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Design and Optimization of Reconfigurable Intelligent Surfaces Structures for Simultaneous Wireless Information and Power Transfer (SWIPT) in Cooperative Relay Networks

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Abstract: This research investigates the design and optimization of reconfigurable intelligent surfaces (RIS) structures to enhance simultaneous wireless information and power transfer (SWIPT) in cooperative relay networks. The integration of RIS technology with SWIPT offers promising opportunities to improve the energy efficiency and spectral efficiency of wireless communication systems. In this study, we propose novel RIS deployment strategies and optimization algorithms to maximize the performance of SWIPT-enabled cooperative relay networks. First, we analyze the fundamental principles of RIS-assisted SWIPT and cooperative relay networks, considering the unique characteristics and challenges of each component. We then formulate optimization problems to jointly optimize the placement of RIS elements, relay selection, transmit power allocation, and RIS phase configuration to achieve the desired trade-off between communication reliability, energy efficiency, and spectral efficiency. Furthermore, we develop efficient algorithms for channel estimation, feedback, and coordination among RIS, relays, and destination nodes to adapt to dynamic channel conditions and user requirements. We also investigate the impact of RIS deployment on the energy harvesting performance of SWIPT-enabled relay nodes, considering factors such as RIS reflection coefficients, relay-RIS distance, and incident signal power distribution. Moreover, we address security and privacy considerations in RIS-assisted SWIPT, including potential vulnerabilities, authentication mechanisms, and privacy-preserving communication techniques. Finally, we validate the proposed design and optimization techniques through comprehensive simulations and real-world experiments, considering practical constraints such as hardware implementation, energy harvesting efficiency, and deployment scenarios. Overall, this research contributes to advancing the understanding and practical implementation of RIS technology for SWIPT in cooperative relay networks, offering insights into the design, optimization, and performance evaluation of next-generation wireless communication systems.

Keywords: RIS, Meta surface, BER, channel Capacity, CRLH, modern communication systems.

I.Introduction

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 is required [1]. Metamaterials (MTM) have been widely used in antenna and microwave systems due to their distinctive properties [2]. Composite Right Left Hand (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 reconfigurable intelligent surface (RIS) 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 Fig. 1.

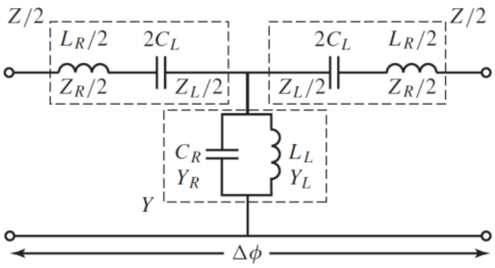

Fig. 1. CRLH TL circuit model.

RIS 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 due to the effects of coupling between the antenna patch based CRLH structure and the ground plane defects. Later on, 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.

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 is required [1]. Metamaterials (MTM) have been widely used in antenna and microwave systems due to their distinctive properties [2]. Composite Right Left Hand (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 reconfigurable intelligent surface (RIS) 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 Fig. 2.

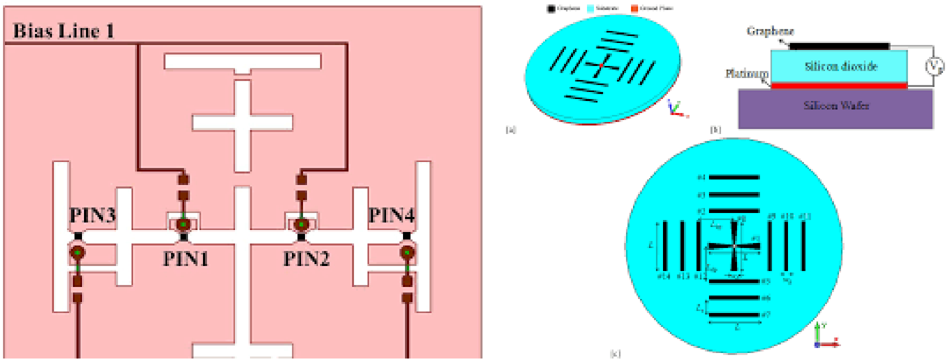

Fig. 3. RIS models [3], [4], respectively.

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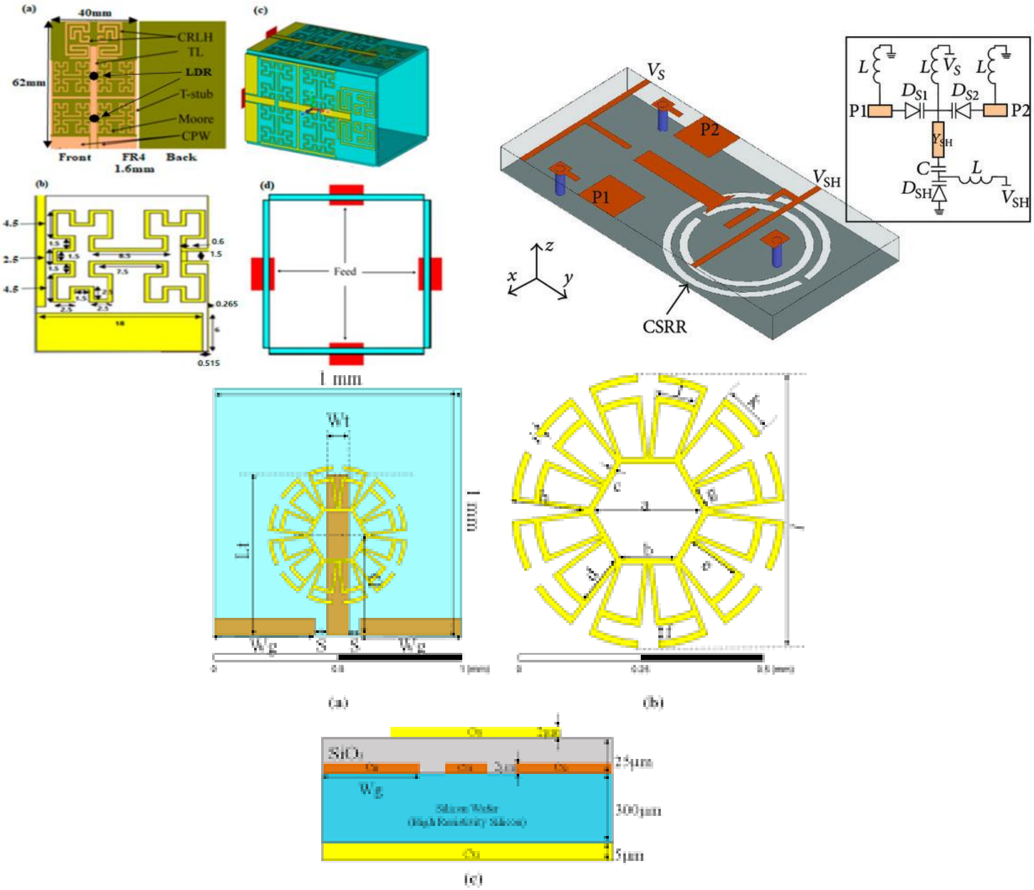


Fig. 3. Reconfigurable RIS models [5], [6], [7], respectively.

II. Problem Statement

In this work, a design of a RIS array structure based on CRLH metasurface 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. Side lobs and back radiation issues

Steering the radiation beams usually realizes field fringing toward the RIS array edges due to the surface wave diffraction which provides sever effects on the channel performance with respect to the main lobe.

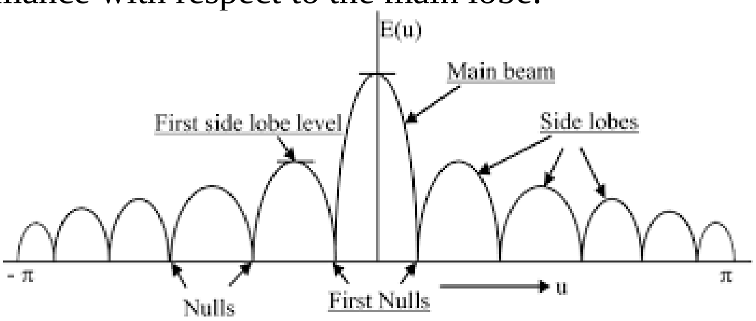


Fig. 4. Side and back lobes [8].

2. Biasing wires effects

In such research, most of the design process is based on active RIS to construct a smart array which requires biasing wires. Such biasing wires could affect negatively on the RIS performance.

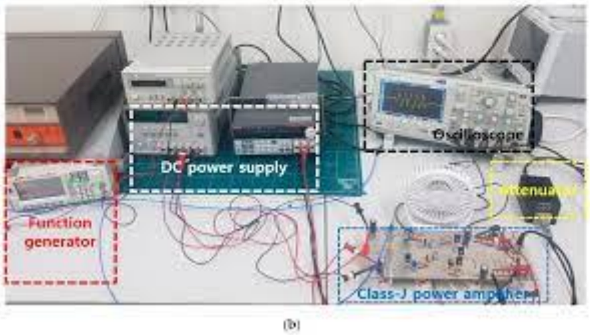


Fig. 5. Biasing wiring mess [9].

3.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.

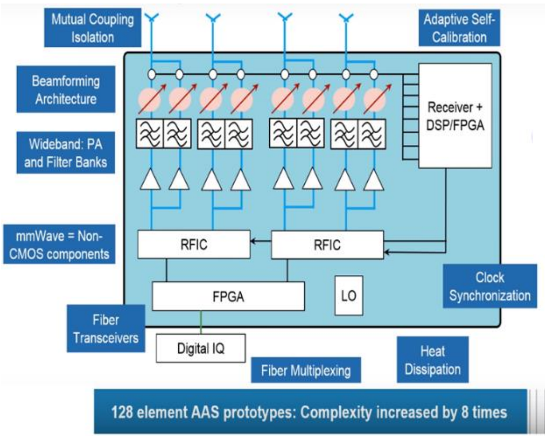


Fig. 6. Typical RIS structure [10].

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.

In this work, a design of a RIS 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- Side lobs and back radiation issues,

Steering 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- Biasing wires effects

In such research, most of the design process is based on active antennas to construct a smart array which requires biasing wires. Such biasing wires could affect negatively on the antenna performance including frequency resonance shift, radiation patterns distortion and, polarizations variation.

3- 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.

4- Squint effects 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. In such manner, channel performance can be enhanced in terms of bite rate and channel capacity.

The research gap: 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.

III. Aim and Objective

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

1- Design a miniaturized antenna element.
2- Design a CRLH unit cell structure to be compacted to the antenna element,
3- Design a miniaturized antenna array structure with enhance performance,
4- Control the array performance using microwave switches and/ or photonic devices remotely controlled.
5- Use case definitions and requirements (including RIS as intelligent repeaters, holographic surfaces, and dual functionality).
6- Deployment scenarios (e.g., frequency bands, antenna design, RF parameters, backhauling etc.).
7- Proof-of-concepting (Prototyping).
8- Channel estimation for RIS-empowered wireless networks.

IV. Expected Contributions

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 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.

Recently, RIS attracted many researchers due to their untraditional properties in comparison microwave devices categories. Therefore, such research area, recently, oriented toward different intelligent and smart applications. Indeed, a great impact is applied to push the limits of such technologies to reach Meta surfaces mm-waves would be an excellent candidate for such research area to improve the communication systems in high multi-path reflection environments. However, there are three main relative problems that are associated with such research including:

1- Biasing circuit technology limits,
2- RIS array size reduction, and
3- Beam steering quality.

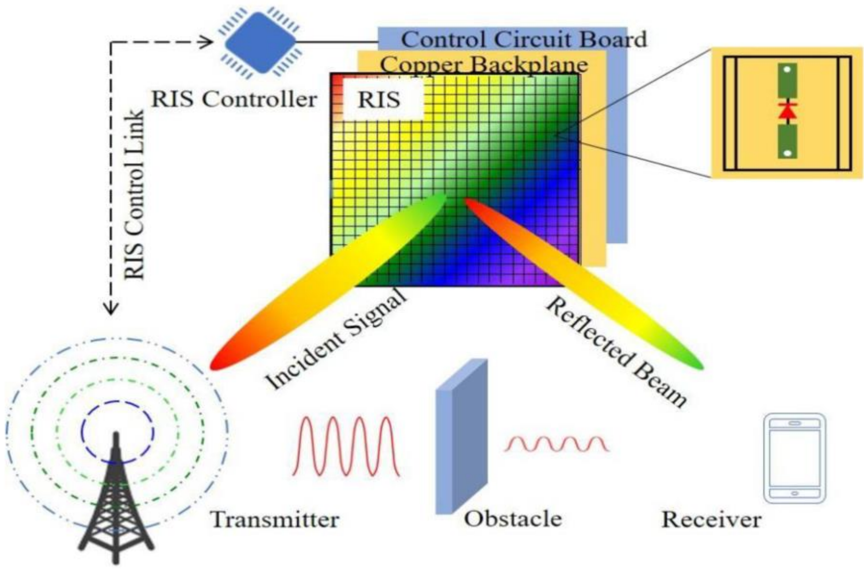


Fig. 7 The structure of RIS [1].

The proposed work adopted is to control provide reasonable solutions to enhance RIS array performance using modern techniques as following:

- ✓ To design a miniaturized RIS unit cell based on a CRLH element to be structured as an array,
- ✓ To design a miniaturized RIS array structure with enhanced performance based metasurface concepts,
- ✓ To control the array performance using microwave switches and/or photonic devices remotely controlled.

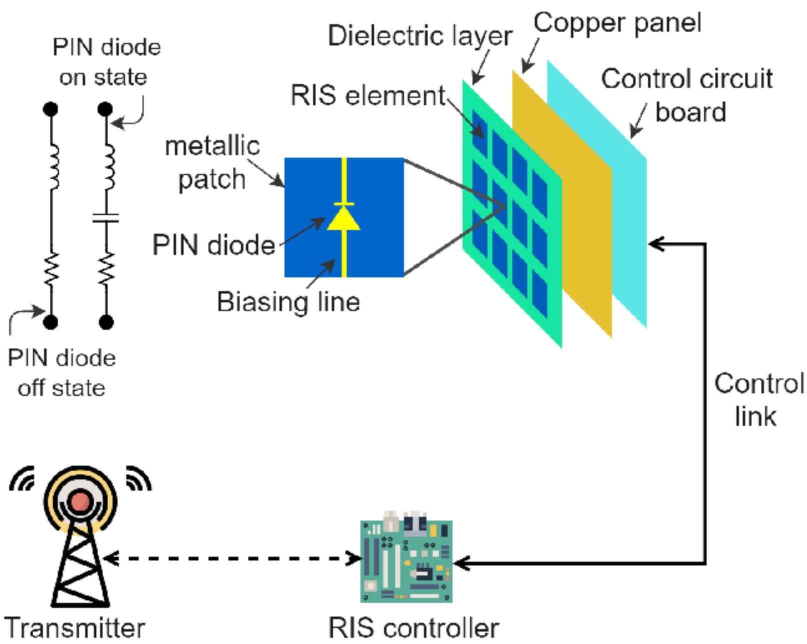


Fig. 8 Hardware architecture of an RIS [2].

V. Methodology and Suggested Solutions

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

1- The first part is the basic antenna element design based on CRLH metasurface 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.

2- The second part is a reconfiguration which is basically the array configuration to produce beam steering 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.

3- 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.

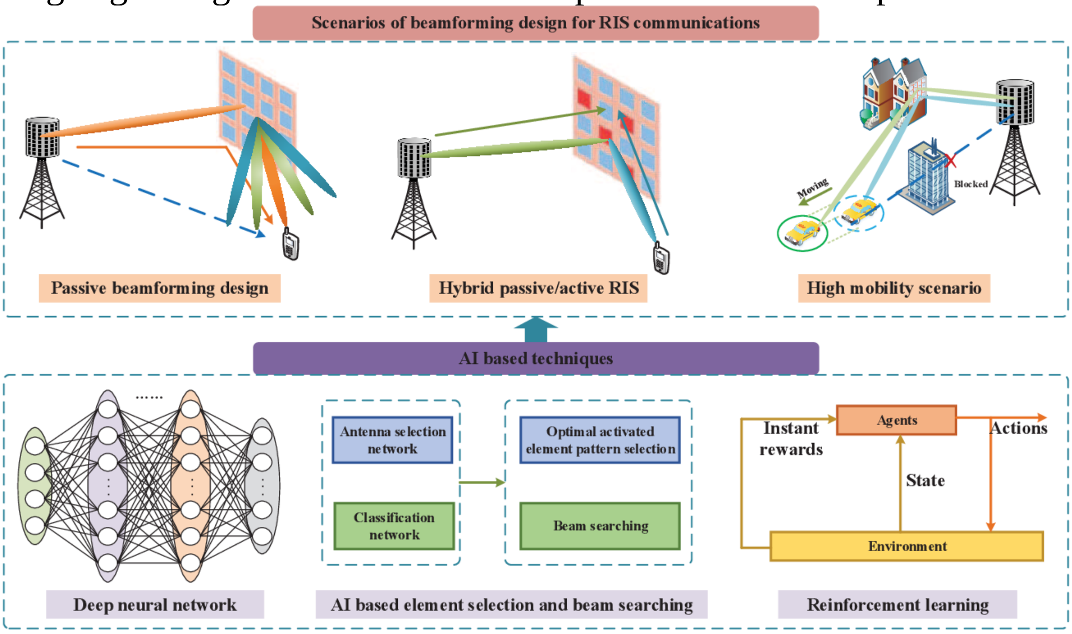
4- The DC biasing and wiring connections could be a serious issue, therefore, the use of CRLH based antenna structures creates good option to keep the wiring systems underneath the radiating elements to avoid any interaction between them.

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.

VI. Research Plan

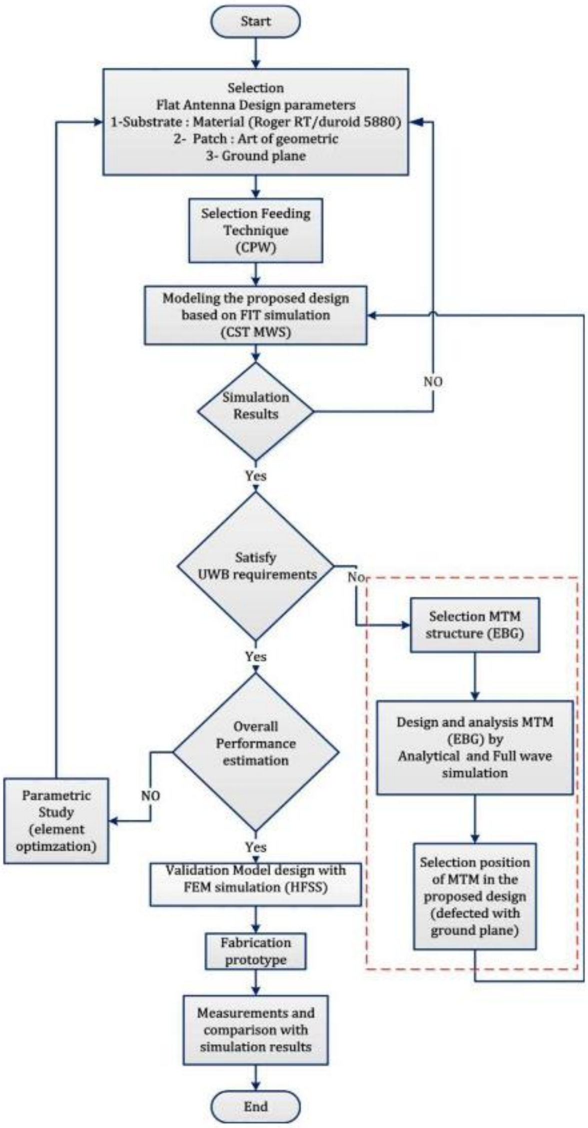
The main originality is to design an RIS layer over a certain bandwidth to realize intelligent beam forming process. Thus, the resulting beam forming would be realized by:

- RIS based a miniaturized meta surface can be realized using CRLH unit cells of unique characteristics to create multifunctional RIS based reconfigurable properties.
- Invoke numerical parametric and/or experimental study to collect the beam steering properties based on different active switching mapping processes for the RIS at different locations and different angles to be used as a training data for multi-path reflection environments.
- Measure the channel performance for each scenario and compare the best arriving angle tough a neural network to optimize the channel performance.



Item	Time (in months)
Literature review in the field of Meta surfaces based on high gain antennas for modern wireless techniques	3 months
The second part of the thesis will be devoted to designing the CRLH meta surfaces using the developed geometries and modelling the interaction with antenna based on a new physical theory	3 months
Design and simulation the second part of the thesis will be devoted to design the meta surfaces using the developed geometries and modelling the interaction with antenna based a new physics theory.	6 months
Experimental measurements of proposed design, publication and thesis writing.	6 months
Publications and thesis writing.	6 months

Finally, the proposed work is constructed according to the following flow chart:



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

1. The first part is to optimize the basic RIS unit cell design based on CRLH structure at the frequency band of interest. The main aim of this part is to study the radiation properties of the RIS unit cell enhancements and radiation leakage at certain frequency bands. Nevertheless, such structures electromagnetic constitutive parameters in terms of (ε or μ) would be evaluated for beam steering process.
2. The second part is to reconfigure the RIS layer from the RIS unit cell and study the reconfiguration process to produce beam steering through the progressive phase shift between the unit cells.
3. 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.

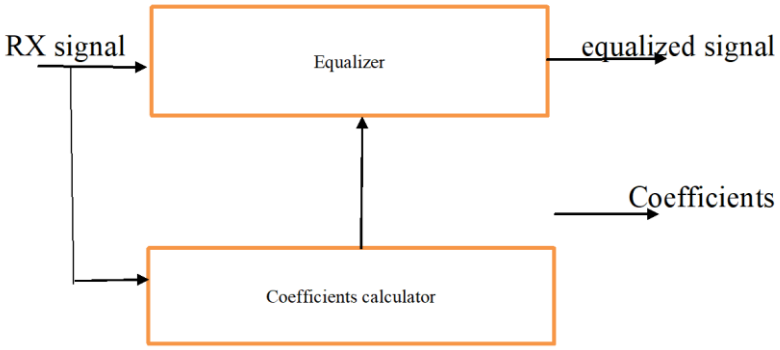
4. Optimizing the channel performance through using a neural network by training the system with input data from beam steering properties of the RIS layer.

This work can be attempted using an equalizer process. The equalizer is an electronic circuit that can be set up to correct imperfections in a radio propagation channel. A generic equalizer can take the form of a tapped delay line filter having a set of coefficients W0-WN, however, there are several other equalizer structures, including neural networks, and other algorithms, that can be used to achieve the same effect. For squinting problem, the equalizer design must consider the following

A- Each angle should be considered as a different channel, and each channel has its own correction coefficients that must be stored in the equalizer to be used in the case of that angle. For the receiver to recognize the angle neural network will be used. The output of the neural network will be the angle of this path.

B- The equalizer needs to know the array response at boresight.

C- Training signal is sent that is known by RX and TX



The coefficients calculator calculates the coefficients by measuring the gain and phase of the received path since the signal is already known and compare it with the gain and phase at the boresight and calculate the coefficients that minimize the error.

Finally, this subject could encompass several aspects of research, including:

1. RIS Deployment Strategies: Investigate optimal placement and configuration of RIS elements in a cooperative relay network to maximize the efficiency of both wireless information and power transfer.
2. Joint Resource Allocation: Develop algorithms for joint optimization of transmit power, relay selection, RIS phase configuration, and energy harvesting policies to achieve the best trade-off between communication reliability, energy efficiency, and spectral efficiency.

3. Channel Estimation and Feedback: Explore methods for accurate channel state information (CSI) estimation and feedback mechanisms between RIS, relays, and

the destination node to enable effective coordination and adaptation to dynamic channel conditions.

4. Energy Harvesting Performance: Evaluate the impact of RIS deployment on the energy harvesting performance of SWIPT-enabled relay nodes, considering factors such as RIS reflection coefficients, relay-RIS distance, and incident signal power distribution.

5. Security and Privacy Considerations: Address security and privacy challenges associated with RIS-assisted SWIPT in cooperative relay networks, including potential vulnerabilities, authentication mechanisms, and privacy-preserving communication techniques.

6. Experimental Validation: Conduct simulations and real-world experiments to validate the proposed RIS design and optimization techniques, considering practical constraints such as hardware implementation, energy harvesting efficiency, and deployment scenarios.

VII. Research Plan

By delving into these areas, researchers can contribute to the advancement of RIS technology in the context of SWIPT-enabled cooperative relay networks, paving the way for more efficient and sustainable wireless communication systems. Reconfigurable intelligent surfaces (RIS) correspond to smart radio surfaces of many small antennas or reconfigurable metamaterial elements which enable controlling the propagation environment through tunable scatterings of electromagnetic waves (EM). The RIS ability in terms of reconfiguring the wireless channel has motivated a host of potential new use cases, including utilizing RIS as intelligent repeaters to enhance performance of field deployments and as holographic massive antenna arrays for implementing low-cost and low complexity multiple-input multiple-output (MIMO) radios. In the last two decades, meta surfaces have become an attractive research area due to their untraditional properties in comparison to other material categories. Therefore, such research area, recently, oriented toward different intelligent and smart antenna arrays for modern wireless applications; in which, a great impact is applied to push the limits of such technologies. Therefore, meta surfaces would be an excellent candidate for such research area to improve antenna beam forming and steering technology. However, there are two main relative problems that are associated with such research including: side lobes effects during the antenna beam steering and front to back ratio reduction due the effects of the back lobes. To explore RIS technology and its applications across the wide spectrum of use cases and deployments, and identify any specification needs that may be required.

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