Practical Realization of Simultaneous Wireless Information and Power Transfer (SWIPT) Systems

M.Tech Thesis

by

Vinish Ranjan

COMMUNICATIONS AND SIGNAL PROCESSING

DEPARTMENT OF ELECTRICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY INDORE

May 2025

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A THESIS

Submitted in partial fulfillment of the

requirements for the award of the degree

of

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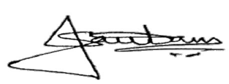

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **Practical Realization of Simultaneous Wireless Information and Power Transfer (SWIPT) Systems** in the partial fulfillment of the requirements for the award of the degree of **Master of Technology** and submitted in the **Department of Electrical Engineering, Indian Institute of Technology Indore,** is an authentic record of my own work carried out during the period from July 2023 to May 2025 under the supervision of Dr. Sumit Gautam, Indian Institute of Technology Indore, India

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other institute.

Vinish Ranjan 02/06/25

Signature of the Student with Date

(Vinish Ranjan)

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

02 June 2025

Signature of the Supervisor with Date

(Dr. Sumit Gautam)

Vinish Ranjan has successfully given his M.Tech. Oral Examination held on **7th May, 2025**.

Signature of Supervisor of M.Tech. thesis

Date: 04 June 2025

Saptarshi Ghosh

Convener, DPGC

Date: 03-06-2025

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Vinish Ranjan

Dedicated to My Family

List of Publications

Publications from Thesis

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ABSTRACT

The rapid advancement of the Internet of Things (IoT) has resulted in the widespread interconnection of systems, where future communication infrastructures will heavily depend on distributed sensors for data collection and environment monitoring. A major obstacle in deploying such large-scale sensor networks is ensuring a reliable and sustainable power source, as traditional batteries are constrained by limited capacity, periodic replacement, and environmental concerns. Interestingly, our surroundings are constantly immersed in radio frequency (RF) signals originating from sources such as mobile towers, satellites, and wireless communication systems. This pervasive RF environment offers an opportunity for energy harvesting, enabling sensors to derive power directly from ambient signals. A highly promising approach to achieve this is Simultaneous Wireless Information and Power Transfer (SWIPT), which enables devices to concurrently decode data and harvest energy from the same RF transmission.

In this experimental setup, two Universal Software Radio Peripherals (USRPs) were utilized along with an RF energy harvesting circuit and various types of antennas to evaluate the SWIPT technique in practical scenarios. The study involved both analog and digital modulation schemes. For analog modulation, audio signals were transmitted using standard techniques such as Amplitude Modulation (AM) and Frequency Modulation (FM), enabling the system to recover intelligible audio while simultaneously harvesting energy. To demonstrate digital modulation, random binary data streams were generated and transmitted. These implementations were designed to demonstrate the feasibility of SWIPT across different modulation formats. The results highlight the potential of SWIPT as a dual-purpose solution—enabling low-power devices to perform reliable communication while also being powered by the RF signals they receive. This makes SWIPT a promising approach for supporting the next generation of battery-free or battery-assisted IoT devices.

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Acronyms

AM	Amplitude Modulation
FM	Frequency Modulation
ASK	Amplitude Shift Key
PSK	Phase Shift Key
FSK	Frequency Shift Key
QAM	Quadrature Amplitude Modulation
USRP	Universal Software Radio Peripheral
SWIPT	Simultaneous Wireless Information & Power Transfer
EH	Energy Harvesters
WPT	Wireless Power Transfer
RF	Radio Frequency
IoT	Internet of Things
ADC	Analog-to-Digital Converter
5G	Fifth Generation Mobile Technology
GUI	Graphical User Interface
SDR	Software Defined Radio
LoS	Line of Sight
ID	Information Decoding
Wi-Fi	Wireless Fidelity
w.r.t.	With Respect To
FPGA	Field Programmable Gate Array
AC	Alternating Current
DC	Direct Current
4G	Fourth Generation Mobile Technology

Chapter 1

Introduction

With the rapid advancement of technology, sensors have become an essential part of modern systems that require real-time data acquisition, control, and monitoring. As communication systems evolve, the Internet of Things (IoT) is expected to become a cornerstone of next-generation networks. These systems will rely heavily on the deployment of a large number of distributed, low-power IoT sensors across diverse environments [1].

However, powering these sensors remains a major challenge. Traditional battery-powered devices face significant limitations in terms of energy capacity, maintenance, and replacement, particularly when deployed at scale or in hard-to-reach areas. This constraint threatens the scalability and long-term sustainability of IoT networks.

To overcome this limitation, the concept of Simultaneous Wireless Information and Power Transfer (SWIPT) has emerged as a viable solution. SWIPT allows a device to extract energy from RF signals while simultaneously decoding transmitted information, making it possible to reduce dependency on conventional power sources. This thesis investigates the practical implementation of SWIPT using analog modulation schemes such as Amplitude Modulation (AM) and Frequency Modulation (FM), with the aid of GNURadio Companion and Universal Software Radio Peripherals (USRPs).

1.1 Problem Overview

The exponential growth of IoT devices has created a pressing need for sustainable and maintenance-free power sources. While RF signals are omnipresent due to communication infrastructure such as radio towers, satellites, and cellular networks, traditional communication systems do not utilize these signals for power harvesting. Battery-powered solutions are not scalable, especially in applications requiring thousands of devices or in areas where physical access is restricted.

Additionally, in practical scenarios, ideal conditions such as Line-of-Sight (LoS) communication are often absent. Varying angles, distances, and environmental obstructions can significantly affect both the quality of data transmission and the amount of energy that can be harvested. Thus, deploying SWIPT in such environments requires a robust and adaptable system design.

This work focuses on implementing a separated antenna architecture, where one antenna at the receiver end is responsible for energy harvesting and the other for information decoding. Experimental setups were tested under varying angles, distances, and antenna configurations to evaluate the system's effectiveness in real-world conditions.

1.2 Research Contributions

This thesis makes the following key contributions: This thesis makes several significant contributions to the practical understanding and implementation of Simultaneous Wireless Information and Power Transfer (SWIPT) using software-defined radio platforms and analog modulation techniques. The key contributions of this work are outlined below:

Experimental Demonstration of SWIPT using AM and FM This work successfully demonstrates a practical realization of SWIPT using analog modulation schemes—Amplitude Modulation (AM) and Frequency Modulation (FM)—employing Universal Software Radio Peripheral (USRP B210) devices and GNURadio. The experiment validates the concept of concurrently harvesting RF energy and decoding modulated audio signals in real time.

Implementation of a Separated Antenna SWIPT Architecture A hardware-based SWIPT system was developed using a separated antenna approach, where one antenna is dedicated to energy harvesting and another to information decoding. This architecture enables simultaneous operation without interference, improving the reliability and modularity of the setup.

Use of Open-Source SDR Tools and Custom Flow Graphs Flow graphs for AM and FM transmission and reception were designed using GNURadio Companion. The system incorporates key signal processing blocks, including rational resamplers, WBFM transmitters/receivers, low-pass filters, and GUI controls, enabling a configurable and flexible SDR platform for SWIPT experimentation.

Energy Measurement and Logging via Raspberry Pi and MCP3008 A custom voltage monitoring setup was developed using an MCP3008 analog-to-digital converter and a Raspberry Pi board to log energy harvesting performance. A Python-based data logging script recorded the capacitor voltage in real time, allowing for detailed analysis of the harvested power during different modulation conditions.

Comparative Analysis under Varying Environmental Conditions Experiments were conducted under diverse conditions, including variations in transceiver distance, antenna orientation (e.g., 0°, 90°, 180°), and antenna types (directional and omnidirectional). The results demonstrate how these parameters influence the energy harvesting capability of the SWIPT system.

Observation of Modulation-Specific Harvesting Performance It was observed that FM generally outperforms AM in energy harvesting efficiency under NLoS and long-distance scenarios, while AM showed better energy performance at closer ranges with specific antenna orientations. This insight is valuable for selecting modulation techniques in different application contexts.

Foundation for Future Digital SWIPT Implementation The outcomes of this analog-based SWIPT implementation provide a strong foundation for future extensions involving digital modulation schemes. This transition is expected to enhance system applicability in modern wireless communication environments, including IoT and military applications.

Chapter 2

Literature Survey

The increasing demand for sustainable energy solutions in wireless systems, particularly in IoT-based networks, has driven significant research into Wireless Power Transfer (WPT) and Simultaneous Wireless Information and Power Transfer (SWIPT). This section reviews key works in this domain and highlights their relevance, contributions, limitations, and how the present research addresses existing gaps.

2.1 Growth of IoT and Power Sustainability Challenges

The proliferation of Internet of Things (IoT) devices has led to the deployment of millions of sensors that require continuous power for data transmission and monitoring. Traditional battery-powered approaches pose limitations in terms of scalability, maintenance, and environmental impact. There is a growing need to develop energy-autonomous systems that can self-sustain without frequent human intervention [1].

2.2 Conceptual Foundation of SWIPT

SWIPT emerges as a promising solution that enables a device to simultaneously receive data and harvest energy from the same RF signal. Unlike traditional communication systems, SWIPT integrates energy harvesting (EH) circuits into communication receivers. The dual-purpose functionality of SWIPT reduces dependency on battery replacement and facilitates long-term, maintenance-free IoT deployment [1, 2].

2.3 Use of Simple Waveforms for WPT

In [2, 3], the use of basic waveform designs, including OFDM, is explored for enabling efficient WPT. The study confirms that even with simple modulations, it is possible to achieve meaningful levels of energy harvesting. A notable aspect of the work is the impact analysis of angular displacement between the transmitter and receiver, revealing that orientation significantly influences EH performance. However, the research is confined to WPT alone and does not explore simultaneous information decoding, a core component of SWIPT. It offers a useful entry point for further exploration of modulation strategies in practical systems.

2.4 Analysis of Distance Impact in LoS Conditions

The authors in [3] investigate how transmitter-receiver distance affects energy transfer efficiency under Line-of-Sight (LoS) conditions. This analysis is important but lacks generalizability, as LoS scenarios are not always feasible in dense or urban deployments. The absence of Non-Line-of-Sight (NLoS) testing is a major limitation, since real-world IoT deployments often operate in obstructed environments. To address this, the present work includes NLoS condition evaluations, offering more realistic insights into SWIPT performance.

2.5 Theoretical Framework of SWIPT Techniques

A comprehensive theoretical study in [4, 5] outlines the architecture, signal processing techniques, and trade-offs involved in SWIPT systems. It compares various implementation methods, such as: Time-switching (alternating between energy harvesting and information decoding), Power-splitting (splitting the received RF signal between EH and decoding paths), Antenna separation (dedicating separate antennas for each function). This study guided the selection of the separated antenna method for the current research, based on its simplicity and effective interference management.

2.6 Modulation Techniques and Practical Implementation

Modulation plays a crucial role in the performance of SWIPT systems, as it directly influences both energy harvesting efficiency and data decoding accuracy. Many existing works focus primarily on digital modulation techniques, such as:

- Amplitude Shift Keying (ASK),
- Phase shift Keying (PSK)
- Quadrature Amplitude Modulation (QAM)

These techniques are widely used in modern wireless communication systems due to their bandwidth efficiency and compatibility with digital data streams. However, analog modulation schemes, such as Amplitude Modulation (AM) and Frequency Modulation (FM), are still prevalent in real-world RF environments (e.g., commercial radio, military communication, public service broadcasting). In the current study, both analog and digital modulation schemes are considered. For analog testing, audio signals are transmitted using AM and FM blocks developed in GNURadio Companion. For digital transmission, random binary data is modulated using general digital schemes (not limited to one type), allowing energy harvesting to occur simultaneously with information decoding. Including both modulation types allows for a comprehensive analysis of SWIPT system performance under different signal formats and practical usage scenarios [6, 7].

Chapter 3

Simultaneous Wireless Information and Power Transmission (SWIPT)

As the number of connected devices continues to grow, particularly in IoT-based systems, the demand for energy-efficient communication has increased significantly. One promising solution to address the power constraints in wireless networks is Simultaneous Wireless Information and Power Transfer (SWIPT). This technique allows a receiver to extract both energy and data from the same incoming radio frequency (RF) signal. Instead of treating communication and energy harvesting as two separate processes, SWIPT enables both to occur simultaneously, offering a more sustainable approach for low-power devices.

3.1 SWIPT Techniques

Simultaneous Wireless Information and Power Transfer (SWIPT) has emerged as a transformative approach for modern wireless systems, particularly in scenarios involving resource-constrained devices such as Internet of Things (IoT) nodes, wireless sensor networks, and next-generation communication devices. Traditional wireless communication systems have focused solely on the transmission of information, with power supplied

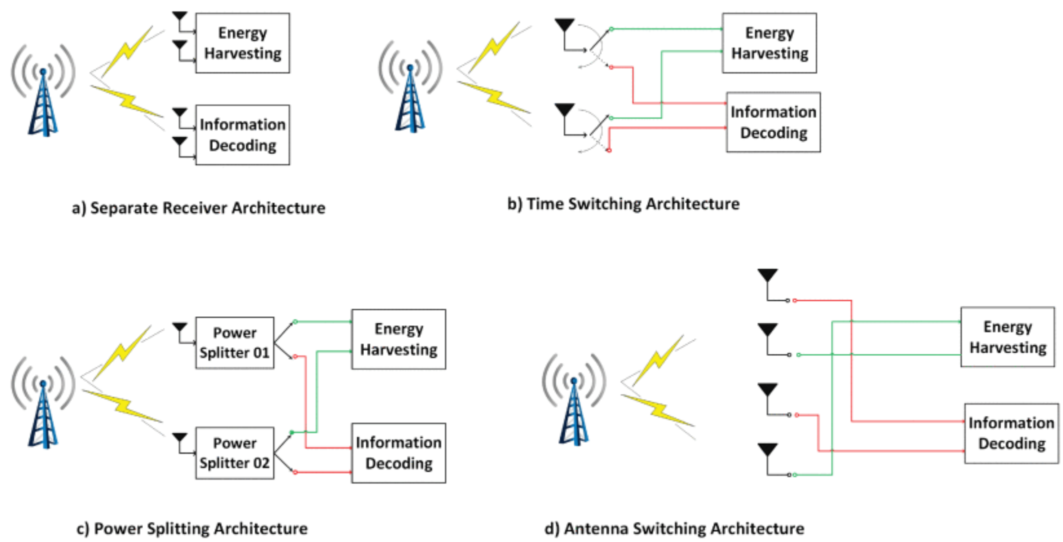


Figure 3.1: SWIPT receiver structures (a) Separated Architecture, (b) Time Switching Receiver (c) Power Splitting Receiver and (d) Antenna Switching Receiver

through batteries or wired sources. However, with the growing demand for energy-efficient and autonomous systems, SWIPT provides an integrated solution by enabling the concurrent reception of data and harvesting of energy from the same radio frequency (RF) signal. SWIPT can be realized through several architectural frameworks that define how the receiver handles the dual functionalities of energy harvesting (EH) and information decoding (ID). These frameworks are generally classified into two major categories: Separated Receiver Architecture and Integrated Receiver Architecture. Each technique presents its own set of trade-offs in terms of complexity, efficiency, practicality, and hardware requirements [8].

3.1.1 Separated Receiver Architecture

In the Fig. 3.1 (a) separated receiver configuration, two independent antennas are employed at the receiver end. One antenna is dedicated exclusively to energy harvesting, while the other focuses on decoding the incoming information. Since both antennas operate over distinct radio channels, this architecture allows EH and ID to be carried out simultaneously and without interference [4].

This method offers a number of practical advantages. First, it eliminates the need for internal signal splitting or switching, which simplifies signal processing at the circuit level. Second, the parallel processing capabilities enable real-time communication and continuous energy acquisition, which are crucial for mission-critical and always-on applications. Moreover, with the availability of channel state information (CSI), the system can adaptively optimize the communication rate and energy harvesting efficiency through dynamic feedback and control mechanisms.

Although the hardware footprint may be slightly larger due to the use of multiple antennas, this drawback is outweighed by the robustness and operational simplicity it provides in practical deployments. This technique is particularly useful in applications where uninterrupted operation is critical, such as smart agriculture, environmental monitoring, and industrial automation.

3.1.2 Integrated Receiver Architecture

In contrast to the separated design, the integrated receiver architecture uses a single antenna to perform both energy harvesting and information decoding [2]. This approach is more compact and suited for devices with strict space and cost limitations. However, since both EH and ID are being performed from the same signal path, sophisticated signal management techniques must be used to separate and process the data and power components.

Integrated architectures can be further subdivided into the following subcategories:

3.1.2.1 Time Switching

Time Switching is one of the simplest and most intuitive forms of SWIPT implementation. In this approach, the receiver alternates between two modes—EH and ID—within different time slots shows Fig. 3.1 (b). A switching mechanism controls the operational state of the antenna, deciding whether it should extract energy from the signal or decode the transmitted data [4].

The primary advantage of TS is its minimal hardware complexity, as no signal splitting components are required. However, because it does not support simultaneous operation, there is always a trade-off between the amount of time dedicated to harvesting energy and the time allocated for data communication. This necessitates precise synchronization and scheduling, especially in fast-changing environments or high-traffic systems. TS is best suited for systems where energy needs are moderate and non-continuous data transmission is acceptable.

3.1.2.2 Power Splitting (PS)

The Power Splitting technique is a more advanced implementation that allows the receiver to process the incoming RF signal simultaneously for both EH and ID. This is achieved by dividing the signal power into two streams using a power splitter shows Fig. 3.1 (c). A certain percentage of the signal, defined by a splitting ratio α, is sent to the energy harvesting module, while the remaining portion is forwarded to the information decoder [4].

The flexibility of PS lies in the ability to fine-tune α based on the desired balance between energy and data requirements. This makes it suitable for systems that need to dynamically adapt to changing energy demands or communication loads. However, implementing

PS comes with increased circuit complexity due to the need for a high-performance splitter and signal routing logic. Additionally, mismatches in power allocation may affect the accuracy of information decoding or the efficiency of energy harvesting if not properly managed.

3.1.2.3 Antenna Switching (AS)

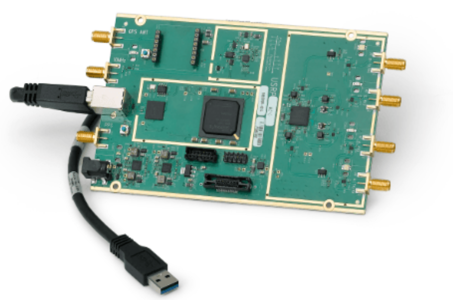
Antenna Switching is a hybrid approach that uses multiple antennas at the receiver, but instead of assigning them fixed roles as in the separated receiver model, the system dynamically allocates antennas to either EH or ID based on current requirements or channel conditions shows Fig. 3.1 (d). For example, one set of antennas may be assigned to EH during certain periods, and then switched to ID mode when energy requirements are met [4].

This method provides flexibility in system operation and can be seen as a variation of the PS technique, where the division is done in the spatial domain rather than power or time. AS requires a moderate level of control logic and coordination but eliminates the need for complex splitters or high-frequency switching hardware. It is especially beneficial in environments with fluctuating energy availability or irregular communication demands.

3.1.3 Hardware Discription

The experimental setup comprises a range of hardware components including a Universal Software Radio Peripheral (USRP) for wireless signal transmission and reception, an energy harvester module for power extraction, the MCP3008 analog-to-digital converter for signal interfacing, various antennas for RF communication, and a Raspberry Pi unit serving as the central processing and control platform. These components collectively support the implementation and evaluation of the proposed system under real-world conditions [2, 3].

(a)



(b)

Figure 3.2: USRP B210 hardware used in the experimental setup.

3.1.3.1 USRP

In Fig. 3.2 (a) & Fig. 3.2 (b) shows the USRP B210 is a compact, software-defined radio (SDR) platform that supports full-duplex communication over a wide frequency range. It offers two transmit and two receive channels, enabling MIMO operations and flexible signal experimentation. The device interfaces with a host computer via USB 3.0, providing high-speed data transfer for real-time signal processing [9]. Its versatility and compatibility with open-source tools like GNU Radio make it ideal for prototyping wireless communication systems [10].

3.1.3.2 Energy Harvester (EH) Module

The Powercast P21XXCSR-EVB is an energy harvesting evaluation board designed to convert ambient radio frequency (RF) energy into usable direct current (DC) power [11]. It incorporates the PCC110 and PCC210 Powerharvester® chips, enabling operation across multiple frequency bands, including GSM-850, GSM-900, GSM-1800, GSM-1900, and Wi-Fi 2.4 GHz. The module captures RF energy through an external antenna [12, 13], stores it in onboard capacitors, and provides a regulated output voltage ranging from 2 V to 5.5 V. This capability makes it suitable for powering low-energy devices or charging energy storage elements in wireless sensor networks and other remote applications.

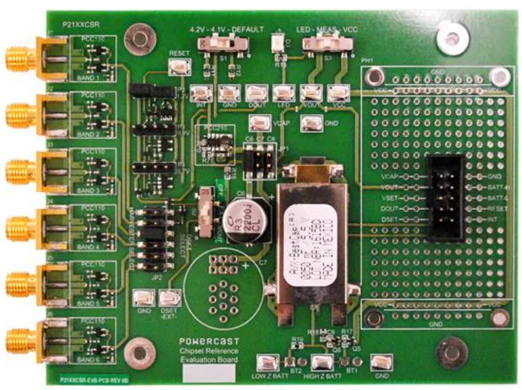


Figure 3.3: EH module used in the experimental study

3.1.3.3 Analog to Digital Converter

The MCP3008 is an 8-channel, 10-bit analog-to-digital converter (ADC) that allows the interfacing of analog sensors with digital systems. It communicates with microcontrollers or single-board computers, such as the Raspberry Pi, via the SPI (Serial Peripheral Interface) protocol [14]. The MCP3008 supports both single-ended and differential input modes, offering flexibility in sensor configuration. Its compact design and reliable performance

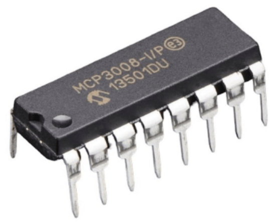


Figure 3.4: ADC used in the experimental study

make it suitable for data acquisition in embedded and IoT-based systems where multiple analog inputs need to be digitized.

3.1.3.4 RaspberryPi

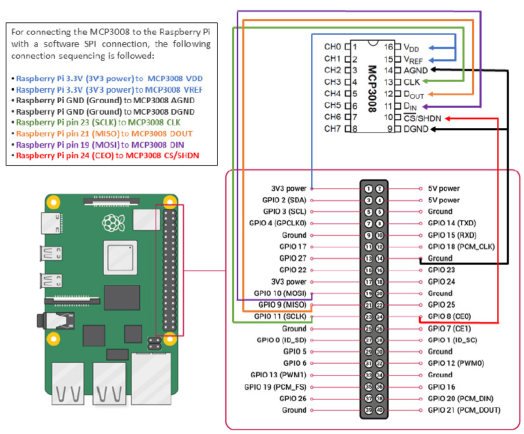


Figure 3.5: Connections between MCP3008 and RaspberryPi

The Raspberry Pi 4 is a compact, single-board computer that offers enhanced processing capabilities and connectivity features, making it ideal for embedded and IoT-based applications. It is equipped with a quad-core ARM Cortex-A72 processor, multiple USB ports, GPIO headers, and built-in Wi-Fi and Bluetooth support. In this work, Raspberry Pi 4 was used as the primary control and processing unit for managing data acquisition and communication tasks [15].

To enable analog sensor interfacing, the Raspberry Pi 4 was connected to the MCP3008 an 8-channel, 10-bit analog-to-digital converter (ADC) via the SPI (Serial Peripheral Interface) protocol. Since the Raspberry Pi lacks native analog input capabilities, the MCP3008 served as a critical component for digitizing analog signals. This setup allowed accurate sampling and real-time processing of sensor data using Python version 3.7, which provided a flexible and efficient programming environment for handling hardware communication, signal processing, and data visualization. Where the Fig. 3.5 shows the connection between the ADC & Raspberry pi [3].

3.1.3.5 Antenna

(a)

(b)

Figure 3.6: (a) Directional antenna (b) Omnidirectional antenna used in the experimental setup.

Antennas are essential devices in any wireless communication system. They serve the purpose of transmitting and receiving electromagnetic waves, acting as a bridge between electrical signals and the airwaves. Two common types of antennas are omnidirectional and directional antennas [16, 17], each with its own distinct features and use cases. Both directional and omnidirectional antennas serve important roles in communication systems. The choice between them depends on your coverage needs, range requirements, and installation environment. Understanding their differences helps in designing efficient wireless networks with optimal performance.

Chapter 4

Practical Realization of SWIPT Systems

4.1 Introduction

Sensors have increasingly become essential tools for data acquisition in modern communication systems. As the world advances toward next-generation communication frameworks, the integration of the Internet of Things (IoT) into everyday infrastructure is becoming more widespread. However, this growing deployment of IoT devices introduces a significant challenge maintaining a reliable power supply, particularly in battery-constrained environments. One promising solution to this issue is Simultaneous Wireless Information and Power Transfer (SWIPT), which enables the concurrent extraction of energy and transmission of information from the same wireless signal [3]. This dual-function capability can be particularly beneficial for powering low-energy devices such as IoT sensors.

In the experimental setup presented in this work, a separated antenna configuration was employed, wherein distinct antennas were used for energy harvesting and information decoding. Amplitude Modulation (AM) and Frequency Modulation (FM) signal blocks were developed using GNURadio Companion to simulate realistic transmission scenarios. The system incorporated energy harvesting modules to collect RF energy during transmission. Given the unpredictability of real-world environments—where Line-of-Sight (LoS) commu-

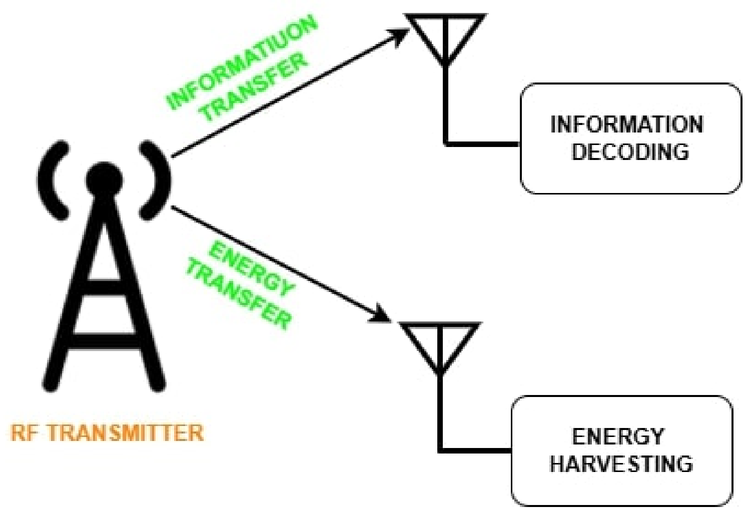


Figure 4.1: Layout of separated antenna technique

nication is not always guaranteed—the experiments were conducted under varying conditions, including different antenna angles, separation distances, and combinations of antenna types. This diversity in test scenarios allowed for a thorough evaluation of the harvested energy in multiple practical contexts.

Audio signals were modulated using AM and FM techniques and transmitted wirelessly using a USRP B210 software-defined radio. On the receiving end, a second USRP device was used to decode the signal, while the connected energy harvester module simultaneously collected RF energy. Observing the charging and discharging behavior of the energy harvester's capacitor allowed for real-time monitoring of voltage variation, indicating the effectiveness of the system. The separated antenna method is the SWIPT approach used in this implementation, where two distinct antennas are employed at the receiving side one for information decoding and the other for EH [4]. Fig.4.1 shows the layout of separated antenna method technique.

The separated antenna method, which uses individual antennas for energy harvesting and data decoding, serves as the basis for this SWIPT implementation. This configuration ensures independent reception of power and information, thereby reducing interference and enabling consistent performance across various operating conditions. The results from this setup illustrate the practicality and potential of SWIPT for real-world deployment in energy-constrained wireless sensor networks.

The main contributions of the work consist of:

1. **Combining Information Transfer with EH**: This research shows it is possible to harvest energy and transmit data at the exact same time, which is necessary for powering low-power IoT sensors.

2. **Separated Antenna Approach**: Our work enhances the efficacy and efficiency of SWIPT systems by utilizing a separated antenna approach, in which one antenna is devoted to capturing energy while the other decodes the information.

3. **Practical Constraint into Consideration**: Investigations were conducted while taking practical constraints, such as separation distance and transceiver angles, into consideration, thus aiding in identifying challenges.

4. **Analysis of Voltage Variation**: In this study, we examine the charging and discharging processes of a capacitor that can be harvested & also decode information to estimate the amount of energy that can be extracted from the audio signal that is transmitted via different modulation techniques.

5. **Comparative Analysis of Antenna Configuration**: The work demonstrates the EH potential and information decoding efficiency achievable with different antenna setups, using various antenna configurations at the transmitter and receiver sides.

6. **Literary Contributions**: This research, offers significant results concerning EH by radio frequency (RF) signals along with information decoding thus illustrating the usefulness of the SWIPT approach.

4.2 System configuration

The system framework for this experiment consists of two desktop PCs labeled as (computers 1 and 2), two USRP B210 devices, a Powercast P21XXCSR-EVB EH module, directional antennas operating at 2.45 GHz, omnidirectional antennas supporting 2.45 GHz to 5 GHz, an MCP3008 ADC, and a Raspberry Pi board, as shown in Fig. **??**. The MCP3008 converts the analog energy collected by the EH module into a digital format, and the Raspberry Pi on Computer 1 records the corresponding data. The EH module performs EH, while the USRP B210 integrated with process decodes the received signal, with the decoded information (spectrum) displayed on Computer 2.

Table 4.1: Equipments used in system configuration

Equipment	**Synopsis**
Computer-1	32GB RAM, Core i7 processor, Window 11 Pro, GNURadio Version 3.8.2
Computer-2	Laptop, 8GB RAM, i7 processor, Ubuntu 20.04, GNURadio Version 3.10.7
SDR	USRP B210 (Ettus Research - National Instruments)
Antenna	2.45 GHz, Raspberry Pi RM502x 5G HAT's Directional antenna and omnidirectional antenna (2.45 GHz-5 GHz) [SMA]
EH Module	Powercast P21XXCSR-EVB
MCP3008	8-channel, 10-bit ADC
RaspberryPi	Version-4, Python Version 3.7

Table 4.2: Parameter value set for experiment

Parameter	**value**
Frequency Band	802.11g (2.4GHz)
centre frequency	2.45 GHz
Message signal	Audio (.wav file)
Sampling rate	1.44MHz
Sample tapping rate	1000 sps
EH settings	6th Band, Capacitor (C1:2200 μF), SW S1:Default, SW S2:Off, SW S3:VCC

A GNURadio companion with a Graphical User Interface (GUI) was used to program the USRP B210. Flow graphs for amplitude and frequency modulations were designed on the transmitter side, with corresponding demodulation flow graphs on the receiver side, as

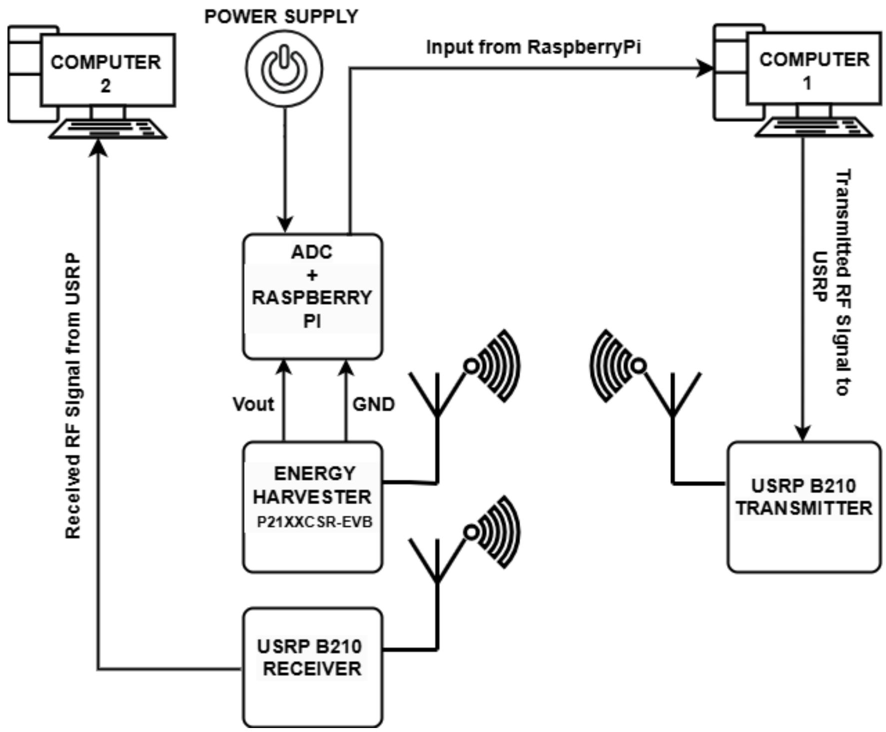


Figure 4.2: Architecture of the experimental study

illustrated in Fig. 4.4 The experiment concurrently employs an EH module and an information decoder (USRP B210). The MCP3008, an 8-channel, 10-bit ADC, converts the harvested energy into digital data. Specifically, the Vout pin of the EH module is con-

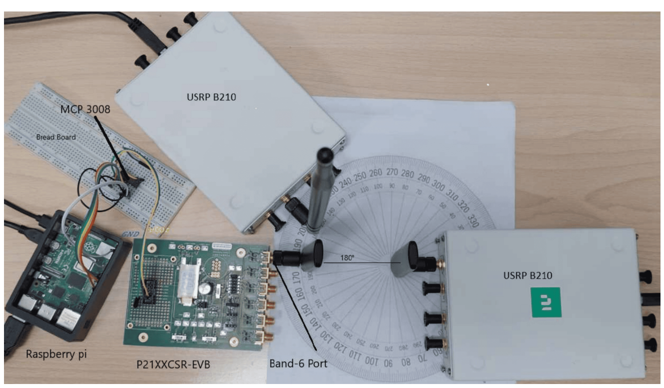


Figure 4.3: Experimental Setup

nected to CH0 of the ADC, enabling the Raspberry Pi to interpret the converted digital signal. The MCP3008's maximum output value corresponds to 1023 or equivalently 3.3

volts. The ADC (MCP3008) logs the output voltage on the Raspberry Pi v4 to digitize the voltage that the EH module receives. We develop the data logging script in Python, which collects voltage changes over time at a sampling rate of 1000 samples per second. Table 4.1 lists the equipment used in the study, while Table 4.2 presents the values of the software and hardware parameters. Fig. 4.2 illustrates the hardware setup, while Fig. 4.4 shows the block diagrams. Specifically, Fig. 4.4 (a) and Fig. 4.4 (c) correspond to the blocks for modulation of amplitude and frequency, respectively, while Fig. 4.4 (b) and Fig. 4.4 (d) represent the blocks for demodulation of amplitude and frequency. The system uses various blocks such as the rational resampler for upsampling and downsampling, and low-pass filters at the demodulation stage to reduce noise, ensuring clear audio reception. The USRP sink block is responsible for transmitting signals, whereas the USRP source block is used for signal reception. The audio sink block enables the playback of the received audio. Additionally, the QT GUI Range block allows for parameter adjustments during the experiment. The audio file source block handles the input audio signal in (.wav) format, which is then transmitted wirelessly. The Wide Band Frequency Modulation (WBFM) transmitter block performs frequency modulation, preparing the message signal for transmission, while the WBFM receiver block demodulates the received signal to retrieve the original audio. Since the system operates in the 2.45 GHz frequency band, which is a high frequency range, additional blocks like QT Frequency and QT Time are used to generate frequency spectrum and amplitude plots for analysis. Fig. **??** displays the actual image of the experimental setup.

4.3 Outcomes and Analysis

As 2.45 GHz is a free band among the other bands that are accessible through EH (P21XXCSR-EVB), it is used as the central frequency for the experiment. The GNURadio uses a sampling rate of 1.44 MHz for both AM and FM modulation. To ensure proper

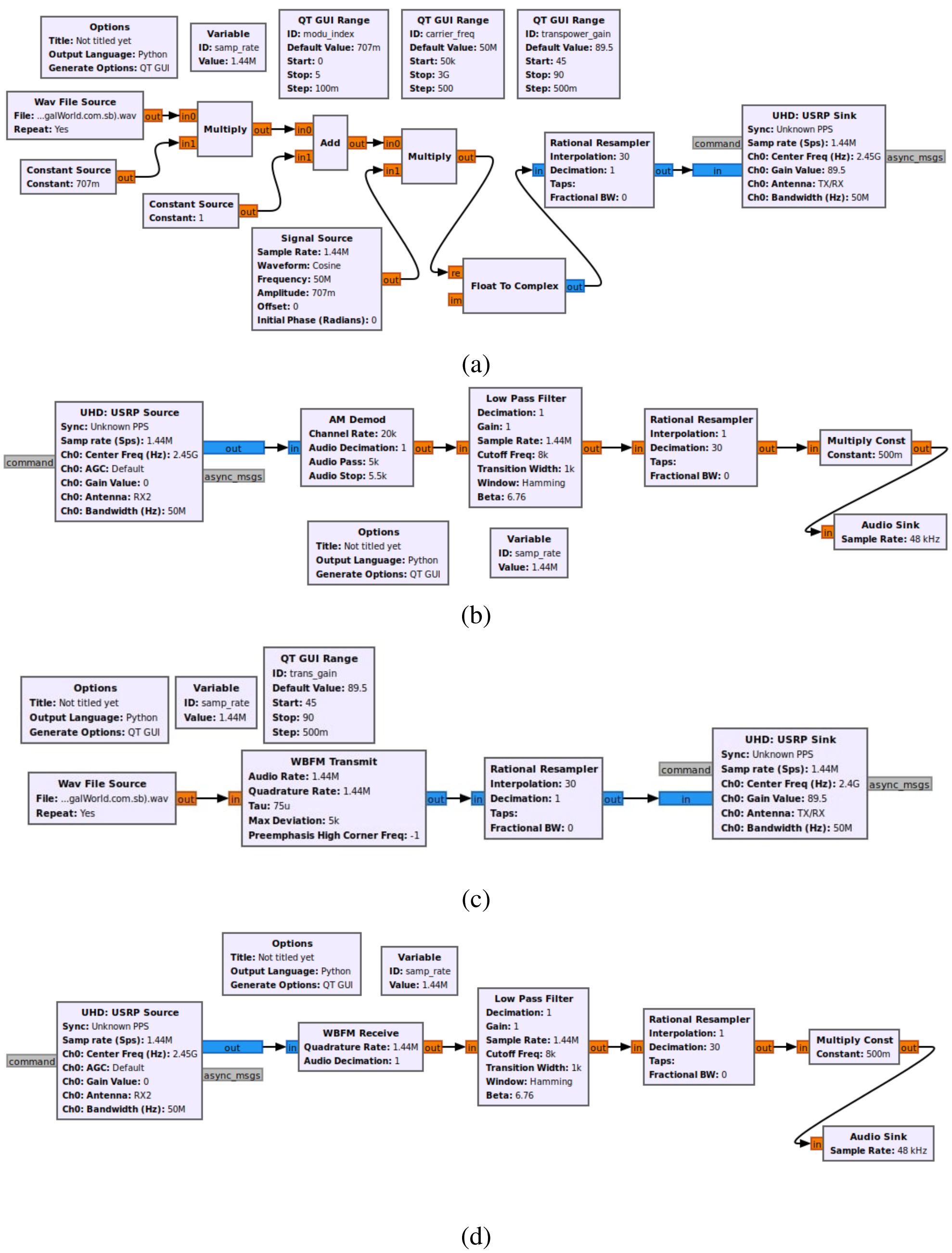


Figure 4.4: GNURadio block design

demodulation of the received signal at the receiver's side, the modulation index for AM was set to $\mu < 1$, corresponding to under-modulation. In contrast, for FM, WBFM was employed with $\beta >> 1$ to modulate the message signal (.wav file)[6]. The primary difference between the AM and FM schemes considered in the experiments lies in the amount of harvested energy. Since the investigations were carried out in a near-field environment, the effect on the quality of the received signal is minimal. The experiments were conducted with both the transmitter and receiver USRPs positioned at the same angle variation, alongside the EH module for harvesting energy. Table II provides the parameters for the 2200μF capacitor that we are employing in the EH module. The MCP3008 10-bit ADC and Raspberry Pi were utilized for collecting measurements of the charging and discharging of capacitors. This allowed us to use the formula for estimating the instantaneous harvested energy.

$$E = \frac{1}{2} \times C \times V^2 \,, \tag{4.1}$$

where V stands for the capacitor's voltage during EH, C for capacitance in farads (F) and E for instantaneous energy in Joules (J). In order to calculate the average energy, we consider the $24,000$ samples. The subsequent sections of this paper presents the discussion on results and corresponding analysis.

4.3.1 Impact of antenna variations of the USRP transmitter, USRP receiver, and EH module is significant

On the other hand, using high-gain antennas on the information decoding side at the receiver can affect the amount of harvested energy. This relationship is illustrated in Fig. 4.5, where antenna Set-2 shows how the energy harvested varies. The harvesting efficiency is influenced by changes in distance and angle, but since the experiment operates within the near-field region, the variation in the received audio signal is minimal, with negligible

Table 4.3: Variation of antennas and transmit power used for the experiments

No.	Transmitter USRP	Receiver USRP	EH Module	Transmitted Power (P_T)
1	Directional antenna (3 dBi)	Directional antenna (3 dBi)	Directional antenna (3 dBi)	100%
2	Directional antenna (3 dBi)	Omnidirectional antenna (9 dBi)	Directional antenna (3 dBi)	100%
3	Omnidirectional antenna (9 dBi)	Directional antenna (3 dBi)	Omnidirectional antenna (9 dBi)	85%

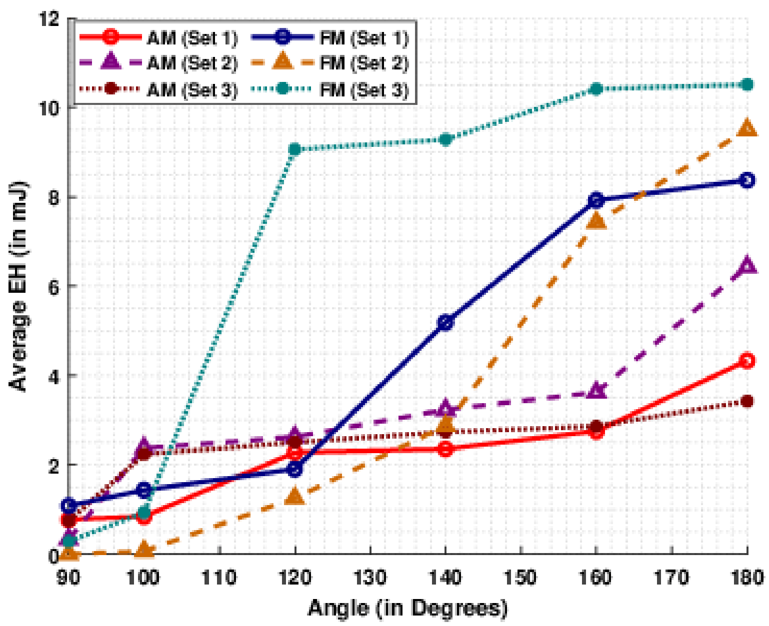
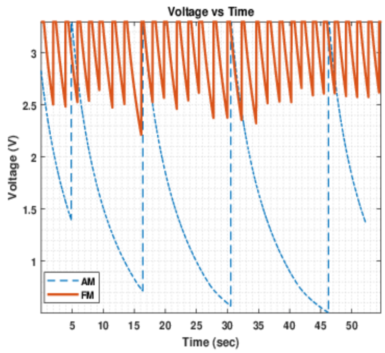


Figure 4.5: Effect of angle variation on average EH for a fixed separation distance of 8 cm and various antenna combinations.

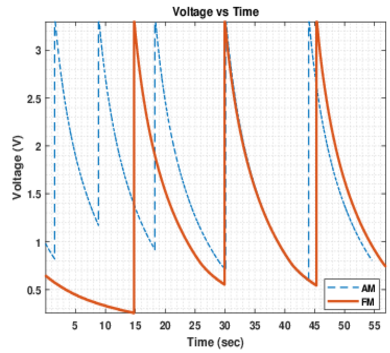
impact on the overall EH. The separated antenna approach is used to harvest energy at a fixed distance between the transmitter USRP and EH module alongside the receiver USRP at different angles in order to evaluate AM and FM. Table 4.3 describe the combination of antenna. Use of the AM and FM first row antenna combination (Set-1), the second row antenna combination (Set-2), and the third row antenna combination (Set-3). When we modify the antenna combination, the outcome shows the effect of utilizing a powerful antenna. When employing P_T is 85% the (Set-3) combination will be able to harvest more energy in FM. Since no changes were seen during information decoding in any of the combinations the benefit was only apparent in the gathered energy we only attain better performance than other antenna combinations.

4.3.2 Impact of angle variation between transmitter USRP, EH module and receiver USRP on SWIPT

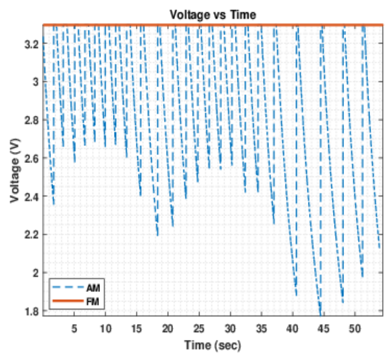
We are aware that LoS communication is not always feasible in real-world situations since the transmitter and user (receiver) are not always parallel due to the user's mobility. As a result, the angle difference between the transmitter and receiver sides will be significant. Angles between 90°and 180°are taken into account[2]. In order to illustrate the other angles condition, we take into account all angles except 180°, where the LoS condition is 180°, meaning that the transmitter and receiver will be parallel, and the cross-polarization effect will occur at 90°, where they will be perpendicular and these effect will shown in Fig. 4.5 as we go closer to 90°under these circumstances, the transmitted signal will attenuate, resulting in low transmitted signal intensity and deterioration of the communication system. From Fig. 4.5 even with a transmitting power (P_T) 85%, the FM will be able to harvest more energy by using (Set-3) form Table III combination of antennas, unlike other sets of combinations. Even at 140°, which is considered to be non-LoS conditions, we observe that



(a)



(b)



(c)

Figure 4.6: Comparison of the charging and discharging of a capacitor when the transmitted audio signal is modulated using AM and FM, while the angle between the transmitter and the EH module alongside the receiver is denoted as $\angle$, the separation distance as D, and the transmitted power as P_T (a) D = 4cm, P_T = 85%, $\angle$ = 140°(b) D = 6cm, P_T = 100%, $\angle$ = 90°(c) D = 10cm, P_T = 100%, $\angle$ = 140°using different combination of antenna given in Table III.

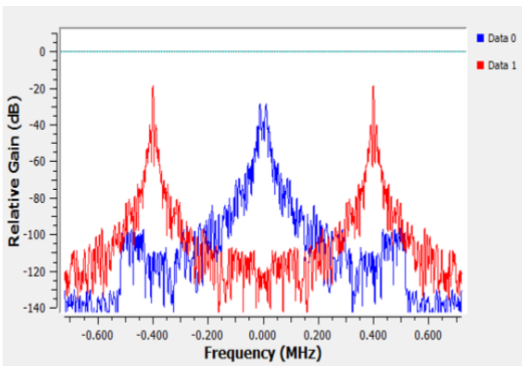
FM will give better results and harvest more energy than AM. Additionally at other angles (except LoS condition), FM will yield better result as compare to AM. However, as we move towards 90°less energy will be harvested but AM will give better results as compared to FM.

4.3.3 Impact of varying transceiver separation

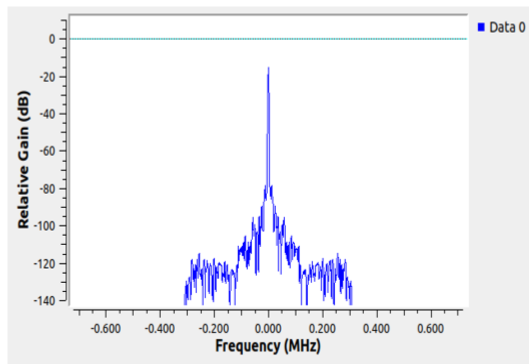
As we consider the distance, the transmitted power will begin to decay due to environmental penetration distortions, as proved by the Friis equation of transmission, which is as follows[18]

$$\frac{P_R}{P_T} \propto \frac{1}{D^2} \tag{4.2}$$

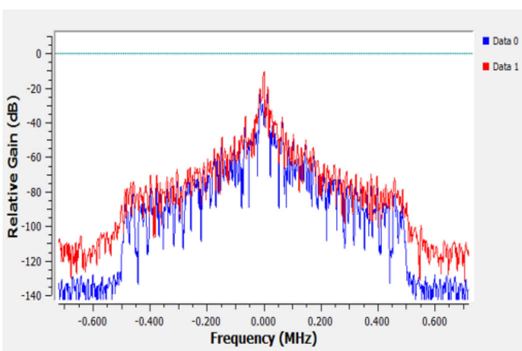
where D is the distance between the transmitter USRP and EH module, along with the receiver USRP, and P_T is the transmitted power and P_R is the received power. As can be seen, the impact of changing distance shows that the amount of energy harvested decreases as the distance between the transmitter and the EH module increases. Fig. 4.6 displays the capacitor's charging and discharging pattern as a function of time in seconds. The capacitor will charge up to a maximum voltage of 3.3V. The antenna combination (Set-1) of Table 4.3 will be used to obtain Fig. 4.6 (a), where the angle is 140°, the distance between the transmitter and EH module alongside the receiver is 4 cm, and the P_T is 85%. The charging and discharging time of the capacitor in the EH module will be faster with FM modulation compared to AM, allowing us to harvest more energy. Fig. 4.6 (b) using the antenna combination (Set-2) of Table 4.3, power P_T is 100% transmitted at a distance of 6 cm between the transmitter and the EH module, which is at a 90°. In the plot, the AM will charge and discharge quickly while the FM charges and discharges more slowly. As a result, the AM will harvest more harvest and energy, even when the cross-polarization effect occurs. Fig. 4.6 (c) using the (Set-3) combination of antennas, Fig. 4.6 (c) will display consistent results even when the transmitter and receiver are positioned 10 cm apart at 140°. When using P_T of 100% in addition, AM will take less time to charge and discharge, but FM will perform better overall than AM. At different distances, the charging and discharging patterns of the capacitor will vary, demonstrating the effect of varying distance between the transmitter and receiver, as shown in Fig. 4.6, which also validates eq. (2). Experimentally, it is observed that FM displays optimal performance when the antenna combination from Table 4.3 (Set-3) is used. With the aid of GNURadio companion software, the frequency spectrum of the transmitted and received audio signals are displayed in Fig. 4.7 above.



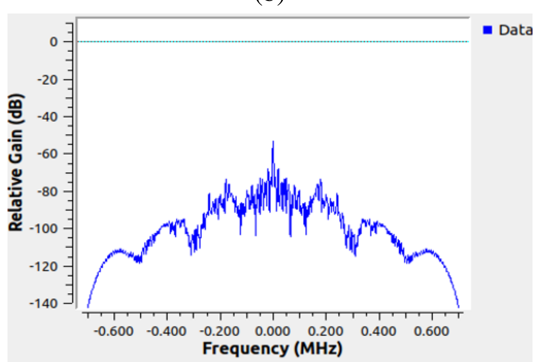
(a)



(b)



caption*(c)



(d)

Figure 4.7: Frequency spectrum of transmitted signal and received signal in both AM and FM.

The (Set-2) antenna combination listed in Table III will be used to get this figure. The original signal, known as Data 0, is defined by the blue color spectrum in Fig. 4.7 (a), while the modulated signal in AM is defined by the red spectrum. Following demodulation using GNURadio, the blue received signal spectrum (Data 0) is shown in Fig. 4.7 (b). The spectrum of the original audio in blue (Data 0) and the frequency modulated (FM) signal in red (Data 1) is shown in Fig. 4.7 (c). The spectrum of the signal received following FM demodulation is shown in blue in Fig. 4.7 (d). Since the audio volume will drop with increasing distance, we therefore conduct this research for the near-field region in order to obtain a spectrum that is roughly the same in every situation. As a result, we correspondingly optimized the information decoding for the near-field region.

4.4 SWIPT via Digital Modulation

As communication technologies continue to evolve toward advanced generations such as 4G, 5G, and beyond, digital modulation techniques are becoming increasingly critical for achieving high data rates, reliability, and spectral efficiency. Recognizing this shift, the present experimental study explored the feasibility of implementing Simultaneous Wireless Information and Power Transfer (SWIPT) using digital modulation schemes. Random digital signals were used as message inputs and modulated using techniques such as Amplitude Shift Keying (ASK), Phase Shift Keying (PSK), and Quadrature Amplitude Modulation (QAM) [6].

The results of the experiment confirm the possibility of achieving effective SWIPT using these digital modulation schemes. The system was not only able to decode the transmitted digital message accurately but also demonstrated the potential to transmit audio signals using the same modulation methods. At the receiver end, the recovered audio was optimized and intelligible, validating the reliability of digital modulation for communication. Simultaneously, a sufficient amount of energy was harvested from the transmitted RF signals to power low-energy devices such as IoT sensors. This confirms the viability of digital modulation-based SWIPT systems for future real-world applications where energy efficiency and wireless data transmission are both essential.

4.4.1 Amplitude Shift Key (ASK)

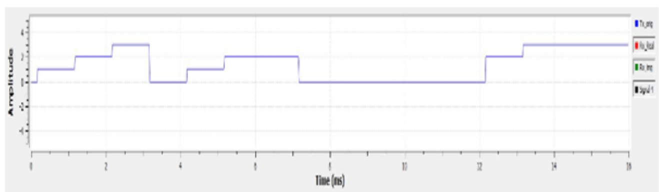


Figure 4.8: Shows the message signal that is being transmitted

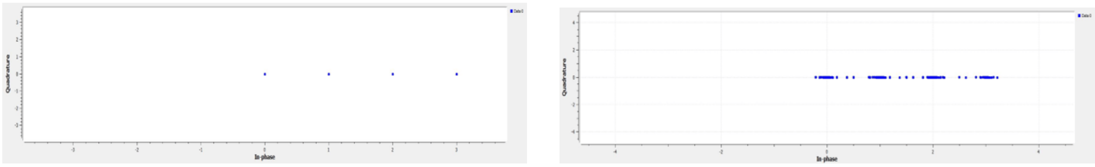
Amplitude Shift Keying (ASK) is a digital modulation technique in which the amplitude of the carrier signal is varied in accordance with the binary data signal. In its simplest form, known as Binary ASK (BASK), the carrier is present to represent a binary '1' and absent (or at a lower amplitude) to represent a binary '0' [6]. Mathematically, the ASK signal can be expressed as:

The amplitude shift keying (ASK) signal can be mathematically expressed as:

$$s(t) = \begin{cases} A \cdot \cos(2\pi f_c t), & \text{for binary 1} \\ 0, & \text{for binary 0} \end{cases}$$

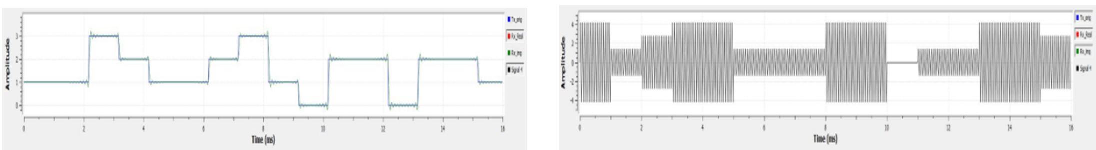
Where:

- A is the amplitude of the carrier signal,
- f_c is the carrier frequency,
- t represents time.



(a) (b)

Figure 4.9: Trasmitted & Received Constellation of 4-ASK



(a) (b)

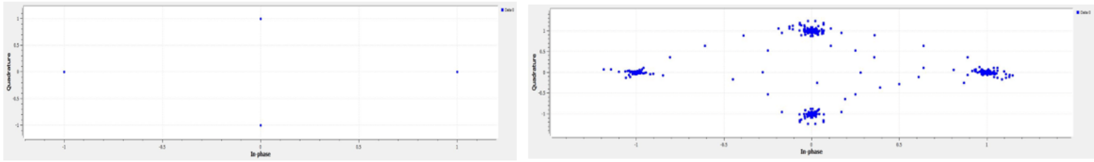
Figure 4.10: Received message signal & Modulated Signal

Fig. 4.8 displays the transmitted random signal, which serves as the input message for both Amplitude Shift Keying (ASK) and Phase Shift Keying (PSK) modulation schemes. Fig. 4.9 (a) illustrates the constellation diagram for the 4-ASK modulated signal, representing the discrete amplitude levels used during transmission. In comparison, Fig. 4.9 (b) shows the constellation at the receiver end, where the points appear scattered due to noise and interference from the surrounding environment, indicating the impact of signal distortion on demodulation accuracy.

In Fig. 4.10 (a), the blue waveform represents the original transmitted signal, while the green waveform depicts the corresponding received signal after demodulation, highlighting how the waveform is recovered. Fig. 4.10 (b) illustrates the amplitude variation of the carrier wave after modulation, reflecting how the carrier's amplitude changes in response to the modulating digital input in ASK.

4.4.2 Phase Shift Key (PSK)

Phase Shift Keying (PSK) is a digital modulation technique where the phase of a constant-frequency carrier signal is altered in accordance with the input binary data. Un-



(a) (b)

Figure 4.11: Trasmitted & Received Contellation of QPSK

like amplitude-based modulation schemes, PSK maintains a fixed amplitude and conveys information by changing the phase of the carrier waveform [6].

The phase shift keying (PSK) signal can be mathematically expressed as:

$$s(t) = A \cdot \cos(2\pi f_c t + \theta)$$

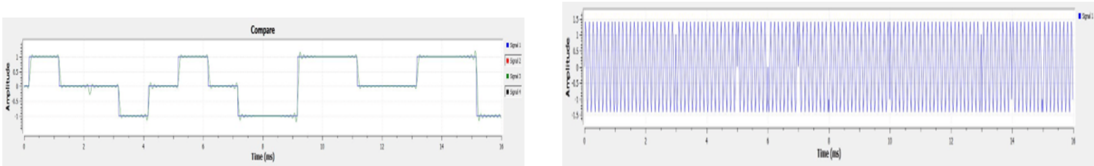
Where:

- A is the amplitude of the carrier signal,
- f_c is the carrier frequency,
- t represents time,
- θ is the phase shift applied based on the input data.

In the case of **Binary Phase Shift Keying (BPSK)**, the phase θ is typically:

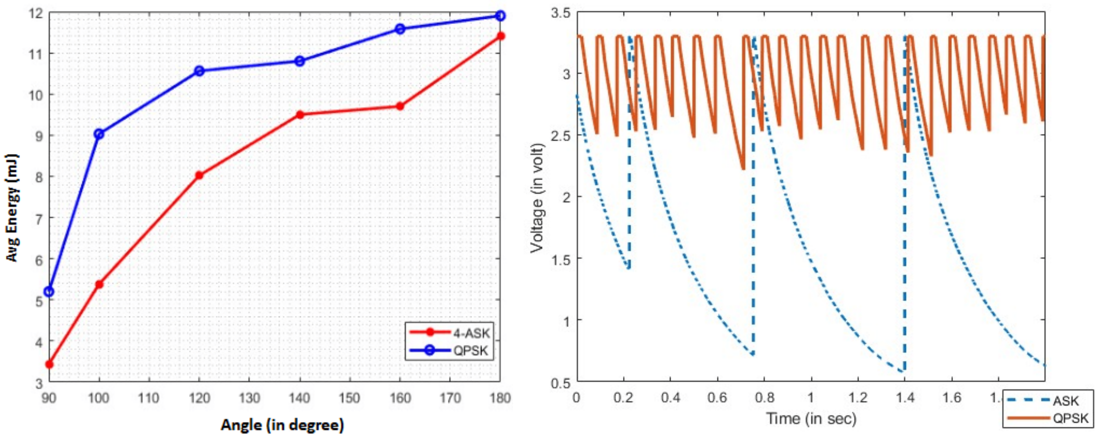
$$\theta = \begin{cases} 0, & \text{for binary 1} \\ \pi, & \text{for binary 0} \end{cases}$$

This results in two distinct signals, where the phase of the carrier is either 0 or π radians, depending on the binary input. Fig. 4.11 (a) represents the constellation diagram of the transmitted message signal using PSK modulation. In contrast, Fig. 4.11 (b) shows the received constellation at the receiver end, which appears distorted due to the presence of noise and signal interference during transmission.



(a) (b)

Figure 4.12: Received message signal & Modulated Signal of QPSK



(a) (b)

Figure 4.13: (a) Shows the average energy harvested at distance 6cm & angle 180°(b) Shows the charge-discharge cycle of capacitor at 8cm and transmitted power 90% at angle 140°

Fig. 4.12 (a) presents a comparison between the transmitted and received message signals at a separation distance of 6 cm. In this figure, the blue waveform indicates the original message signal, while the green waveform corresponds to the received signal after demodulation, highlighting minor distortions introduced during transmission. Fig. 4.12 (b) displays the waveform of the modulated PSK signal, showing the phase variations that carry the binary information.

4.4.3 Comparison of Energy Harvested (EH) from ASK and PSK

This section analyzes the energy harvested using 4-ASK and QPSK modulation formats at a fixed distance of 6 cm. Fig. 4.13 (a) illustrates the average energy harvested at this distance with the transmitter and receiver aligned at an angle of 180 °. The figure also highlights the charging and discharging behavior of the capacitor during the energy harvesting process.

In addition, Fig. 4.13 (b) presents the capacitor's charge-discharge cycle recorded at a distance of 8 cm, where the transmission power was set to 90 % and the alignment angle was adjusted to 140°. The plot provides a clear representation of how environmental factors, such as distance and angle, influence the efficiency and consistency of energy harvesting for both ASK and PSK modulated signals.

4.5 Applications

IoT sensors deployed in remote or hard-to-reach areas often face significant challenges when it comes to power management, particularly because conventional wired charging solutions are either impractical or completely unfeasible. In such scenarios, Simultaneous Wireless Information and Power Transfer (SWIPT) technology offers a transformative solution by enabling these sensors to harvest ambient radio frequency (RF) energy while simultaneously receiving data. This dual functionality eliminates the need for frequent battery replacements or the installation of dedicated power infrastructure [19, 20].

In defense and military sectors, this capability is particularly advantageous. Sensors used for secure communications, battlefield surveillance, target tracking, and situational awareness often need to operate autonomously and continuously in the field for extended periods. SWIPT can provide a reliable source of energy to these critical systems, reducing logistical burdens associated with battery maintenance and allowing for more discreet deployment without exposed power lines or frequent physical intervention.

Furthermore, the technology holds great promise for next-generation aerial platforms such as unmanned aerial vehicles (UAVs) and drones. During flight, drones equipped with communication and sensing modules could benefit from SWIPT by charging their onboard sensors wirelessly from ground stations or other airborne transmitters. This would not only reduce the weight of onboard power storage but also increase the operational range and duration of drones, enabling longer missions with enhanced data-gathering capabilities.

Looking ahead, the integration of SWIPT into various industries could significantly revolutionize power delivery in IoT networks. In smart agriculture, for instance, sensors distributed across vast farmland can continuously monitor soil health, humidity, temperature, and crop conditions without needing frequent recharging. In environmental monitoring, systems placed in remote forests, oceans, or mountain ranges can collect and transmit critical data related to climate change, pollution, and biodiversity without interruption. Similarly, in modern healthcare systems—particularly for wearable or implantable medical devices—SWIPT could support uninterrupted health monitoring, improving patient safety and reducing the need for invasive battery replacement procedures.

Overall, SWIPT presents a scalable, cost-effective, and sustainable approach to powering the rapidly expanding network of IoT devices, particularly in applications where traditional power solutions are limited by geography, infrastructure, or mobility constraints.

4.6 Conclusion

This experimental study demonstrated that SWIPT is achievable under real-time conditions. Practical analysis was conducted under various scenarios, including different distances, angles, and the significant impact of antenna variations. The results indicate that AM modulation achieves maximum EH at 90°, while FM modulation performs better as the system moves towards a LoS configuration. This is achieved by maintaining transmitted power at 85% using a 9 dBi omnidirectional transmitting antenna and a 3 dBi directional receiving antenna. Our findings reveal that at a 10 cm distance, clear audio reception and optimal EH are attainable. When the transmitted power P_T reaches 100%, EH becomes more efficient.

FM is identified as a preferable choice for EH within analog modulation techniques. Further research explores the potential of SWIPT using digital modulation schemes, which are widely implemented in modern communication systems.

In the implemented digital modulation techniques, we utilized 4-ASK and QPSK to explore the feasibility of Simultaneous Wireless Information and Power Transfer (SWIPT) using a random signal as the message input. Experimental results indicate that, under line-of-sight (LOS) conditions at a distance of 6 cm between the transmitter and receiver, and with 100% transmission power, it is possible to harvest more energy effectively. Furthermore, at a 140° angular offset, the QPSK modulation demonstrates better energy harvesting performance compared to 4-ASK. However, the received signal quality remains similar for both modulation schemes due to the short transmission distance, which minimizes signal degradation.

Chapter 5

Conclusion & Future Work

5.1 Conclusion

This experimental study successfully demonstrated the feasibility of Simultaneous Wireless Information and Power Transfer (SWIPT) using analog modulation techniques, specifically Amplitude Modulation (AM) and Frequency Modulation (FM), through a practical testbed built using USRP B210 devices and GNURadio. By utilizing a separated antenna architecture, the system achieved real-time signal decoding and concurrent energy harvesting. The experimental results showed that harvested energy is influenced by several factors including modulation type, antenna configuration, transmission angle, and transceiver separation distance.

Key findings include the observation that FM offers superior energy harvesting capability in non-Line-of-Sight (NLoS) conditions and longer distances, while AM showed better energy collection under certain angular configurations (e.g., 90°) and close-range setups. The use of directional and omnidirectional antenna combinations further validated the significance of antenna gain and radiation pattern in optimizing SWIPT performance. Additionally, voltage analysis through the MCP3008 ADC and Raspberry Pi enabled accurate estimation of the energy captured under different scenarios.

5.2 Future Work

While the current work focuses on analog modulation schemes, it sets the foundation for the next phase of research, which involves the practical realization of SWIPT using digital modulation techniques. The following directions are proposed for future exploration:

1. **Digital Modulation Integration**: Building on this work, future experiments will explore digital modulation techniques such as Binary Phase Shift Keying (BPSK), Quadrature Phase Shift Keying (QPSK), and Quadrature Amplitude Modulation (QAM) for SWIPT, which are more relevant to modern communication systems.

2. **Performance Comparison**: A comparative study between analog and digital modulation schemes in terms of energy harvesting efficiency, bit error rate (BER), and spectral efficiency under identical channel and hardware conditions will be carried out.

3. **Adaptive Modulation for SWIPT**: Development of an adaptive system that dynamically switches modulation techniques based on real-time channel conditions and energy needs can enhance system robustness and energy efficiency.

Real-World Deployment Scenarios: Further research will extend experiments beyond controlled laboratory environments into real-world scenarios, such as outdoor deployments and mobile platforms, including drones and IoT sensor nodes.

4. **Advanced Energy Harvesting Models**: Future work may involve implementing non-linear energy harvesting models to more accurately reflect circuit behavior and improve system-level energy predictions.

5. **Software Optimization**: Incorporation of machine learning algorithms for optimizing modulation parameters and antenna configurations in real time based on harvested energy and signal quality.

This work not only confirms the viability of using SWIPT with simple analog techniques but also establishes a strong baseline for integrating more advanced digital communication methods. As the next generation of IoT and wireless sensor networks emerges, such practical realizations are vital for designing systems that are both energy-aware and communication-efficient.

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