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ON

"Wireless power harvesting in Body Area Network for Healthcare"

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Carve Create Conquer

THE NATIONAL INSTITUTE OF ENGINEERING
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2019-2020

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CERTIFICATE

This is to certify that the project entitled **"WIRELESS POWER HARVESTING IN BODY AREA NETWORK FOR HEALTHCARE"** has been successfully completed by **ADARSH S SRIVATSA (4NI16EC002), AKSHAY VISHWANATH (4NI16EC008), ANUKTHA K C (4NI16EC012), MAHAMMED HARRIS G A (4NI15EC053)** of 8th semester B.E. who carried out the project work under guidance of "**Dr.VIJAY B T"** in the Partial fulfillment for the award of degree of Bachelor Engineering in Electronics and Communication Engineering of Visvesvaraya Technological University, Belagavi during the year 2016-17. It is certified that all corrections/Suggestions indicated during internal assessment have been incorporated in the report. The Project has been approved in partial fulfillment for the award of the said degree as per academic regulations of the National Institute of Engineering (An Autonomous Institution under Visvesvaraya Technological University, Belagavi).

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ABSTRACT

The increasing use of wireless networks and the constant miniaturization of electrical invasive/non-invasive devices have empowered the development of Wireless Body Area Networks (WBANs). A WBAN provides a continuous health monitoring of a patient without any constraint on his/her normal daily life activities. Many technologies have proved their efficiency in supporting WBANs applications, such as remote monitoring, biofeedback and assisted living by responding to their specific quality of service (QoS) requirements. Due to numerous available technologies, selecting the appropriate technology for a medical application is being a challenging task.

Ambient radio frequency (RF) energy harvesting (RF-EH) allows powering low-power electronic devices without wires, batteries, and dedicated energy sources. Current RF-EH circuit designs for ambient RF harvesting are optimized and fabricated for a predetermined frequency band. Thus, a single circuit is tuned for a given band with simple extensions to multiple circuits operating individually in distinct bands. Our approach is different in the sense that it designs and implements a common circuit design that can operate on multiple different RF cellular and ISM bands. First, it presents a study of ambient RF signal strength distribution conducted in Boston, MA, USA, indicating locations and associated RF bands that can point toward the practicality of ambient RF-EH. Second, it demonstrates an adjustable circuit for harvesting from LTE 700-MHz, GSM 850-MHz, and ISM 900-MHz bands with one single circuit. In addition, we characterize the charging performance, and feasibility of powering sensors outdoors such as TI eZ430-RF2500. Results reveal more than 45% PCE for the prototype.

The proposed compact BAN sensor based on multiband wireless energy harvesting is suitable for human body self-monitoring and mobile healthcare.

LIST OF FIGURES

LIST OF ACRONYMS

- WBAN – Wireless Body Area Network
- GSM – Global System for Mobile
- UTM – Urchin Tracking Module
- TD LTE – Time Division Long Term Evolution
- MIM – Metal Insulator Metal
- RF – Radio Frequency
- WSN – Wireless Sensor Network
- WEH – Wireless Energy Harvesting
- SRR - Split Ring Resonator
- RIS – Reactive Impedance Surface
- CST – Computer Simulation Technology
- IMN – Impedance Match Network
- ADS – Advanced Design System
- MPPC – Maximum Power Point Control

1. INTRODUCTION

1.1 OVERVIEW

Mobile healthcare is getting more and more attention for prevention and better management of chronic diseases, nursing care of the aging society, and saving medical expenses. The key technologies for mobile healthcare or remote medical care are body area networks (BAN) for the real-time monitoring of various physiological signals of human body. Nevertheless, the BAN must have smaller nodes relative to a conventional wireless sensor networks (WSN) for comfortable user experience. Smaller nodes imply smaller batteries, creating strict tradeoffs between the consumed energy and the performance. The capacity of the high energy density of lithium-based batteries is limited in diminutive BAN enclosures. The need to replace or recharge batteries frequently makes BAN less desirable, which will hamper the widespread adoption of these devices in daily healthcare. The self-sustainable BAN has the potential to pave the road towards the massive utilization of wireless wearable sensors.

In this context, energy harvesting (EH) technologies, which take energy from ambient sources (such as mechanical, thermal, and electromagnetic (EM) sources), are used to power autonomous wireless systems. Wireless energy harvesting (WEH) is to harvest surrounding EM energy to supply continuous power to the self-sustainable standalone devices, which provides a solution to replace the battery or save maintenance cost. Although the main drawback of WEH is the low power density, the available ambient wireless sources keep increasing due to the ever-expanding wireless communication and broadcasting infrastructure. Moreover, ambient EM energies are available at all day and night.

Hence, EM energy becomes a relatively reliable and steady ambient energy source, which has been applied to wireless structural health monitoring sensors, continuous health monitoring sensors, biotelemetry communication, etc. Dedicated radio frequency (RF) sources are necessary for the wirelessly powered wearable sensors. Here we focus on harvesting ambient RF energy from the air to power a BAN battery-free sensor node, which may continuously communicate with personal monitor/remote medical staff through BT/Wi-Fi or Internet. Figure 1(b) shows the block diagram of a typical BAN battery-free sensor node, which is composed of a rectifying antenna, a DC energy management and storage module, a microcontroller, a sensing module, and a communication module.

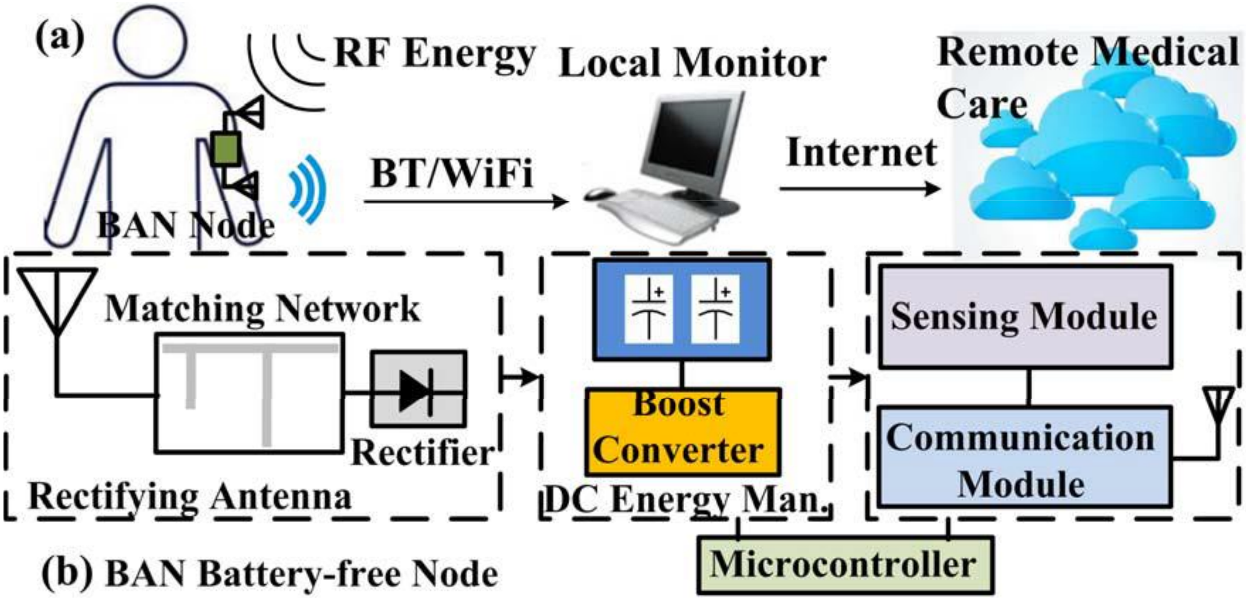


Fig. 1.1: (a) Future application of WEH battery-free sensor networks for daily healthcare. (b) Block diagram of a BAN battery-free node.

The rectifying-antenna (rectenna) that converts the incident EM power into direct current (DC) power is the most vital device for the WEH system. A multiband or broadband rectenna is desirable to effectively capture the free energy from these frequency bands simultaneously. To design a multiband or broadband rectenna is very challenging, since the input impedance of the rectifier circuit varies as a function of the operating frequency, input power level, and load impedance. High efficiency multiband and broadband rectennas have been proposed.

Firstly, due to BAN node placement variability and uncertainty about the user’s exposure to ambient energy, the antenna for WEH should be of wide half power beam width to harvest ambient energy incident from random angles. Secondly, the BAN nodes are generally smaller (less area covered) and have fewer opportunities for redundancy. Hence, compared to the rectifier circuit, power management system, or sensor module, the volume of the antenna for WEH is too large and it should be electrically small.

A wideband rectenna operating within 900-2450 MHz for wearable sensors in outdoor environments was introduced. A fully autonomous integrated RF energy harvesting system for wearable applications was described, which harvests RF energy from GSM 900/1800 and wireless fidelity in 2.4 GHz on user request. However, the harvesting antenna is still a little large (150 mm × 150 mm).

1.2. WIRELESS ENERGY HARVESTING

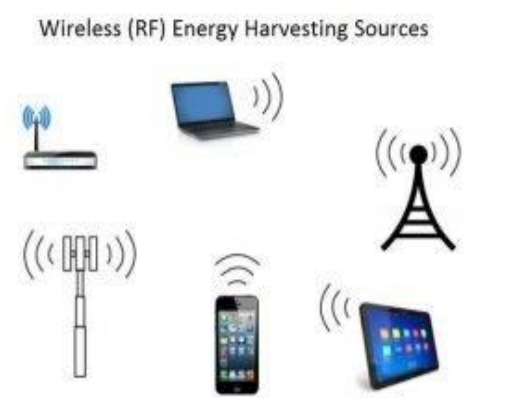


Fig. 1.2: Wireless Energy Harvesting sources

Energy harvesting also known as power harvesting or energy scavenging or ambient power is the process by which energy is derived from external sources captured, and stored for small, wireless autonomous devices, like those used in wearable electronics and wireless sensor networks. Energy harvesters provide a very small amount of power for low-energy electronics. While the input fuel to some large-scale generation costs resources (oil, coal, etc.), the energy source for energy harvesters is present as ambient background. One of the earliest applications of ambient power collected from ambient electromagnetic radiation (EMR) is the crystal radio.

Energy harvesting devices converting ambient energy into electrical energy have attracted much interest in both the military and commercial sectors. Some systems convert motion, such as that of ocean waves, into electricity to be used by oceanographic monitoring sensors for autonomous operation. Future applications may include high power output devices deployed at remote locations to serve as reliable power stations for large systems.

Another application is in wearable electronics, where energy harvesting devices can power or recharge cellphones, mobile computers, radio communication equipment, etc. All these devices must be sufficiently robust to endure long-term exposure to hostile environments and have a broad range of dynamic sensitivity to exploit the entire spectrum of wave motions. Energy can also be harvested to power small autonomous sensors such as those developed using MEMS technology. These systems are often very small and require little power, but their applications are limited by the reliance on battery power. Scavenging energy from ambient vibrations, wind, heat or light could enable smart sensors to be functional indefinitely.

Wireless energy harvesting (WEH) technique has emerged as a fascinating solution to extend the lifetime of energy-constrained wireless networks and has been regarded as a key functional technique for almost perpetual communications. With the WEH technology, wireless devices are enabled to harvest energy from, e.g., ambient light or RF signals broadcast by ambient/dedicated wireless transmitters to support their operation and communications capabilities. The WEH technology has been expected to have even wider range of upcoming applications for, e.g., wireless sensor networks, Machine-to-Machine (M2M) communications, and the Internet of Things (IoT). Fundamental performance and available reliability of the communicating and harvesting functionalities are derived and analyzed, together with extensive numerical results evaluated in different practical scenarios for low power, low bandwidth, and low bitrate sensor type communication applications using organic solar cell harvester model.

1.3. AMBIENT RADIO FREQUENCY

Radio frequency (RF) is the oscillation rate of an alternating electric current or voltage or of a magnetic, electric or electromagnetic field or mechanical system in the frequency range from around 20 kHz to around 300 GHz. Radio frequency energy harvesting (RFEH) is an energy conversion technique employed for converting energy from the electromagnetic (EM) field into the electrical domain (i.e., into voltages and currents). RFEH is a very appealing solution for use in body area networks as it allows low-power sensors and systems to be wirelessly powered in various application scenarios. Extracting energy from RF sources sets a challenging task to designers and researchers as they find themselves at the interface between the electromagnetic fields and the electronic circuitry. Therefore, knowledge from both domains is required in order to design a high-performance RF energy harvester.[4]

RF (Radio Frequency) energy harvester is used for powering low power dev ices. This design consists of three main parts:

- Transducer
- Energy conditioning unit.
- Energy storage unit.

The transducer converts RF energy into electrical form, which is then easier to condition and store. Three types of antennas used as transducer. Before store energy into a storage unit, conditioning subsystem rectifies and increases the voltage level up to a desired level. Available RF energy varies with the time. So, store energy into a storage unit which is a super capacitor is done as far as harvesting. Devices such as wireless sensor nodes, calculators, remote controllers which consume extremely low energy during its employment are the most suitable devices to energize. Using efficient system, it is possible to energize selected low power devices using RF energy.

1.4 BATTERY FREE SENSOR NODE

A sensor node, also known as a mote, is a node in a sensor network that can perform some processing, gathering sensory information and communicating with other connected nodes in the network. Sensors are used by wireless sensor nodes to capture data from their environment. They are hardware devices that produce a measurable response to a change in a physical condition like temperature or pressure. Sensors measure physical data of the parameter to be monitored and have specific characteristics such as accuracy, sensitivity etc.

The continual analog signal produced by the sensors is digitized by an analog-to-digital converter and sent to controllers for further processing. Some sensors contain the necessary electronics to convert the raw signals into readings, which can be retrieved via a digital link (e.g. I2C, SPI). Most sensor nodes are small in size, consume little energy, operate in high volumetric densities, be autonomous and operate unattended, and be adaptive to the environment. As wireless sensor nodes are typically very small electronic devices, they can only be equipped with a limited power source of less than 0.5-2 ampere-hour and 1.2-3.7 volts.

Sensors are classified into three categories:

- Passive, omni-directional sensors.
- Passive, narrow-beam sensors.
- Active sensors.

Passive sensors sense the data without manipulating the environment by active probing. They are self-powered; that is, energy is needed only to amplify their analog signal. Active sensors actively probe the environment, for example, a sonar or radar sensor, and they require continuous energy from a power source. Narrow-beam sensors have a well-defined notion of direction of measurement, like a camera. Omnidirectional sensors have no notion of direction involved in their measurements.

Networks of sensors placed on the skin can provide continuous measurement of human physiological signals for applications in clinical diagnostics, athletics and human-machine interfaces. Wireless and battery-free sensors are particularly desirable for reliable long-term monitoring, but current approaches for achieving this mode of operation rely on near-field technologies that require proximity between each sensor and a wireless readout device.

Wireless sensor nodes are battery-powered devices, since it is generally difficult or impossible to run a mains supply to their deployment site. Power to the wireless sensor nodes is usually provided through primary batteries. Although the utilization of WSNs has increased continuously over the years, battery technology has not improved at the same rate. Therefore, batteries are seen as the limitation of wireless sensor nodes. Though there are several energy-harvesting techniques, small-sized energy-harvesting devices based on these techniques cannot directly power sensor nodes. Wireless sensor nodes communicate via their radio modules. Two nodes are directly connected if they can transmit/receive data to/from each other. A sensor communication model is a mathematical model that quantifies the direct connectivity between sensor nodes.

1.5. MOBILE HEALTHCARE

Mobile healthcare is an important extension of electronic healthcare. It enables the caregivers to have a ubiquitous and uninterrupted access to patients' clinical data and the latest medical knowledge; concurrently, it allows patients with chronic conditions to remain under constant observation without needing to be physically present at the clinic. The critical challenges to a full-scale implementation include establishing interoperability among electronic health records, developing better display technologies and security controls for mobile devices and developing smart algorithms to detect clinically significant events before notifying caregivers.[1]

Mobile technology's presence in healthcare has exploded over the past five years. As healthcare systems move toward a more value-driven model of care, patient centeredness and engagement are the keys to success. Mobile healthcare will provide the medium to allow patients to participate more in their care.

Financially, mHealth brings to providers the ability to improve efficiency and deliver savings to both them and the healthcare consumer. However, mHealth is not without challenges. Healthcare IT departments have been reluctant to embrace this shift in technology without fully addressing security and privacy concerns. Providers have been hesitant to adopt mHealth as a form of communication with patients because it breaks with traditional models.

Because of mobile healthcare, new opportunities for physician-patient joint decision-making and personalized healthcare are beginning to take shape. Accompanying them are the challenges of mindset adjustment, the empowerment of patients with medical knowledge in everyday language and ensuring the confidentiality of patient data.

1.6. WIRELESS BODY AREA NETWORK

WBANs for healthcare applications are mainly used in patient monitoring tasks. In this type of network, the sensors are distributed on the human body measuring different physiological parameters, which represent the most widely used solution within this domain. Sensors nodes around the body with wireless capabilities are of special interest to this kind of WBAN, since they provide a comfortable and user-friendly way to monitor a patient's health status over extended periods of time, avoiding the use of cables wired around the patient. Generally, the composition of the human body tissue has different amounts of water. Because of this, the propagation of electromagnetic signals through the human body is variable and subject to absorption and reflections within the body.

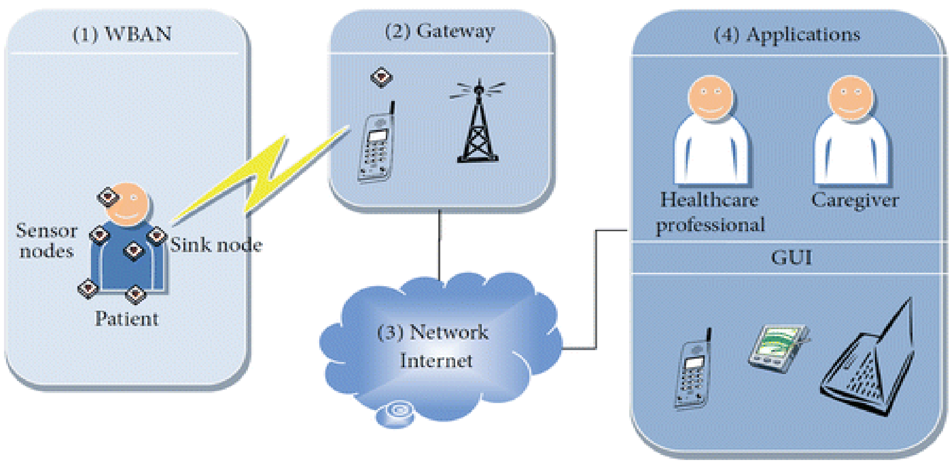


Fig. 1.3: Typical WBAN architecture.

WBAN architectures have been successfully tested, specifically in fitness applications. In these architectures, the BAN gateway is a mobile phone or a personal digital assistant (PDA) transported by person. The PDA is the sink node *i.e.*, it is part of the WBAN and can connect to the healthcare center via Internet using GSM, GPRS, UMTS, Mobile WiMAX, or other technologies. This mode of operation increases mobility of WBAN. With regard to the actual hardware, body sensors must be small, thin, noninvasive, and wireless-enabled and must be able to operate at a low power level. A sensor system in medical appliances should be comfortable to wear and not intrusive, and it should require no skillful preparation to apply to patients, nor accurate positioning.

The WBAN design phase must consider several significant requirements influencing performance:

- Energy-management policy.
- Energy-efficient design.
- Link reliability.
- Robustness.
- Scalability support.
- Interoperability.
- Self-organization.
- Point-to-point reliability.
- Security.
- Mobility support.

1.6.1 Medical Applications of WBAN:

Many technologies have proved their efficiency in supporting WBANs applications, such as remote monitoring, biofeedback and assisted living by responding to their specific quality of service requirements. Due to numerous available technologies, selecting the appropriate technology for a medical application is being a challenging task.

WBAN applications cover numerous fields in order to improve the user's quality of life. These applications are categorized mainly according to whether they are used in medical field or in non-medical field.

- Non-medical applications include motion and gestures detection for interactive gaming and fitness monitoring applications, cognitive and emotional recognition for driving assistance or social interactions and medical assistance in disaster events, like terrorist attacks, earthquakes and bush fires.
- Medical applications comprise healthcare solutions for aging and diseased populations. Typical examples include the early detection, prevention and monitoring of diseases, elderly assistance at home, rehabilitation after surgeries, biofeedback applications which controls emotional states and assisted living applications, which improve the quality of life for, people with disabilities.

Generally, body sensors used in health monitoring can be either:

(a) Physiological sensors used to measure human body vital signals internally or externally, like body temperature, blood pressure or Electrocardiography (ECG).

(b) Biokinetic sensors able to collect human body movement-based signals as acceleration or angular rate of rotation. To offer additional information about ambient temperature, environment pressure, light or humidity, ambient sensors can be combined to body sensors.

1.7 TRIPLE BAND RECTENNA

A triple-band rectifying circuit for ambient RF energy harvesting serves as a power supply for the central unit in Wireless Body Sensor Networks (WBSN). It fully utilizes the RF energy in ambient and converts it into DC power with high efficiency. It covers the public telecommunication bands of GSM-900, UTMS-2100, and TD-LTE bands,[7] which are measured to hold the major RF energy in ambient. Simultaneous multiband energy collection helps in achieving high conversion efficiency, which is around twice that of the conventional separate single-band inputs.

1.7.1 GSM-900:

GSM (Global System for Mobile communication) is a digital mobile network that is widely used by mobile phone users in Europe and other parts of the world. GSM uses a variation of time division multiple access (TDMA) and is the most widely used of the three digital wireless telephony technologies: TDMA, GSM and code-division multiple access (CDMA). GSM digitizes and compresses data, then sends it down a channel with two other streams of user data, each in its own time slot. The term GSM900 is used for a GSM system which operates in any 900 MHz. The total GSM900 band defined in the standard ranges from 876 - 915 MHz paired with 921 - 960 MHz. Mobiles transmit in the lower band and base stations transmit in the upper band.

1.7.2 UTMS-2100:

The Universal Mobile Telecommunications System (UMTS) is a third-generation mobile cellular system for networks based on the GSM standard. Developed and maintained by the 3GPP (3rd Generation Partnership Project), UMTS is a component of the International Telecommunications Union IMT-2000 standard set and compares with the CDMA2000 standard set for networks.

UMTS uses wideband code division multiple access (W-CDMA) radio access technology to offer greater spectral efficiency and bandwidth to mobile network operators. UMTS specifies a complete network system, which includes the radio access network (UMTS Terrestrial Radio Access Network, or UTRAN), the core network and the authentication of users via SIM cards. A possible mobile spectrum allocation for mobile operators that offer 2G/3G services is WCDMA 2100MHz system co-existing with a GSM 1900MHz system in the same coverage area.

1.7.3 TD-LTE:

TD-LTE (Time Division Long Term Evolution) uses a single carrier frequency for both uplink and downlink, dividing the radio frame into subframes that can be allocated to either uplink or downlink as per the immediate user need. TD-LTE's use of single frequency rather than paired spectrum is advantageous to any operator in countries where spectrum is limited or where an operator only has access to a single unpaired frequency.

1.8 AMBIENT SOURCES OF ENERGY:

Ambient energy sources are amenable to power autonomous sensors. They can be classified into five main groups: radiant, mechanical, thermal, magnetic, and biochemical. In general, it is considered that energy is already present in the environment, although in some cases energy can be expressly distributed, in a process called remote powering. The choice of the ambient energy source strongly depends on the ambient energy density at the autonomous sensor’s location and on the load’s power needs, which together will determine the size of the transducer. Energy density can be estimated from typical values provided in the literature and complemented with specific measurements performed at the final placement of the autonomous sensor.[1][4]

Although ambient mechanical and thermal energy are classified as the largest forms of renewable energy among those available, they are also considered to provide desired power for low-power electronic devices by using piezoelectric and pyroelectric materials. Ambient mechanical and thermal energy are produced naturally and non-naturally; for example, ambient mechanical energy is produced naturally from different sources, such as hydroelectricity, ocean or river waves, and wind. It is also produced non-naturally due to the forced motion of objects, such as human and machine motion. Conversely, thermal energy is generated naturally from sun rays or geothermal waves, and non-naturally from artificial light and microwaves. The ultimate goal is to convert ambient or aero elastic vibrations to operate low-power electronic devices, such as micro-electro-mechanical systems (MEMS), structural health monitoring (SHM) sensors, and wireless sensor nodes (WSNs), or replacing small batteries that have a finite life span or would require difficult and expensive maintenance.

1.9 SELF SUSTAINABLE STANDALONE DEVICES

"Green" self-sustainable operation is one of the most important issues in today's low-power electronics for smart environments (Internet of Things, smart skins, smart cities, etc.). Energy-harvesting technologies harnessing energy from ambient power sources, such as vibration, heat, and electromagnetic waves, have recently attracted significant attention, and numerous energy-harvesting systems, including energy-harvesting devices, topologies, and circuitries, have been developed for "zero-power" self-sustainable standalone electronics. Among the multiple ambient energy sources, the wireless energy-harvesting technology has dramatically grown recently due to prevalence of wireless signals, such as TV, radio, cellular, satellite, and Wi-Fi signals, especially after the early 1990s. The concept of wireless energy harvesting has been raised by Nikola Tesla and Heinrich Hertz: radiate wireless power to free space and convert the wireless power to usable direct current (dc) power. This concept of wireless power transfer requires no motion, pressure, or heat flows to generate power.[1]

1.10 WIRELESS ENERGY HARVESTING AND ITS DRAWBACK

The concept of energy harvesting is to receive energy from surroundings sources and convert it into a useful form to power any applications or store the energy for future usage. In wireless (RF) energy harvesting, electromagnetic energy from multiple sources received by an antenna, converts it into an electric energy and use as a power source for other devices.[4]

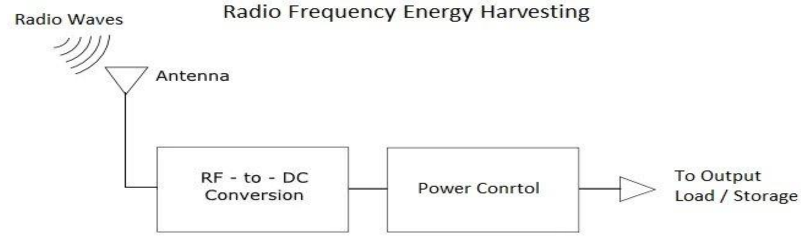


Fig. 1.4: Radio Frequency Energy Harvesting

There are mainly three components in a typical RF energy harvesting device. An antenna designed and perfectly tuned to a specific frequency which receives signals from its surroundings. Antenna converts electromagnetic waves into low power electrical signals which will be feed to an AC to DC converter. DC voltage will be controlled by a controlling unit which regulates the output to the load or storage. Most common radio wave sources are mobile base stations, radio broadcasting stations, TV broadcasting, satellites, wireless LAN transmitters (Wi-Fi) and mobile devices.

Applications of wireless energy harvesting

- Battery-less power source
- RF tags for shopping
- Smart lighting applications
- Smart switches for home automation used with ZigBee technology
- Internet of Things applications
- Recharging of devices
- Power source for smart sensors
- Simple design and cost effective
- Easier implementation

Disadvantages of wireless energy harvesting

- Conventional power sources can be replaced
- Unlimited spectrum of sources
- Efficient source of energy
- No wastage, green energy
- No need for periodic replacement of battery
- Extended life for devices due to recharging of storage battery during sleep mode

Limitation of wireless energy harvesting

Wireless energy harvesting has lot of limitations due to its dependency on external sources which are prone to atmospheric changes, physical obstacles and radio wave source uptime. Received power from the sources is too low and level is often varying in time.

- System efficiency is reduced over time due the performance of the components used in the devices like capacitors, diodes, back up storage battery etc.

- Design of receivers in wide frequency range is often challenging, device designed to operate at one frequency band is limited only on that spectrum.

1.11. COMMUNICATION THROUGH BT/WIFI

1.11.1 Bluetooth:

Bluetooth is a short-range wireless communication technology that allows devices such as mobile phones, computers, and peripherals to transmit data or voice wirelessly over a short distance. The purpose of Bluetooth is to replace the cables that normally connect devices, while still keeping the communications between them secure. Bluetooth technology brings together a broad range of devices across many different industries through a unifying communication standard.

Fig. 1.5: Bluetooth

Bluetooth uses less power and costs less to implement than Wi-Fi. Its lower power also makes it far less prone to suffering from or causing interference with other wireless devices in the same 2.4GHz radio band. Bluetooth is considered a reasonably secure wireless technology when used with precautions. Connections are encrypted, preventing casual eavesdropping from other devices nearby. Bluetooth devices also shift radio frequencies often while paired, which prevents easy invasion.

Devices also offer a variety of settings that allow the user to limit Bluetooth connections. The device-level security of "trusting" a Bluetooth device restricts connections to only that specific device. With service-level security settings, you can also restrict the kinds of activities your device is permitted to engage in while on a Bluetooth connection.

Connecting with Bluetooth:

Many mobile devices have Bluetooth radios embedded in them. PCs and some other devices that do not have built-in radios can be Bluetooth-enabled by adding a Bluetooth dongle.

The process of connecting two Bluetooth devices is called "pairing." Generally, devices broadcast their presence to one another, and the user selects the Bluetooth device they want to connect to when its name or ID appears on their device.

Bluetooth Limitations

There are some downsides to Bluetooth.

- The first is that it can be a drain on battery power for mobile wireless devices like smartphones, though as the technology has improved, this problem is less significant than it used to be.
- The range is fairly limited, usually extending only about 30 feet, and as with all wireless technologies, obstacles such as walls, floors, or ceilings can reduce this range further.
- The pairing process may also be difficult, often depending on the devices involved, the manufacturers, and other factors that all can result in frustration when attempting to connect.

1.11.2 Wi-Fi

Wi-Fi is a family of wireless networking technologies, based on the IEEE 802.11 family of standards, which are commonly used for local area networking of devices and Internet access. Devices that can use Wi-Fi technologies include desktops and laptops, smartphones and tablets, smart TVs, printers, digital audio players, digital cameras, cars and drones.

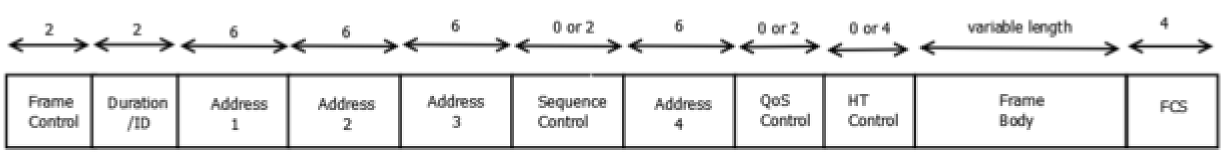


Fig. 1.6: 802.11 generic frame format

Wi-Fi uses multiple parts of the IEEE 802 protocol family and is designed to interwork seamlessly with its wired sibling Ethernet. Compatible devices can network through wireless access points to each other as well as to wired devices and the Internet. The different versions of Wi-Fi are specified by various IEEE 802.11 protocol standards, with the different radio technologies determining radio bands, and the maximum ranges, and speeds that may be achieved. Wi-Fi most commonly uses the 2.4 gigahertz (120 mm) UHF and 5 gigahertz (60 mm) SHF ISM radio bands; these bands are subdivided into multiple channels. Channels can be shared between networks but only one transmitter can locally transmit on a channel at any moment in time.

Wi-Fi is part of the IEEE 802 protocol family. The data is organized into 802.11 frames that are very similar to Ethernet frames at the data link layer, but with extra address fields. MAC addresses are used as network addresses for routing over the LAN. Ethernet's cable-based media are not usually shared, whereas with wireless all transmissions are received by all stations within the range that employ that radio channel. While Ethernet has essentially negligible error rates, wireless communication media are subject to significant interference.

Fig. 1.7: WIFI

Therefore, the accurate transmission is not guaranteed so delivery is, therefore, a best-effort delivery mechanism. Because of this, for Wi-Fi, the Logical Link Control (LLC) specified by IEEE 802.2employs Wi-Fi's media access control (MAC) protocols to manage retries without relying on higher levels of the protocol stack.

1.12 REMOTE MEDICAL CARE

Remote Medical Care is a telemedicine service, which allows constant monitoring of the patient’s condition and performance of preventive and control check-ups outside medical facilities. This form of care is made possible using mobile devices which measure vital signs. Results are transmitted to the Remote Medical Care Center, where they are automatically analyzed. If any abnormalities are detected, medical staff contact the patient and calls an ambulance in the event of an emergency.[6]

- Remote patient monitoring center, where medical staff monitors patients’ health and wellbeing 24/7.
- Telemedicine services, particularly in the case of cardiac, obstetric, and senior care, to allow continuous monitoring of patients’ health, as well as prophylactic and control tests outside the hospital.
- Specialists from the center continuously analyze data received from portable medical devices that record specific vital signs and coordinate further actions in the event of alarms.

Benefits for patients

- Online appointments with selected doctor (visit in person or teleconsultation), remotely requesting prescriptions and referrals.
- Access to specialists without the need to leave home. Possibility of continuing treatment and monitoring vital signs at home.

Fig. 1.8: Healthcare

- Automatic reminders about the need to perform measurements and administer medication.
- Greater sense of security owing to quick and easy contact with medical staff. Possibility of contacting specialists, with the lead doctor who understands the medical context and is aware of the patient's medical history in attendance.
- Easy and secure access to medical data, continuous viewing of doctor's recommendations and test results. Customized medical knowledge base.

2. LITERATURE SURVEY

1) “*Design and Simulation of Rectenna for RF Energy Harvesting*” by K.L. Narayana1 | P. Rajani2

An alternate energy source has become essential as the demand for power increases. In the last energy decades energy obtained from external sources such as thermal energy, solar power, wind energy, and RF energy has been in use for various purposes. To provide unlimited energy for the lifespan of electronic devices, energy harvesting uses inexhaustible sources with no adverse environmental effect. This paper focuses on RF energy harvesting. The receiving antenna captures the RF energy from surrounding sources, such as nearby mobile phones, wireless LANs (WLANs), radio signals, broadcast television signals and rectified into a usable DC voltage. One possibility to overcome their power limitations is to extract (harvest) energy from the environment to either recharge a battery, or even to directly power the electronic device. To meet various objectives in last few years, several antenna designs of rectenna have been proposed for use in RF energy harvesting.

2) “*A WBAN Reader Antenna to Improve the Wireless Link with an In-Body WBAN Antenna*” by S. Kahng, C. Lee, H. Park, G. Namgoong1, J. Kwon

A method is proposed to improve the wireless link of an in-body wireless body-area network (WBAN) antenna with the off-body signal-reading system. A small WBAN antenna embeddable in the human body is designed. A wide-band size-reduced reader antenna is proposed to cope with frequency shift resulting from a short distance between the agent and reader antennas, and attenuation by the human tissue. The transmission from the in-body agent antenna to the reader is shown to improve by over 50 db.

3) “*Monitoring physical activities using WBAN*” by R. Meena, S. Ravishankar, J. Gayathri

We propose a WBAN-based prototype system for remotely monitoring mobile user’s physical activities and health-status via the Internet. The system consists of a WBAN and a remote monitoring server (RS). The WBAN comprises a personal server (PS) and several custom-made wireless sensor nodes each featuring a motion sensor for monitoring physical activity, and a temperature sensor for monitoring body temperature. The PS is a minicomputer equipped with a GPS receiver for tracking and monitoring user’s location, a ZigBee module for communication with the sensor nodes, and a GPRS module for communication with the RMS. The RMS is an internet enabled PC. The sensors measure body motions and temperature and send the measurement data to the PS via a ZigBee network. The PS collects the data, process them and uploads them via GPRS to the RMS where the data can be visualized and displayed for user inspection and/or stored in a file system/database for post analysis.

3. PROBLEM STATEMENT

The capacity of the high energy density of lithium-based batteries is limited in diminutive BAN enclosures. The need to replace or recharge batteries frequently makes BAN less desirable, which will hamper the widespread adoption of these devices in daily healthcare. The self-sustainable BAN has the potential to pave the road towards the massive utilization of wireless wearable sensors.

Advancements in ultra-low power or power-stingy electronics devices also a major driving factor for this type of technology. A power source combined with energy harvesting can provide wireless devices for low maintenance cost and extended battery life. In addition to the challenge of transmitting the communication signal, a good rectifier which converts RF to DC signal, is needed to maximize the throughput. It should have high efficiency to convert as much of that energy as possible to use power.

Energy harvesting (EH) technologies, which take energy from ambient sources such as mechanical, thermal, and electromagnetic (EM) sources, are used to power autonomous wireless systems. Wireless energy harvesting (WEH) is to harvest surrounding EM energy to supply continuous power to the self-sustainable standalone devices, which provides a solution to replace the battery or save maintenance cost.

Hence, EM energy becomes a relatively reliable and steady ambient energy source, which has been applied to wireless structural health monitoring sensors, continuous health monitoring sensors, biotelemetry communication, etc. Dedicated radio frequency (RF) sources are necessary for the wirelessly powered wearable sensors. Here we focus on harvesting ambient RF energy from the air to power a BAN battery-free sensor node, which may continuously communicate with personal monitor/remote medical staff through BT/Wi-Fi or Internet.

We demonstrate a prototype of a wirelessly powered battery-free BAN sensor for mobile healthcare, consisting of the electrically small triple-band rectenna, DC energy management and storage module, microcontroller, and sensing and communication module. The electrically small triple-band rectenna covers GSM-900, UTMS-2100, and TD-LTE bands and has successfully supplied power for the battery-free BAN sensor node. The electrical size of the antenna is only $0.21 \times 0.2\lambda$, while the gains reach 1, 2.64, and -0.19 dBi at the operating frequencies 0.9, 2.025, and 2.36 GHz, respectively.

4. ANTENNA

4.1 INTRODUCTION

An antenna is the interface between radio waves propagating through space and electric currents moving in metal conductors, used with a transmitter or receiver.[1] In transmission, a radio transmitter supplies an electric current to the antenna's terminals, and the antenna radiates the energy from the current as electromagnetic waves (radio waves). In reception, an antenna intercepts some of the power of a radio wave in order to produce an electric current at its terminals, that is applied to a receiver to be amplified. Antennas are essential components of all radio equipment. An antenna is an array of conductors (elements), electrically connected to the receiver or transmitter. Antennas can be designed to transmit and receive radio waves in all horizontal directions equally (omnidirectional antennas), or preferentially in a direction (directional, or high-gain, or “beam” antennas). An antenna may include components not connected to the transmitter, parabolic reflectors, horns, or parasitic elements, which serve to direct the radio waves into a beam or other desired radiation pattern.

4.2 TYPES OF ANTENNA

4.2.1 Isotropic

An isotropic antenna (isotropic radiator) is a hypothetical antenna that radiates equal signal power in all directions. It is a mathematical model that is used as the base of comparison to calculate the directionality or gain of real antennas.

4.2.2 Dipole

The dipole is the prototypical antenna on which a large class of antennas are based. A basic dipole antenna consists of two conductors (usually metal rods or wires) arranged symmetrically, with one side of the balanced feedline from the transmitter or receiver attached to each. half-wave dipoles are used alone as omnidirectional antennas, they are also a building block of many other more complicated directional antennas.

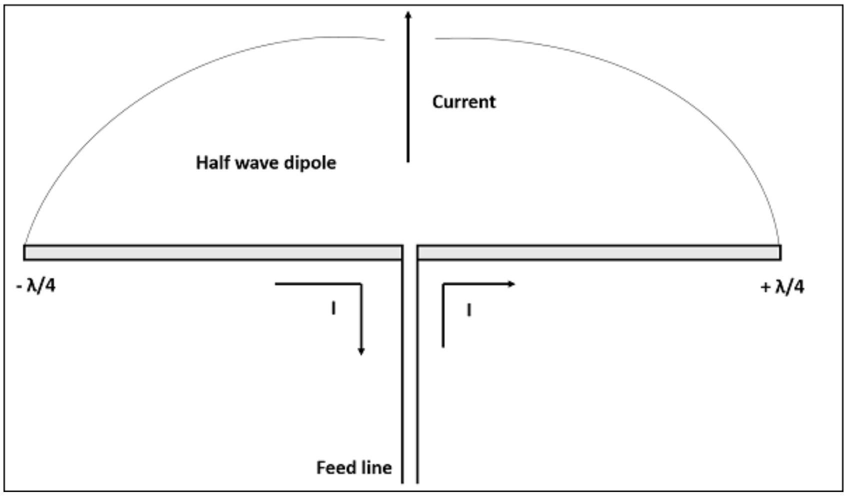


Fig. 4.1: Dipole

- Corner reflector – A directive antenna with moderate gain of about 8 dBi often used at UHF frequencies. Consists of a dipole mounted in front of two reflective metal screens joined at an angle, usually 90°. Used as a rooftop UHF television antenna and for point-to-point data links.

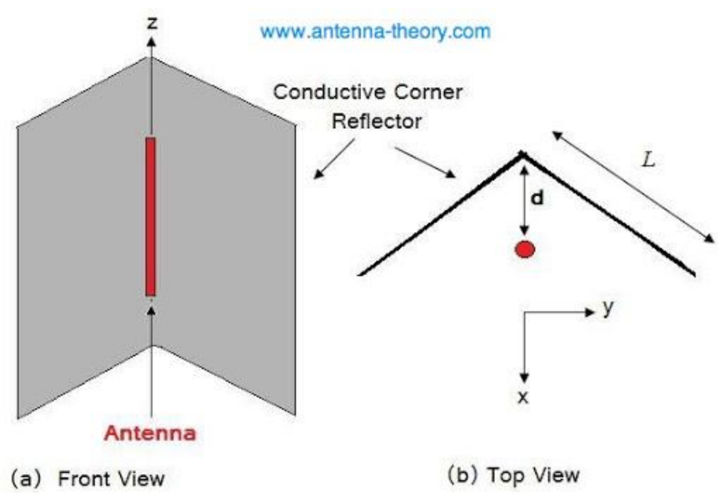


Fig. 4.2: Corner antenna

- Patch (microstrip) – A type of antenna with elements consisting of metal sheets mounted over a ground plane. Like dipole with gain of 6–9 dBi. Integrated into surfaces such as aircraft bodies.

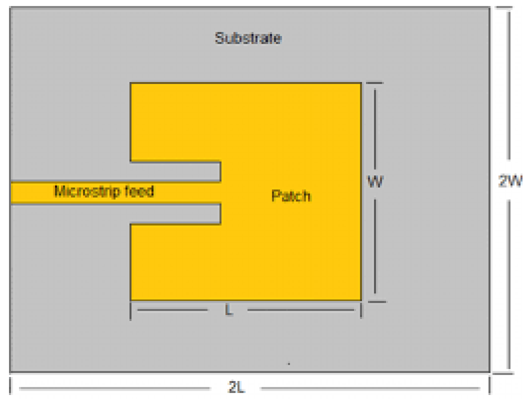


Fig. 4.3: Microstrip

4.2.3 Monopole

A monopole antenna consists of a single conductor such as a metal rod, usually mounted over the ground or an artificial conducting surface (a so-called ground plane). One side of the feedline from the receiver or transmitter is connected the conductor, and the other side to ground or the artificial ground plane.

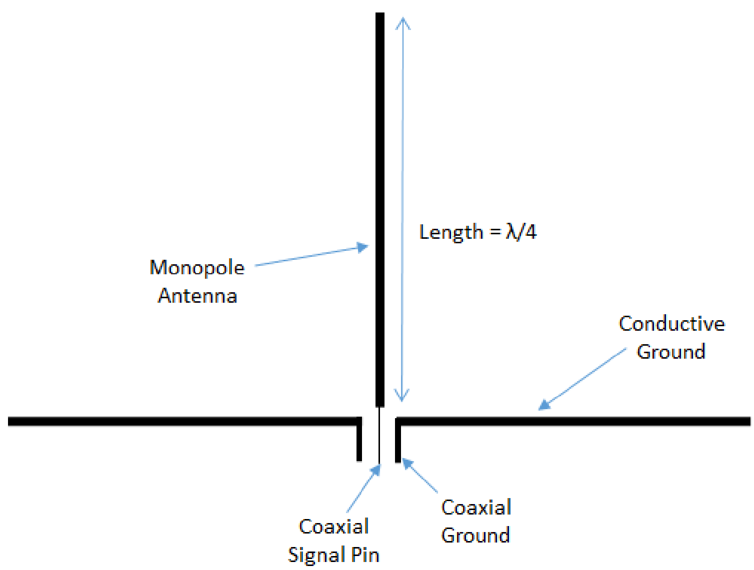


Fig. 4.4: Monopole

Ground plane – A whip antenna with several rods extending horizontally from base of whip attached to the ground side of the feedline. Since whips are mounted above ground, the horizontal rods form an artificial ground plane under the antenna to increase its gain

Whip – Type of antenna used on mobile and portable radios in the VHF and UHF bands such as boom boxes, consists of a flexible rod, often made of telescoping segments

Umbrella – Very large wire transmitting antennas used on VLF bands. Consists of a central mast radiator tower attached at the top to multiple wires extending out radially from the mast to ground, like a tent or umbrella, insulated at the ends.

4.2.4 Array

Array antennas consist of multiple simple antennas working together as a single compound antenna. Broadside arrays consist of multiple identical driven elements, usually dipoles, fed in phase, radiating a beam perpendicular to the antenna plane.

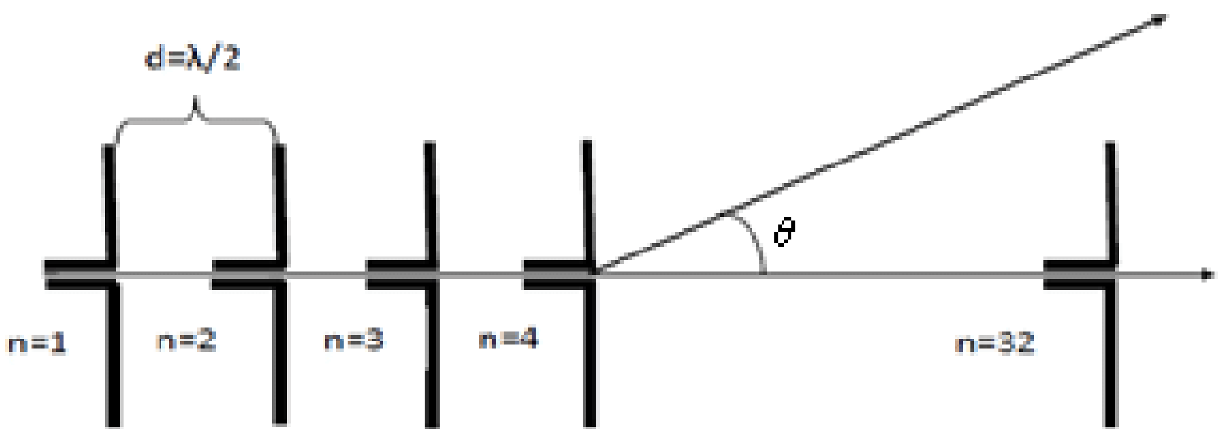


Fig. 4.5: Array

Collinear – Consist of several dipoles in a vertical line. It is a high-gain omnidirectional antenna, meaning more of the power is radiated in horizontal directions and less wasted radiating up into the sky or down onto the ground.

Microstrip – an array of patch antennas on a substrate fed by microstrip feedlines. Microwave antenna that can achieve large gains in compact space.

Reflective array – Multiple dipoles in a two-dimensional array mounted in front of a flat reflecting screen. Used for radar and UHF television transmitting and receiving antennas.

4.2.5 Loop

Loop antennas consist of a loop (or coil) of wire. Loop antennas interact directly with the magnetic field of the radio wave, rather than its electric field, making them relatively insensitive to electrical noise within about a quarter-wavelength of the antenna

Fig. 4.6: Loop

Aperture

Aperture antennas are the main type of directional antennas used at microwave frequencies and above.[2][12] They consist of a small dipole or loop feed antenna inside a three-dimensional guiding structure large compared to a wavelength, with an aperture to emit the radio waves.

Parabolic – The most widely used high gain antenna at microwave frequencies and above. Consists of a dish-shaped metal parabolic reflector with a feed antenna at the focus.

Slot – consists of a waveguide with one or more slots cut in it to emit the microwaves. Linear slot antennas emit narrow fan-shaped beams.

Horn – a simple antenna with moderate gain of 15 to 25 dBs that consists of a flaring metal horn attached to a waveguide.

Lens – a lens antenna consists of layer of dielectric or a metal screen or multiple waveguide structure of varying thickness in front of a feed antenna.

4.3 IMPLEMENTATION

4.3.1 Metamaterial antenna

Metamaterial antennas are a class of antennas which use metamaterials to increase performance of miniaturized (electrically small) antenna systems.[1] Their purpose, as with any electromagnetic antenna, is to launch energy into free space. However, this class of antenna incorporates metamaterials, which are materials engineered with novel, often microscopic, structures to produce unusual physical properties. Antenna designs incorporating metamaterials can step-up the antenna's radiated power.[8]

4.3.2 Split-ring resonator

A split-ring resonator (SRR) is an artificially produced structure common to metamaterials. Their purpose is to produce the desired magnetic susceptibility (magnetic response) in various types of metamaterials up to 200 terahertz. These media create the necessary strong magnetic coupling to an applied electromagnetic field, not otherwise available in conventional materials. For example, an effect such as negative permeability is produced with a periodic array of split ring resonators.

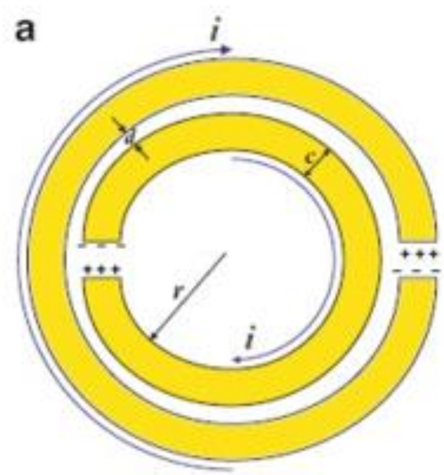


Fig. 4.7: Split ring resonator

Split ring resonators (SRRs) consist of a pair of concentric metallic rings, etched on a dielectric substrate, with slits etched on opposite sides. SRRs can produce an effect of being electrically smaller when responding to an oscillating electromagnetic field

4.3.3 Spoof surface plasmon

Spoof surface plasmons, also known as spoof surface plasmon polaritons, are surface electromagnetic waves in microwave and terahertz regimes that propagate along planar interfaces with sign-changing permittivity. Spoof surface plasmons are a type of surface plasmon polariton, which ordinarily propagate along metal and dielectric interfaces in infrared and visible frequencies. Since surface plasmon polaritons cannot exist naturally in microwave and terahertz frequencies due to dispersion properties of metals, spoof surface plasmons necessitate the use of artificially engineered metamaterials.[3]

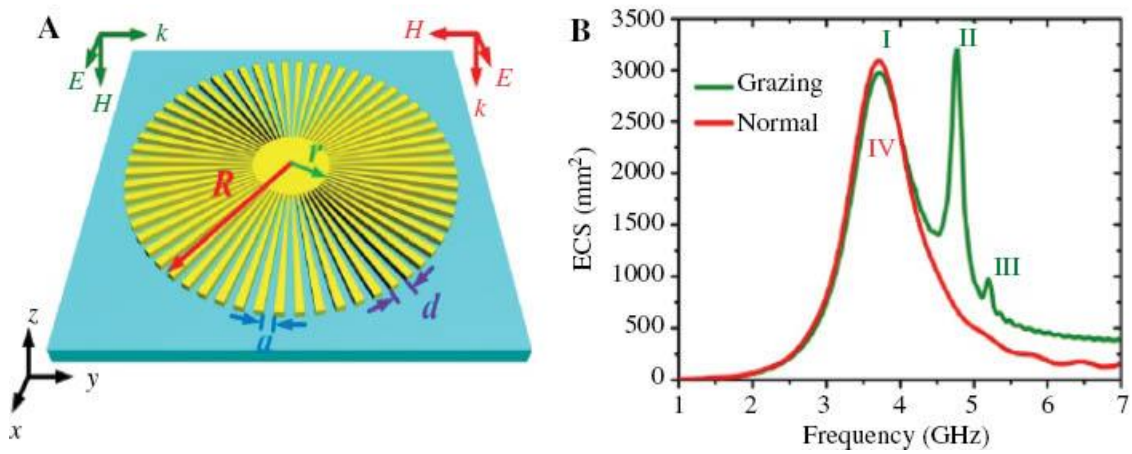


Fig. 4.8: Spoof Surface plasmon

Spoof surface plasmons share the natural properties of surface plasmon polaritons, such as dispersion characteristics and subwavelength field confinement.

4.4 ANTENNA DESIGN

Metamaterials are composed of sub-wavelength particles that can achieve parameters not possible within naturally occurring materials. Recently, metamaterials are also used to harvest EM energy in the microwaves regime, including a flower-like structure composed of four electrically small split-ring resonators (SRRs) a circular slotted truncated corner square patch radiator placed on reactive impedance surface (RIS) a parallel connection of five SRRs loaded with embedded devices etc. However, the previous design was mainly for a single narrow frequency band and required a relatively high input power level. Many antennas based on spoof SPPs have been demonstrated. While the near field characteristics of spoof LSPs have been fully investigated, their far field behaviors are still unknown. [8]

Loop antennas over artificial magnetic conductor surface for dual-band energy harvesting have been proposed. But the size of the antenna is not compact. Since spoof surface plasmons (SPs) are not constrained by the diffraction limit and can achieve subwavelength confinements to the EM waves, they have important potential applications in the miniaturization of spoof plasmonic circuits.

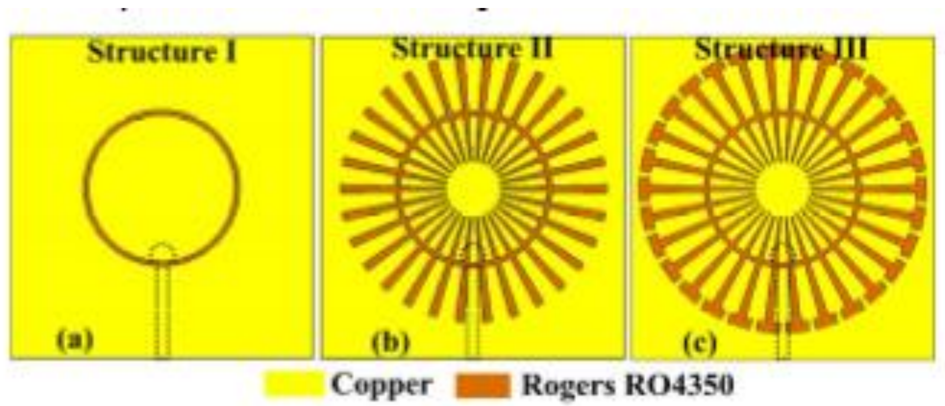


Fig. 4.9: Structure

To our knowledge, only a sub-wavelength unidirectional antenna was designed by combining two spoof LSPs resonators. Here we propose a multiband antenna based on spoof LSPs resonator, as shown in, which is composed of an annular ring slot and periodic array of T-shaped grooves. The corrugated slot line ring is printed on the substrate (Rogers RO4350), with relative dielectric constant of 3.48 and loss tangent of 0.004. It is fed by a 50-Ω microstrip line. The metal disk at the end of the microstrip conductor is used to increase the coupling degree of electromagnetic energy. The fabricated multiband antenna based on spoof LSPs resonator. rectangle grooves and T-shaped grooves, respectively. The dispersion curves for these three kinds of waveguides are calculated by use of the eigenmode solver of the commercial software, CST Microwave Studio. It is known that the slot ring resonator antenna can form multimode resonances

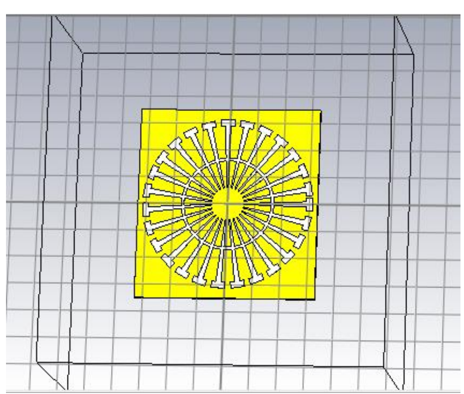


Fig. 4.10: Design

S-parameters are a means for describing the behavior of electromagnetic circuits (e.g. antennas, microwave components, etc.) A plane wave excitation is mostly used to get Radar Cross Sections (RCS) which is a measure of the target's ability to reflect electromagnetic energy towards a receiver. As the source is often assumed to be in the Far Field of the target a plane wave excitation is a good assumption.

S-parameters (or scattering parameters) are used to describe how energy can propagate through an electric network. S-Parameters are used to describe the relationship between different ports, when it becomes especially important to describe a network in terms of amplitude and phase versus frequencies, rather than voltages and currents.

The corresponding resonant frequencies are 0.6 GHz, 0.8 GHz, 1.548 GHz and 2.022 GHz, which include the GSM-900, UTMS-2100 and TD-LTE bands.[7]

The radiation patterns of E-plane at the four resonant frequencies are simulated and measured. The proposed multiband antenna exhibits radiation characteristics similar to the dipole antenna in all frequency bands, with broad half power beam width.

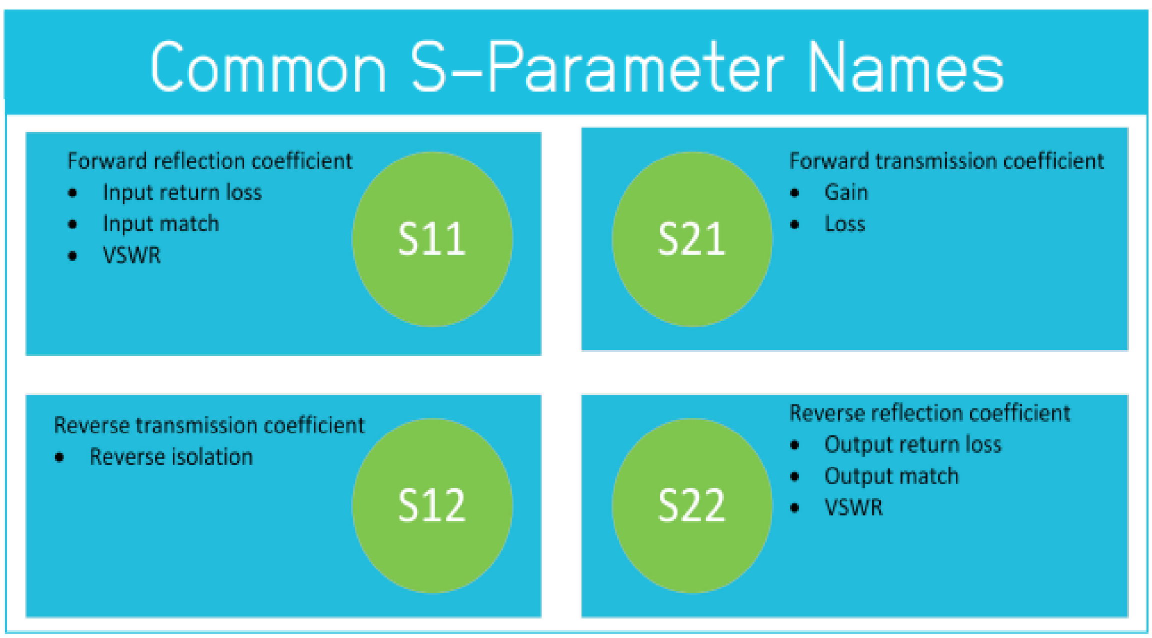


Fig. 4.10: Common S-Parameters

The near field and far field are regions of the electromagnetic field (EM) around an object, such as a transmitting antenna, or the result of radiation scattering off an object. Non-radiative 'near-field' behaviors dominate close to the antenna or scattering object, while electromagnetic radiation 'far-field' behaviors dominate at greater distances.

5. DC RECTIFIER

5.1 INTRODUCTION

A rectifier is an electrical device comprises of one or more diodes which allow the flow of current only in one direction. It basically converts alternating current into direct current. Depending on the type of alternating current supply and the arrangement of the rectifier circuit, the output voltage may require additional smoothing to produce a uniform steady voltage. The filter capacitor is used to store energy during the part of the AC cycle which is released when the AC source does not supply any power, that is, when the AC source changes its direction of flow of current. The smoothing filters utilize multiple components to efficiently reduce ripple voltage to a level tolerable by the circuit.

In radio frequency (RF) energy harvesting using microstrip antenna has gained a great research interest for low power applications. It consists of microwave antenna that collect ambient electromagnetic energy from the surrounding environment and a rectifier circuit which convert the collected RF energy to dc power. Since available energy can be received from any direction, an omnidirectional antenna with high gain is required to receive both horizontally and vertically polarized waves. Antenna can be designed for single band as well as multiple band reception. This basic multiband antenna with higher gain can be used in a RF energy harvesting system to collect ambient RF energy from the surrounding environment/BTS towers. An impedance matching network is essential for the efficient transmission of received power to the rectifier stage. After that the RF signals is converted into DC using highly efficient rectifier circuits. This is illustrated using the following simplified block diagram.[5]

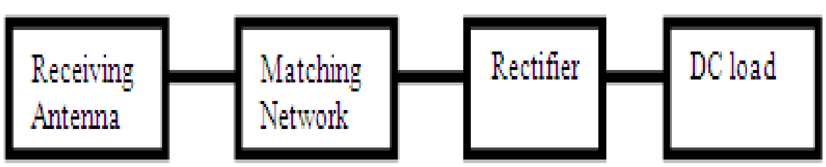


Fig. 5.1: Block diagram of rectenna

In addition to the challenge of transmitting the communication signal, a good rectifier which converts RF to DC signal, is needed to maximize the throughput. It should have high efficiency to convert as much of that energy as possible to use power.

5.2 TYPES OF RECTIFIERS

Rectifiers are classified based on parameters like circuit's configurations, controlling capability, type of supply, type of input, single and three phase rectifiers etc. Based on the type of rectification circuit does, the rectifiers are classified into two categories.

5.2.1 Half Wave Rectifier:

A Type of rectifier that converts only the half cycle of the alternating current (AC) into direct current (DC) is known as halfwave rectifier. a half-wave rectifier is the simplest of them all as it is composed of only a single diode. A half wave rectifier that converts only the positive half cycle and blocks the negative half cycle. A negative half wave rectifier converts only the negative half cycle of the AC into DC.

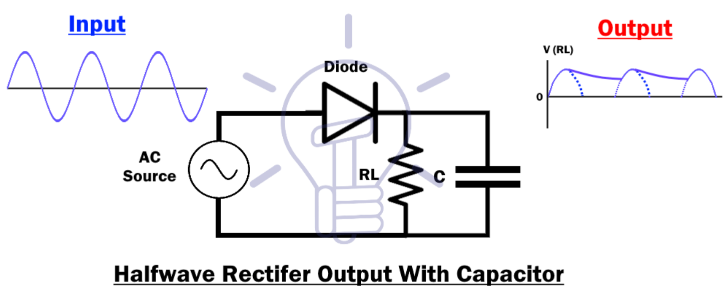


Fig. 5.2: Half wave rectifier

5.2.2 Full Wave Rectifier:

A full wave rectifier converts both positive and negative half cycles of the AC (alternating current) into DC (direct current). It provides double output voltage compared to the halfwave rectifier. A bridge rectifier uses four diodes to convert both half cycle of the input AC into DC output.

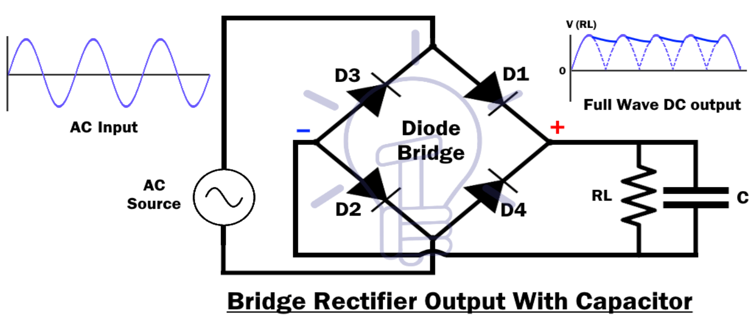


Fig. 5.3: Full wave rectifier

5.3 ARCHITECTURE

The proposed triple band rectifier circuit is quite novel as it is designed using interdigital capacitors (IDCs) in lieu of lumped capacitors in order to achieve better stability. An efficient rectifier system along with an impedance matching network is suitable for operation. The overall rectenna is optimized for its efficient operation at relatively low RF power level due to its multi-band operation, which makes the design quite appropriate for extracting energy from the ambient RF source.

The overall work involves design and development of a triple band differentially fed receiving antenna and a rectifier circuit operating in the UMTS (2.1 GHz), lower WLAN/Wi-Fi (2.4 GHz-2.48 GHz) and WiMAX (3.3 GHz-3.8 GHz) frequency bands.[7]

However, this kind of method is more complicated, and cannot produce high DC voltage. Thus, by using transmission line and active elements such as Schottky diode, rectifier with high DC-conversion voltage and optimum efficiency can be produced.

5.3.1 Impedance Matching Network

Impedance matching is the practice of designing the input impedance of an electrical load or the output impedance of its corresponding signal source to maximize the power transfer or minimize signal reflection from the load.

A matching network is connected between a source and a load, and its circuitry is usually designed such that it transfers almost all power to the load while presenting an input impedance that is equal to the complex conjugate of the source's output impedance.

A proper matching circuit is needed to transfer maximum signal from source to diode. Impedance matching network is designed using two microstrip lines.

This matching circuit is designed using Lumped Components. Ideal Transmission Lines tool is used for impedance matching. Fig. 5.4 shows the impedance matching circuit which matches the source and load impedance.[5]

Fig. 5.4: Impedance matching circuit

5.3.2 Schottky Diode

Schottky diode is another type of semiconductor diode but have the advantage that their forward voltage drop is substantially less than that of the conventional silicon pn-junction diode. It's a low voltage diode. The power drop is lower compared to the PN junction diodes. Schottky diodes have many useful applications from rectification, signal conditioning and switching, through to TTL and CMOS logic gates due mainly to their low power and fast switching speeds.

Schottky diodes are also used as high power rectifiers. Their high current density and low forward voltage drop mean that less power is wasted than if ordinary PN junction diodes were used. This increase in efficiency means that less heat must be dissipated, and smaller heat sinks can be used, thereby saving weight and cost. The diode HSMS-2850 is suitable for the low power application, whose threshold and breakdown voltages are 0.15 V and 3.8 V. However, its impedance is complex and frequency dependent.

The DC-pass filter is composed of two cascaded radial open stubs, which is used to block the fundamental wave and the harmonics and to smooth the output DC power. The resistive load of 2 kΩ is attached to the output port for collecting the DC power.[3]

5.3.3 T-shaped transmission lines

This structure is used for the impedance match at the first resonant frequency (around 0.9 GHz) and the last resonant frequency (around 2.36 GHz) is achieved. However, this approach can match at only two frequency points. Therefore, to match the diode in triple-band, another T-shaped structure is adopted, which mainly affects the impedance match at the other resonant frequency (around 2.025GHz). Hence, the final IMN consists of two T-shape transmission lines and the final optimized parameters of the rectifier by use of HFSS software.[10]

5.4 DESIGN OF PROPOSED IMPEDANCE MATCHING NETWORK AND RECTIFIER CIRCUIT

The antenna for the energy harvesting system is operated at 2.5 GHz with output impedance of 50 ohm. The input impedance of the rectifier is to be matched with the output impedance of the antenna to maximize the power transfer and minimize the signal reflection from the load.

Designing the matching network is not straightforward since the rectifier is a nonlinear load with complex impedance that varies with frequency and input power level. One design approach is to model the rectifier circuit using experimental characterization at the minimum power level required by the application. This can be done by measuring the input impedance (extracted from S_{11}) of the rectifier circuit (with all components) without a matching network at that power level. Using the impedance results from the experimental characterization (i.e., rectifier impedance) and assuming a 50- source load, the matching circuit design is rather straightforward. Using input RF power from -25 to +10 dBm. S_{11} Measurement is conducted by utilizing the at 2.45 GHz.

Rectifier system for better RF to DC conversion is designed using a bridge rectifier. Two center taps are added to the input network and the output network to find out the input impedance of the rectifier. Now if the output load (R_D) is equally divided then there will be no current flow along the connection between the center taps, alternating voltages V_1 and V_2 must be symmetric about a DC offset at half the output voltage.

If, $V_{in} = V_p \sin\varphi$

then $V_1 = (V_m + V_p \sin\varphi) / 2$

and $V_2 = (V_m - V_p \sin\varphi) / 2$ ....(1)

These two voltages are identical apart from 180^0 phase difference and the AC component in each case is half of the input voltage. It appears that the bridge circuit splits the input voltage into two halves in antiphase. These two halves are then simultaneously applied to a pair of voltage doubler. Since there is no overall voltage multiplication.

The input impedance is

$R_{zin} = (R_D + 2R_{diode}) / 2$ .... (2)

Here R_D is considered as 500 ohm and C_D = 0.5pF. A Schottky diode (HSMS8101) having cut-in voltage 0.25 V and dynamic resistance 9.64 ohm is used as rectifying element in the bridge rectifier circuit. Now, from equation 2 the calculated input impedance (R_{zin}) of the rectifier is 259.64 ohm. The impedance matching circuit is designed by adding two microstrip lines having W_1 = 0.257045mm, L_1 = 15.6270mm, and W_2 = 0.257045mm, L_2 = 4.944530mm.

These two voltages are identical apart from 180^0 phase difference and the AC component in each case is half of the input voltage. It appears that the bridge circuit splits the input voltage into two halves in antiphase. These two halves are then simultaneously applied to a pair of voltage doubler. Since there is no overall voltage multiplication

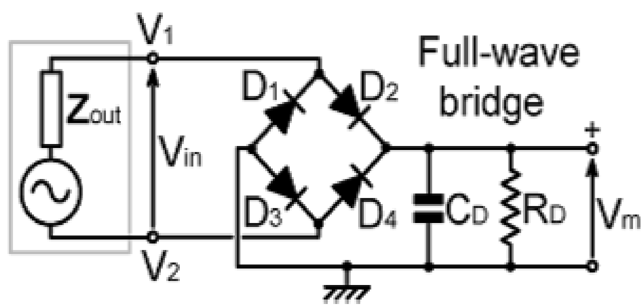


Fig. 5.5: General circuit diagram of the Full wave bridge rectifier

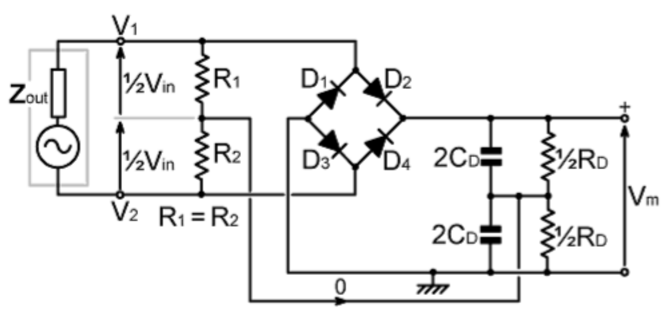


Fig. 5.6: General circuit diagram of the Full wave bridge rectifier with center taps

Calculation of Rectifier Efficiency

The antenna is directly connected with the simply bridge rectifier circuit with impedance matching. The efficiency of the RF to DC conversion is defined as the ratio of the output dc power (P_{out}) and input RF power (P_{in}). The efficiency of the rectifier (η) can be calculated by

$\eta = P_{out} P_{in}$ ....(3)

Where, $P_{out} = V_{2out}, DC / R_{load}$ ....(4)

V_{out} = Output DC Voltage

R_{load} = Resistive load present at the output

The RF-DC conversion efficiency in a rectifier circuit may be affected by variations in the input power level and in the output load resistance. This means when designing a rectifier, it is of key importance to minimize the effect these variations will have on the rectifier performance by selecting a rectifier architecture that is insensitive to power and load changes. Efficiency of the rectifier is calculated for different input power and presented in the below Table.

Input Power(dBm)	**Input Power (mW)**	**V_{out} (Volt)**	**Rectifier Efficiency (%)**
0	1	0.131	3.43
5	3.16	0.502	15.94
7	5.012	0.742	21.96
10	10	1.23	30.26
12	15.84	1.68	35.63
15	31.62	2.58	42.10
17	50.12	3.39	45.86
20	100	5.01	50.20
23	199.52	6.94	48.28

Table. 3.1: Calculated Efficiency of the Bridge Rectifier

5.5 IMPLEMENTATION

The main objective of this project is to design a rectifier with an impedance matching circuit for RF energy harvesting system. The first step in designing the process is to find and gather the information regarding to the project such as from journal and paperwork on the internet.

Here we focused on design and analysis as well as testing and measurement for rectifier with impedance matching circuit to improve the efficiency of RF energy harvesting. National Instruments Advanced Wireless Resolution (AWR) software is used for simulating the design process of rectifying with an impedance matching network. Toward this goal, we found that a modified version of the single-stage full-wave rectifier, depicted in Fig. 4, provides an efficient rectification scheme.

The AWR Design Environment platform provides an integrated high-frequency circuit simulation technologies and design automation to develop physically realizable electronics ready for manufacturing. The platform helps designers manage complex integrated-circuit (IC), package, and printed-circuit board (PCB) modeling, simulation, and verification, addressing all aspects of circuit behavior to achieve optimal performance and reliable results for first-pass success.[5]

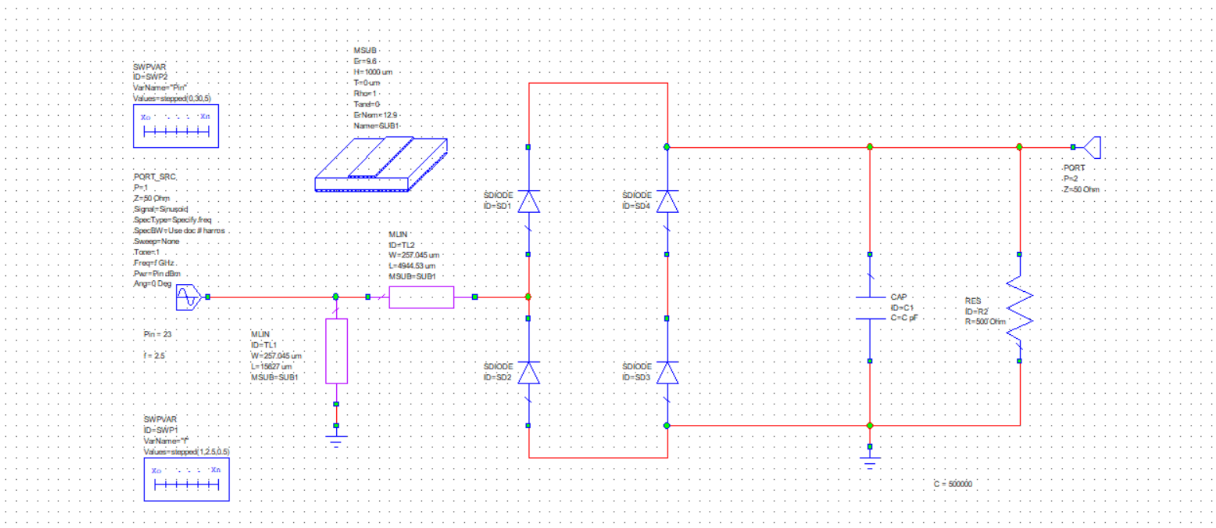


Fig. 5.7: Schematic circuit connectivity for the rectifying system along with the impedance matching network

The rectifier along with impedance matching network is highly efficient with maximum efficiency of 50.20% for the 20dBm input power. The proposed rectifier system can produce enough DC voltage form low incident RF power. This simple rectifier system is very efficient for design of a RF energy harvesting system. The input power versus efficiency variation is shown in Fig. 5.8. [5]

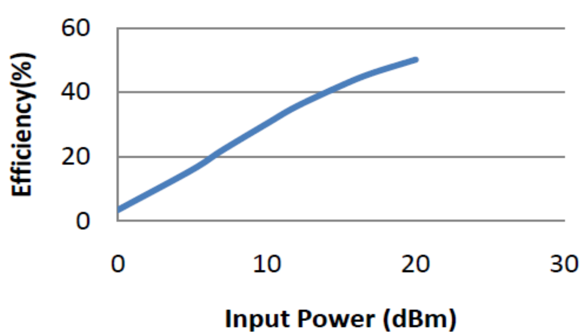


Fig. 5.8: Input power Vs Efficiency graph

A comparative study of the rectifier performance, with and without impedance matching network is shown in Fig. 5.9. It is observed that due to impedance matching the efficiency of RF to DC conversion is so high.

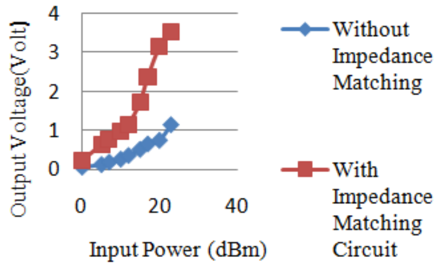


Fig. 5.9: Output voltage versus input power

When all the specification meets the requirement, the fabrication process of the rectifier circuit will be carried out were finalized design was fabricated with developing and etching technique, using FR4 substrate. The process of rectifier on PCB also involves testing and measurement of the fabricated rectifier which will be compared with all the calculated and simulated results.

6. DC ENERGY MANAGEMENT AND STORAGE

After designing and developing the WEH harvester, an additional goal is to use this energy to supply a BAN node. The node consists of four main blocks: the rectenna, the DC energy management and storage module, the microcontroller, and the sensing and communication module. Since the output voltage from the RF energy harvester depends on the quantity of cellular communications traffic and is only 0.65 V when the input RF power is -10 dBm and the load is 2 MΩ, a DC/DC boost converter is necessary to control the voltage that is delivered to the capacitor from the rectifier circuit. [7]

6.1 DC/DC BOOST CONVERTOR

A boost converter is a DC-to-DC power converter that steps up voltage or while stepping down current from its input supply to its output load. It is a class of switched-mode power supply (SMPS) containing at least two semiconductors namely a diode and a transistor and at least one energy storage element: a capacitor, inductor, or the two in combination. To reduce voltage ripple, filters made of capacitors and sometimes in combination with inductors are normally added to such a converter's output load-side filter and input supply-side filter.

Boost Converter Schematic:

The basic principle of a Boost converter consists of 2 distinct states.

- In the on-state, the switch S is closed, resulting in an increase in the inductor current.

- In the off state, the switch is open, and the only path offered to inductor current is through the fly back diode D, the capacitor C and the load R. This results in transferring the energy accumulated during the on-state into the capacitor.
- The input current is the same as the inductor current. So, it is not discontinuous as in the buck converter and the requirements on the input filter are relaxed compared to a buck converter.

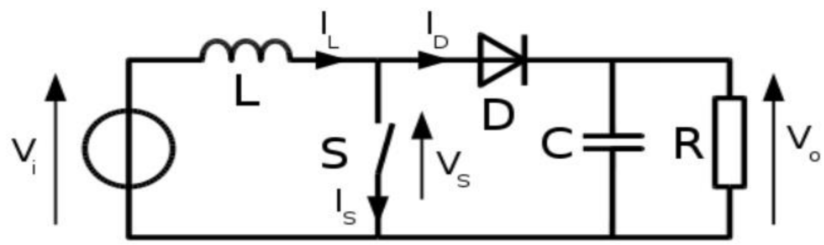


Fig. 6.1: Boost Converter Schematic

TEGs (thermoelectric generators) and fuel cells. A user programmable MPPC set point maximizes the energy that can be extracted from any power source. Burst Mode operation, with a proprietary self adjusting peak current, optimizes converter efficiency and output voltage ripple over all operating conditions.

The boost converter is based on a high efficiency step-up DC/DC chip (LTC3105, Linear Tech.), which can operate from input voltages as low as 225 mV. The maximum power point control (MPPC) circuit integrated in LTC3105 allows the user to set the optimal input voltage operating point for a given power source, which dynamically regulates the average inductor current to prevent the input voltage from dropping below the MPPC threshold.[7]

The MPPC pin voltage is set by connecting a resistor between the MPPC pin and GND, which is determined by the equation:

$$VMPPC = 10\mu A \bullet RMPPC$$

For example, when the input start-up voltage is 0.65 V, it is easy to calculate the necessary resistance to program the activation point for the MPPC loop. Peak current limits are automatically adjusted with proprietary techniques to maintain operation at levels that maximize power extraction from the source according to the LTC3105 datasheet.

The LTC3105 has been optimized for use with high impedance power sources such as photovoltaic cells and thermoelectric generators. The input start-up voltage is measured using an input voltage source with a series resistance of approximately 200mΩ and MPPC enabled. Use of the LTC3105 with lower resistance voltage sources or with MPPC disabled may result in a higher input start-up voltage.

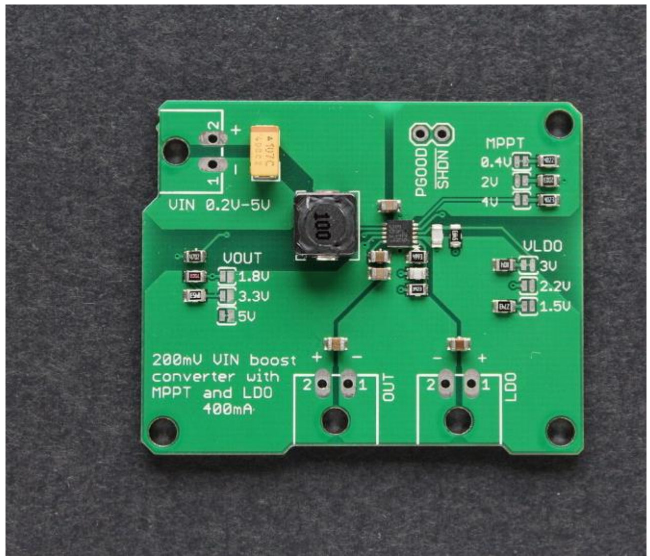


Fig. 6.2: LTC3105 Energy Harvesting Demo Module

LTC3105 features:

- Low Start-Up Voltage: 250mV n Maximum Power Point Control
- Wide VIN Range: 225mV to 5V
- Auxiliary 6mA LDO Regulator
- Burst Mode® Operation: IQ = 24µA
- Output Disconnect and Inrush Current Limiting
- VIN > VOUT Operation
- Ant ringing Control
- Soft Start
- Automatic Power Adjust
- Power Good Indicator
- 10-Lead 3mm × 3mm × 0.75mm DFN and 12-Lead MSOP Packages

Pin Configuration of LTC3105

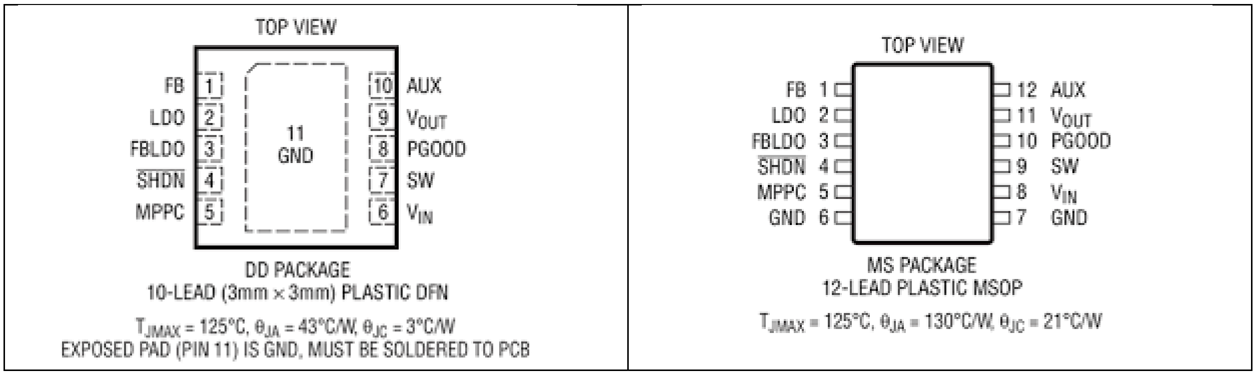


Fig. 6.3: Top View of LTC3105 DC/DC chip

The LTC3105 is a high efficiency step-up DC/DC converter that can operate from input voltages as low as 200mV. A 250mV start-up capability and integrated maximum power point controller (MPPC) enable operation directly from low voltage, high impedance alternative power sources such as photovoltaic cells, TEGs (thermoelectric generators) and fuel cells. A user programmable MPPC set point maximizes the energy that can be extracted from any power source. Burst Mode operation, with a proprietary self-adjusting peak current, optimizes converter efficiency and output voltage ripple overall operating conditions.

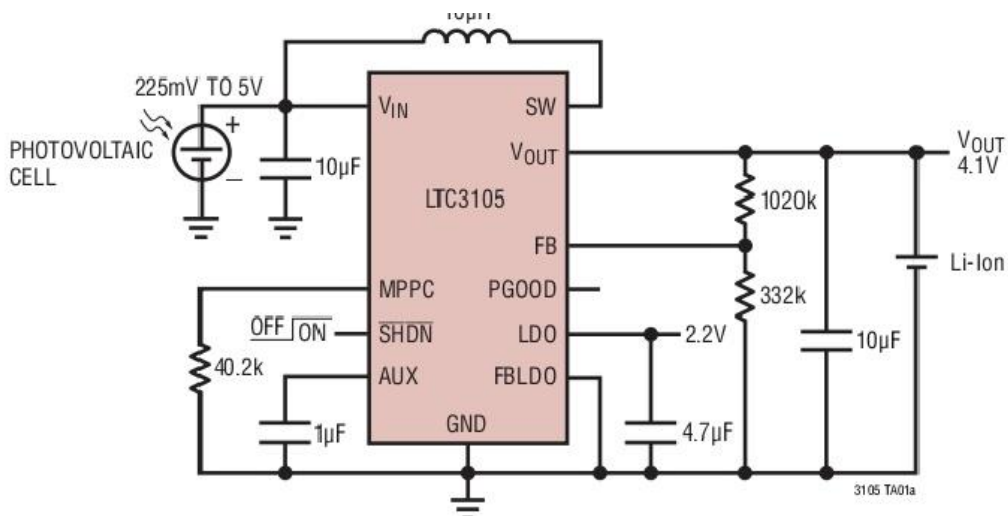


Fig. 6.4: Single Photovoltaic cell Li-ion Trickle Charger

6.2 SUPER CAPACITORS

A supercapacitor (or ultracapacitor) differs from an ordinary capacitor in two important ways: its plates effectively have a much bigger area and the distance between them is much smaller, because the separator between them works in a different way to a conventional dielectric.[4]

Conventional rechargeable battery-based energy storage systems present some disadvantages by:

- Not allowing a precise estimation of the remaining energy
- Having a limited number of recharge/discharge cycles
- Higher environmental impact when batteries are improperly disposed

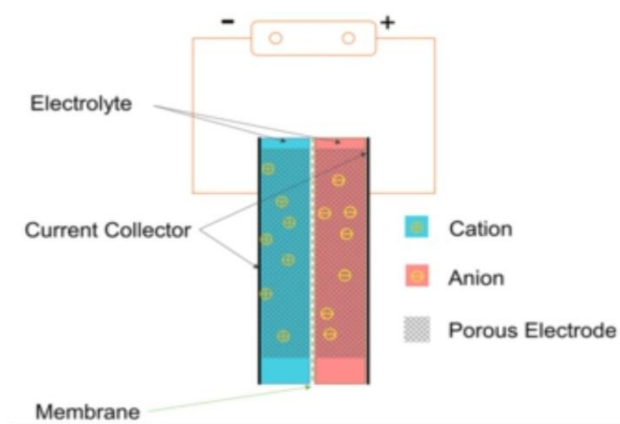


Fig. 6.5: Schematic Illustration of SuperCapacitor

Unlike ordinary capacitors, supercapacitors do not use the conventional solid dielectric, but rather, they use electrostatic double-layer capacitance and electrochemical pseudocapacitance, both of which contribute to the total capacitance of the capacitor, with a few differences:

- Electrochemical pseudocapacitors use metal oxide or conducting polymer electrodes with a high amount of electrochemical pseudocapacitance additional to the double-layer capacitance. Pseudocapacitance is achieved by Faradaic electron charge-transfer with redox reactions, intercalation or electrosorption.
- Hybrid capacitors, such as the lithium-ion capacitor, use electrodes with differing characteristics: one exhibiting mostly electrostatic capacitance and the other mostly electrochemical capacitance.

Fig. hierarchical classification of supercapacitors and capacitors of related types.

Here a super-capacitor storing system for the energy harvested from the EM waves is developed. After it achieves a stable voltage in the super-capacitor bank, the microcontroller (MSP430F5529LP, TI) starts using the energy stored in the super-capacitor bank in order to self-sustain its management activity.

Fig. 6.6: Supercapacitor

The technology for rapid-fire power-ups has been around for decades—in supercapacitors. Supercapacitors not only charge faster than batteries, they last longer because they don't suffer the physical toll in charging and discharging that wears down batteries. They also have several safety advantages**.** Instead of the chemicals that make batteries difficult to manage, supercapacitors use a sort of static electricity for storing power. That means their performance is more predictable, their materials are more reliable and less vulnerable to temperature changes, and they can be fully discharged for safety.

Advantages of Supercapacitors

- Use of activated carbon material increases capacitance value, so supercapacitors have high energy storage capacity as compared to electrolyte capacitors and batteries.
- Long shelf life as compared to batteries. In batteries, the energy is stored and released via a chemical reaction inside electrode material which causes degradation.
- Supercapacitors can recharge in short time and supply high and frequent power demand peaks.
- Supercapacitors have high power density and can provide large power burst for short duration.

Disadvantages of Supercapacitors

- Supercapacitors' super-size they must be much larger to hold the same energy as batteries.
- Super-high cost.

7. BODY AREA NETWORK NODE

A prototype of a self-sustained body area networks (BAN) sensor, which consists of the electrically small triple-band rectenna, the direct current (DC) energy management and storage module, the microcontroller, and the sensing and communication module.

A body area network (BAN), also referred to as a wireless body area network (WBAN) or a body sensor network (BSN) or a medical body area network (MBAN), is a wireless network of wearable computing devices. BAN devices may be embedded inside the body as implants, may be surface mounted on the body in a fixed position, or may be accompanied devices which humans can carry in different positions, such as in clothes pockets, by hand, or in various bags. While there is a trend towards the miniaturization of devices body area networks consist of several miniaturized body sensor units (BSUs) together with a single body central unit (BCU). Larger decimeter (tab and pad) sized smart devices, accompanied devices, still play an important role in terms of acting as a data hub or data gateway and providing a user interface to view and manage BAN applications.[1]

7.1 INTRODUCTION

The technology of WSNs for medical monitoring is an attractive alternative to traditional medical systems. It is important to communicate the data measured by a detection device (sensor) to other devices that will concentrate and process information. Therefore, it is important to have a communication network biomedical sensor. This would have a radical impact on the quality of life of patients and their treatment success rates. One can also have a wide range of future applications, such as monitoring of cardiovascular disease, diabetes and asthma consultation through telemedicine and health systems, etc.

Body area networks (BAN) have recently emerged as a solution to solve this problem. BANs are a new generation of WSNs suitable for human body monitoring. A BAN consists of a small set of nodes equipped with biomedical sensors, motion detectors and wireless communication devices. These nodes collect vital signs of the body which are then transmitted wirelessly to a united central database where all information collected is processed. Because of its wireless nature, BAN nodes have many advantages, such as ubiquitous connectivity, mobility and interoperability. Some nodes can also be equipped with actuators, such as pacemakers or instruments for storing and injecting drugs. Smart phones can be used to convey all information collected with the outside world (health, emergency services, etc.)

7.2 WBAN Architecture

A body area network is simply a WSN where the wireless sensors are placed over, or inside the body of a patient or individual, to collect biomedical data. The biosensors generate data and transmit them to one or more sinks for storing or processing. A simple structure of such networks is illustrated in the following figure.[1]

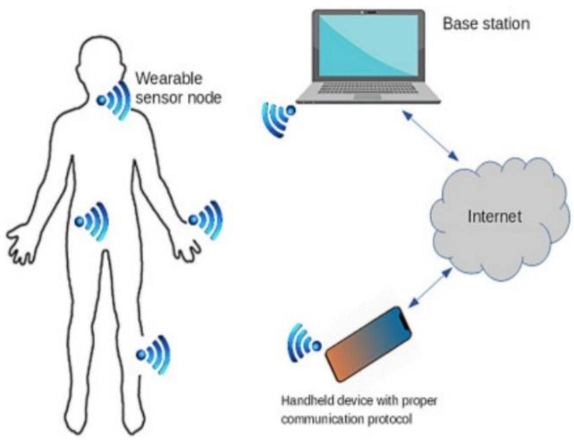


Fig. 7.1: WBAN model

Designing a BAN involves classical WSN issues such as deciding the topology of the network and how the data are to be routed from the biosensors to the sinks, along with specific challenges relating to their presence on the human body. The high-loss propagation behavior of wireless signals through and over the human body cannot be solved by increasing power emissions as in typical wireless networks. In BANs, power emissions must be contained to both avoids damages to human tissues due to overheating, and to preserve the charge of sensor batteries, whose substitution can be very uncomfortable and inconvenient for patients.

Hence, controlling energy consumption is a major aim in BAN design, typically achieved through multi hop routing, implemented through the addition of intermediate relay nodes between sinks and sensors. Several works exist in the field of energy-efficient routing protocols for BANs. The proposed compact BAN sensor based on multiband wireless energy harvesting is suitable for human body self-monitoring and mobile healthcare.

7.3 HARDWARE

7.3.1 Microcontroller

A microcontroller is a small computer on a single metal-oxide-semiconductor (MOS) integrated circuit chip. In modern terminology, it is similar to, but less sophisticated than, a system on a chip (SoC); a SoC may include a microcontroller as one of its components. A microcontroller contains one or more CPUs along with memory and programmable input/output peripherals. Program memory in the form of ferroelectric RAM, NOR flash or OTP ROM is also often included on chip, as well as a small amount of RAM. Microcontrollers are designed for embedded applications, in contrast to the microprocessors used in personal computers or other general purpose applications consisting of various discrete chips.

MSP430F5529LP

The Texas Instruments MSP430™ family of ultra-low-power microcontrollers (MCUs) consist of severaldevices featuring different sets of peripherals targeted for various applications. The MSP-EXP430F5529LP is aninexpensive and simple development kit for the MSP430F5529 USB microcontroller. It offers an easy wayto start developing on the MSP430 MCU, with onboard emulation for programming and debugging as wellas buttons and LEDs for a simple user interface.
The MSP430F5529 16-bit MCU has 128KB of flash memory, 8KB of RAM, 25-MHz CPU speed,integrated USB, and many peripherals – plenty to get you started in your development.

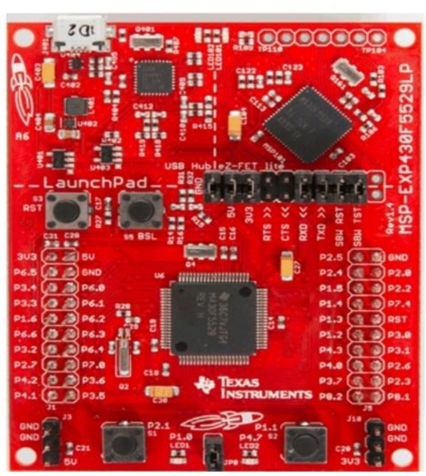


Fig. 7.2: MSP430F5529 LaunchPad Development Kit

Hardware Features

The MSP430F552x is one of several USB-equipped MSP430 MCU families. It offers:

• 1.8-V to 3.6-V operation
• Up to 25-MHz system clock
• 128KB flash memory, 8KB RAM (in addition to 2KB shared RAM with the USB module)
• Ultra-low-power operation
• Full-speed USB with 14 endpoints – enough for almost any USBapplication
• Five timers, up to four serial interfaces (SPI, UART, or I2C), 12-bit analog-to-digital converter, analogcomparator, hardware multiplier, DMA.

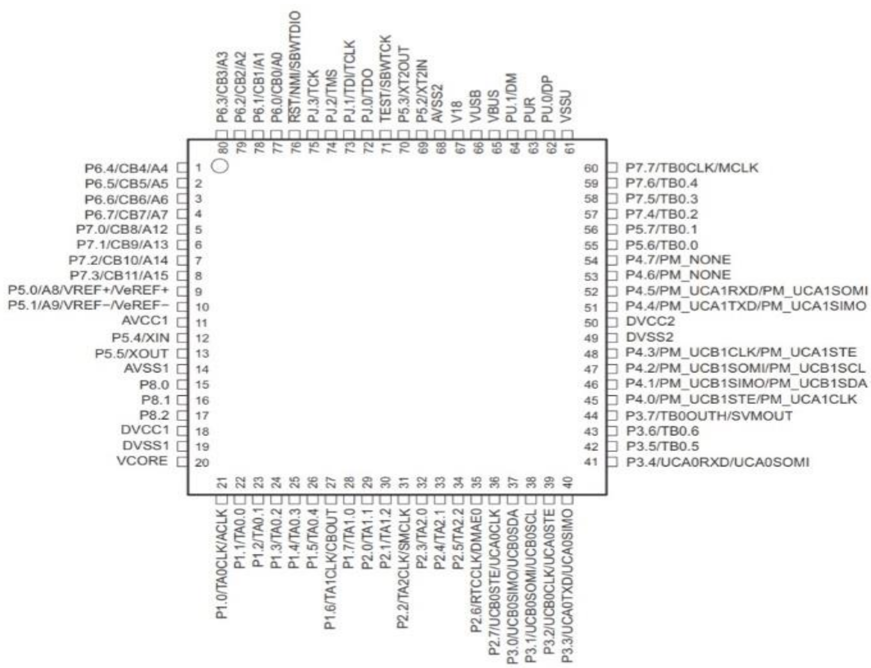


Fig. 7.3: MSP430F5529 Pinout

7.3.2 Digital Temperature Sensor TMP102

The TMP102 device is a digital temperature sensorideal for NTC/PTC thermistor replacement where highaccuracy is required. The device offers an accuracyof ±0.5°C without requiring calibration or external component signal conditioning. Device temperaturesensors are highly linear and do not require complex calculations or lookup tables to derive thetemperature.The on-chip 12-bit ADC offersresolutions down to 0.0625°C.

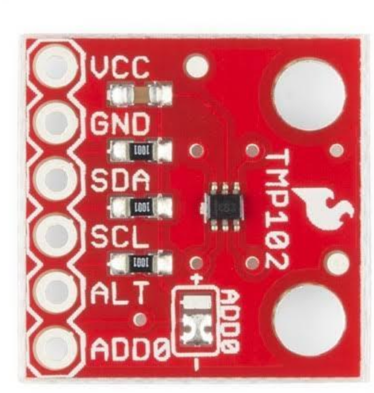


Fig. 7.4: Digital Temperature Sensor TMP102

The 1.6-mm × 1.6-mm SOT563 package is 68%smaller footprint than an SOT-23 package. TheTMP102 device features SMBus™, two-wire and I2Cinterface compatibility, and allows up to four deviceson one bus. The device also features an SMBus alertfunction. The device is specified to operate oversupply voltages from 1.4 to 3.6 V with the maximumquiescent current of 10 µA over the full operatingrange.

The TMP102 device is ideal for extended temperaturemeasurement in a variety of communication,computer, consumer, environmental, industrial, andinstrumentation applications. The device is specifiedfor operation over a temperature range of –40°C to125°C.

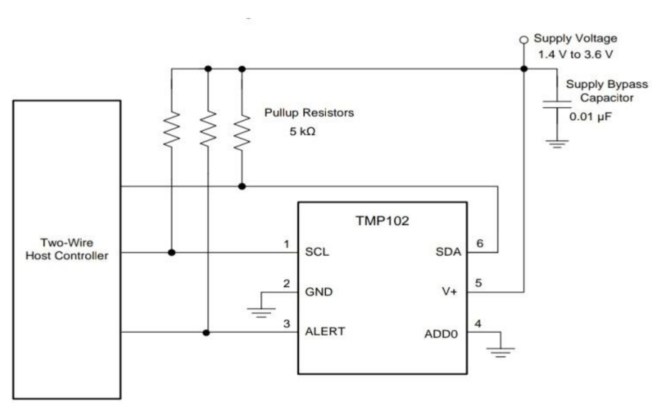


Fig. 7.5: Schematic of TMP102

7.3.3 Communication module - nRF24L01

nRF24L01 is a single chip radio transceiver for the worldwide 2.4 - 2.5 GHz ISM band. The transceiver consists of a fully integrated frequency synthesizer, a power amplifier, a crystal oscillator, a demodulator, modulator and Enhanced ShockBurst™ protocol engine. Output power, frequency channels, and protocol setup are easily programmable through a SPI interface. Current consumption is very low, only 9.0mA at an output power of -6dBm and 12.3mA in RX mode. Built-in Power Down and Standby modes makes power saving easily realizable.

Fig. 7.6: Communication module nRF24L01

7.4 WORKING CODE

```
#include <SPI.h>
#include <Enrf24.h>
#include <nRF24L01.h>
#include <string.h>

Enrf24 radio (P2_0, P2_1, P2_2);  // P2.0=CE, P2.1=CSN, P2.2=IRQ
const uint8_t txaddr[] = { 0xDE, 0xAD, 0xBE, 0xEF, 0x01 };

const char *str_on = "ON";
const char *str_off = "OFF";

void dump_radio_status_to_serialport(uint8_t);
```

```
void setup () {
  Serial.begin(9600);

  SPI.begin();
  SPI.setDataMode(SPI_MODE0);
  SPI.setBitOrder(MSBFIRST);

  radio.begin();  // Defaults 1Mbps, channel 0, max TX power
  dump_radio_status_to_serialport(radio.radioState());

  radio.setTXaddress((void*)txaddr);
}

void loop () {
  Serial.print("Sending packet: ");
  Serial.println(str_on);
  radio.print(str_on);
  radio.flush();  // Force transmit (don't wait for any more data)


  dump_radio_status_to_serialport(radio.radioState());  // Should report IDLE
  delay(1000);

  Serial.print("Sending packet: ");
  Serial.println(str_off);
  radio.print(str_off);
  radio.flush();
  dump_radio_status_to_serialport (radio.radioState ());  // Should report IDLE
  delay (1000);
}

void dump_radio_status_to_serialport (uint8_t status)
{
  Serial.print("Enrf24 radio transceiver status: ");
```

```
  switch (status) {
    case ENRF24_STATE_NOTPRESENT:
      Serial.println("NO TRANSCEIVER PRESENT");
      break;

    case ENRF24_STATE_DEEPSLEEP:
      Serial.println("DEEP SLEEP <1uA power consumption");
      break;

    case ENRF24_STATE_IDLE:
      Serial.println("IDLE module powered up w/ oscillators running");
      break;

    case ENRF24_STATE_PTX:
      Serial.println("Actively Transmitting");
      break;

    case ENRF24_STATE_PRX:
      Serial.println("Receive Mode");



      break;

    default:
      Serial.println("UNKNOWN STATUS CODE");
  }
}
```

8. RESULTS

The proposed antenna is composed of corrugated metal-insulator-metal (MIM) plasmonic structures, which covers triple frequency bands, including GSM-900, UTMS-2100, and TD-LTE bands. Its electrical size is only $0.21\lambda \times 0.2\lambda$ at 900 MHz. The gains reach 1 dBi, 2.64 dBi, and -0.19 dBi at 0.9 GHz, 2.025 GHz, and 2.36 GHz, respectively. A triple-band rectifier for low power application is designed to convert the harvested radio frequency (RF) power into DC power. The maximum RF to DC conversion efficiency of the rectifier reaches 59% when the input power is -10 dBm.

8.1 Antenna : Port parameters

1) Port Signal

Port Signal gives you the incident (i1) and reflected signal (o1,1) on given port (1) with respect to time.

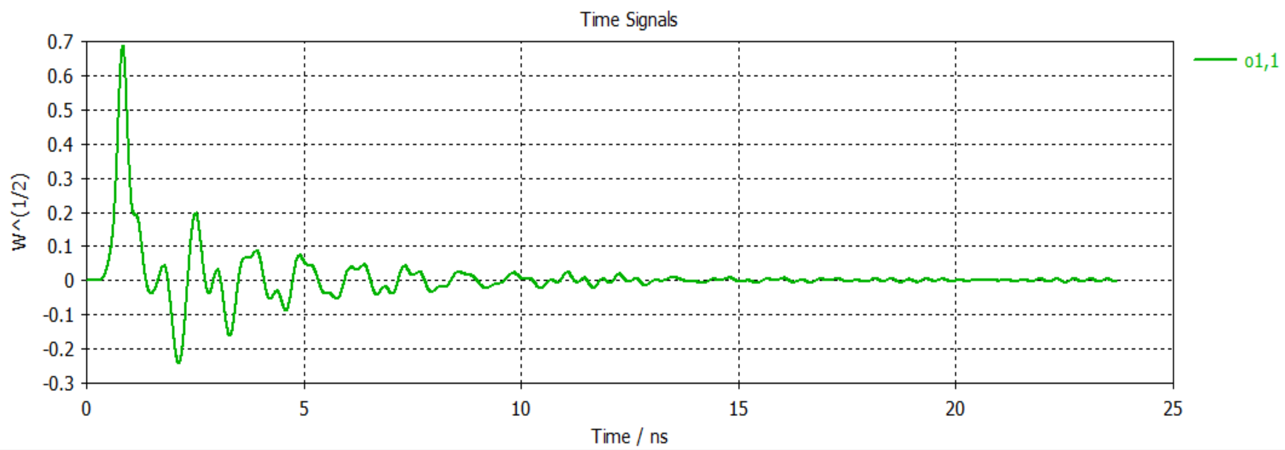


Fig. 8.1: Port Signal

For your antenna to show strong resonance the port signal should start at zero and after some resonance should tend towards zero.

2) Balance

Balance express the power loss vs frequency in a structure in a through radiation for given excited port. In a case of a lossless structure the balance =1

e.g. Port 1*: Balance (1) =sqrt(|s11|^2+|s21|^2).*

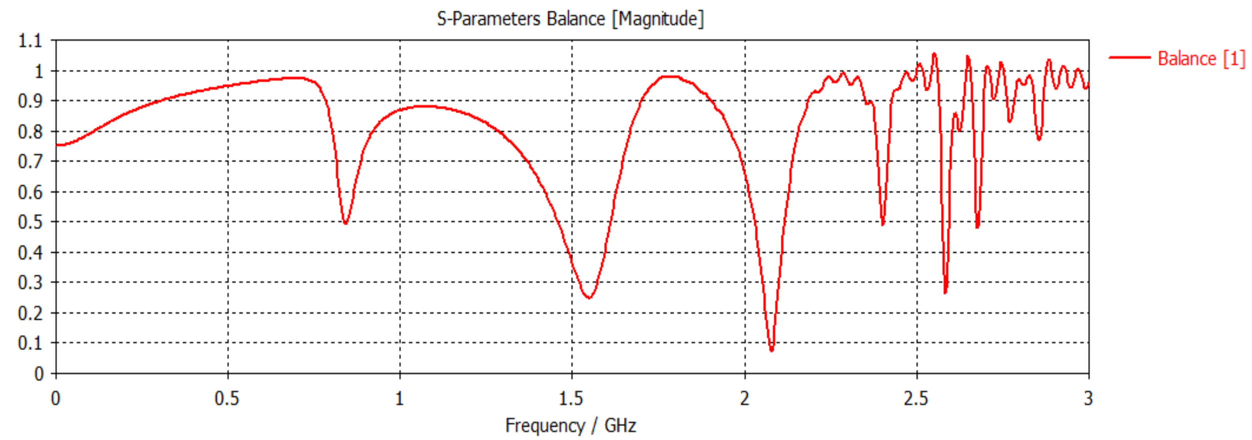


Fig. 8.2: Balance

3) S-parameters

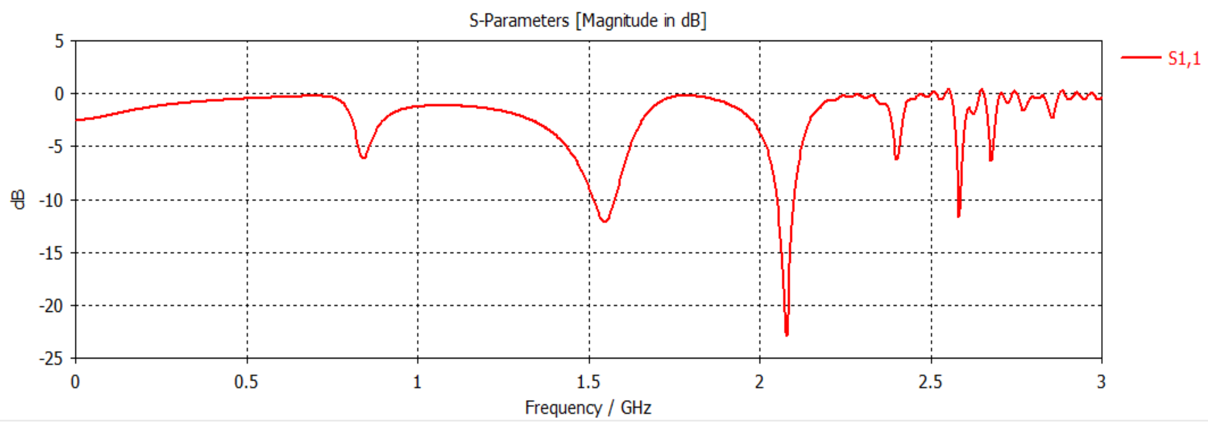


Fig. 8.3: S-Parameters

4) Power

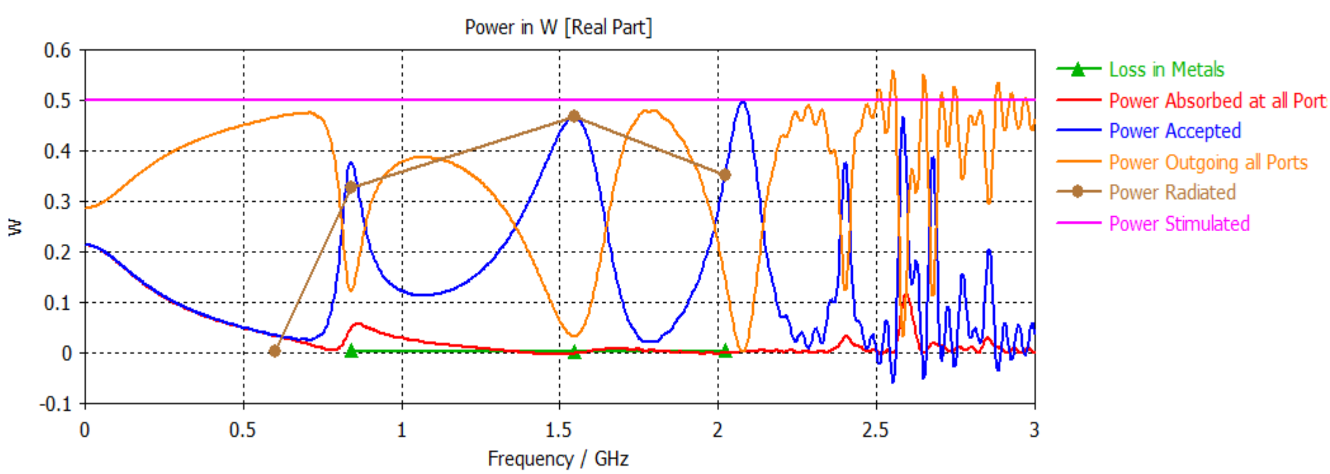


Fig. 8.4: Power

The proposed multiband antenna exhibits radiation characteristics like the dipole antenna in all frequency bands.

8.2 Antenna: Far-Field Analysis

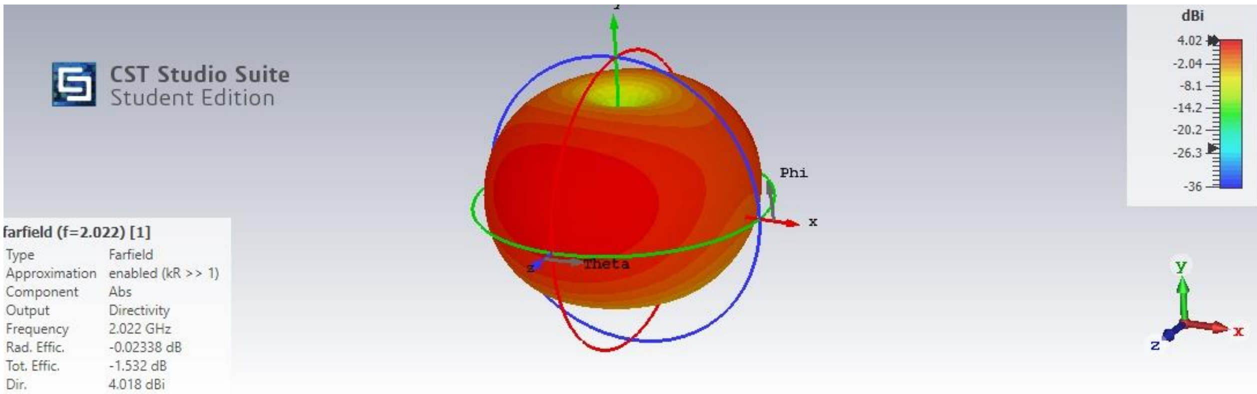
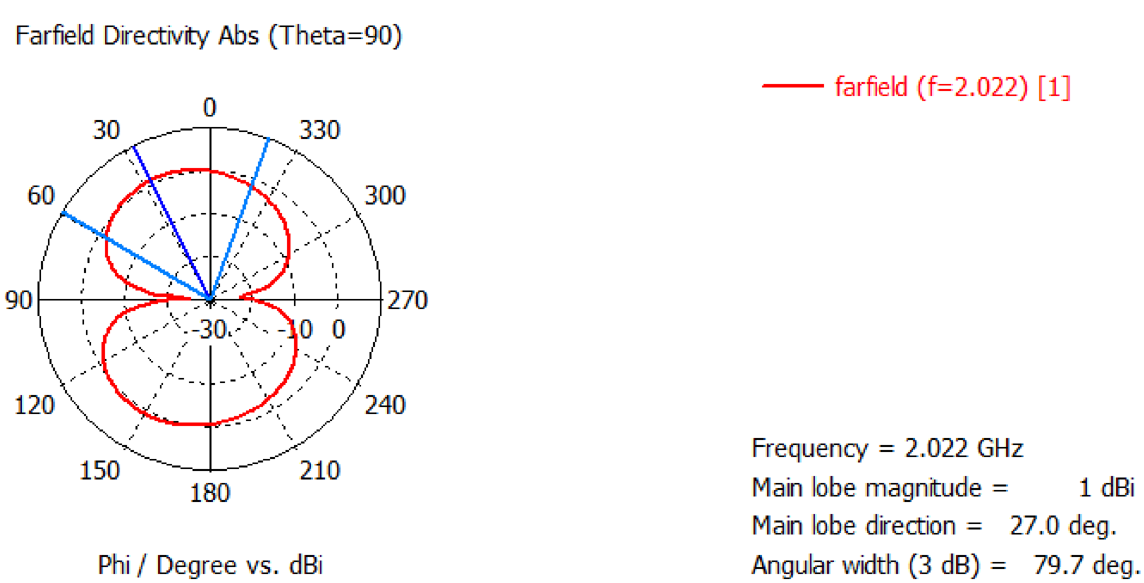
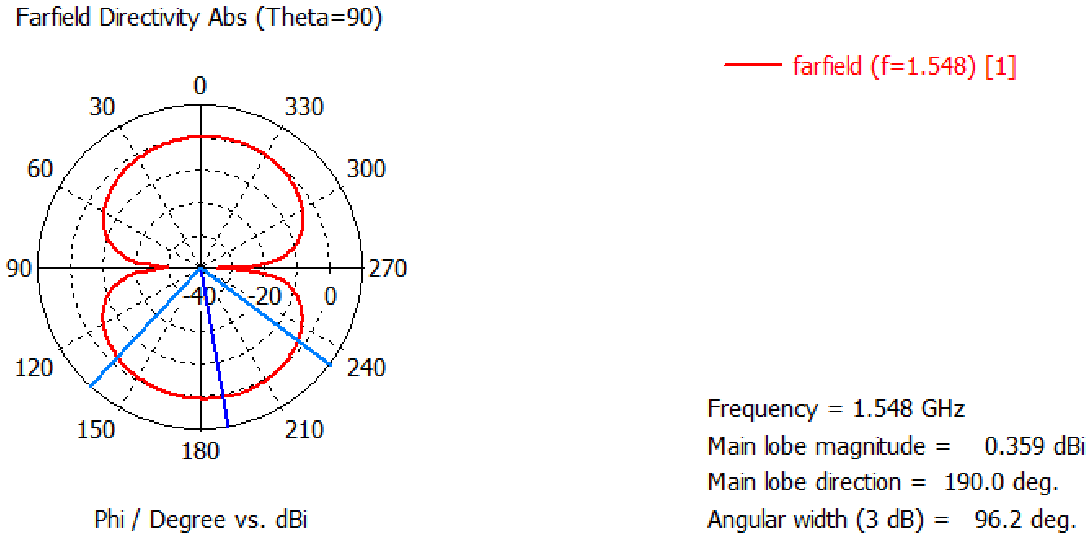


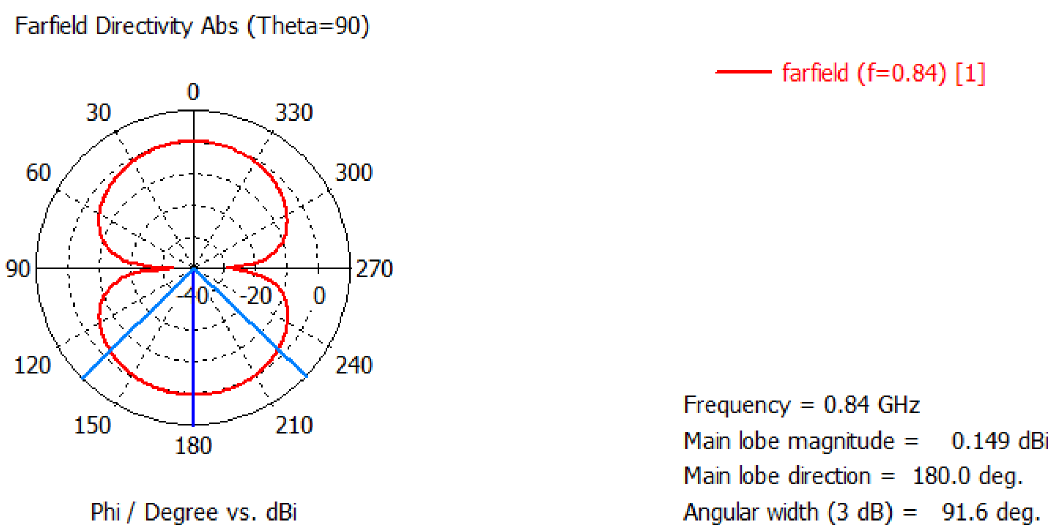
Fig. 8.5: Directivity field in 3D

The measured radiation efficiencies are 42.2%,61.3%, 72.6%, 32.8% at 0.9 GHz, 1.575 GHz, 2.025 GHz and 2.36 GHz, respectively. The gain is expected to increase when the operating frequency is increased, due to the increased electrical size.

When the metal is changed from perfect conductor (PEC) to copper, the radiation efficiencies at m2and m3 decrease 1.1% and 4.9%, respectively, while the efficiency at m4 decreases 7.6%. When the loss tangent of the dielectric substrate is changed from 0.004 to 0.01 (the metal is still copper), the efficiencies at m2 and m3 decrease 3.2% and 9.7%, respectively, while the efficiency at m4 decreases 15.8%. Hence, the m4 mode (2.36 GHz) is more sensitive to the metal loss and dielectric loss, which may lead to the decreased radiation efficiency and gain.[7]







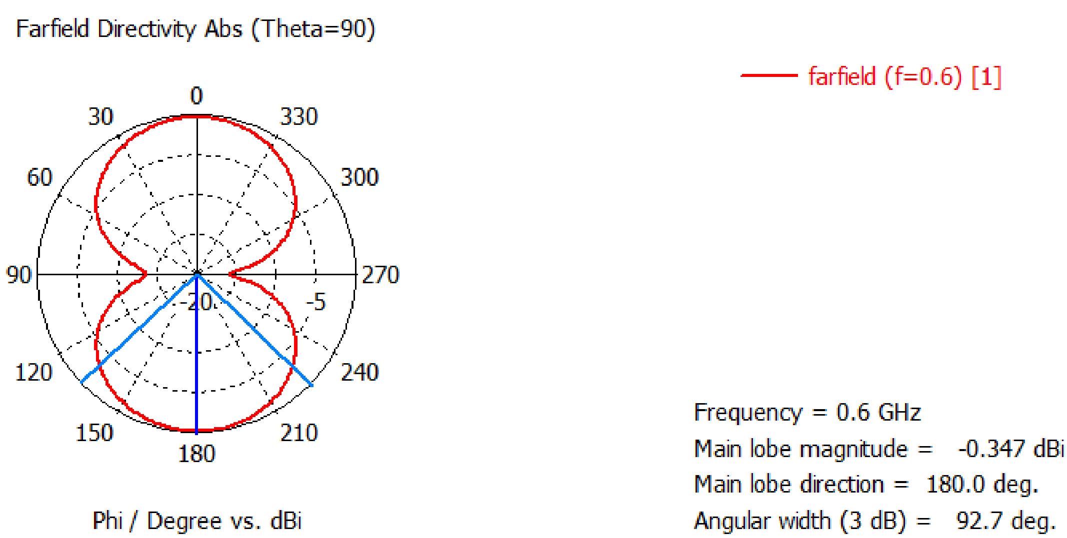


Fig. 8.6 Direction of far field

8.3 Rectifier Output

The output of rectifier yields the dc signal required for energy management module. Compared with the simulated result, the measured one has a slight shift, which may be caused by the manual welding process However, the dimension of the rectifier is still big, compared to the electrically small antenna.

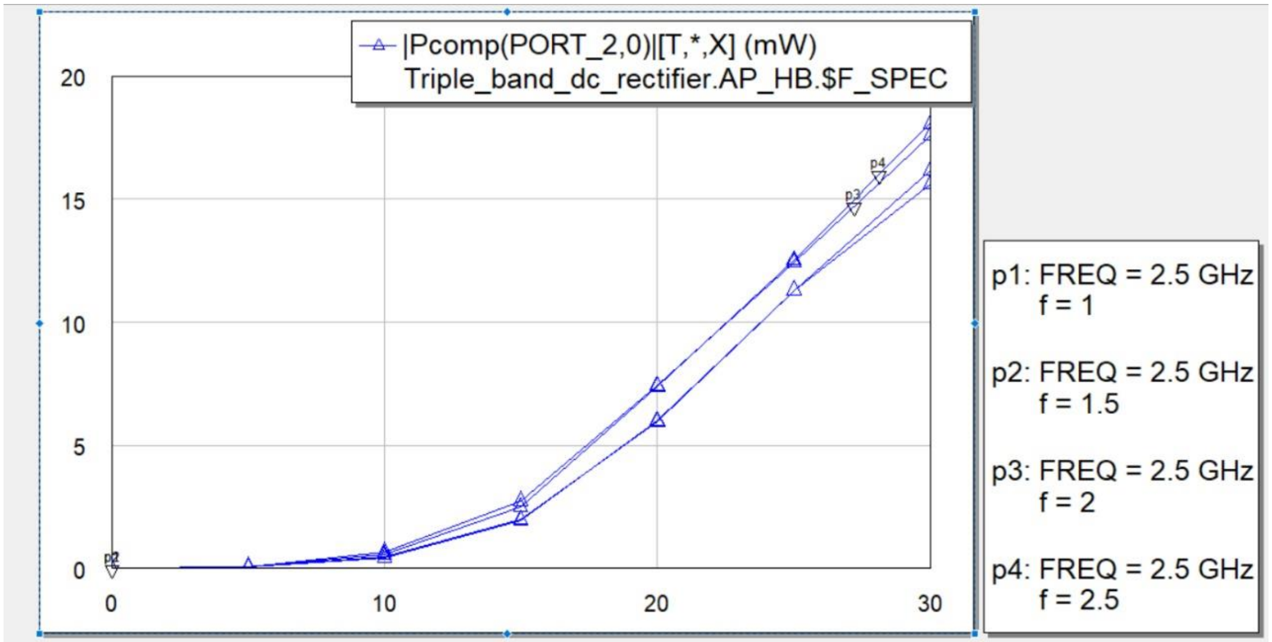


Fig 8.7 Rectifier output across different frequencies

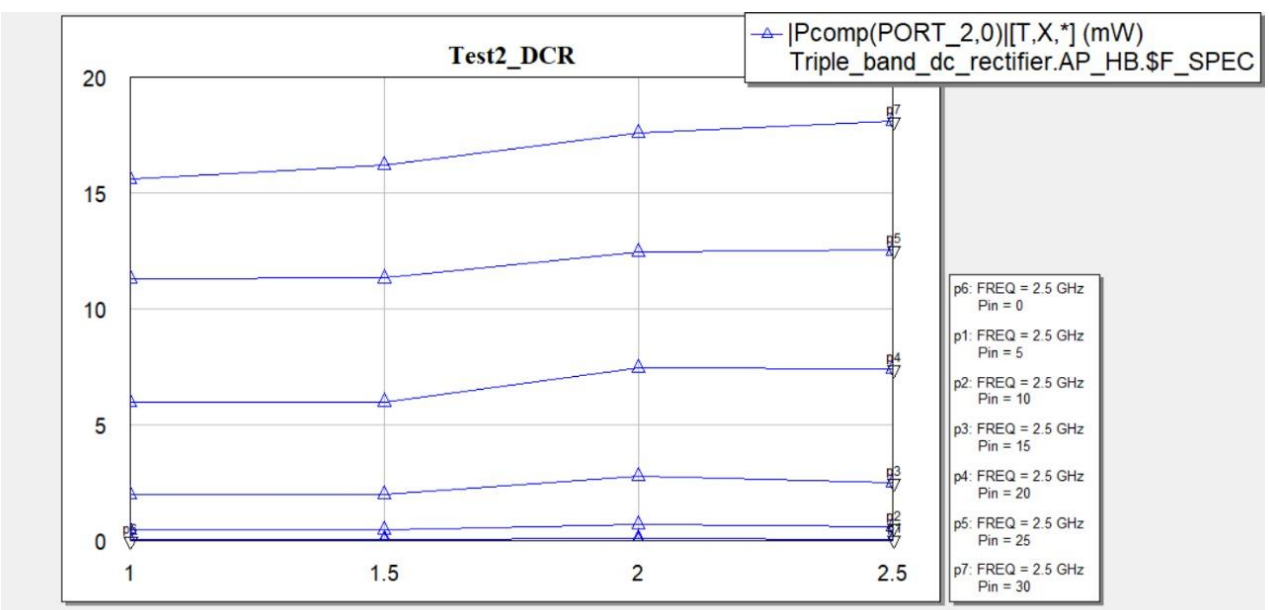


Fig. 8.8 Rectifier output across different inputs

9. CONCLUSIONS AND FUTURE SCOPE

9.1 CONCLUSION

An electronically small multiband rectenna covering GSM-900, UTMS-2100 and TD-LTE triple bands has been demonstrated. For the multiband antenna, our design is very compact, and the electrical size is the smallest in comparisons with other existing designs. Its electrical size is only $0.21\lambda \times 0.2\lambda$ at 0.9 GHz, while the gains remain 1Bi, 2.64 dBi, and -0.19 dBi at the operating frequencies 0.9 GHz, 2.025 GHz, and 2.36 GHz, respectively.[7] A triple-band rectifier is optimized to match the antenna. The measured RF to DC conversion efficiency remains 47% when the input power is -11.1 dBm. A prototype of a battery-free BAN node has been demonstrated, where the rectenna has successfully supplied power for the node consisting of the DC energy management and storage module, the microcontroller, and the sensing and communication module. The proposed compact sensor based on multiband WEH is suitable for human body self-monitoring and mobile healthcare. More compact sensor with miniaturized rectifying circuit and stacked multilayer structure is still under development.

9.2 FUTURE WORK

- The dimension of the rectifier is still big, compared to the electrically small antenna. In the next work, the dimension of the rectifier can be miniaturized by use of metamaterials [8], lumped elements, stacked multilayer structure [9], and so on.
- Development of novel network protocol for wireless battery free sensor network to minimize the power consumption without effecting the performance.
- Effective energy management of node by using multilevel modes of power supply based on the node activation state, which indeed is guided by the network protocol set-up in the wireless sensor nodes.
- Integrating vital health monitoring system to provide remote assistance in healthcare domain especially for people suffering from cognitive disorders like Alzheimer’s, Parkinson’s or similar diseases.

10. REFERENCES

[1] A. Darwish and A. Hassanien, “Wearable and implantable wireless sensor network solutions for healthcare monitoring,” *Sensors*, vol. 11, no. 6, pp. 5561–5595, June 2011.

[2] S. Kahng1, C. Lee1, H. Park1, G. Namgoong1, J. Kwon1 has published "A WBAN Reader Antenna to Improve the Wireless Link with an In-Body WBAN Antenna".

[3] Liu Yang, Yong Jin Zhou, Chao Zhang, Xin Mi Yang has published "Compact multiband wireless energy harvesting based battery free body area network sensor for mobile health care".

[4] C. Song, Y. Huang, J. Zhou, J. Zhang, S. Yuan, and P. Carter, “A high efficiency broadband rectenna for ambient wireless energy harvesting,” *IEEE Trans. Antennas Propag.*, vol. 63, pp. 3486-3495, May 2015.

[5] V. Kuhn, C. Lahuec, F. Seguin, and C. Person, “A multi-band stacked RF energy harvester with RF-to-DC efficiency up to 84%,” *IEEE Trans. Microw. Theory Techn.*, vol. 63, pp. 1768-1778, Apr. 2015.

[6] M. Dini, M. Filippi, A. Costanzo, A. Romani, M. Tartagni, M. D. Prete, and D. Masotti, “A fully-autonomous integrated RF energy harvesting system for wearable applications,” in *Microwave Conf. (EuMC)*, European, 2013, pp. 987-990.

[7] Liu Yang, Yong Jin Zhou, Chao Zhang, Xin Mi Yang, Xue-Xia Yang, and Chong Tan “Compact multi-band wireless energy harvesting based battery-free body area networks sensor for mobile healthcare”, Citation information: DOI 10.1109/JERM.2018.2817364, IEEE Journal of Electromagnetics, RF and Microwaves in Medicine and Biology.

[8] S. Choi, A. Salim, H. Jeong, and S. Lim, “High-efficiency and compact metamaterial-inspired 900 MHz rectifier,” *J. Microw. Power Electromagn. Energy*, vol. 50, no.3, pp. 168-181, 2016.

[9] K. Niotaki, S. Kim, S. Jeong, A. Collado, A. Georgiadis, and M. M. Tentzeris, “A compact dual-band rectenna using slot-loaded dual band folded dipole antenna,” *IEEE Antennas Wirel. Propag. Lett.*, vol. 12, pp. 1634-1637, 2013.

[10] M. A. Nikravan, and Z. Atlasbaf, “T-section dual-band impedance transformer for frequency-dependent complex impedance loads,” *Electron. Lett.*, vol. 47, no. 9, pp. 551-553, Apr. 2011.