-based algorithm surpassed baseline methods in terms of weighted sum secrecy computation efficiency (WSSCE). A cooperative jamming technique, incorporating DRL for RIS-enhanced secure cooperative network in the IoT, was introduced in [231], considering the presence of eavesdroppers. The primary objective was maximizing the ASR by jointly optimizing transmit and jamming beamforming matrices and the RIS phase-shift matrix, where the DDPG optimization algorithm was proposed. The obtained results show improvements in secrecy rate compared to benchmark schemes. Secure communication within diverse multi-device IoT environments was explored in [264]. The classification of legitimate devices into trusted and untrusted categories addressed varying levels of network security in the presence of potential eavesdroppers. A joint optimization problem involving active and passive beamforming was formulated to maximize the SSR of trusted devices while ensuring performance guarantees for all trusted and untrusted devices. An algorithm based on DDPG was introduced to obtain the optimal phases for RIS and the transmit beamforming matrix. The results demonstrated a significant increase in the SR of trusted devices. The authors of [109] introduced a DRL-based approach for a secure VLC system utilizing RIS. The adjustment of BF weights at light fixtures and mirror orientations within the mirror array sheet to optimize SR was controlled by the DDPG-based algorithm. The adaptability of the DDPG-based algorithm in managing the system's high complexity and user mobility was demonstrated. Findings indicated enhancing the security of the VLC communication system. In [185], the robust and secure transmission of RIS-assisted mmWave UAV communications was explored. A DDPG algorithm was introduced to maximize the SR rate for all authorized users. Simulation results confirmed that superior performance could be attained compared to several benchmark methods through the joint optimization of UAV trajectory and active (passive) beamforming.

2) *Deep Q-learning Algorithm*: deep Q-learning (DQN) extends the capabilities of the Q-learning algorithm by incorporating deep neural networks to manage intricate and high-dimensional state spaces effectively. In DQN, the conventional Q-table is replaced with a neural network called the Q-network, which approximates Q-values for each action within a given state. This adaptation equips DQN to navigate scenarios with continuous or extensive state spaces proficiently. The neural network undergoes training to minimize the disparity between its predicted and target Q-values, computed using the Bellman equation. DQN has demonstrated notable success in tackling demanding problems within reinforcement learning, especially in domains like playing intricate video games, where the conventional Q-learning approach encounters challenges due to the expansive and continuous state space. Integrating deep neural networks enables DQN to generalize and acquire insights into intricate patterns, establishing it as a robust tool in artificial intelligence.

Secure communications enabled by ARIS were explored in [193], employing ARIS deployment and passive beamform-

ing, with the strategic design leveraging DQN. The simulation results revealed that the proposed DQN successfully approximated optimal deployment, resulting in significant improvements in security performance compared to baseline methods. Moreover, a better performance could be achieved with more reflecting elements. The authors of [201] presented ARIS, wherein UAV and RIS capabilities were utilized to enhance average downlink achievable rates in wireless networks. The implementation used Q-learning and DQN algorithms to evaluate the approach's effectiveness in enhancing security. The findings indicated that the DQN algorithm was more suitable than the Q-learning algorithm for systems with huge action and state spaces. In [294], the security of RIS-enabled wireless networks was investigated in the presence of intelligent attackers. DQN was introduced to enable adaptive modulation of BS and RIS reflection beamforming. When an eavesdropping attempt was detected, the base station allocated a portion of transmit power to emit AN, disrupting eavesdroppers. The results demonstrated the efficacy of the proposed strategy, contributing to enhancing the SR in RIS-assisted wireless communication systems.

B. Unsupervised Learning

Unsupervised learning-based algorithms do not rely on labeled training data to enhance and optimize processes. Instead, these algorithms autonomously uncover patterns and structures within the data, making them particularly valuable in situations where labeled data is limited or costly to obtain. In [254], an average secrecy rate maximization for secure RIS-aided aeronautical ad-hoc networks (AANET) has been designed through a deep unsupervised learning algorithm. Specifically, the proposed algorithm relied on a projection-based deep neural network (DNN) to get suitable solutions. The DNN addresses the given optimization problem without constraints. Simultaneously, the projection method ensures that the DNN's output is subsequently mapped to the constrained domain.

C. Lessons Learnt

The lessons learnt from this section can be summarized as follows.

- Integrating machine learning techniques into wireless communications for enhancing PLS offers significant potential in diverse characteristics. ML, mainly supervised and unsupervised learning algorithms, enables proactive detection and prevention of threats, such as eavesdropping attempts, jamming attacks, and unauthorized access. The DRL, notably the DDPG algorithm, offers innovative approaches to address security challenges within wireless communication networks, specifically in RIS-assisted PLS scenarios. In addition, DDPG demonstrates effectiveness in handling continuous action spaces, making it suitable for optimizing decision-making processes related to PLS. Moreover, the deterministic policy inherent in DDPG facilitates precise and strategic decision-making for secure wireless communication systems. Furthermore,

DDPG-based algorithms have successfully optimized various parameters in secure communication systems, such as RIS phase shift, power control, and beamforming matrices, significantly improving secrecy performance.

- The DQN algorithm extends the capabilities of traditional Q-learning by incorporating deep neural networks to manage complex and high-dimensional state spaces effectively. In addition, DQN has been applied to enhance security in wireless communication networks, particularly in scenarios involving RIS-enabled systems. Moreover, DQN-based approaches have demonstrated success in approximating optimal deployment strategies, improving security performance compared to baseline methods, and mitigating security risks posed by intelligent attackers.
- Unsupervised learning-based algorithms offer valuable insights into optimizing PLS without relying on labeled training data. Deep unsupervised learning algorithms, such as projection-based deep neural networks, autonomously uncover patterns and structures within data, making them particularly suitable for scenarios where labeled data is limited or costly to obtain. These algorithms have been applied to maximize average SR in secure RIS-aided networks, effectively addressing optimization problems without constraints and mapping outputs to constrained domains.

VIII. PERFORMANCE ANALYSIS FOR RIS-ASSISTED PLS

The performance analysis for RIS-assisted PLS represents an essential aspect of evaluating the potential of RIS technology in enhancing the security of wireless communication systems. In PLS, RIS holds promise for strengthening security measures by selectively adjusting signal characteristics, managing interference, and mitigating eavesdropping attempts. This section focuses on conducting a comprehensive performance analysis to assess the impact of RIS-assisted PLS in terms of SNR improvement, SC enhancement, and SOP reduction. By examining the performance of RIS-enabled systems under different scenarios, valuable insights can be gained into the significance and feasibility of leveraging RIS to enhance wireless communication systems' PLS.

A. SNR Improvement with RIS

This subsection explores the SNR enhancement via RIS within the paradigm of PLS, highlighting its crucial role in mitigating noise and optimizing signal strength. Significantly, the adaptive nature of RIS facilitates dynamic adjustments, a feature of paramount significance in addressing varying interference patterns and ensuring high SNR. The high SNR extends to fortifying communication links, particularly in challenging urban settings. This increases communication reliability and directly impacts security by strengthening communication links against eavesdropping and other security threats. The secrecy capabilities of wireless communication systems enhanced by using the RIS were examined in the presence of a potential eavesdropper, where the RIS was placed on the strategic placement between the source and the intended user, creating an intelligent environment to maintain

link security. The results confirmed the positive influence of RIS utilization on improving the secrecy performance of wireless systems [209], [316]. The performance analysis of secure communications assisted by RIS for discrete phase shifts was investigated in [308], [310], [317]. The security performance of a communication system aided by RIS was examined in [196], with spatially random UAVs serving as eavesdroppers. The obtained results highlighted the security enhancements achieved through the deployment of RIS. The secrecy performance of a relay communication system utilizing an RIS on a UAV was investigated in [318] in the presence of multiple ground eavesdroppers. Specifically, a UAV equipped with a RIS was a passive relay, forwarding signals from the base station to users. Secrecy performance for integrated satellite and UAV relay networks with multiple vehicle eavesdroppers was investigated in [236] by employing RIS. The UAV was used to relay the legitimate signal to the destination user, facilitated by RIS. The authors in [75], proposed a novel technique by designing active elements in RIS to overcome the double-fading problem introduced in the RIS-aided link in a wireless communications system to secure the transmission data. In this approach, the reflected incident signal was amplified by RIS's active elements, departing from the sole reflective function observed in passive RIS modules. The analysis and simulations revealed a significant reduction in the required size of the RIS to achieve a specified performance level when active elements were employed. Additionally, a practical design for active RIS was proposed.

B. Secrecy Capacity Enhancement

This subsection focuses on enhancing SC through using RIS within the context of PLS. Recent research conveys how the reconfigurable nature of RIS strategically influences channel dynamics, strengthening the system's capacity for secure data transmission through adaptive configurations that dynamically manipulate signal propagation, offering insights into potential gains in secure communication. The results illustrate how the RIS contributes to heightened SC by dynamically adapting to the communication environment and strategically configuring itself to minimize the impact of potential eavesdropping attempts. Comparative analyses against scenarios without RIS intervention further highlight the high improvements in SC obtained by RIS. This integrated approach clarifies how RIS enhances SC, establishing its role as a promising technology in improving PLS. The effectiveness of STAR-RIS in enhancing security within the MISO network was explored in [319]. Three transmission protocols, energy splitting, mode selection, and time splitting, were examined to maximize the weighted sum secrecy rate. In [222], high passive beamforming gains for signal enhancement were achieved by RISs through the dynamic adjustment of their reflection coefficients, improving wireless security and RF-based wireless power transfer efficiency. A RIS-assisted secure SWIPT system was investigated for transferring information and power. The worst-case downlink secure communication scenario was addressed in [251], applying RIS-UAV as an aerial passive relay to enhance communication. The objective was to maximize the

TABLE VII
SUMMARY OF PERFORMANCE ANALYSIS RELATED LITERATURE FOR RIS-ASSISTED PLS SYSTEMS

[#]	Phase-shift resolution	Security attack	Eavesdropper type	Performance metric(s)	Main Findings
[304]	Continuous	Jamming	Passive	SOP	Impacting of electromagnetic interference's on secrecy performance
[305]	Continuous	Eavesdropping	Passive		Enhancing PLS using RIS
[115]	Continuous	Eavesdropping	Passive		Analyzing secure RIS-assisted HAP-UAV joint MU mixed RF/FSO system
[306]	Continuous	Eavesdropping	Passive		Utilizing cooperative jamming and BF design to improve PLS of NOMA
[307]	Continuous	Eavesdropping	Passive		Utilizing cooperative jamming and BF design to improve PLS of NOMA
[308]	Discrete	Eavesdropping	Passive		Revealing the SOP's scaling law for RIS's elements and quantization's bits
[309]	Continuous	Eavesdropping	Passive		Reducing the secrecy performance due to residual hardware impairments
[250]	Continuous	Eavesdropping	Passive		Enhancing secrecy performance of V2V communications with the aid of RIS
[209]	Continuous	Eavesdropping	Passive	SOP, PNSC	Friendly Jamming Eve using RIS to improve the security performance
[211]	Continuous	Eavesdropping	Passive		Improving the secrecy performance of primary network using secondary RIS
[221]	Continuous	Eavesdropping	Passive		Designing phase shift to maximize information at the legitimate destination
[75]	Continuous	Eavesdropping	Passive		Enhancing secrecy performance of wireless network using active RIS
[265]	Continuous	Eavesdropping	Passive	SOP, PNSC, ASR	Improving a secure data transmission between an IoT sensor and a gateway in LPWAN applications.
[169]	Continuous	Jamming	Active		Reducing the secrecy performance due to residual hardware impairments
[310]	Discrete	Eavesdropping	Passive	SOP, ASR	Unveiling the secrecy loss due to phase resolution
[311]	Continuous	Eavesdropping	Passive	SOP, ASC	Investigating the effect of the number of RIS elements on the secrecy diversity orders
[172]	Continuous	Eavesdropping	Passive	SOP, ESC	Showing that increasing the BS power or transmit antennas do not affect the SOP and ESC significantly, rather increasing the number of RIS reflecting elements do affect these metrics
[312]	Continuous	Eavesdropping	Passive	SOP, ANT	HARQ is beneficial to improve system security-reliability balance and reliability-delay balance performance of security-required user
[116]	Continuous	Eavesdropping	Passive	SOP, ASC, SPSC, EST, IP	Exploring secure RIS-assisted relaying system for mixed RF/FSO system
[313]	Discrete	Eavesdropping	Passive	PNSC, ESC	Investigating the influence of RIS's size and location on the secrecy performance
[131]	Continuous	Eavesdropping	Passive	SR	Enhancing the security by using RIS as a source of multiplicative randomness
[168]	Continuous	Spoofing	Active	Sum SR	Detecting spoofing and designing BF to improve secrecy performance
[157]	Continuous/Discrete	Eavesdropping	Passive	Sum achievable security data rate	Showing the significance of utilizing an RIS in enhancing the security performance
[145]	Continuous	Eavesdropping	Passive	SER	Reducing the side-lobe energy toward Eve
[196]	Continuous	Eavesdropping	Passive		Enhancing the secrecy performance by integrating multiple antennas with RIS
[314]	Continuous	Eavesdropping	Passive	IP	Improving secrecy performance by using friendly jamming and RIS
[245]	Continuous	Spoofing	Active	Avg. leakage rate, ASR	Utilizing RIS in increasing the reliability of CF mMIMO systems
[315]	Continuous	Eavesdropping	Passive	Secret key rates	Analyzing the impact of cooperative multi-Eve scheme against the RIS-secured
[189]	Discrete	Eavesdropping	Passive	ESR	Investigating secure transmission of a LEO satellite to a UAV vis RIS-equipped HAP.
[220]	Continuous	Eavesdropping	Passive	ESC	Enhancing the PLS of WPC system vis RIS

worst-case downlink secrecy rate by optimizing power allocation, RIS passive beamforming, and UAV trajectory. The results demonstrated the effectiveness of the proposed scheme compared to other benchmarks. The impact of hardware impairments on the secrecy performance of a mmWave system assisted by an RIS was investigated in [187]. In this regard, a system model was constructed without considering hardware impairments, and optimal solutions were presented for signal and AN powers, beamforming design, and phase shifts of the RIS elements. The authors in [320] explored the PLS of active RIS-assisted NOMA networks in the presence of external and internal eavesdroppers. Specifically, closed-form expressions for SOP and secrecy system throughput were derived, considering both imperfect SIC and perfect SIC. An innovative approach to enhancing the secrecy performance of a low power wide area network (LPWAN) by integrating an RIS with a UAV was introduced in [265]. The primary goal was to improve the secure data transmission between an IoT sensor and a gateway in LPWAN applications. Closed-form expressions for the SOP, PNSC, and ASR were derived for the proposed network operating over Nakagami- m fading channels. Additionally, the practical impact of the eavesdropper's location was explored. The obtained results illustrated that integrating a RIS-UAV significantly improves the secrecy performance of the LPWAN, enabling reliable long-range transmission.

C. Secrecy Outage Probability Reduction

By employing thorough techniques, RIS has great promise in reducing SOP in wireless communication. Through selective signal reflection and beamforming, RIS directs signals precisely to the intended receiver, minimizing the risk of information leakage. The dynamic adaptability of RIS allows real-time adjustments in response to changing wireless conditions, enhancing secrecy against evolving threats. Intelligent jamming approaches strengthen the communication link, while controlled AN and collaborative RIS networks add complexity to intercepted signals, maintaining confidentiality and reducing SOP. Utilizing RIS presents an opportunity to increase PLS in wireless communication systems, as highlighted in [169]. One strategy involves leveraging RIS to implement virtual beamforming, enabling the product of multiple directed beams toward different users. This can potentially enhance the secrecy performance of cellular networks by reducing the signal strength at unintended receivers, thereby confounding the eavesdroppers and decreasing the SOP. Also, RIS can establish a secure communication zone by directing the signal towards the intended receiver while diverting it away from potential eavesdroppers [196]. Additionally, RIS can serve as a friendly jammer to disrupt eavesdropper signals [146]. The unique capabilities of RIS extend to detecting and identifying eavesdropper locations. By doing so, RIS can assess the proximity of unintended receivers and adjust beamforming to minimize signal strength at those locations. To secure the transmission link, the RIS was strategically placed near the eavesdropper, effectively shortening information disclosure and heightening the confidentiality of the wireless network [127]. The secrecy

performance of a communication system assisted by RIS was investigated in [172] in the presence of spatially random eavesdroppers, where closed-form expressions for the SOP and the eavesdropper secrecy capacity were derived. To evaluate the SOP, the STAR-RIS-assisted cognitive NOMA-hybrid automatic repeat request (HARQ) network was investigated in [312]. The reviewed performance analysis works on RIS-assisted PLS are summarized in Table VII.

D. Lessons Learnt

The lessons learnt from this section can be summarized as follows.

- Incorporating RIS technology within the PLS framework provides vital capabilities for dynamically adjusting signals, optimizing signal strength, and reducing noise in challenging urban settings. Placing RIS strategically between the source and intended user creates an intelligent environment that enhances communication links, strengthening security against eavesdropping and other threats, thereby significantly improving the secrecy of wireless communication systems. Additionally, deploying RIS in relay communication systems, including satellite and UAV networks, enhances security against multiple ground eavesdroppers and facilitates secure signal transmission [265]. Integrating active elements in RIS design addresses issues like double-fading, resulting in smaller RIS sizes while maintaining performance, thus emphasizing the crucial role of RIS in improving signal quality and securing communication networks in wireless systems.
- By adapting to the communication environment and mitigating potential eavesdropping, RIS enhances SC for enabling technologies, offering promising advancements in PLS. RIS's effectiveness has been demonstrated in multi-user networks, achieving significant passive beamforming gains to maintain wireless security and efficiency. Investigations into hardware limitations and active RIS-supported NOMA-enabled networks [321] provide valuable insights into practical implementations and system robustness. Furthermore, integrating RIS with UAVs highlights considerable improvements in secure long-range transmission, underscoring the breadth of RIS applications and its significant potential in increasing SC and optimizing PLS performance.
- RIS technology presents promising approaches to decrease the SOP in wireless communication systems. By employing precise signal directing, dynamic adaptability, and intelligent jamming techniques, RIS minimizes information leakage and improves secrecy against evolving threats. Utilizing virtual beamforming, RIS confounds eavesdroppers by reducing signal strength at unintended recipients, while strategic deployment near eavesdroppers reinforces network confidentiality. RIS's abilities extend to establishing secure communication zones, identifying eavesdroppers, and enabling collaboration within networks, all contributing to SOP reduction and network security. Evaluations of RIS-assisted systems offer valuable

insights into SOP reduction strategies, highlighting the considerable potential of RIS in improving secrecy performance and enhancing network security within wireless communication systems [209], [211].

IX. OPEN RESEARCH CHALLENGES AND FUTURE DIRECTIONS

This section highlights key challenges and future research directions for RIS-assisted PLS in emerging RF and OWC networks to improve wireless network security.

A. RIS-Assisted Secure Multi-antenna Communications

A promising avenue for future research involves leveraging RIS to increase the security and efficiency of advanced MIMO technologies, such as mMIMO, Holographic MIMO, and 3D-MIMO. Strategic deployment of RIS elements within the communication environment makes it feasible to manage reflections and manipulate signals to amplify spatial multiplexing gain, reduce interference, and enhance spectral efficiency. Moreover, RIS can improve coverage and direct signals toward specific users or regions, maintaining coverage, capacity, and strength against eavesdropping and jamming threats. Exploring the integration of RIS technology with advanced MIMO systems represents a trajectory for future research by addressing security challenges for various deployment scenarios. Future potential investigations may explore the RIS-assisted secure multi-antenna communications enhancement, considering the challenges of imperfect or outdated CSI [59].

B. RIS-Assisted Secure mmWave and THz Communications

Integrating RIS into mmWave and THz communications is a significant technique in maintaining security measures. RIS's inherent adaptability facilitates dynamic adjustments to the propagation environment, establishing secure communication channels within mmWave and THz contexts. Its pivotal role in optimizing beamforming and channel characteristics directly addresses the directional communication requisites characteristic of mmWave and THz technologies, thereby mitigating the risk of unauthorized interception. Moreover, RIS enhances security by employing dynamic signal jamming and controlled reflections, preventing potential eavesdropping activities. Additionally, its collaboration with PLS techniques ensures the maintenance of secure communication channels among legitimate users. In this respect, such integration opens the door for more investigation for future research by handling the technical issues related to mmWave and THz technologies, such as the short coverage region issue due to the high propagation losses [322] in the presence of eavesdroppers.

C. RIS-Assisted Secure UAV Swarms Communications

Exploring the integration of RIS for securing UAV swarms represents a promising avenue for future research direction in UAV operations. Leveraging the dynamic capabilities of RIS, which entail programmable metasurfaces for manipulating electromagnetic waves, can improve signal quality, maintaining the robustness and reliability of communication

links within UAV swarms. Employing a swarm of UAVs with ARIS shows a practical avenue for increasing ground users' PLS through control of phase shifts, spatial placement, and strategic movement [275]. Moreover, deploying RIS technology could be harnessed to establish secure communication zones, selectively manipulating signals to enhance security measures against potential threats.

D. RIS-Assisted Secure D2D Communications

Adopting RIS into D2D communication can be considered a future research direction to address the spectrum scarcity problem encountered in future cellular communications [209]. Although D2D has emerged as a pioneering technology for future wireless systems, its potential benefits can only be fully achieved with a reliable channel between legitimate devices. However, wireless D2D communications are prone to security/eavesdropping attacks (given the presence of potential eavesdroppers), which may jeopardize their security and reliability. Based on its ability to control transmissions in a wireless environment by selectively manipulating the reflected and refracted in specific directions, the RIS technology can be deployed to provide more secure D2D communication.

E. RIS-Assisted Secure CRNs

In the context of CRNs, incorporating RIS is intended to augment the network's PLS. By taking advantage of the numerous reflective elements deployed in the RIS, it becomes feasible to establish a highly directional and controllable wireless transmission environment. This capability facilitates improving the signal strength of the legitimate user or attenuating the malicious' signal, enhancing the CRN's overall security [211]. Moreover, the intelligent control mechanisms enabled by RIS extend beyond security enhancements to contain spectrum utilization and interference mitigation improvements. By intelligently manipulating the propagation characteristics of electromagnetic waves, RIS can facilitate more efficient allocation and utilization of the available spectrum resources, thereby maximizing spectral efficiency and minimizing interference levels. This optimization of spectral resources enhances the CRN's overall performance and ensures its continued operability in challenging and dynamic deployment scenarios. Such integration needs more investigation to improve the security of the secondary and primary networks.

F. RIS-Assisted Secure WPC/SWIPT

RISs hold immense potential in enhancing PLS of the WPC/SWIPT systems. From a security perspective, RISs typically reconfigure the wireless channels of legitimate receivers and malicious eavesdroppers to enhance signal strength at the former and weaken signal reception for the latter. In the realm of wireless power transfer efficiency, RISs utilize intelligent reflections and refractions to establish energy harvesting/charging zones in locations beyond the direct reach of BSs. This dual capability, improving both security and service coverage, presents intriguing research avenues. These

include optimization frameworks for adjusting RIS parameters, allocating RIS elements to multiple users, and determining time switching/power splitting ratios to jointly optimize secured information and wireless power transfer. Furthermore, exploring diverse RIS deployment strategies such as placement location and the choice between distributed and single RIS, and user-type (i.e., energy vs. information users) distributions will yield valuable insights into their impact on system performance. Lastly, there is a need for multi-objective optimization frameworks that consider conflicting design objectives like EE of wireless power transfer and secrecy EE, along with tailored solution methods for comprehensive examination.

G. RIS-Assisted Secure MEC

The integration of RISs into secure MEC systems represents a compelling avenue for enhancing the security of task offloading. The potential advantages offered by MEC, such as supporting computation-intensive and delay-sensitive applications, can only be fully realized if the communication links employed for computation offloading are close to being perfect [323]. Furthermore, the introduction of wireless task offloading brings about significant security challenges, given the presence of potential eavesdroppers and the risk that their channel gain may surpass that of the legitimate link. RISs can be exploited to mitigate propagation-induced impairments (e.g., link blockages) and improve the channel gain of legitimate users while simultaneously nullifying that of eavesdroppers to facilitate secure tasks offloading. In the context of RIS-assisted secure MEC systems, the joint optimization of communication and computational resources and RIS tuning parameters to achieve the optimal trade-off among secure offloading, computing delay, system energy consumption is an exciting avenue for future research. Additionally, the design considerations for RIS-assisted secure MEC systems must account for the distribution of MEC servers, BSs, users and RISs, the diverse QoS requirements of users (e.g., delay and energy consumption), and the computational capabilities of wireless devices. Lastly, exploring the optimization problem of user-RIS-edge association in RIS-assisted secure MEC systems presents another intriguing challenge for future research.

H. RIS-Assisted Secure Satellite Communications

Satellite communications are envisioned to be an important component of next-generation wireless networks due to their global coverage and high data rate capabilities. However, satellite signals are more vulnerable to eavesdropping by unauthorized users both in space and on ground. Malicious users in space can exploit signal side lobes while ground users can tap into the broader reach of these signals and intercept confidential information. RISs can improve the PLS of satellite communications by exploiting their signal reflection, refraction, and absorption properties to establish additional propagation paths. In transmitter design, RISs can play a crucial role in mitigating the risk of signal interception by malicious users by minimizing signal side lobes. Side lobes are undesired radiations that occur alongside the main lobe of the transmitted signal. Malicious users or eavesdroppers often exploit

these side lobes to intercept confidential information. RISs can control the directionality and spatial distribution of the transmitted signal, allowing for the suppression of side lobes in certain directions. This calls for further studies on the design of RIS-enabled transmitters for satellite communications. When deployed in the channel, RISs can act as green jammers by producing jamming signals to attack eavesdroppers and provide solutions to coverage holes and enhance the signal strength of legitimate users by reflecting or refracting signals from satellites. Typically, the channel characteristics for the satellite links between legitimate users and eavesdroppers can be very similar since, compared with the distance between the satellites and legitimate users, the distance between legitimate users and eavesdroppers is negligible. Hence, optimization and machine learning-based frameworks for the joint design of RIS phase and amplitude configuration, RIS deployment, RIS node selection, and satellite spectrum and power allocation are required to improve PLS. Finally, an investigation on the theoretical performance limit of deploying multiple RISs in secure satellite communications is another open research problem.

I. RIS-Assisted Secure Multicast Communications

The PLS of multicast communication systems is an important and challenging issue since the shared wireless medium can be easily eavesdropped. The deployment of RISs in multicast communication systems to enable robust secure transmission by weakening the wiretap channels and enhancing the multicast channels has been investigated in a few studies [239]–[242]. In these papers, the authors focused on optimizing parameters such as transmit beamforming, reflect beamforming, and covariance matrix. The objective functions involved critical metrics like secrecy capacity, secure EE, secrecy rate, and overall system transmit power. Notably, most of the aforementioned works considered a system model featuring a single RIS and passive RISs. While these studies have laid foundational groundwork, there remain research gaps for further exploration in the area of RIS-assisted secure multicast communication systems. Future research should examine scenarios involving multiple RISs while jointly optimizing their placement and phase shifts. Additionally, the investigation of passive, active, and hybrid RISs presents an intriguing avenue for advancing the state-of-the-art in secure multicast communications. Finally, the existing studies have predominantly relied on optimization techniques, which typically have high complexity and require more iterations. Looking ahead, a promising avenue for future research lies in the application of machine learning or hybrid learning schemes to various optimization problems and to develop proactive solutions.

J. RIS-Assisted Secure Cell-free Networks

The integration of RISs into cell-free networks holds immense promise, offering significant energy savings, enhanced data rates, and improved PLS performance. RISs can effectively replace BSs and relays within cell-free networks, providing benefits such as enhanced received signal strength, absence of noise amplification inherent in relays, and reduced

energy consumption compared to traditional BSs and relays. Despite these advantages, research on RISs-assisted secure cell-free networks remains limited. However, only the studies in [244] and [245] have investigated RISs-assisted secure cell-free networks. The aforementioned studies examined RISs phase shift optimization and BS beamforming with the former focusing on sum secrecy rate maximization and the latter on minimizing information leakage to eavesdropper. Numerous avenues for future research exist in this domain. Firstly, investigations into secure transmissions in both the uplink and downlink directions are warranted. Moreover, future studies should consider the presence of active RISs and eavesdroppers, as their dynamics can significantly impact the PLS of cell-free networks [75]. Additionally, the impact of hardware impairments on PLS in RIS-enabled networks warrants investigation. Factors such as imperfect channel estimation, hardware non-linearity, and imperfections in RIS elements can degrade the security performance of the system. Analyzing these effects and developing mitigation techniques will be vital for ensuring the practical viability of RIS-assisted secure cell-free networks. Finally, it is worthwhile to study how the number of RISs and their size affect secure EE in a cell-free setting.

K. RIS-Assisted Secure Relay-aided Networks

The integration of relays and RISs in wireless networks offers another synergistic approach to improving PLS. Relays are traditionally employed in wireless networks to extend coverage, enhance signal strength, and mitigate fading effects by forwarding signals between the transmitter and receiver. By strategically placing relays, the network can improve signal quality and reliability, thereby enhancing security by reducing the vulnerability to eavesdropping and interception [16]. On the other hand, RISs can dynamically manipulate the wireless propagation environment by controlling the reflection properties of electromagnetic waves. When deployed together, Relays can assist in extending coverage and enhancing signal quality, while RISs can further optimize the propagation environment to enhance security by controlling signal reflections and attenuating signals in directions where potential eavesdroppers may be present. However, only [247] and [246] have examined RIS-assisted secure relay-aided networks. The authors in [247] focused on the design of the IRS reflection coefficient vectors and buffer-aided relay selection to maximize the secrecy rate. By considering an untrusted relay and cooperative jamming, the authors in [246] optimized RIS phase shifts and BS and untrusted relay power allocation for confidential and jamming signal to maximize the secrecy rate. Exciting future directions in this area include jointly optimizing power allocation, relay deployment and selection, and RIS placement and phase shifts. Moreover, the design of RIS assisted secure multi-antenna relay-aided networks is another interesting research for future work.

L. RIS-Assisted Secure Vehicular Communications

Deploying RISs in vehicular networks offers an appealing solution to enhance PLS in various ways. First, RISs can

mitigate security vulnerabilities in vehicular networks by intelligently controlling signal reflections to create secure communication zones, thereby reducing the risk of eavesdropping and interception. Second, in vehicular environments where vehicles are in close proximity, RISs can be strategically placed along roadways or intersections to create secure communication links between vehicles while preventing unauthorized access to sensitive information. Moreover, can improve the reliability and robustness of vehicular communication systems even in challenging conditions such as urban environments with high vehicular densities and signal obstructions. Motivated by this, [250] analyzed the secrecy outage performance of RIS-aided vehicular communications. The authors in [251] investigated the optimization of power allocation, RIS passive beamforming, and UAV trajectory to achieve the maximum worst-case downlink secrecy rate. However, these papers did not consider the mobility of vehicles, their speed, and associated handoff cost and Doppler effects. Moreover, it is important to explore optimization frameworks that consider factors such as RIS placement, density, and configuration to enhance PLS while minimizing deployment costs and overhead.

M. RIS-Assisted Secure WBAN

WBANs, while promising for healthcare applications, face significant security challenges, particularly vulnerability to active eavesdropping. In this context, adversaries may employ sophisticated techniques such as simultaneous sniffing and jamming to raise the sensor transmit power and compromise the network's integrity. RISs can dynamically control the reflection/transmission direction of sensor signals to simultaneously increase signal power received by legitimate user and decrease that of the eavesdropper and, thus, improve the security of WBANs. The study in [253] is the only work on RIS-assisted secure WBAN to date. In this paper, the authors proposed a WBAN transmission scheme in which the legitimate user (also called coordinator) determines the sensor encryption key, the RIS phase shifts, and the sensor transmit power. To improve the security of the WBAN, the authors developed an algorithm that enables the coordinator to optimize the sensor encryption key and transmit power, as well as the RIS phase shifts against active eavesdropping. However, the authors focused on a WBAN with a single sensor, a single user, and a single antenna system which limits broader applicability. Extensive experiments in indoor and outdoor environments to validate the security improvements for RIS-assisted secure WBANs and their practical feasibility are lacking in the literature. Moreover, exploring on-body RISs deployment to help collect more information about body parts [324], and also augment WBANs security is another exciting future research direction.

N. RIS-Assisted Secure Ad-hoc Networks

Integrating RIS into decentralized ad-hoc networks represents a promising area for future research in wireless communication systems. Such integration offers opportunities to improve network performance, reliability, and efficiency. Key

research areas include developing dynamic control mechanisms for RIS and designing customized routing and communication protocols for addressing security and privacy issues. This research direction has the potential to bring significant advancements in decentralized wireless communication systems, enabling secure networks for various practical scenarios.

O. RIS-Assisted Secure ISAC

ISAC systems face significant security challenges since communication signals-enabled radar sensing or radar probing signals utilized for communication are vulnerable to eavesdropping attacks due to signal waveform reuse. Recent research has explored leveraging RISs to enhance the security of ISAC systems [255]–[258], [260], [261]. Despite the various attempts that have been made, the research in this emerging area is still in its infancy and requires further studies before practical implementation. Promising areas worth investigating are discussed as follows. One area for exploration is the assumption in existing studies that sensing targets act as eavesdroppers. This assumption may not always hold, as eavesdroppers could be any type of user or even unknown. Additionally, while some studies focused on passive RISs [256]–[258], [260], [261], and [255] examined active ones. Notably, no research has investigated hybrid RIS configurations, combining passive and active elements, which could offer new opportunities for optimizing secure ISAC. Such configurations could be tailored to serve sensing targets, communication users, or both, and could potentially disrupt eavesdropper secrecy rates. Furthermore, developing comprehensive performance metrics that integrate communication, sensing, and security aspects could provide valuable insights into RIS-assisted secure ISAC systems. This holistic approach would enable a deeper understanding of system behavior and facilitate more informed design decisions.

P. RIS-Assisted Secure IoE, IIoT, and IoMT

Exploring the prospective utilization of RIS to fortify the security of the IoE emerges as a promising research direction to optimize communication channels and mitigate security vulnerabilities. The real-time adaptability of RIS enables adjustments in signal propagation and reception, thereby addressing concerns related to unauthorized access and enhancing the confidentiality and integrity of IoE data exchange [265]. The fourth industrial revolution (Industry 4.0) triggers many IoE applications, such as IIoT and internet of medical things (IoMT). Integrating RIS into secure IIoT environments is considered an open research direction, representing an advanced strategy for improving communication reliability and strengthening security measures. By incorporating intelligent components within surfaces, RIS facilitates real-time adjustments to wireless communication properties, enhancing legitimate signal quality and minimizing leaked signals. In IIoT security, this improvement shows potential in establishing secure zones within industrial settings, reinforcing security performance. RIS can actively mitigate jamming attacks by intelligently redirecting signals, ensuring the protection of communication channel robustness. RIS's dynamic access control features also

provide a versatile and adaptable security framework, enabling precise control over resource access based on evolving security policies. Given the paramount importance of energy efficiency in IIoT, RIS's ability to optimize communication channels contributes significantly to the overall sustainability of industrial systems. The benefits of integrating RIS in MEC to secure the IIoT networks were investigated in [230]. Although the implementation of RIS in IIoT poses challenges, its potential advantages in enhancing communication and security make it a compelling avenue for investigation and development in the industrial environment.

Investigating the potential of RIS to enhance IoMT security represents a promising direction for future research. IoMT devices, containing various medical sensors and wearables, are interconnected to facilitate real-time health monitoring, yet they are susceptible to security vulnerabilities stemming from wireless data transmission. Strategically deploying RIS within medical environments makes it possible to manipulate wireless signals, thereby strengthening security measures dynamically [325]. The integration of RIS with IoMT systems can enhance patient privacy and data security, advancing the realm of connected healthcare while upholding the principles of patient confidentiality and safety.

Q. RIS-Assisted Secure Backscatter Communications

Backscatter communication (BackCom) is envisioned as a key-enabling energy harvesting (EH) technology for the ubiquitous connection of low-power devices in future wireless networks. However, the simple coding/modulation adopted in this technology, and the double-fading effect due to the forward and backward links, may increase its vulnerability to wireless security attacks such as eavesdropping and jamming. RIS can be adopted into BackCom systems to provide secure transmissions as attested by some recent research efforts [267]–[269]. Nonetheless, the research on RIS-assisted secure BackCom systems is still in its infancy and numerous research directions are worthwhile to be explored in future studies. One potential avenue warrants the investigation of the secrecy performance of RIS-assisted symbiotic BackCom systems to improve both the spectrum and energy efficiencies of wireless communication while achieving a mutualistic spectrum sharing between the direct-link and backscatter-link transmissions. Moreover, the investigation of simultaneous transmitting and reflecting reconfigurable intelligent surface (STAR-RIS)-aided symbiotic radio (SymR) from a PLS perspective is an interesting problem that can: (a) enhance the flexibility of network deployment by addressing the *half-space* problem seen in conventional RIS systems; (b) improve the secrecy performance of the system.

R. RIS-Assisted Secure Wireless Sensor Networks

RIS-assisted secure WSNs represent a research avenue aimed at strengthening the security and efficacy of WSNs by integrating RIS. Through strategic RIS deployment in WSNs environments, opportunities arise to enhance communication reliability, extend network coverage, and fortify resilience

against malicious activities such as eavesdropping and jamming. Moreover, RIS can contribute to energy-efficient data transmission by optimizing signal paths and decreasing power consumption. Furthermore, RIS-assisted secure WSNs hold considerable potential in tackling the evolving security challenges and scalability concerns inherent in traditional WSNs, laying the groundwork for advancing more robust and efficient wireless sensing systems.

S. RIS-Assisted Secure FSO Communications

Despite providing more security and interference immunity, an FSO communication is still prone to security threats due to significant performance degradation caused by various channel impairments such as atmospheric turbulence, scattering channels, beam divergence, and pointing errors. In this context, the deployment of RIS in FSO systems emerges as an appealing research direction for future investigations to mitigate security vulnerabilities. This is feasible in practical setups through the use of intelligent mirrors (e.g. optical RISs) that can control the direction of the reflected legitimate beam with negligible scattering. Some insightful open research problems for RIS-assisted secure standalone FSO systems include (a) the investigation of the impact of pointing errors on secure FSO systems assisted by meta-surface-based and mirror-based RIS; (b) The capabilities of the mirror-based RIS by steering the reflected beam in the direction of the legitimate user and of the meta-surface-based RIS by the construction of complex shapes of the reflected waterfront, can be exploited in the optimization of the RIS. (c) the investigation of the meta-surface-based and mirror-based designs with channel estimation for secure FSO systems.

T. RIS-Assisted Secure VLC

Similar to FSO, VLC technology offers several advantages including higher bandwidth and security [102]. On the latter issue, VLC is inherently secure mainly in indoor environments due to the directivity and high-obstacle impermeability of the optical signals. However, security still remains a concern in VLC systems as VLC links are susceptible to security threats by malicious users under the same coverage area. Moreover, the loss of signal due to human obstructions specifically in indoor scenarios is likely to further contribute to security challenges. A promising solution is the integration of RIS into VLC systems to enhance the PLS. Unlike its RF counterpart, the investigation of RIS-enabled PLS in standalone VLC systems remains unexplored in the existing literature. This is attributed to the specificities in the VLC transmission protocols and modulation schemes which are fundamentally different from the RF especially in a programmable and partially deterministic environment. Consequently, several challenging issues—pertaining to the RIS design and resource optimization algorithms for the PLS maximization, multiple RIS distribution for higher secure beamforming, dynamic and randomized multipath reflections to maximize intended users' channel gain for the former scenario and to produce AN to confound the eavesdropper(s) for the latter—remain to be tackled in future research directions.

U. RIS-Assisted Secure HAPS

Integrating RISs with HAPS promises to improve wireless communication networks by extending coverage, reducing interference, and providing secure connectivity. This combination addresses challenges such as optimizing RIS deployment and resource optimization. RIS-assisted secure HAPS networks have applications in disaster recovery, military operations, and smart cities, offering robust infrastructure with enhanced coverage, security, and connectivity. Although combining RIS with HAPS is beneficial, limited research on RIS-assisted secure HAPS networks exists. Only the works in [115], [189], [273] have examined secure HAPS assisted by RIS. Exploring this research direction involves creating innovative solutions to advance future wireless networks while meeting developing security and reliability requirements.

V. RIS-Assisted Secure Wireless Communications From Optimization Techniques Perspective

The optimization of RIS-assisted secure wireless communications usually involves challenging mathematical problems due to the multiple and typically coupled variables, nonconvex objective functions and constraints, the presence of discrete and continuous decision variables, and the high dimensionality of the optimization problems. As a result, most proposed approaches adopt relaxation, approximation and decomposition techniques which lead to suboptimal performance or result in heuristics without any performance guarantee. This calls for studies on advanced optimization techniques such as global optimization solutions (e.g., [326]) and non-convex non-smooth optimization (e.g., [327], [328]). Metaheuristics on the other hand can tackle various optimization problems without any stringent requirements (e.g., convexity, continuity, and differentiability) for objective functions and constraints, and can cope with high dimensional optimization problems. It is therefore important to examine the application of some recently proposed metaheuristics [329] in optimizing RIS-assisted secure wireless systems.

W. RIS-Assisted Secure Wireless Communications via Advanced ML Techniques

Utilizing advanced ML techniques with RIS (see [330] and the references therein) offers a compelling avenue to increase PLS within wireless communication systems. Federated learning, characterized by decentralized model training while preserving data privacy, could be utilized to collectively optimize RIS configurations across distributed network nodes, protecting sensitive information. Graph learning techniques have the potential to facilitate the analysis of complex interaction patterns between RIS components and wireless channels, thereby enabling more accurate prediction and mitigation of potential security vulnerabilities. Transfer learning, involving knowledge transfer from related tasks to enhance RIS configuration optimization for PLS, could expedite the convergence of security-aware RIS designs. Quantum learning techniques, leveraging the computational power of quantum computing, could offer unprecedented capabilities for optimizing RIS

configurations and cryptographic protocols, strengthening PLS against quantum-based attacks. Additionally, meta-learning strategies could empower RIS to autonomously adapt and refine their security mechanisms based on past experiences and emerging threats, strengthening the resilience of wireless communication systems against security challenges. Exploring the integrated deployment of these advanced ML techniques with RIS represents a promising future research direction to advance PLS within wireless communication systems.

X. *Illegal/Malicious RIS*

Most research studies on RIS-assisted PLS in the current literature have mainly focused on the legitimate deployment of RIS as an enabler for the PLS enhancement. However, scenarios where illegal or eavesdroppers can alter the configuration of the PLS micro-controller or to introduce another RIS to degrade the security performance of the system, are seldom reported. The works of [331]–[333] have recently demonstrated the viability of such RISs based on the broadcast nature of the wireless environment coupled with the operating principles of the RIS technology. To this end, the concept of illegal reconfigurable intelligent surface (RIS) has been proposed in [334] wherein the security risks/threats posed by the illegal utilization of RIS are discussed namely, signal leakage and interference attack. In [335], the authors investigate the impact of signal leakage caused by a malicious RIS in a RIS-aided mmWave MIMO wiretap system. A destructive beamforming design seen from a malicious RIS perspective is studied in [336]. The adoption of RISs in the present context is undeniably of considerable interest since it is likely to bring forth issues, designs, and challenges that are different from the case of legitimate RIS.

Y. *RIS-Assisted Secure Communications With Other Emerging Wireless Technologies*

This subsection highlights key challenges and future research directions for communication systems that do not yet have investigation about securing its communication through RIS technology.

1) *RIS-Assisted Secure CoMP Communications:* RIS-assisted secure coordinate multi-point (CoMP) Communications are considered an open research area that aims to enhance the performance and security of wireless networks. By integrating RIS within the CoMP framework, the technology endeavors to optimize parameters such as signal strength, coverage, and overall system capacity while simultaneously addressing issues such as interference mitigation and signal confidentiality enhancement. Key areas of research focus include the development of efficient strategies for RIS deployment and joint optimization of CoMP and RIS to increase the security level. Despite the complexity of such challenges, RIS-assisted secure CoMP communications maintain significant promise in securing wireless communication networks by offering enhanced performance and security capabilities that align with the evolving requirements of next-generation applications and services.

2) *RIS-Assisted Secure Blockchain Technology:* Integrating RIS into secure blockchain technology is an innovative strategy for reinforcing the security and confidentiality of distributed ledgers [337]. RIS actively plays a role in mitigating potential attacks, such as jamming from malicious nodes, by intelligently redirecting and optimizing communication links. Consequently, the security of blockchain technology is improved, establishing a more robust and reliable framework. Moreover, the adaptability and flexibility of RIS align with the decentralized nature of blockchain, offering an additional layer of security. Despite existing challenges in deployment and integration, the prospective advantages of RIS-assisted secure blockchain technology lie in its ability to elevate the reliability and robustness of decentralized systems, resulting in secure and efficient blockchain applications.

3) *RIS-Assisted Secure AR and VR Communications:* The research direction on integrating RIS for secure gIsAR and VR Communications focuses on leveraging RIS to enhance the security of communication channels in AR and VR applications. The goal is strategically deploying RIS elements, ensuring the confidentiality of sensitive data transmitted in immersive environments. The investigation addresses challenges such as adapting RIS configurations to the dynamic nature of AR and VR and balancing security needs with low-latency communication.

4) *RIS-Assisted Secure Under-water Communications:* Achieving secure wireless communications in underwater is a necessity for governments, commercial companies, and the military. This is because underwater wireless communications play an important role in both civil applications such as oil and gas exploration and military applications. Exploring the potential of securing both underwater optical wireless communications that has a medium communication range that spans between 50-100 meters and underwater RF wireless communications that is suitable for short-distance propagation of around 10 meters can be an attractive area for future research. One possible way to attain this is by mounting RISs on underwater entities (e.g., autonomous underwater vehicles, submarines, divers, etc.) or at the sea level or at the ground level under the sea while employing one of PLS techniques.

X. CONCLUSION

This paper has provided a comprehensive review on the up-to-date research for the information-theoretic security of RIS-enabled for future wireless systems. To begin with, an overview of the PLS fundamentals has been presented by focusing on the various types of attacks in PLS, the techniques used to achieve PLS and the secrecy performance metrics. Moreover, the working principles and architecture of the RIS technology have been explored followed by its corresponding deployment strategies for future wireless communication systems. Besides, the RIS technology suited for OWC has also been presented. Subsequently, the RIS-enabled PLS scenarios and techniques in both RF and OWC systems have been discussed. Furthermore, the state-of-the-art optimization techniques for PLS have been reviewed and some existing optimization methods for secrecy performance maximization

have been summarized. To address the complexity issues associated with the rapid increase in the number of interactions between users and infrastructures in future wireless networks, the adoption of ML in RIS-assisted PLS-based systems has been well investigated. A comprehensive discussion on the performance analysis of RIS-assisted PLS-based wireless systems have been presented, and useful insights into the adoption of the RIS technology for performance improvement have been provided. Finally, some insightful open research challenges have been proposed and thoroughly discussed, and corresponding future research directions have ensued to further close the knowledge gap towards the development of forthcoming wireless technologies. We hope that this survey paper will serve as a valuable resource for researchers and practitioners in an effort to bring the deployment of RIS-assisted PLS in emerging wireless systems closer to reality.

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