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بسم الله الرحمن الرحيم

COMPOSITE LEFT-RIGHT HAND META SURFACE IRS FOR MODERN APPLICATIONS

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Abstract:
A meta surface (MTS) is a 2D planner structure of an array of two dimensions. MTS structure is composed from a unit cell structure that is periodically configured to form a surface. A Composite Left-Right Hand (CLRH) Meta surface Intelligent Reflecting Surface (IRS) represents a cutting-edge approach in modern communication and sensing technologies. By integrating left-handed and right-handed materials within a meta surface, this hybrid structure leverages the unique electromagnetic properties of both to enhance signal manipulation and control. The IRS technology is pivotal in applications such as wireless communication, where it can dynamically adjust the propagation environment to optimize signal quality and reduce interference. The composite design offers enhanced bandwidth, polarization control, and tunability, making it ideal for next-generation wireless networks, radar systems, and other advanced electromagnetic applications. The integration of CLRH meta surfaces into IRS platforms presents a significant advancement in the development of reconfigurable and adaptive electromagnetic environments, essential for the growing demands of 5G/6G communication systems and beyond.

Keywords: 5G, CRLH, IRS, MTM, MTS.

I.Introduction and basic concepts

In the pursuit of advancing wireless communication systems for modern applications, this research introduces a novel approach utilizing composite left-right hand meta surface arrays (CLRH-MSAs) integrated with solar panels. The integration of meta surfaces with solar panels offers a multifunctional platform, enabling efficient utilization of space and resources for both energy harvesting and communication purposes. This paper presents the design, simulation, and analysis of such a system, focusing on its potential applications and benefits in the context of modern networks.

The proposed CLRH-MSA configuration harnesses the unique properties of meta surfaces to manipulate electromagnetic waves, enabling precise control over signal propagation, polarization, and beamforming. By incorporating both left-handed and right-handed meta materials within the array structure, the system achieves enhanced versatility and adaptability across different operating conditions and frequency bands, characteristic of 6G communication systems. Moreover, the integration of solar panels within the meta surface array offers a sustainable energy solution, leveraging ambient light to power the communication infrastructure. This integration not only reduces the overall footprint of the system but also enhances its energy efficiency and environmental sustainability, addressing the growing demand for eco-friendly technologies in wireless communication networks. Through extensive simulation studies and performance evaluations, the effectiveness of the proposed CLRH-MSA configuration for 6G applications is demonstrated. Key metrics such as gain, beam-steering capability, and energy harvesting efficiency are evaluated under various scenarios, showcasing the system's robustness and adaptability in dynamic operating environments.

Due to the massive developments in different mobile communication systems such as Wi-Max, USB, WLAN, an urgent need for a low cost, lightweight, high bandwidth, and well controlled radiation pattern antennas are required [1]. Metamaterials (MTM) have been widely used in antenna and microwave systems due to their distinctive properties [2]. CRLH transmission line was invented by Caloz and Itoh [2] through combining the left-hand (LH) and right-hand (RH) properties to deliver the highest bandwidth enhancements with minimum losses for microwave and waveguide devices over the last decade [3]. The series interdigital capacitor (IDC) and the shunt stub inductor (SSI) were the main elements of the CRLH transmission line [1]. They can be constructed using microstrip lines and coplanar waveguides to realize a combination that can be described by a circuit model is shown in Figure1.

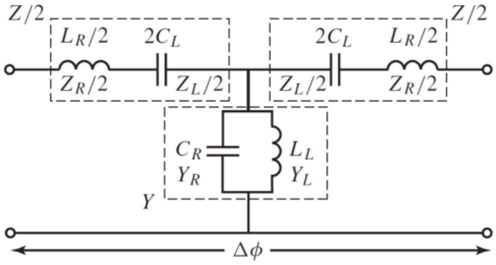


Figure 1. CRLH TL circuit model.

Composite left-right hand (CLRH) meta surface-based antennas attracted researchers because of their desirable properties in antenna design for many modern communication systems. Such structures realize narrow beamwidth that effectively reduces signals interference and improves the system capacity [1]. A distinctive feature of the CRLH transmission line is the zero-order resonance by which miniaturization is achieved. At zero-order resonance, the frequency becomes independent of the antenna size and depends only on the equivalent distributed lumped parameters. This feature has been studied in-depth and used in various communication system applications, a brief overview of some of these applications will be given in this section. A backfire-to-end-fire fan-beam CRLH leaky-wave antenna was introduced in [1]. However, the proposed design suffered from a low gain about 8dBi for an array of 28-unit cells due to the unit cell miniaturization effects. A MTM antenna based on asymmetric coplanar strip ACS feeding structure with asymmetric CRLH unit cell was designed and tested in [2] to realize a gain 2.4 dBi at 5.5GHz on zero-order resonance. The open-end MTM antenna was designed and tested in [3]. The antenna was constructed from an interdigital capacitor and a spiral inductor to provide a gain of 2dB at zero order frequency modes.
Later, several techniques were proposed to enhance the antenna performance based on CRLH meta surfaces. For example, in [4], authors introduced a high gain bandwidth product antenna based on electromagnetic band gap defects with CRLH structure for UWB applications. However, the proposed antenna shows low radiation efficiency because of coupling between the antenna patch based CRLH structure and the ground plane defects. Later, another study was proposed to enhance the antenna radiation efficiency for RF harvesting applications in [5]. However, their proposed antenna suffered from a significant back lobe with un-directive radiation patterns. The proposed design in [6] showed a significant gain enhancement with a directive radiation pattern at certain frequency, but the proposed design was 3D profile with bulky size. The design that was proposed in [7] improved the concept of bandwidth enhancement based on ground plane defects with Vivaldi structure-based antenna; the design was conducted based on a single antenna instead of antenna array structure as well as the antenna back radiation was significant issue due to the feeding technique. Therefore, another design was introduced in [8] to overcome the back radiation effects in [9] by

introducing a reflector layer; however, the design was relatively 3D and bulky size. The antenna design that was suggested in [10] showed excellent gain control using reconfigurable CRLH structure, however, the antenna bandwidth was significantly affected due to the wiring systems. In [11], authors proposed a reconfigurable meta surface through varactor diodes designed to realize an 8-phase shift keying wireless transmitter.

Moreover, several attempts were applied to realize the antenna performance reconfiguration using active and passive switches through controlling the MTM properties such as: An antenna based on a CRLH layer was proposed to control the gain using PIN diodes for LoRa systems [12]. Another design was proposed in [13] to control the radiation patterns of a monopole antenna using two PIN diodes connected to CRLH unit cell. In [14], the author controlled the antenna radiation patterns based on CRLH patched switched with a passive photo-resistors. An end fire printed monopole antenna based on CRLH structure was proposed for the Wi-Fi applications in [15]. The antenna main lobe direction was controlled using PIN diodes were connected between the monopole and the CRLH structure.

Fractal structures would be introduced as a candidate to the proposed RIS structure to ensure multiple frequency tunning using control switches. Such introduction, fractal structures, can significantly enhance its capabilities by enabling multiple frequency tuning by control switches. Integrating fractal structures into RIS allows for enhanced multiple frequency tuning, leveraging the unique properties of fractals such as self-similarity and scalability. This approach uses control switches to dynamically adjust the phase shifts and amplitudes of the RIS elements, optimizing wireless communication across multiple frequency bands. By combining fractal designs with AI techniques like machine learning (ML), Nural Network (NN), and deep learning (DL), the RIS can adaptively steer beams and improve channel performance in real-time, ensuring robust signal quality and coverage. This integration not only expands the operational frequency range but also enhances the flexibility and efficiency of the RIS in dynamic wireless environments, providing a versatile solution for next-generation communication systems.

II. Problem Statement

One significant challenge in modern communication systems is the efficient utilization of available spectrum resources while ensuring reliable and high-speed connectivity. Conventional antenna arrays often struggle to provide the desired beamforming capabilities and adaptability across a wide range of frequencies and operating conditions. Additionally, the integration of renewable energy sources into communication infrastructure presents an opportunity to enhance sustainability and reduce dependency on conventional power sources. However, existing solutions for combining solar panels with communication systems often lack integration and efficiency.

Motivated by these challenges, this research proposes a novel approach leveraging composite left-right hand meta surface arrays (CLRH-MSAs) integrated with solar panels for 6G applications. The integration of meta surfaces with solar panels offers a multifunctional platform that addresses the dual challenges of spectrum management and energy sustainability in wireless communication networks. The CLRH-MSA configuration enables precise control over electromagnetic wave propagation, polarization, and beamforming, facilitating adaptive and dynamic communication systems suitable for 6G networks. By incorporating both left-handed and right-handed meta materials within the array structure, the system achieves enhanced versatility and adaptability, overcoming the limitations of traditional antenna arrays. Furthermore, the integration of solar panels within the meta surface array addresses the energy consumption challenges of communication infrastructure. Harnessing ambient light for energy harvesting reduces the reliance on conventional power sources, leading to cost savings and environmental benefits. However, the seamless integration of solar panels with meta surface arrays poses design and optimization challenges that need to be addressed.

Overall, this research aims to develop a comprehensive solution that not only meets the stringent requirements of 6G communication systems but also promotes sustainability and energy efficiency through the integration of renewable energy sources. By addressing the dual challenges of spectrum management and energy sustainability, the proposed CLRH-MSA with solar panel integration offers a promising pathway towards the realization of future-proof and eco-friendly wireless communication infrastructure. In this work, a design of a reconfigurable antenna array structure based on CRLH meta surface arrays for radiation beam forming and steering will be proposed for 5G wireless communication systems. The proposed study will be extended to realize solutions to the associated problems with such research including:

1-Gain Enhancement,

The antenna radiation usually realizes field fringing toward the array edges due to the surface wave diffraction which provides sever effects on the side antenna lobes. For the back radiation problem, which is due to the total internal reflection from the antenna structure and field diffractions at the substrate edges, the back lobs become an effective problem during the array design process.

2-Size problem and design complexity

Most such designs acquire a huge number of antenna elements that increases the system complexity and size. The related work with such structures suffers from an issue of a bulk size with complicated designs due to the reconfiguration features.

3-Radiation efficiency reduction

The radiation efficiency could be degraded due to the metallic and dielectric losses. On the other side, it could be affected by adjacent coupling between the antenna elements which store the propagating energy.

Therefore, it is subjected to this research to realize effective solutions to the previous listed problems. These problems are inherent issues that can be resolved with several stages based on using nontraditional technique based on using CRLH meta surfaces and/or sub-wavelength plasmonic antenna elements-based array configurations.

As a research gap, achieving efficient broadband or multi-band operation with CLRH Meta surfaces is difficult due to the complex interplay of left-handed and right-handed properties. Developing a meta surface design that can operate effectively over a wide range of frequencies. Experiment with hybrid designs that combine CLRH properties with tunable elements and fractal structures to achieve multi-band functionality.

Objectives

The proposed work is to control the antenna array performance using modern techniques as follows:

Design a miniaturized antenna element operating at sub-6GHz for 5G applications,

Design a CRLH unit cell structure to be compacted to the antenna element at sub-6Ghz,

Design a miniaturized IRS array structure with enhanced performance to suit the 5G communication networks.

The main objective of such a study is to design a high gain antenna over a certain bandwidth with direct antenna modulation process to realize an intelligent beam forming process. Thus, the resulted beam forming would be applicable for many applications including the OFDM technology with high data rate processing to suit the current state of the art.

- Meta surface is used for its unique characteristics to create a multifunctional antenna that is used as the basis for future wireless communication system
- From such study several achievements can be obtained such as antenna beam forming and steering, polarization reconfiguration, and direct antenna modulation. As a result, multiple modulation states can be performed with different carriers for multiplexing and transmitting multiple data streams that increases the system capacity and efficiency.
- With a reconfigurable antenna, the overall cost, size and weight will be minimized due to its ability to dynamically reconfigure transmission and reception across multiple bands, and its ability to change the radiation pattern to suit all environmental qualifications.
- Reconfigurable phased arrays have a problem with high side lobes and grating lobes. A reconfigurable antenna offers a solution to this problem, where the system performance is enhanced in terms of interference reduction, spatial filtering, power saving, and system security.

Literature Review

A comprehensive literature survey on reconfigurable antennas for 5G applications reveals a significant evolution in IRS based antenna technology, driven by the need to support the dynamic and diverse requirements of modern telecommunication systems. Various studies highlight the pivotal role of reconfigurable antennas in achieving adaptable radiation patterns, polarization, and frequency bands to optimize network performance and reliability. According to recent publications, the adoption of technologies like MEMS (Micro-Electro-Mechanical Systems), PIN diodes, and varactor diodes has been crucial in facilitating the dynamic tuning of antenna characteristics to better suit changing operational conditions.in the first part introduced MTM unit cell as antenna then MTS as superstate, the last part with MTM as isolation technique for MIMO antenna.

In 2018, Bharathi Anantha el al. [10] A 2 × 2 polarization reconfigurable planar microstrip array antenna is introduced. It is depended on electrical switching technology using PIN diodes. The corporate feed technique helps to stimulate each component of the array. A prototype was fabricated on a 1.6 mm thick RT Duroid substrate with a relative permittivity of 2.2. This involved testing the antenna in different polarization states over an operating band of 5.7-6.0 GHz, suitable for C-band point-to-point communication applications.

In 2019, Bashar A. F. Esmail el al. [7] This article describes the integration of a planar antenna with a low loss adjacent square shaped resonator (ASSR) for beam tilting applications at the 3.5 GHz 5G band. The positive and negative deflection angles of the proposed antenna have been achieved by embedding an array of 6 × 7 adjacent square shaped resonator unit cells onto the same substrate along the azimuth plane. The results indicate that the dipole antenna's beam is deflected by +25 and −24 angles. Also, the gain is improved respectively by 3 dB and 2.7 dB for positive and negative deflection angles.

In 2020, Adamu Y el al. [15] This work presents design of wideband frequency reconfigurable MTM antenna with double H slots. CRLH-TL technology serves as the basis for this design. The series left-handed capacitor CL transmission line characteristic was used to increase bandwidth. The design has several benefits include efficient BW to cover lower Application bands. The results show that the antenna acquired bandwidth range covered (2.3-5.2) GHz which approximately equal to 77% fractional BW. Frequency reconfiguration techniques are used in reconfiguring the wideband antenna. The results show that the antenna can be switched from wideband to two single bands which resonate at 2.4 GHz and 4.2

GHz and to dual band which resonate at 2.4 GHz and 4.2 GHz. 96% was obtained of maximum efficiency. The antenna can be used for WLAN, lower 5G band. In (2019), Huy Hung Tran el al. [6] It has been proposed The MTS based pattern reconfigurable. The design contains a reconfigurable feeding network and a 4 × 4-unit cells meta surface (MTS) with 4-slots in the ground plane. The primary beam of antenna can be directed in the desired direction and the unit cells of the MTS can be excited with varied phases by offsetting the slots from the center of the meta surface. The pattern reconfigurability is easily achieved by electrically controlling the ON/OFF states of 4- PIN diodes on the feeding network to excite the appropriate slot. The antenna, operating at the center frequency, has a low profile of 0.04λo. The operating bandwidth of 10.4% and 5.6 dBi peak gain value. With the mentioned characteristics, the proposed antenna can be a good choice for 5G applications.

In 2019, Amit Kumar Singh el al. [3] Patch antenna radiators and conventional wide C-band wave guiding port radiators are used in the design of a high gain Fabry-Perot cavity antenna (FPC) for narrow band and wide band improved gain BW, respectively. The ideal height of the cavity and high gain antenna are designed by placing the MTS over the radiator at ideal height. The antenna is designed to operate efficiently within a 1.42 GHz reflection band from 4.55 to 5.97 GHz. This design enhances the antenna's gain across a broad frequency band, making it highly suitable for diverse applications, including 5G networks.

In 2020, Mohammad Ameen el al. [4] This study uses a modified artificial magnetic conductor AMC-MS based reflector with 4 × 3 MTS unit-cells positioned under the CRLH-TL inspired dual-band radiator antenna to improve radiation performance, gain, and beam width, gain values of 6.46 and 7.12 dBi for the two bands at centered at 3.27 and 5.11 GHz that suitable for airborne applications.

In 2020, M. Faizal Ismail el al. [18] A pattern reconfigurable antenna introduces diverse pattern configurations and beam steering to cater the congested signal environment problem while maintain the performances and operating frequency, also enhance the signal and data security. The pattern reconfigurable antenna using EBG structure is proposed in this paper for beam-steering configurations. In this work, the structure offers high efficiency as the RF switches are not embedded to the radiating patches. A dual-band slotted pattern reconfigurable antenna using EBG structure is designed and analyzed. The EBG patches are located at the right and left of the radiating edge of the antenna. The EBG is designed so that its surface wave of band gap covers the radiation of the antenna. The results show that the surface waves excited by the patch antenna are prohibited from propagating by the EBG and caused the radiation pattern to be tilted to another side. The operating frequency of the antenna is 2.45 GHz and 5.8 GHz for the dual-band antenna. The proposed antenna is able of having beam shifting at three different angles (0°, +26°, and - 26°).

In 2021, Zhen Zhao el al. [5] A multi-beam antenna based on annular slot and uneven meta-surface is proposed. Through using the uneven meta surface formed

by patches with different dimensions as radiator, the directed beam at θ = 32o. And by employing compound double annular slot on the ground plane, the gain is further increased, and the backward radiation is reduced. Steering the beam in the elevation plane is realized by arranging uneven MTS above the feeding network.
In 2021, Hayder Almizan el. al. [8] This work introduces a method of a microstrip antenna to control gain enhancement based on a reconfigurable meta surface layer. The proposed layer is keeping the antenna composed of 5 × 5-unit cells. The proposed unit cell has four PIN diodes for the structure of reconfiguration into states ON and OFF. As a result, the layer may have several ON-OFF unit cell distribution patterns. Antenna gain can be increased up to a certain amount with each unique distribution pattern. It is recommended to use four patterns for the layer to increase the antenna gain from approximately 1 dBi 2, 5, 8, and 11 dBi.
In 2022, Zhan Wang el. al. [21] A vertically polarized, aperture-shared, zeroth-order resonance (ZOR)-based, meta surface antenna with pattern reconfigurability is proposed for sub-6 5G application in this paper. The proposed pattern reconfigurable meta surface radiator may operate at 9 radiations by investigating an aperture-shared ZOR meta surface using only four PIN diodes. The analysis of this new reconfigurable ZOR meta surface is done using field distribution, equivalent circuit, and array theory. The low profile of 0.05λ0 vertically polarized meta surface-based pattern reconfigurable antenna is constructed and measured in order to verify the suggested design guidelines and functioning principles It shows a 4.5 dBi peak gain in various radiation conditions and an 11.5% overlapping −10 dB impedance bandwidth 3.40–3.8 GHz, well spanning (B42/B43 LTE bands). It is ideally positioned thanks to its benefits, which include a small size, flexible pattern switching capacity, broadband, good radiation performance, and a straightforward design.
In 2022, TAMARA Z. FADHIL et. al. [27] The antenna utilizes a meta surface made up of SSRR and U-shaped unit cells on an FR-4 substrate. The meta surface configuration allows for the manipulation of surface current and the division of the radiation pattern beams into two beams at ±45°.Testing shows that the antenna resonates well at 3.5 GHz with a reflection coefficient of less than −10 dB. This makes it suitable for future 5G Pico cell base stations, particularly in areas where network capacity and interference management are critical. Despite advancements, the meta surface design still presents challenges in terms of size and complexity with higher fabrication costs.
In 2023, Sandeep Kumarel el. al. [14] A CPW-fed multiband CRLH antenna, a class of MTMs is proposed in this work. It is designed by embedding 2-unit cells of CRLH transmission line on the top and bottom surfaces of an FR4 epoxy substrate with the help of metallic via. By creating four resonances because of the ground plane, feed patch, and CRLH unit-cells, the multiband characteristic is achieved. Three frequency bands with return losses of less than 10 dB are shown in the simulated findings, spanning 1.3 - 1.87 GHz, 2.36 - 2.63 GHz, and 3.14 - 4.62 GHz. At the resonant frequencies of 1.57, 2.4, 3.4, and 4.2 GHz, respectively,

the realized gains have been determined to be 2.5, 2.56, 4.85, and 4.9 dB. The efficiency of the radiation is more than 77% at each resonant frequency with peak value of 94.76%. Applications for the proposed antenna include the 1.57 GHz GPS, 2.4 GHz Industrial, ISM, Scientific and 3.3–4.2 GHz 5G sub6 infrastructure. In 2023, Duygu Nazan et. al. [17] proposed a reconfigurable antenna design for sub-6 GHz applications that used a unique combination of antenna parts and control techniques. The antenna is designed of an inner spiral resonator and an outer split-ring resonator. It can be remotely adjusted with Single Pole Double Throw (SPDT) switches or a PIN diode the design offers compactness, an omni-directional radiation pattern. The antenna requires an external control system (like an Arduino unit) for frequency reconfiguration, which could complicate integration into existing systems without such control capabilities.

Methodology

In this work, the proposed problem basically can be resolved in the following parts:

The first part is the basic antenna element design based on CRLH meta surface structure. A metamaterial-based unit cell of composite left-right hand structure would be introduced to the strip line for gain and radiation beam width enhancements rather than being fetched with or without slots to realize radiation leakage at certain frequency bands. Such structures provide single negative electromagnetic constitutive parameters (-ve ε or -ve μ) that reduce the back radiation effects and the side lobs issues during the beam steering process.

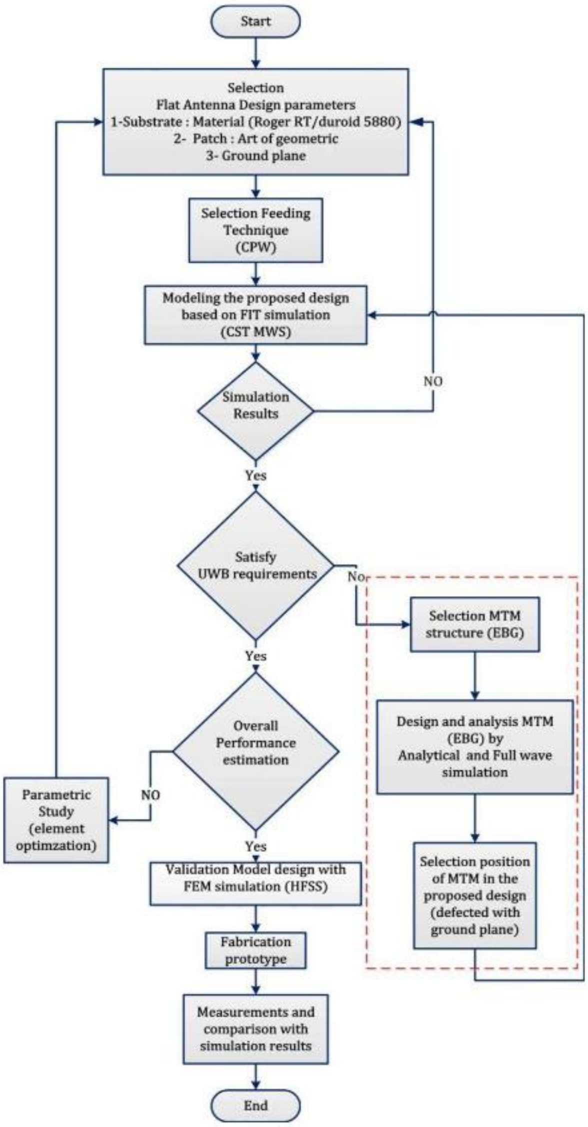
The second part is integrating solar panel with the antenna based Meta surface structure which is basically introduced for self-powered enhancements. Such an introduction can be realized in a location that shows no significant effects on the antenna performance.

The proposed IRS could be realized to enhance the channel performance through controlling the switching configuration to produce electromagnetic beam radiation enhancements through the progressive phase shift between the unit cells. Such technique provides a good solution, as well as, to the adjacent antenna coupling to enhance the antenna radiation efficiency.

The introduction of PIN and/or Varactor diodes would be an excellent candidate for the proposed study for isolating the RF signal path and/or the capacitance value; a phase change could be achieved between the array elements. Therefore, a beam steering could be controlled via a group of PIN/ varactor diodes switching process. In such case, the complexity due to the phase shifters and attenuators could be reduced significantly.

The DC biasing and wiring connections could be a serious issue, therefore, the use of CRLH based antenna structures creates good option to keep the wiring systems underneath the radiating elements to avoid any interaction between them.

The reconfigurable CRLH meta surfaces can control the antenna array radiation pattern according to the status of the PIN and/or varactor diodes. Therefore, it would be subjected to this research to achieve the proposed solutions. The proposed work is constructed according to the following flow chart:



The Use of AI Technology

The proposed research is based on RIS technology. Therefore, logically, using AI algorithms to control proposed RIS performance in an adaptive environment is one of the useful techniques. Using AI to control RIS for beam steering involves dynamically adjusting the phase shifts of RIS elements to optimize wireless communication performance in adaptive environments. By leveraging NN techniques, such as supervised learning for predicting optimal configurations and reinforcement learning (RL) for real-time adaptation, the RIS can be configured to maximize metrics like signal-to-noise ratio (SNR) and data rate. This process involves collecting and preprocessing data, training models to predict the best RIS settings based on environmental conditions, and continuously monitoring and refining the model to adapt to changes. This AI-driven approach enhances signal quality, coverage, and efficiency in wireless networks. In this case, the bit error rate (BER) and channel capacity (CC) enhancements by optimizing the RIS configuration to reach the best performance for each scenario.

Conclusions

This paper explored the design and application of a Composite Left-Right Hand (CLRH) meta surface integrated with Intelligent Reflecting Surfaces (IRS) for modern communication and sensing technologies. The CLRH meta surface, with its unique ability to support both left-handed and right-handed modes, offers enhanced control over electromagnetic wave propagation, enabling dynamic beamforming, polarization manipulation, and reflection characteristics. This capability is crucial for modern applications in wireless communication, including 5G and beyond, as well as advanced radar and imaging systems. The integration of CLRH Meta surfaces with IRS technology has demonstrated promising results in improving spectral efficiency, reducing power consumption, and enabling flexible deployment in complex environments. Simulation and practical experiments confirmed the ability of CLRH-based IRS to adaptively manage signal direction, minimize interference, and enhance overall system performance in scenarios such as urban communication networks and smart environments. This research contributes significantly to the ongoing development of meta surface-based technologies for advanced wireless communication and sensing applications. The versatility and tunability of CLRH Meta surfaces offer a pathway to more efficient, adaptive, and sustainable communication systems. Future work will focus on optimizing the meta surface designs for different frequency bands, refining the control algorithms, and exploring large-scale deployment in real-world settings.

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