DESIGN OF MULTIPORT RECTENNA FOR WIRELESS ENERGY HARVESTING IN WEARABLE APPLICATIONS

A PROJECT REPORT
(PHASE – I)

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Certified that this project report **"DESIGN OF MULTIPORT RECTENNA FOR WIRELESS ENERGY HARVESTING IN WEARABLE APPLICATIONS"** is the bonafide work of **"ELAKSHME DEVI C. [REGISTER NO: 21UEC046], DHARSHINI M.R. [REGISTER NO: 21UEC039], SINDUJA R. [REGISTER NO: 21UEC172]"** submitted to the Pondicherry University, Puducherry for the award of the degree of **Bachelor of Technology in Electronics and Communication Engineering**. The contents of this project, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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ABSTRACT

The rapid evolution of wearable technology demands innovative solutions for efficient and sustainable power sources. This project aims to design and optimize a multi-port rectenna to enhance wireless energy harvesting for wearable devices. The rectenna, integrating antenna and rectifier circuits, efficiently captures and converts ambient RF energy from sources like Wi-Fi and cellular signals. The antenna is meticulously designed for high gain and wideband performance, ensuring effective energy capture, while the rectifier circuit maximizes power conversion efficiency. The multi-port configuration further optimizes energy harvesting by enabling simultaneous energy capture from multiple sources. Through rigorous simulations, optimizations, and prototyping, the project seeks to deliver superior performance, surpassing conventional designs. This research lays the foundation for a new era of self-sustaining wearable devices, reducing reliance on traditional batteries and paving the way for a more sustainable future.

***Keywords*:** Multi Port Rectenna, Wireless Energy Harvesting, Wearable Applications, Enhanced Gain, RF Energy Conversion, Power Conversion Efficiency

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LIST OF ABBREVIATIONS

AC	Alternating Current
AR	Augmented Reality
DC	Direct Current
EBG	Electromagnetic Band Gap
ECG	Electrocardiogram
FCC	Frequency Communication Commission
GPS	Global Positioning System
ISM	Industrial, Scientific, and Medical band
IoT	Internet of Things
MIMO	Multiple Input and Multiple Output
PCB	Printed Circuit Board
RF	Radio Frequency
RFID	Radio Frequency Identification

CHAPTER-1

INTRODUCTION

1.1 INTRODUCTION

Wearable technology has become an integral part of contemporary life, encompassing various applications from health monitoring and fitness trackingto smart textiles that enhance user experience. As the functionality of these devices continues to expand, powering them effectively presents a significant challenge. Traditional battery systems are often inadequate, requiring frequent recharging and adding unwanted bulk to the devices, compromising comfort and usability. Thisreliance on batteries limits the operational time of wearables, necessitating innovative solutions for sustainable power sources. Wireless energy harvesting has emerged as a promising alternative, allowing devices to capture and utilize ambient environmental energy.

Among the various methods available, rectennas (rectifying antennas) stand out as highly effective solutions for converting ambient RF energy into usable DC power. A rectenna combines the functions of an antenna and a rectifier, making it capable of capturing RF signals and converting them into electricity efficiently. This proposed work aims to enhance the performance of rectennas by focusing on the design and optimization of a multi-port configuration with improved gain. Integrating multiple antennas allows the system to harvest energy from various RF sources simultaneously, significantly increasing the overall energy capture. This design improves efficiency and ensures reliable power generation, accommodating the dynamic nature of wearable devices. Through meticulous design adjustments and optimization, the proposed work seeks to develop a compact, efficient, and sustainable power solution that addresses the limitations of traditional battery systems, paving the way for more advanced and longer-lasting wearable technologies.

The benefits of this approach are manifold. Firstly, it significantly increases the operational time of wearable devices which is depicted in Fig 1.1, reducing the need for frequent battery replacements. Secondly, it enhances the reliability of the power supply, as the device can harvest energy from multiple sources, even in environments with varying RF signal strengths. Thirdly, it contributes to the development of sustainable and environmentally friendly technologies by reducing reliance on batteries.

Fig 1.1 Different Types of Wearable Technology

1.1.1 Wireless Power Transmission

Wireless Power Transmission (WPT) is a groundbreaking technology that promises to revolutionize the way we power our devices which is shown in Fig 1.2. By harnessing the principles of electromagnetic induction or radiation, WPT enables the transfer of electrical energy without the need for physical cables. This advancement holds the potential to transform various industries, from consumer electronics to automotive and medical fields.

One of the most promising applications of WPT lies in the realm of wearable technology. By integrating textile antennas into clothing, we can create self-powered devices that continuously receive energy from a nearby power source. This eliminates the need for frequent battery replacements, enhancing the convenience and user experience of wearable gadgets. Textile antennas are designed to be flexible, lightweight, and seamlessly integrated into fabrics, making them ideal for a wide range of wearable applications. However, the integration of WPT with textile antennas presents several challenges. One major hurdle is the efficient conversion of electromagnetic energy into usable electrical power. Textile materials often have lower conductivity compared to traditional electronic components, which can impact the overall efficiency of the system. Additionally, ensuring the durability and reliability of textile antennas under various conditions, such as washing and wear and tear, is crucial.

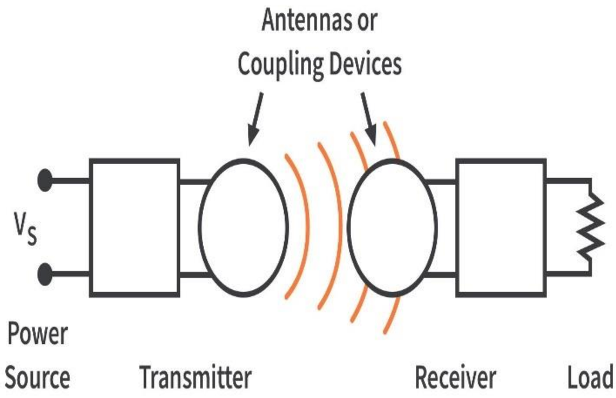

Fig 1.2 Block diagram of Wireless Power Transmission

Despite these challenges, ongoing research and development efforts are focused on addressing these limitations. Researchers are exploring innovative materials and design techniques to improve the efficiency and durability of textile antennas. By optimizing the antenna's geometry, material selection, and integration methods, it is possible to achieve high-performance WPT systems that can power a variety of wearable devices. In conclusion, the combination of wireless power transmission and textile antennas represents a significant step forward in the field of wearable technology. By overcoming the technical challenges and leveraging advancements in materials science and electronics, we can unlock the full potential of this technology and create a future where our devices are truly wireless and self-sufficient.

1.1.2 Multiple Input and Multiple Output (MIMO)

MIMO (Multiple Input Multiple Output) is a wireless communication technology that uses multiple antennas at both the transmitter and receiver to transmit and receive more than one data signal simultaneously over the same frequency channel which is shown in Fig 1.3.This improves the overall capacity, speed, and reliability of the communication systemwithout needing additional spectrum.

MIMO works by leveraging the spatial diversity of signals and the multiple antennascreate different paths for data to travel, which the system can exploit to increase data throughput, reduce signal fading, and enhance overall performance.

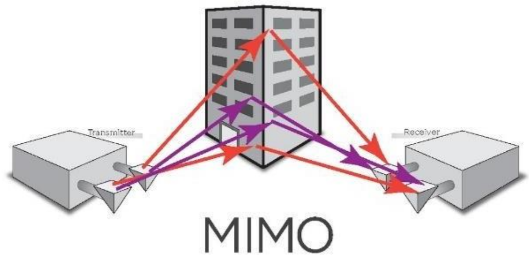

Fig 1.3 Concept of MIMO

1.2 MONOPOLE ANTENNA

A monopole antenna is a type of radio antenna consisting of a straight, vertical conductor mounted above a conductive ground plane. It's essentially half of a dipole antenna, with the ground plane acting as a virtual image of the antenna element. This is half of a dipole antenna arranged above a conducting ground plane. So the quarter-wave monopole antenna is the most common type where this antenna is around 1/4 of radio wave wavelength. These antennas are used in internet networks & mobile communications which is depicted in Fig 1.4.

A type of radio antenna that includes a straight rod-shaped conductor that is perpendicularly mounted above a ground plane is known as a monopole antenna. This antenna is a simple and single-wire antenna, mainly used for both transmitting & receiving signals, so broadly used in wireless communication systems. In a monopole antenna, the conductor rod works like an open resonator mainly for radio waves & oscillates by standing voltage & current waves through its length. The antenna's length is simply determined depending on the desired radio wave wavelength. The monopole antenna frequency range is from 1.7- 2 GHz, with a 3.7 dBi average gain.

Fig 1.4 Monopole Antenna

1.2.1 Monopole Antenna Design

A monopole antenna is ½ (one-half) of a dipole antenna which is nearly mounted on top of some type of ground plane. So, this antenna is mounted on an infinite ground plane with an 'L' length as shown below. By image theory, the fields on the ground plane can be found through the antenna within free space which is shown in the second diagram. This is just a dipole antenna with twice a monopole antenna's L (length).

In Fig 1.5, the fields on the ground plane are equal to the fields. The fields of the monopole antenna under the ground plane within this figure are zero. The monopole antenna's directivity is related to a dipole antenna directly. If a dipole antenna's directivity with length 2L is D1, then the monopole antenna's directivity with length 'L' will have D1+3 which means, the monopole antenna's directivity is double the dipole antenna's directivity. The main reason for this is only because no radiation takes place under the ground plane; thus, the antenna is efficiently doubled as "directive".

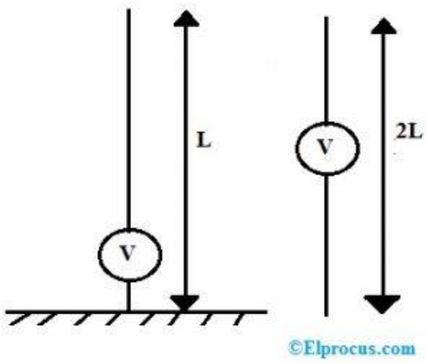

Fig 1.5 Monopole Antenna design

1.2.2 Monopole Antenna Working Principle

The working principle of a monopole antenna is; that when the power is fed to a monopole then it is radiated similarly in all directions vertical to the antenna's length above the ground plane on which it is mounted. The radiation pattern of this antenna is omnidirectional, so it radiates with equivalent power within all directions at right angles to the antenna. The radiated power from the antenna changes with elevation angle through the radiation dropping off to zero at the peak on the axis of the antenna.

1.2.3 Monopole Antenna Types

There are different types of monopole antennas like a whip, helical, rubber ducky random wire, umbrella, mast radiator, inverted-L, T-antenna, ground plane, folded unipole & inverted-F.

1.2.3.1 Whip Antenna

A whip antenna is a type of monopole antenna that is very flexible and does not crack simply which is depicted in Fig 1.6. The name of this antenna was derived from the whip-like motion that was exhibited once disturbed. This antenna includes a straight flexible rod or wire, and the bottom is simply connected to the radio transmitter or receiver. For portable radios, these antennas are frequently designed with a set of interlocking telescoping metal tubes, thus they can be pulled back once not in use. Longer whips are mainly designed to be mounted on vehicles as well as structures which are designed with a flexible fiberglass rod approximately a wire core & can be up to 11 m long. The perfect length of this antenna can be determined through the radio waves wavelength.

Fig 1.6 Whip Antenna

1.2.3.2 Helical Antenna

A helical antenna includes a minimum of one or above conducting wires which are wounded in a helix form which is shown in Fig 1.7. When a helical antenna is designed with one helical wire then this antenna is known as monofilar whereas antennas designed with a minimum of 2 or 4 wires within a helix are then called quadrifilar/bifilar.

Fig 1.7 Helical Antenna

1.2.3.3 Random Wire Antenna

Random wire antenna includes a long wire that is suspended over the ground where the wire is straight or may be strung back & forth in between walls or trees just to get the sufficient wire into the air. Because of the huge variability in the antenna structure, efficiency can change from one fix to another.

Random wire antennas as shown in fig 1.8 are extensively used as receiving antennas on the short wave, medium wave & long wave bands, and these antennas are used as transmitting antennas on these bands mainly for emergency or temporary transmitting stations, small outdoor & in places where more permanent antennas cannot be mounted.

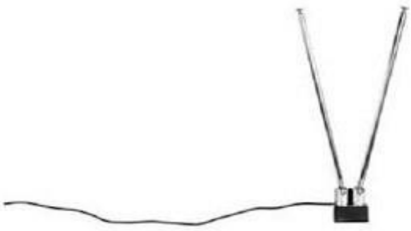

Fig 1.8 Random wire Antenna

1.2.3.4 Rubber Ducky Antenna

The rubber ducky antenna in Fig 1.9 is a short monopole antenna that works fairly as a base-loaded whip antenna. This antenna includes a narrow helix-shaped springy wire closed within a plastic or rubber jacket to guard the antenna. These antennas are used in various portable radio devices like walkie-talkies, scanners portable transceivers where security and robustness take priority above electromagnetic performance.

Fig 1.9 Rubber Ducky Antenna

1.2.3.5 Mast Radiator

A mast radiator is a type of monopole antenna which is depicted in Fig 1.10. This is a radiating tower or radio mast which is where the metal structure is energized & works as an antenna. This is normally used for transmitting antennas that function at low frequencies within the MF & LF bands, particularly used for AM radio broadcasting stations. This antenna's base is normally mounted on a nonconductive support to protect it from the ground.

Fig 1.10 Mast Radiator

1.2.4 Benefits of Monopole Antenna

Monopole antennas are typically smaller and more compact than dipole antennas, making them easy to integrate into portable devices like mobile phones, GPS systems, and IoT devices. The monopole antenna consists of just a single conductive rod mounted above a ground plane, which simplifies the design and manufacturing process, reducing overall cost. Monopole antennas have an omnidirectional radiation pattern in the horizontal plane, meaning they radiate signals equally in all directions, providing broad coverage. This makes them ideal for mobile communications. With a ground plane, a quarter-wave monopole antenna impedance is around 37 ohms, which is close to the typical 50-ohmimpedance of transmission lines. This reduces the need for complex impedance-matching circuits. The ground plane acts as a reflector, effectively doubling the length of the antenna (compared to dipole designs), allowing a smaller physical antenna to achieve similar performance. Due to its small size and simple design, the monopole antenna can easily be integrated into compact electronic systems and portable devices without requiring significant space. Monopole antennas have a simple and robust structure, making them highly durable in harsh environmental conditions. They are commonly used in outdoor applications, including vehicles and military equipment. The simplicity of the monopole design, requiring fewer materials and less complex manufacturing processes, makes it cost-effective formass production, especially for consumer devices like mobile phones. Monopole antennas naturally produce vertically polarized waves, which are advantageous for ground-based applications like mobile communication, where vertical polarization is preferred for efficient signal propagation over long distances.

1.3 WIRELESS ENERGY HARVESTING

Wireless energy harvesting is an innovative technology that captures and converts ambient energy from the environment into usable electrical power, eliminating the need for traditional wired power sources or batteries which is depicted in Fig 1.11. This approach is particularly significant in today's technology landscape, where the proliferation of wireless devices,Internet of Things (IoT) applications, and wearable technology has created a demand for efficient and sustainable energy solutions.

The primary sources of ambient energy that can be harvested include radio frequency (RF) signals, solar energy, thermal energy, and kinetic energy. Among these, RF energy harvesting has gained considerable attention due to the widespread presence of wireless communication systems, such as Wi-Fi, cellular networks, and broadcast signals. Devices designed for wireless energy harvesting typically incorporate rectifyingantennas (rectennas) that capture RF energy and convert it into direct current (DC) power. This conversion process enables the harvested energy to be stored or used immediately to power low-energy devices, such as sensors, medical implants, or smart wearables. One of the key advantages of wireless energy harvesting is its potential to create self-sustaining systems that require minimal maintenance. By harnessing ambient energy, devices can operate independently of traditional power sources, reducing reliance on batteries that must be periodically replaced or recharged. This feature is particularly beneficial in remote or hard-to-reach locations, where frequent maintenanceis impractical.

Wireless energy harvesting technologies also contribute to environmental sustainability by minimizing electronic waste and reducing the carbon footprint

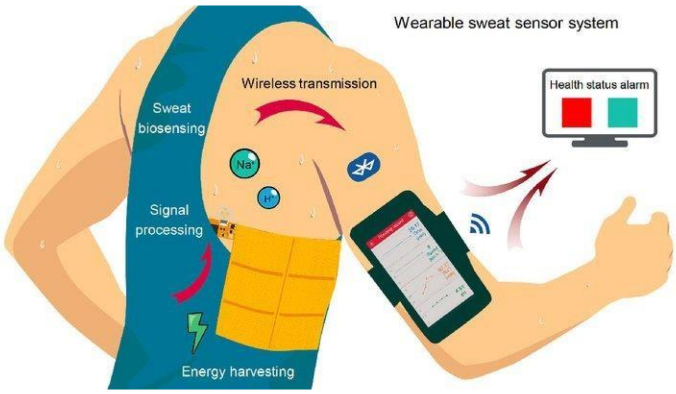

Fig 1.11 Wireless Energy Harvesting

associated with battery production and disposal. As energy demands continue to rise inan increasingly connected world, wireless energy harvesting presents a promising avenue for powering the next generation of smart devices and applications.

Therefore, wireless energy harvesting is a transformative technology that captures and converts ambient energy into usable power, facilitating the development ofself-sustaining electronic systems. Its ability to utilize existing RF signals and other energy sources makes it a vital component in the pursuit of sustainable and efficient energy solutions for a wide range of applications.

1.3.1 Key Characteristics of Wireless Energy Harvesting

Ambient RF signals from sources such as Wi-Fi,cellular networks, and radio broadcasts. Higher frequency radiation often used for specificapplications. Although primarily not "wireless," solar panels can be combinedwith WEH technologies to create hybrid systems. A device that combines an antenna (for capturing RF signals) and a rectifier (for converting AC signals to DC). It effectively captures RF energy and transforms it into usable power. The process of converting alternating current (AC) into direct current (DC) to charge batteries or power electronic devices. Systems often include energy storage to smooth out the energy supply, ensuring the device can operate continuously despite fluctuations in harvested energy.

1.3.2 Benefits of Wireless Energy Harvesting

Wireless energy harvesting significantly decreases reliance on traditional batteries, which can be harmful to the environment. Batteries contribute to pollution during their production, use, and disposal, often leaking toxic substances. By harnessing ambient energy, WEH promotes a more sustainable approach to powering electronic devices, contributing to a reduction in electronic waste. WEH taps into renewable energy sources, suchas radio frequency (RF) waves and solar energy, that are naturally occurring inthe environment. This alignment with renewable energy principles supports global efforts to transition to greener energy solutions. Devices powered by WEH can operate indefinitelywithout the need for battery replacements. This maintenance-free operation is particularly advantageous for devices located in remote or hard-to-reach areas,such as environmental sensors in forests or ocean buoys. With no need for regular battery changes or maintenance, the overall operational downtime of devices is minimized. This reliability is crucial in applications such as industrial monitoring, where continuous data collection is essential. Over time, the savings associated with not having to purchase and replace batteries can be substantial, especially in large-scale deployments. This cost-effectiveness is significant for industries that require many sensors or devices, such as agriculture and smart cities. Maintenance tasks, such as battery replacement and disposal, require labour and resources. Wireless energy harvesting eliminates these costs, making it a more economically viable solution. Devices that do not require physical power connections can be more easily deployed in various locations. With the elimination of battery compartments, the design of electronic devices can be streamlined, allowing formore compact and lightweight products. This is especially beneficial for wearable technology and portable devices, where size and weight are critical factors. Wireless energy harvesting can be applied to various fields, including IoT, healthcare, agriculture, and smart infrastructure. This versatility makes it a suitable solution for powering sensors, monitoring devices, and communication systems across diverse industries.

1.4 RECTIFIER CIRCUIT

A rectifier is an essential electronic component that transforms alternating current (AC), which flows in both directions, into direct current (DC), which flows in one direction which is shown in Fig 1.12. This conversion is critical for many applications, including power supplies, battery chargers, and renewable energy systems. Rectifiers are utilized in everything from small electronic devices to large industrial applications, making them fundamental element of electrical engineering.

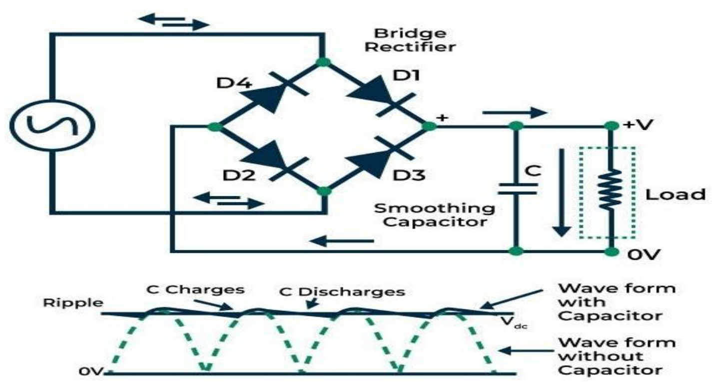

Fig 1.12 Rectifier circuit

1.4.1 Working principle of rectifier

Rectifiers operate on the principle of controlling the direction of current flow. They typically use semiconductor diodes, which allow current to flow in only one direction. In doing so, they effectively block the negative portion of the AC waveform, resulting in a unidirectional output that constitutes DC.

1.4.2 Types of rectifiers

Half-Wave Rectifier uses a single diode to allow only one half of the AC waveform to pass, blocking the negative half. It produces a pulsating DC output with a significant ripple and is less efficient for power conversion. Full-Wave Rectifier utilizes multiple diodes (often in a bridge configuration) to allow both halves of the AC waveform to be used. This resultsin a smoother DC output with reduced ripple, improving efficiency. Bridge Rectifier is a specific form of the full-wave rectifier, the bridge rectifieruses four diodes arranged in a bridge configuration. It converts the AC input into a unidirectional output, providing better performance than half-wave rectifiers.

1.4.3 Components of rectifier

Diodes are the primary components that allow current to flow in only one direction, thereby enabling the conversion of AC to DC. Capacitors often used in conjunction with rectifiers to smooth the outputvoltage by filtering out the ripple, creating a more stable DC signal. Voltage Regulators are used to maintain a constant DC output voltagedespite variations in the input voltage or load conditions.

1.4.4 Parameters for rectifiers

The maximum voltage a diode can withstand in the reverse direction without conducting. It's crucial for determining the diode's suitability for a particular application. The voltage drop across the diode when it is conducting. Lower forward voltage drops lead to higher efficiency. A measure of the AC component present in the output DCvoltage. Lower ripple factors indicate smoother DC outputs. Efficiency is defined as the ratio of output DC power to input AC power.Higher efficiency indicates better performance in converting AC to DC. Load regulation is the ability of the rectifier circuit to maintain a constantoutput voltage despite variations in load current.

1.5 RECTENNA

A rectenna, short for rectifying antenna, is a specialized device that combines an antenna with a rectifier to convert radio frequency (RF) energy into direct current (DC) electricity. It operates by capturing ambient RF signals from various sources, such as Wi-Fi and cellular networks, through its antenna. The captured RF energy is then fed into a rectifier circuit, which converts the alternating current (AC) signal generated by the antenna into usable DC power. Rectennas are designed for high efficiency, maximizing the conversion of captured energy, and many can operate across multiple frequency bands, enabling them to harvest signals from various sources simultaneously which is shown in Fig 1.13.Their compact design makes them suitable for integration into portable and wearable devices, leading to a range of applications, including powering smartwatches, fitness trackers, and self-sustaining Internet of Things (IoT) sensors.

By providing a sustainable energy source, rectennas contribute to the development of self-powered electronic devices, reducing reliance on traditional batterysystems and promoting environmentally friendly technologies.

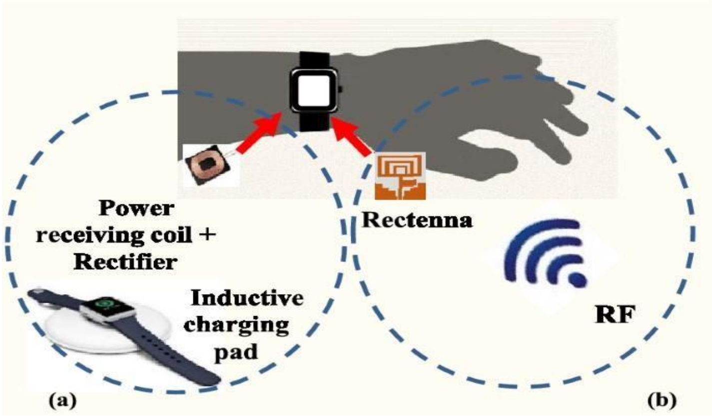

Fig 1.13 Rectenna in wearable

1.5.1 Classification of Rectennas

Multi-Port Rectenna advanced design incorporates multiple antennas or ports, allowing simultaneous energy harvesting from various RF sources. It enhances efficiency by operating across multiple frequency bands. Single-Port Rectenna is a straightforward design featuring a single antenna connected to a rectifier, optimized for capturing energy from a specific frequency range. It is cost-effective but limited in energy capture compared to multi-port designs. Wideband Rectenna is designed to function over a broad frequency range, wideband rectennas can capture RF signals from multiple sources effectively. They utilize broadband matching networks for efficient energy harvesting across different communication standards. Microstrip Rectenna is characterized by a flat, printed circuit board design, microstrip rectennas are lightweight and suitable for integration into compact devices, making them ideal for applications in wearables and mobile technology. Planar Rectenna feature a planar design, often using thin-film technology, which allows for flexibility and conformability in applications such as smart textiles and flexible electronics. Array Rectenna comprises of multiple rectenna elements arranged in a grid formation, array rectennas enhance overall gain and directivity, improving energy capture from specific directions for higher efficiency. Textile Rectenna is integrated into fabric materials, textile rectennas are lightweight and flexible, making them perfect for wearable applications like smart clothing and health-monitoring devices.

1.5.2 Multiport Rectenna

Of these types of rectenna available, we choose multiport rectenna because of the following advantages,

Multiport rectennas can capture energy from multiple sources or frequencies simultaneously, enhancing overall energy conversion efficiency. This is particularly beneficial in environments where RF signals arescattered across different bands. By integrating multiple rectifying ports, these rectennascan produce higher DC output power compared to single-port designs. This makes them suitable for powering larger devices or multiple low-power devices once. Multiport rectennas can be designed to accommodate various operating conditions and applications which is depicted in Fig 1.14. They can be tuned to specific frequency bands or adjusted to optimize performance for different energy harvesting scenarios.

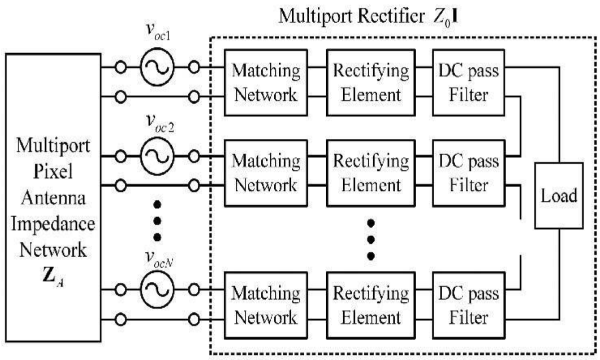

Fig 1.14 Block diagram of multiport rectenna

Multiport rectennas can be integrated into compact designs, allowing them to be embedded in small devices or wearables without significantly increasing size or weight. This is crucial for applications in portableelectronics. By effectively utilizing ambient RF energy, multiport rectennas contribute to reducing dependence on traditional batteries, promoting sustainability and lowering electronic waste. With multiple ports, rectennas can better match theload requirements of connected devices, ensuring efficient power transfer and minimizing energy loss. Multiport rectennas can be employed in various fields,including IoT, healthcare, and smart cities, making them versatile solutions for diverse energy harvesting needs. These rectennas can incorporate advanced power management systems to optimize energy distribution among connected devices, ensuring that each device receives the necessary power without waste. As the demand for wireless power grows, multiportrectennas can be adapted to incorporate emerging technologies and new frequency bands, ensuring their relevance and effectiveness in the evolving landscape of energy harvesting.

1.6 RECTENNA IN WEARABLE TECHNOLOGY

A rectenna (rectifying antenna) is an advanced device that seamlessly integrates an antenna with a rectifier to convert ambient electromagnetic energy into usable direct current (DC) electricity. In the realm of wearable technology, rectennas present a groundbreaking solution for energy harvesting, allowing devices to harness energy from their surroundings, such as radio frequency (RF) signals emitted by Wi-Fi networks, celltowers, and other wireless communication sources which is shown in Fig 1.15. This technology enhances the sustainability and efficiency of wearable devices by reducing reliance on conventional batteries, which not only diminishes environmental impact but also minimizes the frequency of battery replacements. The ability to convert harvested energy into DC power enables wearables—like smartwatches, fitness trackers, and smart textiles—to operate continuously without the constraints of limited battery life. Moreover, the compact and lightweight nature of rectennas allows them to be embedded within the design of various wearable products, maintaining comfort and aesthetic appeal while ensuring that devices remain powered for extended periods. The integration of rectennasinto wearables significantly contributes to the development of Internet of Things (IoT) ecosystems, where continuous operation and connectivity are crucial for real-time datamonitoring and communication. As the demand for sustainable and efficient energy solutions grows, rectennas are poised to play a vital role in the evolution of wearable technology.

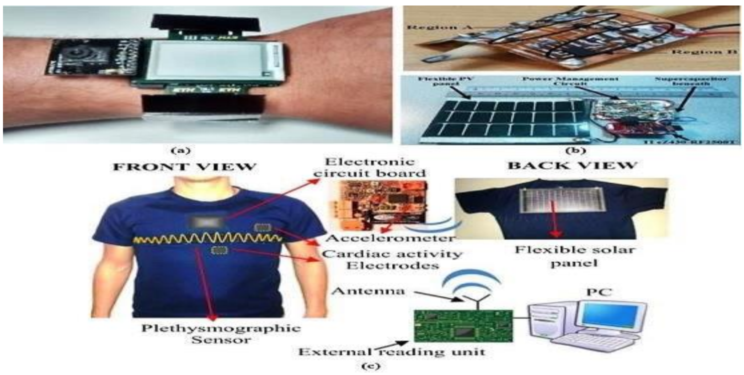

Fig 1.15 Rectenna in wearable technology

1.7 SCOPE OF THE PROJECT

The project aims to design, develop, and test a novel textile antenna integrated with MIMO technology to enhance wireless energy harvesting efficiency and reliability for wearable electronic devices. This involves designing a textile antenna array, developing a WPT system, implementing MIMO signal processing, designing power management circuitry, and integrating and testing the entire system. The project will focus on core aspects like antenna design, WPT system optimization, MIMO signal processing, and power management, excluding large-scale production, in-depth material analysis, and long-term reliability testing. The final deliverables will include detailed design specifications, a fabricated prototype, comprehensive test results, and a technical report documenting the entire process.

1.8 MOTIVATION OF THE PROJECT

The increasing demand for wearable electronic devices, coupled with the limitations of battery technology, has motivated the development of self-powered devices. Wireless energy harvesting (WEH) offers a promising solution to eliminate the need for frequent battery replacements. However, traditional WEH systems often suffer from low efficiency and limited range. To address these challenges, the integration of MIMO technology with textile antennas provides a synergistic approach to enhance energy harvesting efficiency and reliability. By leveraging the benefits of spatial diversity and multiplexing, MIMO can improve the signal-to-noise ratio, extend the range of energy transfer, and enable simultaneous data communication and energy harvesting. This project aims to push the boundaries of wearable technology by developing a self-sufficient and sustainable solution that can power a wide range of wearable devices, from smartwatches and fitness trackers to medical sensors and environmental monitors.

1.9 OBJECTIVES OF THE PROJECT

- Design and optimize a multi-port rectenna to efficiently capture ambient RF energy from various sources.
- Enhance the gain of the rectenna to maximize energy harvesting efficiency.
- Convert the harvested RF energy into usable DC power with minimal loss.

1.10 ORGANIZATION OF THE REPORT

The Organization of the report is as follows,

Chapter 1: Discusses overview of the wearable technology, monopole antenna, its characteristics and types. It also discusses the background of the project.

Chapter 2: Review of relevant scholarly papers and prior research related to energy harvesting for wearables design and development. Analysis of existing antenna designs and their performance based on specific parameters.

Chapter 3: Describes the proposed system design and its implementation.

CHAPTER-2

LITERATURE SURVEY

2.1 OVERVIEW

The quest for advanced and efficient energy harvesting solutions is a vital endeavor within the rapidly evolving field of wearable technology. This project delves into the promising area of rectenna systems, specifically focusing on the development of a compact multiport rectenna designed to convert ambient radio frequency (RF) energy into usable direct current (DC) power. By integrating cutting-edge design principles and materials, this initiative aims to enhance the energy-harvesting capabilities of wearable devices, addressing the critical need for sustainable and self-sufficient power sources.

We begin by exploring the fundamental concepts of energy harvesting and the pivotal role of rectennas in capturing RF energy from diverse sources, such as Wi-Fi, Bluetooth, and cellular networks. This foundational overview highlights the limitations of conventional battery systems and emphasizes the necessity for innovative power solutions that can support the increasing demand for autonomous wearable technologies.

The discussion then transitions to the specifics of rectenna design, emphasizing the advantages of multiport configurations that enable simultaneous energy capture from multiple RF sources. By analyzing existing rectenna designs, we identify key strengths and challenges that inform our approach to developing a compact, efficient multiport rectenna. The core of this exploration lies in the unique characteristics of the proposed design, including its efficiency, adaptability, and potential for seamless integration into various wearable applications.

2.2 LITERATURE SURVEY

M. Fernández et al., (2024) [1] proposed a fully woven textile-integrated circularly polarized rectenna for wireless power transfer (WPT) applications at 2.4 GHz. Addressing the demand for self-powered wearable devices in healthcare and sports, the design features a rectangular patch antenna with truncated corners for circular polarization, mitigating polarization mismatches. A T-match feeding structure was introduced to optimize input impedance for efficient power transfer to the rectifier, a single-diode topology woven into the fabric. The integrated textile design, suitable for large-scale production, achieved 45% efficiency under realistic conditions, showcasing its potential for powering low-power IoT devices like wearable sensors.

Zhu Liu et al., (2023) [2] proposed a body-wide RF energy harvester using a textile-based surface plasmonic antenna (SSP) array for wearable wireless power transmission applications. The system integrates four patch antennas and SSP waveguides into clothing to collect and convert RF energy into DC power via a contactless, flexible rectifier and loop configuration. Unlike traditional designs requiring complex matching networks, this harvester uses surface plasmon waves to aggregate energy efficiently from multiple paths. Fabricated with flexible, off-the-shelf materials, the system produced a maximum DC output of 108.89 μW under a power density of 7.96 $\mu W/cm^2$ in the 2.4-2.45 GHz ISM band, making it ideal for powering wearable health and fitness sensors. Its scalability and manufacturability position it for widespread use in wearable technologies.

Aboualalaa et al., (2023) [3] proposed a high-gain, triple-band rectenna system designed to power IoT devices in smart office settings. The system operates in three frequency bands: one for energy harvesting (1.86–2.65 GHz) and two for data communication (2.84–3.64 GHz and 5.34–6 GHz). A stacked four-layer antenna with a voltage doubler rectifier achieves 69.7% power conversion efficiency (PCE), delivering 1.9 V at 2 dBm input power. With high antenna gains (8.1 dBi at 2.3 GHz, 8.9 dBi at 3.5 GHz, and 9 dBi at 5.7 GHz) and compliance with safety standards through SAR evaluations, the system supports simultaneous wireless power transfer and data communication, making it ideal for low-power IoT applications.

Battistini et al., (2024) [4] proposed a 3D-printed dual-port rectenna designed for energy harvesting and ultra-wideband (UWB) backscattering, enabling precise indoor localization and sensing. Fabricated using low-cost, biodegradable polylactic acid (PLA), the rectenna features cross-polarized antennas operating at UHF (around 2.47 GHz) for energy harvesting and UWB for passive pulse backscattering. The system generates quasi-UWB signals for localization while harvesting approximately 80 nW of power from a UHF signal at -15 dBm input, making it ideal for energy-autonomous wearable and low-power IoT devices in applications like healthcare and asset tracking.

The use of 3D-printed PLA enhances adaptability for integration onto curvilinear surfaces, broadening its potential in wearable technology.

Lacerda et al., (2024) [5] proposed a detailed behavioral model for RF-based energy harvesting in wireless power transfer (WPT) systems designed for batteryless IoT devices. Their model highlights the use of supercapacitors as sustainable storage elements, enabling multiple recharge cycles and addressing concerns over finite battery life and environmental impact. By analyzing components like matching networks, rectifiers, and power management units (PMUs), the model evaluates efficiency and charging times, emphasizing the role of circuit elements in optimizing energy flow. Validated experimentally, the framework supports eco-friendly IoT applications, particularly in industrial settings where battery replacement is impractical and costly.

Lin et al., (2022) [6] proposed a wearable rectenna specifically designed for low-power RF energy harvesting in healthcare applications, showcasing innovative advancements in wireless energy capture. Their rectenna operates at the 2.45 GHz Wi-Fi frequency band and integrates a patch antenna with a Greinacher rectifier circuit, enabling efficient capture and conversion of ambient RF signals into usable direct current (DC) power. This design optimizes performance for use on the human body, producing an output voltage of up to 2.2V, which makes it particularly suitable for powering medical devices such as health monitors and sensors, effectively reducing reliance on traditional batteries and addressing the sustainability challenges faced in healthcare technology.

Kou et al., (2022) [7] proposed an all-fabric flexible rectenna that operates at 1.64 GHz, achieving a remarkable energy conversion efficiency of 48.27%. This innovative design leverages conductive fabric materials, making the rectenna lightweight, comfortable, and easy to integrate into everyday garments. Their research emphasizes the potential of fabric-based rectennas to power wearable technology, which facilitates the development of self-sustaining Internet of Things (IoT) devices. By embedding these rectennas into clothing, they pave the way for new applications in smart textiles and health-monitoring systems, where continuous power supply is critical.

Wu and Yang et al., (2023) [8] proposed a cooperative beam selection scheme aimed at enhancing RF energy harvesting in wireless sensor networks, addressing the challenges of efficiently capturing energy from multiple users. Their research focuses on improving energy efficiency in multiuser MIMO (Multiple Input, Multiple Output) systems by optimizing beamforming strategies, which allow the system to dynamically adjust to varying signal conditions. This adaptive approach leads to significant improvements in the amount of energy harvested, making it especially beneficial for low-power sensor nodes deployed in wireless networks. Their findings underscore the importance of implementing advanced techniques to maximize energy capture and ensure reliable performance in real-world applications.

Alkhalaf et al., (2023) [9] proposed a flexible meta-patch rectenna array operating at 2.45 GHz in the ISM band, specifically designed to energize low-power wearable medical sensors (WMS). Their innovative textile-based metasurface interlayer patch antenna demonstrated improvements in gain, efficiency, and bandwidth. The design employed a seven-stage Cockcroft-Walton voltage multiplier rectifier, achieving a 34 power conversion efficiency (PCE) of up to 56%, which is a significant advancement for wearable RF energy harvesting (RFEH). This work is important as it offers a viable solution for overcoming the limitations of conventional batteries in WMS, such as their short operational life and the need for frequent replacements, which can be invasive for patients with implanted sensors.

Wagih et al., (2023) [10] proposed a wearable rectenna module integrating e-textile technology with energy harvesting and storage systems. The design features a flexible coplanar waveguide rectenna filament combined with a spray-coated supercapacitor, achieving an RF-to-DC conversion efficiency of up to 80%. Capable of wirelessly charging a textile-based supercapacitor that stores 8.4 mJ in 4 minutes at a 4.2-meter distance from the RF source, this system demonstrates the viability of textile-based energy storage for wearable devices. Its flexibility and durability make it suitable for real-world applications, addressing challenges like movement and path losses while enabling sustainable, efficient power for medical and consumer electronics.

T. T. Le et al., (2024) [11] proposed an all-textile broadband circularly polarized 2 × 2 array antenna using a metasurface (MTS) for wearable applications. The design features a metasurface radiator and a 90° phase difference feeding network to achieve high bandwidth and circular polarization. Diagonal slits are incorporated for miniaturization, enhancing adaptability. Performance tests in free space and on human body models demonstrate improved impedance bandwidth and compliance with SAR safety standards, contributing to lightweight, high-performance wearable technology.

Usman Ali et al., (2023) [12] proposed an work on enhancing the performance of a dual-band textile antenna for wireless body area networks (WBAN). They address challenges related to backward radiation and Specific Absorption Rate (SAR) by introducing an Artificial Magnetic Conductor (AMC) as a ground plane, which improves gain and radiation efficiency while reducing SAR by over 98% at 2.45 GHz and 5.8 GHz. Constructed on a flexible felt substrate, the antenna maintains stability during bending and performs well in both on- and off-body scenarios. The study demonstrates the AMC's potential to enhance safety and functionality in wearable WBAN devices, making it valuable for applications requiring low-profile, flexible antennas with low SAR.

Ilgvars Gorn et al., (2023) [13] proposed a wearable energy-harvesting system tailored for smart clothing applications, integrating electromagnetic and thermoelectric harvesters to capture energy from human motion and body heat. The system utilizes a shared energy storage capacitor, ensuring a continuous power supply for environmental sensors and wireless data transmission modules. Built with off-the-shelf components, the main electronic module offers compatibility and adaptability for various wearable devices. Their treadmill testing demonstrated sustained operation with up to 21% efficiency, showcasing the feasibility of energy-autonomous wearable electronics and supporting the development of stable and efficient power sources for smart textiles.

Madavarapu et al., (2024) [14] proposed the IoT Heterogeneous Energy Harvesting (IHEH) technique, which powers smart home appliances by utilizing multiple energy sources: thermal, piezoelectric, and light energy. The system comprises four layers—Energy Harvesting, Control and Sensing, Information Processing, and Application—achieving an overall energy efficiency of 90%. This approach ensures continuous operation, reduces reliance on conventional power sources, and enhances energy management, making it a promising solution for future IoT applications.

H. Y. Alkhalaf et al., (2024) [15] proposed an work on the design and development of a flexible meta-patch rectenna array aimed at powering low-power wearable medical sensors. The array features a meta-patch antenna operating at the 2.45 GHz ISM band, paired with a seven-stage Cockcroft-Walton Voltage Multiplier

(CWVM) rectifier optimized for high DC output at low input power. Fabrication and measurement results demonstrate a power conversion efficiency (PCE) of 56%, delivering 450 μW of DC output at an input power of -1 dBm. This work contributes to the advancement of efficient and sustainable power sources for wearable medical devices.

S.-J. Kim et al., (2023) [16] proposed a compact broadband stepped bow-tie antenna for ambient RF energy harvesting. The proposed antenna utilizes simple stepped and bow-tie shapes to achieve a wide bandwidth and compact dimensions. Designed for the mobile communication band, it exhibits a fractional bandwidth of 125%, with high efficiency exceeding 80% and a maximum realized gain of 4.74 dBi. Additionally, the antenna is integrated with an RF energy harvesting circuit to demonstrate its feasibility for IoT applications.

D. R. Sandeep et al., (2023) [17] proposed a performance analysis of a skin-contact wearable textile antenna in a human sweat environment. The antenna, made from natural jute fiber, is designed for on-body applications and evaluated under varying sweat conditions, including light spray, partial exposure, and complete absorbency. The study highlights how sweat affects the antenna's resonating frequencies, gain, axial ratios, and efficiency, while maintaining circular polarization and functionality in the WLAN, Wi-Max, and ISM bands. This research supports the development of robust wearable antennas for harsh body sweat environments.

A. L. S. Giftsy et al., (2023) [18] proposed a comprehensive review of flexible and wearable antennas for biomedical applications. The paper emphasizes the significance of wearable technology in healthcare and the challenges of designing antennas that can function near the human body. Various techniques, including flexible substrates, conductive materials, and metamaterials, are discussed for antenna design. Key challenges like achieving high gain and low specific absorption rate (SAR) are addressed. The review provides insights into the current advancements and outlines future research directions in wearable antennas for biomedical use.

Rizwan et al., (2023) [19] proposed a compact textile monopole antenna for wearable devices designed to monitor bone fracture healing. Constructed from jeans fabric and copper, it ensures comfort, flexibility, and durability. Operating in the UWB range of 3.22–10.9 GHz, the antenna achieves an average gain of 3.83 dBi and 95.86%

radiation efficiency while adhering to FCC SAR safety guidelines. Using Principal Component Analysis (PCA), it analyzes signals for real-time fracture healing tracking. Validation on a bovine tibia demonstrated its capability to distinguish between fractured and healthy bones by detecting blood clots, offering a lightweight, non-invasive solution requiring no specialized technicians.

Gorn et al., (2023) [20] proposed a wearable energy-harvesting system for smart clothing that utilizes both human motion and body heat to generate power. The system combines an electromagnetic (EM) harvester with flat spiral coils and magnets and a thermoelectric (TE) generator to ensure continuous energy supply, even when stationary. Energy from both harvesters is stored in a shared capacitor to power a microcontroller that monitors parameters like temperature and humidity. An energy-aware algorithm optimizes power usage based on energy availability. Treadmill tests showed 38 mW peak power from the EM harvester and stable TE generator performance, offering reliable, battery-free operation with reduced power fluctuations.

Mohamed Aboualalaa et al., (2023) [21] proposed a novel rectenna system for IoT applications, integrating a triple-band high-gain antenna with a voltage doubler rectifier. The design enables efficient RF energy harvesting while supporting simultaneous data transmission and reception, enhancing energy efficiency and reliability in power-constrained environments. The triple-band antenna provides operational flexibility across various frequency bands, adapting to diverse network requirements.Its high-gain properties optimize energy harvesting and communication reliability, even in challenging conditions. The voltage doubler rectifier ensures high power conversion efficiency, maximizing usable energy for IoT devices.

Yuchao Wang et al., (2022) [22] proposed a seven-band omnidirectional rectenna for efficient RF energy harvesting across multiple frequency bands. This design integrates a novel seven-band rectifier with a broadband omnidirectional antenna, achieving high conversion efficiency and wideband operation to cover GSM, LTE, Wi-Fi, and 5G bands. It represents a significant advancement over three- and four-band rectennas, addressing the need for multiband energy harvesting to power self-sustaining devices. The study supports the development of rectennas capable of leveraging diverse wireless communication technologies for applications in various environments.

Hongcai Yang et al., (2022) [23] proposed a dual-band, dual-CP textile antenna for wearable applications, operating at 3.5 GHz (WiMAX) and 5.8 GHz (ISM) bands. Utilizing PRAMC, it enables independent LHCP and RHCP radiation while ensuring flexibility and comfort through a textile substrate. The design is robust against human body effects, structural deformations, and substrate variations. Fabrication methods like laser cutting and screen printing were explored, addressing the need for wearable antennas with dual-band operation, circular polarization, and resilience for off-body communication.

Tu Tuan Le et al., (2023) [24] proposed an all-textile antenna for wearable devices in wireless body area networks (WBANs) operating at 5.8 GHz. The design employs a hexagonal slot radiator and a nonuniform metasurface (MS) to achieve broadband circular polarization by converting linear polarization to CP waves. The nonuniform MS, with a smaller center unit-cell, enhances bandwidth compared to uniform designs. Performance validation in free space and on a phantom head confirms its suitability for wearable applications, with SAR compliance meeting US and EU safety standards. This antenna offers a robust solution for WBAN applications.

Esra Çelenk et al., (2023) [25] proposed a novel all-textile antenna for military applications. The antenna is shaped like a military badge and operates in the X-band. It uses a SIW topology and has a bandwidth of 26% with low sidelobes. The antenna's measured gain and efficiency are high. It is designed to be worn on the body and performs well on conformal surfaces. The SAR values are within safety limits. The antenna is fabricated using standard textile techniques, making it suitable for mass production. This research presents a promising new antenna design for military applications.

Chengyang Luo et al., (2022) [26] proposed an embedding UHF-RFID antennas into surgical masks for healthcare applications. They tested three progressively designed antennas using a chip with lower sensitivity, all achieving good resonance. The final design (Design 3) demonstrated a maximum read range of 2.5 meters in air and maintained functionality when bent or worn on the face, with a read range of 1.1 meters. This design is suitable for tracking and social distancing alerts during epidemics and has the potential for adaptation with various textile sensors in the future.

Jie Cui, Feng-Xue Liu et al., (2022) [27] proposed a novel textile antenna design for wearable applications that features pattern reconfigurability without the need for external power sources. Based on a coupled-mode substrate-integrated cavity (CMSIC) topology, the antenna employs metallic snap buttons as switches to control its radiation pattern. Operating at a fixed frequency of 2.45 GHz, it can be reconfigured to direct a main beam towards the +z-axis for OFF-body communication or to create two beams between the +z-axis and ±x axes for ON-body communication.

Feng-Xue Liu et al., (2023) [28] proposed a textile bandwidth-enhanced half-mode substrate-integrated cavity (HMSIC) antenna for WLAN communications. By incorporating a V-slot, the antenna shifts the resonance frequency to achieve a wider operating bandwidth. A prototype demonstrated stable coverage over the 5 GHz WLAN band, maintaining performance under bending and proximity to the human body. While the bandwidth is slightly lower than some designs due to a low-loss substrate, the antenna offers high radiation efficiency and robustness, making it suitable for wearable applications.

Giovanni Andrea Casula et al., (2023) [29] proposed a novel design for wearable textile dual-band antennas utilizing a substrate integrated waveguide (SIW) cavity. By employing the eighth-mode of the SIW cavity, the study achieves significant size reduction compared to traditional dual-band SIW antennas, enhancing suitability for wearable applications. The antenna covers both the European and North American LoRa bands, ensuring flexibility for various regions. With an emphasis on low-cost fabrication and good isolation from the human body, this design offers a compact and efficient solution for wearable LoRa applications, building on advancements in SIW technology and textile antenna design.

Haiyan Li et al., (2022) [30] proposed a novel textile antenna for Wireless Body Area Network (WBAN) applications, operating in multiple frequency bands, including 2.45/5.8 GHz ISM and 3.3-4.0 GHz for WiMAX and 5G. The antenna features a circular patch design with slots for tuning high-order modes, ensuring multiband functionality. With a compact size of 60x60x1.17 mm and made from conductive fabric on denim, it offers flexibility and comfort. The design demonstrates good radiation patterns and low specific absorption rate (SAR) values, making it suitable for wearable devices.

2.3 COMPARISON OF THE EXISTING SYSTEM

The existing systems in wireless energy harvesting, particularly rectennas, have undergone significant advancements in design and functionality. Traditional single-port rectennas have been widely used to capture and convert ambient RF energy into usable electrical power, focusing on improving parameters like gain, bandwidth, and conversion efficiency. However, limitations in energy capture from a single source led to the development of multi-port rectennas, which are capable of harvesting energy from multiple RF sources simultaneously. These advanced designs enhance energy conversion rates and provide redundancy, making them more effective for wearable and IoT applications where power availability from various RF signals is crucial. Additionally, research has focused on the use of novel materials and simulation techniques to further optimize rectenna performance, including increased efficiency and reduced size. These existing models which is depicted as a comparison table in Table 2.1 provides a solid foundation for the ongoing exploration of more efficient, versatile, and scalable wireless energy harvesting systems. The existing system for wireless energy harvesting, particularly in single-port rectennas, operates by capturing ambient RF signals through an antenna and converting them into usable DC power via a rectification circuit. The antenna collects radio frequency waves from sources like Wi-Fi or cellular signals, which are then passed to the rectifier that converts these alternating current (AC) signals into direct current (DC). While effective, traditional single-port rectennas often suffer from limited gain and bandwidth, reducing their ability to efficiently capture and convert RF energy, especially from distant or weaker sources. Multi-port rectennas, an advancement in this field, address these limitations by using multiple antennas or ports to harvest energy from different RF sources simultaneously. This improves overall energy capture and conversion efficiency, making multi-port systems more suitable for environments with varying signal strengths and more reliable for applications like wearables and IoT devices. Despite these improvements, further optimization is needed to enhance gain and energy harvesting efficiency.

Table 2.1: Performance comparison of Existing works

R. No	TYPE OF ANTENNA	ANTENNA SIZE [L x W x T] mm^3	FREQUENCY OF OPERATION (GHz)	GAIN (dBi)	η (%)
[1]	Circularly polarized textile integrated patch	40.1 x 8 x 0.8	2.4	5	45
[2]	Textile surface plasmonic antenna array square plot patch	46.17 x 4.4 x 1.5	2.4-2.45	10.9	36.83
[3]	Triple band Antenna characterized by SSR structure	25.3 x 15 x 0.76	2.3,3.5,5.7	8.1, 8.9 and 9	69.7
[4]	Dual port antenna	70 x 55 x 2	2.47	4.76	-
[5]	Dual port antenna	34.77 x 38.02 x 1.6	2.4	3	-

2.4 SUMMARY

From the above literature review, it could be understood that the published information on design of multiport rectenna for wireless energy harvesting technique isvery much useful in terms of obtaining reference for this project. The previously proposed works, which are implemented at different domains and applications, are combined in order to build a new system which would stimulate the user about the rectenna designs in prior. The disadvantages of the existing systems designed by different authors acts as a base for the new proposal. Thus, the literature review gives more importance and very recent reviews among the researches and this indicates the high priority of researches towards this area.

CHAPTER-3

DESIGN AND IMPLEMENTATION OF BASIC MICROSTRIP PATCH ANTENNA

3.1 OVERVIEW OF THE PROPOSED SYSTEM

The proposed system focuses on designing a microstrip patch antenna for wireless energy harvesting applications. The microstrip patch antenna is lightweight, compact, inexpensive, and are capable of maintaining high performance over a wide range of frequencies preferred. The rectangular patch is designed with different parameters like return loss, VSWR, directivity along directions, radiation pattern, and impedance matching are simulated using CST Microwave Studio simulation software.

Microstrip Patch Antenna is an integral part of the reduced wireless system. The frequency selective surface impedance matching networks, multiple resonators, the modification geometry of the radiating element, and the of the substrate of low dielectric constant or increase in the thickness of the substrate. The operation and performance of a Microstrip patch antenna are based on the geometry of the printed patch and the material characteristics of the substrate against which the antenna is printed.

To analyze antenna characteristics such as impedance and radiation characteristics, the CST Studio suite is utilized. This suite provides robust simulation capabilities, ensuring flexibility and compatibility.

3.2 PROPOSED ANTENNA DESIGN

The proposed antenna is the microstrip patch antenna designed on a FR4 substrate, which is a flame retardant, glass reinforced epoxy resin laminate. The dielectric constant of FR4 typically ranges from 4.2 to 4.6, which affects the antenna's performance in terms of resonance frequency, impedance matching and bandwidth. FR4 has a relatively high tangent, it is inexpensive and easy to fabricate for prototyping and low-cost applications.

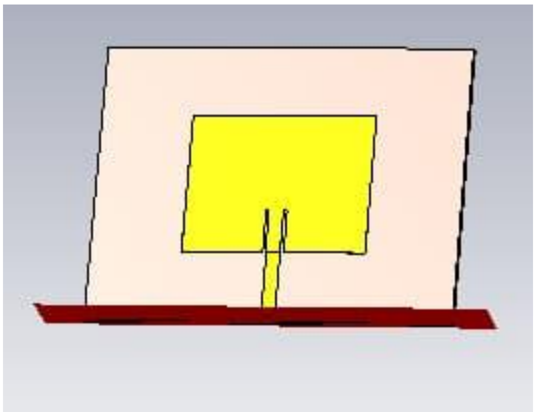

Fig 3.1 Schematic of the proposed antenna

The overall schematic representation of the designed antenna is represented in Fig 3.1. The FR4 substrate of size 1.6 mm designed, where the length and width is regarded as the major parameters. Using the CST software suite, the antenna parameters such as return loss(S11), realized gain and radiation pattern are measured across the targeted frequency bands making them suitable for wireless energy harvesting applications.

3.3 DESIGN METHODOLOGY OF PROPOSED ANTENNA

For a miniaturized antenna design, length and width play crucial roles and must be optimized to achieve the desired resonance frequency, efficiency, bandwidth, and radiation performance. The length and width of the conducting material have been calculated using the following formulas to ensure their better performance.

3.3.1 Mathematical Calculations

a) Length of the conducting material

$$L = \frac{c}{4f\sqrt{\varepsilon_{eff}}} \qquad \ldots (3.1)$$

The equation 3.1 calculates the length of the monopole planar antenna which is approximately a quarter of wavelength ($\lambda/4$). Where, c is the Speed of light, f is the Operating Frequency in Hz and ε_{eff} is Effective permittivity of the substrate material.

b) Width of the Transmission line

$$\frac{w}{h} = \frac{2}{\pi}[B - 1 - \ln(2B - 1) + \frac{\varepsilon r+1}{\varepsilon r-1}\{\ln(B - 1) + 0.39 - \frac{0.61}{\varepsilon r} \quad \dots (3.2)$$

This equation 3.2 determines the width of the transmission line relative to the height of the substrate. It includes the factors like dielectric constant and a parameter BBB, accounting for the physical properties of the material.

c) Length of the Transmission lines

$$L = \frac{90(\frac{\pi}{180})}{\sqrt{eff} \times K_0} \quad \dots (3.3)$$

This equation 3.3 calculates the length of the transmission line based on the effective dielectric constant and free space wave number

d) Effective dielectric constant

$$eff = \frac{(\varepsilon r+1)}{2} + \frac{(\varepsilon r-1)}{2}(\frac{1}{\sqrt{1+\frac{12h}{w}}}) \quad \dots (3.4)$$

The equation 3.4 determines the effective di-electric constant of the monopole planar antenna which influences the size, impedance, radiation characteristics and overall performance of the antenna.

e) Free space wave number in antenna

$$K_0 = \frac{2\pi f}{c} \quad \dots (3.5)$$

The equation 3.5 is the free space wave number in monopole antenna which determines the spatial variation of the electromagnetic wave in free space. Where, f is the operating frequency in Hz and c is the Speed of light

f) Ground

$$W_g = 6h + w \quad \dots (3.6)$$

$$L_g = 6h + L_p + L_T \quad \dots (3.7)$$

Equation 3.6 and 3.7 denote the Ground plane width and Ground plane length of the monopole antenna which plays a vital role in extending sufficiently beyond the patch and ensuring proper radiation. Where, W_g is the Ground plane width, L_g is the Ground plane length, h is the Substrate height W is the Patch width and L is the Patch length.

3.4 SURFACE CURRENT CHARACTERISTICS

The surface-current characteristic of the proposed antenna is illustrated in Fig 3.2, which is critical for the analyzation of the radiation mechanism. The surface current distribution is observed at 2.4 GHz. The phase of the current is 225 deg, indicating the current distribution at particular time.

The maximum current density is observed as 110.862 A/m. The red regions correspond to the feed where current is maximized. The blue areas correspond to the minimal current flow.

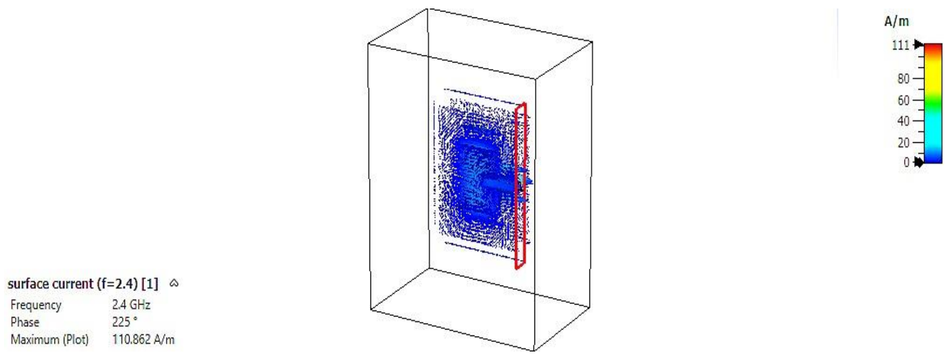

Fig 3.2 Surface Current Characteristics

3.5 IMPEDANCE CHARACTERISTICS

The impedance is seen at the antenna’s feed point wherethe transmission line connects. It consists of both a real part (resistance) and animaginary part (reactance). For maximum power transfer from the transmission line to the antenna, the input impedance of the antenna should ideally match the characteristic impedance of the transmission line (commonly 50 ohms in most RF systems). If the impedance is mismatched, some power will reflect back intothe transmission line, reducing efficiency.

3.5.1 VSWR

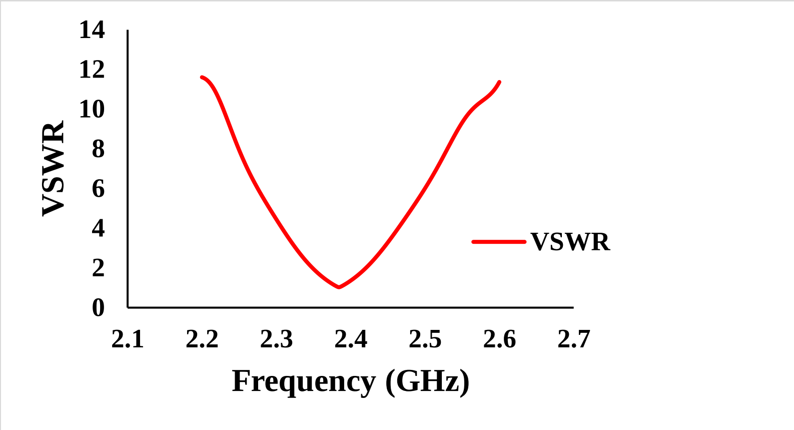

Fig 3.3 VSWR of the proposed Antenna

The graph Fig 3.3 demonstrates the Voltage Standing Wave Ratio (VSWR) as a function of frequency. The VSWR is the calculation of impedance mismatch. The VSWR of proposed antenna is found as 11.028 as shown in Fig 3.3, which should lie in between 10 to 12.

3.5.2 Reflection Coefficient

The Fig 3.4 below demonstrates the S11 parameter or return loss which measures the reflection coefficient between 2 and 2.7 GHz. Better impedance matching and less power reflection are indicated by lower values on the y-axis, which shows the return loss in decibels (dB). The frequency in GHz is shown in x-axis. This S11 analysis is necessary to determine the operational bandwidth and efficiency of the antenna.

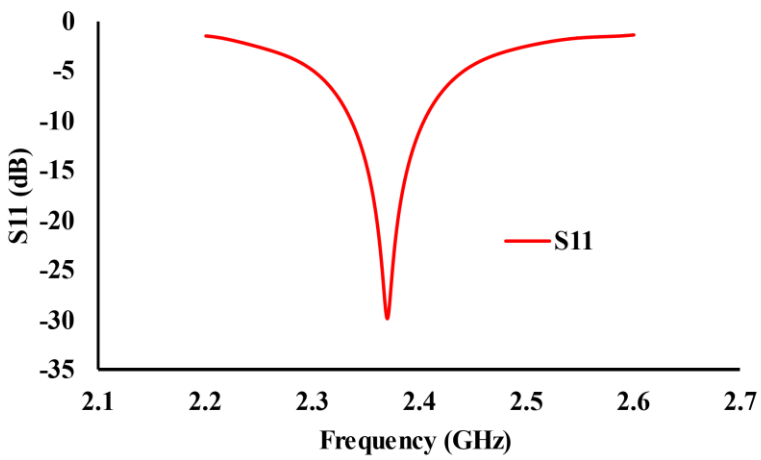

Fig 3.4 S11 Parameter of the proposed antenna

3.6 RADIATION CHARACTERISTICS

An antenna is a device that radiates or receives electromagnetic waves. Its performance is characterized by several key parameters such as Gain, Radiation pattern.

3.6.1 Gain

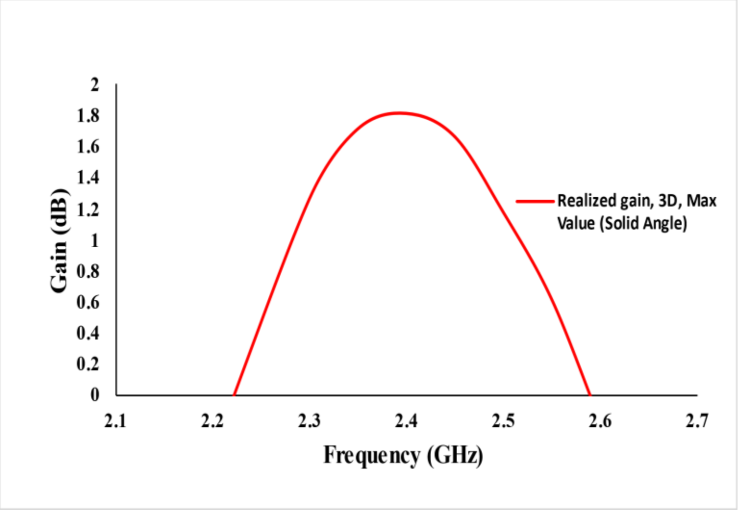

Fig 3.5 Gain characteristics of the proposed antenna

Gain represents the ability of the antenna to focus or direct its radiation pattern in a specific direction which is shown in Fig 3.5. It is a measure of the antenna's effectiveness in transmitting or receiving signals. Antenna gain is a critical antenna parameter that quantifies its ability to direct or focus electromagnetic energy in a particular direction compared to an isotropic radiator (an idealized point source that radiates equally in all directions).

3.6.2 Efficiency

The efficiency (in %) of the proposed antenna versus frequency (in GHz) is illustrated in Fig 3.6. The x-axis represents the frequency range starting from 2.1 GHz to approximately 2.7 GHz. The y-axis represents the total efficiency starting from 0 % to 90 %. This graph suggests the proportional relationship between frequency and efficiency.

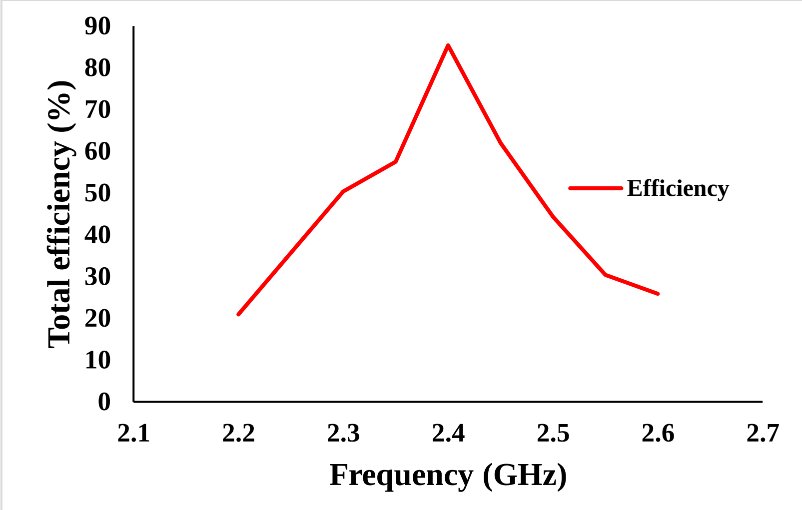

Fig 3.6 Efficiency characteristics of the proposed antenna

3.6.3 Radiation pattern

The antenna's spherical form and nearly omnidirectional radiation characteristic as demonstrated in fig 3.7. transmits energy in all directions with minimal variations at 2.4 GHz. The colour gradient of the pattern provides a visual deception of the gain levels with red hues denoting bigger gains and blue tones the smaller ones.

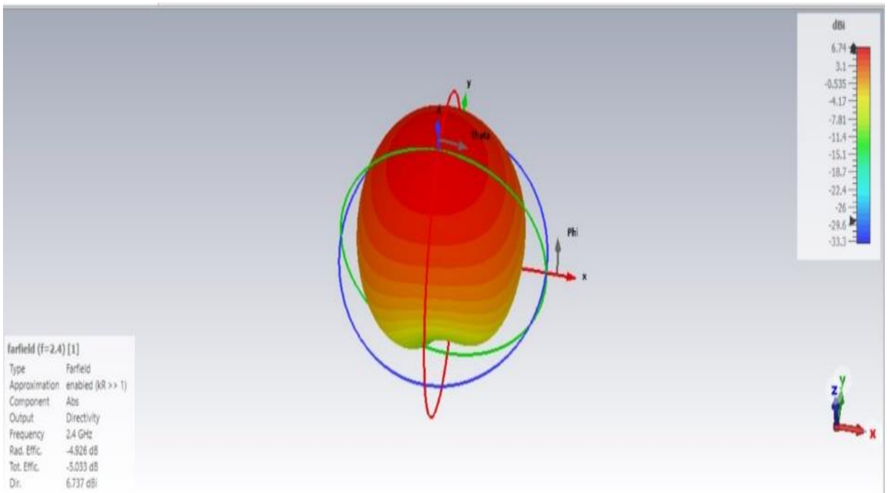

Fig 3.7 Radiation Pattern of the proposed antenna design

The antennas realized gain of 4.15 dBi indicates the moderate radiation efficiency. Analysis of the antenna's efficiency metrics and emission pattern at 2.4 GHz points to possible ultra-wideband.

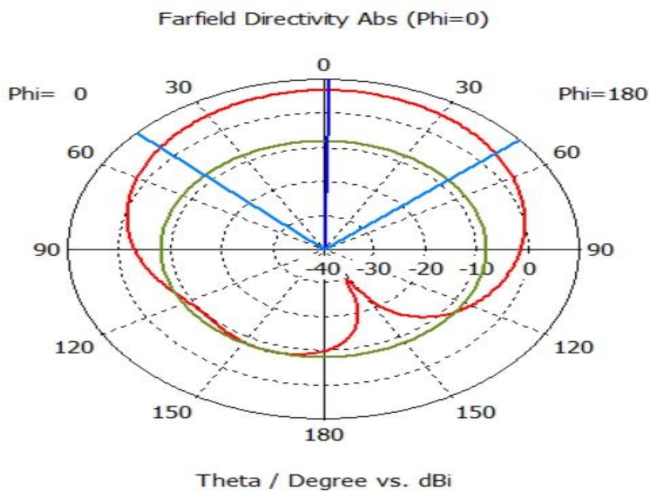

Fig 3.8 Far Field Radiation Plot at Phi=0°

The polar plot in Fig 3.8. below illustrates the far-field realized gain of 2.4 GHz which shows how the antenna radiates energy in the far-field region at the fixed azimuthal angle (Phi=0) by plotting the gain against the elevation angle (Theta) in degrees. The major lobe has a symmetrical radiation pattern with a 180 degree peak gain of 4.15 dBi. This directed radiation demonstrates the antenna's ability to focus energy in certain direction which is crucial for uses like focused communication or power distribution.

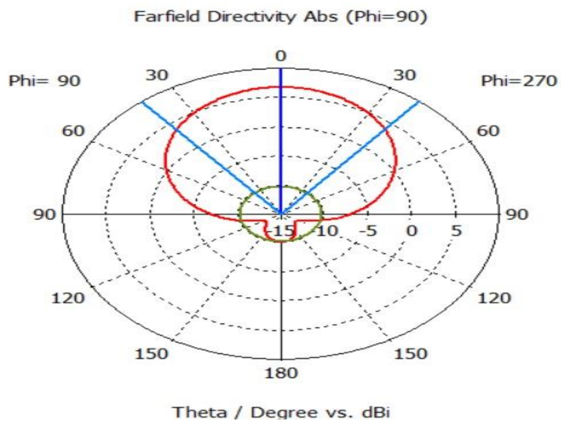

Fig 3.9 Far Field Radiation Plot at Phi=90°

The polar plot in Fig 3.9 illustrated below shows the far field realized gain of an antenna at 2.4 GHz at an azimuthal angle of Phi=90. It shows how the antenna's gain is impacted by the elevation angle (Theta) in degrees. The major lobe of the radiation pattern has a peak gain of 4.15 dBi and is positioned at 160° in the Theta plane. The beam width as measured by 3 dB angular width, is 96.5°, whereas the side lobe level is -15.0 dB, indicating the decreased energy radiated in directions other than main lobe.

3.7 SUMMARY

The design and construction of an Multiport rectenna for wireless energy harvesting in wireless applications is the main goal of this research. Communication across a wide spectrum is ensured by the antenna's efficient performance in the frequency range of 2.4 GHz. Because of their flexibility and durability the substrates find usage in textile applications. The size of the design guarantees outstanding performance and ease of integration. The realized gain of 4.15 dBi, which provides accurate measure of antenna's performance. In order to meet the increasing demand for dependable and effective wireless communication systems, this study highlights the significance of cutting-edge materials and small antenna design in the RF energy harvesting is particularly advantageous due to the widespread availability of ambient RF signals. It plays a critical role by converting captured RF signals into usable DC power. Each antenna port operates to capture ambient RF energy from different directions and polarizations, ensuring a more consistent power output in dynamic wearable scenarios. This unified approach results in a high efficiency multi-port rectenna capable of capturing and converting RF energy for wearable technology applications.

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