COMPREHENSIVE ANALYSIS AND QUANTIFICATION OF KEY PERFORMANCE MATRICES OF SWIPT SYSTEM

PROJECT REPORT (Phase II)

Submitted in partial fulfilment of the requirements for the award of
B. Tech Degree in Electronics and Communication Engineering
from the APJ Abdul Kalam Technological University

SUBMITTED BY

MP FARDEEN(SCT21EC069)

RAJARAM G(SCT21EC083)

SANDEEP S(LSCT21EC126)

DEPARTMENT OF ELECTRONICS & COMMUNICATION ENGINEERING
SREE CHITRA THIRUNAL COLLEGE OF ENGINEERING,
THIRUVANANTHAPURAM - 695018

MARCH 2025

SREE CHITRA THIRUNAL COLLEGE OF ENGINEERING,

THIRUVANANTHAPURAM - 695018

VISION OF THE INSTITUTION

To be an Engineering and Technology institution which is renowned for producing professionally capable and socially responsible engineers.

MISSION OF THE INSTITUTION

To create a teaching learning process for students to acquire engineering fundamentals, in an environment that encourages analysis, team work, entrepreneurship and ethical values, thus preparing them for productive careers.

DEPARTMENT OF ELECTRONICS & COMMUNICATION ENGINEERING

VISION OF THE DEPARTMENT

To be a centre of quality education and research in the field of Electronics and Communication Engineering, to mould socially responsible engineering professionals.

MISSION OF THE DEPARTMENT

1. To provide quality education ensuring systematic teaching-learning process.
2. To create an ambience to promote and foster research, entrepreneurship and industry interaction.
3. To impart value-based education to prepare students to become socially committed engineering professionals.

DEPARTMENT OF ELECTRONICS & COMMUNICATION ENGINEERING

SREE CHITRA THIRUNAL COLLEGE OF ENGINEERING,
THIRUVANANTHAPURAM - 695018

CERTIFICATE

Certified that the project phase I report entitled **"COMPREHENSIVE ANALYSIS AND QUANTIFICATION OF KEY PERFORMANCE MATRICES OF SWIPT SYSTEM"** is a bonafide report submitted by **MP FARDEEN(SCT21EC069), RAJARAM G(SCT21EC083) and SANDEEP S(LSCT21EC126)** in partial fulfilment for the award of Bachelor of Technology in **ELECTRONICS AND COMMUNICATION ENGINEERING** from **APJ Abdul Kalam Technological University.**

Prof. Salim Paul	**Dr. Renjith R J**
Project Guide	**Project Co-ordinator**
Associate Professor,	**Assistant Professor,**
Dept. of ECE,	**Dept. of ECE,**
SCTCE	**SCTCE**

Dr. Nisha Jose K
Head of the Department,
Dept. of ECE,
SCTCE

DECLARATION

We declare that this report titled **Comprehensive Analysis and Quantification of Key Performance Matrices of SWIPT System** in partial fulfilment for the award of the degree of Bachelor of Technology in **Electronics and Communication Engineering** of APJ Abdul Kalam Technological University, is a record of original work carried out by us and has not formed the basis for the award of any other degree or diploma, in this or any other Institution or University. In keeping with the ethical practice in reporting scientific information, due acknowledgements have been made wherever the findings of others have been cited.

Thiruvananthapuram

11th March 2025

MP FARDEEN(SCT21EC069)

RAJARAM G(SCT21EC083)

SANDEEP S (LSCT21EC126)

ACKNOWLEDGEMENT

We take this opportunity to thank all the people without whom conception and realization of this project would not have been possible. Our deep gratitude towards **Dr. C. Sathish Kumar, Principal, Sree Chitra Thirunal College of Engineering, Pappanamcode, Thiruvananthapuram**, for providing us with the opportunity and necessary facilities for the completion of the project. We acknowledge our sincere gratitude to **Dr. Nisha Jose K, Head of the Department, Department of Electronics and Communication Engineering**, for the valuable suggestions and advice during the course of work. We are immensely indebted to our project Co-ordinator, **Dr. Renjith R J, Assistant Professor**, **Department of Electronics Communication Engineering**, for his kind cooperation and encouragement, guiding us in every phase of work. We would like to convey our sincere thanks to our project guide, **Prof. Salim Paul, Associate Professor, Department of Electronics and Communication Engineering,** for providing his full-fledged support in making this project a success. We thank him from the bottom of our hearts for helping us and giving valuable suggestions for completing the project. We thank all other faculty members, technical and administrative staff of the Department of Electronics and Communication Engineering for their valuable support and heartfelt cooperation.

MP FARDEEN(SCT21EC069)

RAJARAM G(SCT21EC083)

SANDEEP S (LSCT21EC126)

ABSTRACT

In recent years, the integration of wireless power transfer with data communication has gained substantial attention, particularly in IoT and remote sensing applications where the availability of power sources is limited. This project delves into the comprehensive design, implementation, and performance evaluation of a Simultaneous Wireless Information and Power Transfer (SWIPT) system. SWIPT technology enables the simultaneous harvesting of energy and decoding of information from a unified wireless signal, which facilitates energy autonomy in connected devices and reduces the reliance on traditional power supplies.

The project’s objectives encompass the creation of a SWIPT model, extensive simulation to understand its operational dynamics, and the derivation of a mathematical model for precise quantification of critical performance metrics. Utilizing MATLAB and Simulink, the SWIPT model is designed and simulated to explore the efficiency of power conversion and the robustness of information transmission. Key performance metrics are analyzed, including Signal-to-Noise Ratio (SNR), Bit Error Rate (BER), throughput, energy conversion efficiency, and energy outage probability, each of which offers insights into the system's reliability and energy utilization.

The mathematical model derived for the SWIPT system provides equations that describe these performance metrics, enabling quantitative analysis and predictive modeling of system behavior under varying conditions. Simulation results highlight the effectiveness of the SWIPT system in environments characterized by different noise levels and energy requirements, offering a benchmark for future SWIPT implementations.

This project contributes to the growing body of knowledge on wireless energy and information systems, with implications for IoT, sensor networks, and remote agricultural monitoring. The findings underscore the potential for SWIPT systems to enhance operational efficiency in energy-constrained environments, supporting applications in agriculture, healthcare, and industrial IoT where uninterrupted data flow and power availability are paramount.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND ABBREVIATIONS

SWIPT	Simultaneous wireless Information and Power Transfer
EH	Energy harvesting
ID	Information Decoding
PSR	Power splitting Relay
BER	Bit Error Rate
SNR	Signal To Noise Ratio
BPSK	Binary Phase Shift Keying
DC	Direct Current
IoT	Internet Of Things
AWGN	Additive White Gaussian Noise
LOS	Line Of Sight
NLOS	Non-Line of Sight
5G	Fifth-Generation Wireless Technology
6G	Sixth-Generation Wireless Technology
MIMO	Multiple Input Multiple Output
OFDM	Orthogonal Frequency Division Multiplexing
CSI	Channel State Information
QoS	Quality of Service

CHAPTER 1

INTRODUCTION

Simultaneous Wireless Information and Power Transfer (SWIPT) is an emerging wireless communication technology that enables the concurrent transmission of both energy and data over a shared wireless channel. Unlike conventional systems that transmit only information, SWIPT facilitates energy harvesting from the received signal, allowing energy-constrained devices to function without relying solely on battery power. This technology is particularly beneficial for Internet of Things (IoT) networks, wireless sensor networks (WSNs), biomedical applications, and next-generation (5G and beyond) communication systems. In a SWIPT system, a wireless signal transmits both power and information concurrently. This setup allows IoT devices, such as sensors and cameras, to capture data, decode information, and harvest energy from the same signal, significantly optimizing energy consumption. This project focuses on designing and implementing a SWIPT model capable of supporting information decoding and energy harvesting, using MATLAB and Simulink to simulate the SWIPT system's behavior under real-world conditions.

Simultaneous Wireless Information and Power Transfer (SWIPT) is an advanced wireless communication technology that enables devices to harvest energy while receiving data, making it crucial for IoT, 5G, wireless sensor networks, and biomedical applications. SWIPT employs power splitting (PS) techniques at the receiver to balance energy harvesting and information decoding. The whole project is focused on MATLAB Simulink model was developed to analyse SWIPT performance under Rayleigh fading and AWGN noise, supported by a mathematical framework evaluating SNR, BER, and outage probability. This project contributes to ongoing advancements in SWIPT technology, providing a foundation for developing sustainable, self-powering IoT devices. The insights gained from this study will serve as a guideline for optimizing SWIPT systems, with implications for real-world applications where long-term, reliable power and data transmission are essential.

CHAPTER 2

LITERATURE REVIEW

Simultaneous Wireless Information and Power Transfer (SWIPT) has gained significant interest in recent years due to its potential in enhancing energy efficiency and data reliability in wireless communication networks. As IoT, remote sensing, and autonomous sensor networks continue to expand, SWIPT offers an innovative solution to the constraints of limited power sources by allowing devices to both communicate and recharge using the same RF signal. The literature on SWIPT covers various aspects, including theoretical frameworks, energy harvesting models, modulation techniques, and practical implementations across different fields. This survey provides a comprehensive review of key contributions in the SWIPT domain.

SWIPT System Design and Energy Efficiency Optimization

S. Bi, C. K. Ho, and R. Zhang, "Wireless powered communication: Opportunities and challenges," *IEEE Communications Magazine*, vol. 53, no. 4, pp. 117-125, Apr. 2015. This paper provides a comprehensive analysis of wireless powered communication networks (WPCNs), focusing on the integration of energy harvesting and information transfer in SWIPT systems. The authors discuss the fundamental trade-offs between harvested energy and data rate, considering various system architectures such as time-switching and power-splitting receivers. The study highlights the need for optimal power allocation and beamforming strategies to improve system efficiency while minimizing bit error rate (BER).Performance Metrics and Mathematical Modelling

Rate-Energy Tradeoff in SWIPT Networks

X. Zhou, R. Zhang, and C. K. Ho, "Wireless information and power transfer: Architecture design and rate-energy trade-off," *IEEE Transactions on Communications*, vol. 61, no. 11, pp. 4757-4767, Nov. 2013.

This paper introduces an analytical framework for understanding the trade-off between information rate and harvested energy in SWIPT systems. The study categorizes SWIPT architectures into separated, co-located, and integrated receiver designs and evaluates their performance under practical wireless fading conditions. It demonstrates that increasing the power splitting ratio (ρ) improves energy harvesting but results in a degradation of the signal-to-noise ratio (SNR), leading to higher BER. This trade-off is crucial in resource-constrained IoT applications, where both energy and data reliability are critical.

Optimization of Power Splitting in SWIPT for IoT Applications

S. Yin, Z. Qu, and W. Liu, "Resource allocation and performance optimization in SWIPT-enabled IoT networks," *IEEE Internet of Things Journal*, vol. 6, no. 5, pp. 8254-8265, Oct. 2019.

This paper focuses on resource allocation techniques to optimize power splitting and energy harvesting in SWIPT-based IoT networks. The authors propose a novel game-theoretic approach to dynamically adjust the power splitting ratio based on the real-time energy demands of IoT devices. Their results show that an adaptive power splitting strategy can significantly enhance energy efficiency while maintaining an acceptable BER. The study is particularly relevant for low-power IoT sensor networks, where energy efficiency is crucial for prolonged operation.

SWIPT in 5G and Future Wireless Networks

X. Lu, P. Wang, D. Niyato, D. I. Kim, and Z. Han, "Wireless networks with RF energy harvesting: A contemporary survey," *IEEE Communications Surveys & Tutorials*, vol. 17, no. 2, pp. 757-789, 2015.

This survey paper provides an extensive review of RF energy harvesting and SWIPT techniques in the context of 5G and beyond wireless networks. It discusses beamforming, cooperative communication, and relaying strategies to enhance SWIPT performance. The paper also highlights challenges in security, interference management, and hardware constraints for practical implementation. The findings suggest that machine learning-based resource allocation could be a key enabler for adaptive power control and energy-efficient communication in future SWIPT-enabled networks.

CHAPTER 3

AIM AND OBJECTIVES

3.1 AIM

The primary aim of this study is to analyze, model, and optimize the performance of a Simultaneous Wireless Information and Power Transfer (SWIPT) system by evaluating its fundamental parameters, including Signal-to-Noise Ratio (SNR), Bit Error Rate (BER), and Outage Probability. The SWIPT system is a crucial component in modern wireless networks, especially for Internet of Things (IoT) applications, where wireless devices require both energy and data transmission simultaneously. This study aims to explore the trade-offs between energy harvesting (EH) and information decoding (ID) in a wireless system where a portion of the received signal is used for energy harvesting, while the remaining portion is used for decoding information.

To achieve this, both theoretical analysis and experimental evaluation will be conducted. The theoretical framework will involve deriving mathematical models to describe how system parameters vary under different conditions, particularly in the presence of Rayleigh fading channels, which represent a realistic wireless environment. Additionally, Monte Carlo simulations will be implemented to verify theoretical findings and provide deeper insights into system behavior through numerical experiments.

By comparing theoretical and experimental results, the study aims to optimize the power splitting ratio to ensure an efficient balance between wireless energy transfer and communication performance. The findings from this research will help in the design and deployment of SWIPT-enabled IoT networks, wireless sensor systems, and smart agriculture applications, where energy efficiency and reliable communication are essential.

3.2 OBJECTIVES

1. Theoretical Analysis of SWIPT System Parameters (SNR, BER, Outage Probability
    - Develop mathematical models to describe the behavior of SWIPT systems under different wireless channel conditions.
    - Derive expressions for SNR, BER, and Outage Probability for various power splitting ratios in a Rayleigh fading channel.
    - Study the trade-off between information decoding and energy harvesting efficiency to optimize system performance.

2. Conducting Experimental Analysis Using Monte Carlo Simulations
    - Implement Monte Carlo simulations in MATLAB to model the performance of SWIPT systems over multiple random channel realizations.
    - Generate large-scale simulation data to statistically analyze the effect of fading, noise, and power allocation on system performance.
    - Evaluate the impact of different power splitting ratios on energy harvesting efficiency and communication reliability.

3. Comparison of Theoretical and Experimental Results
    - Validate theoretical models by comparing them with simulation results.
    - Analyze the deviations between theoretical and experimental outcomes to identify practical constraints and real-world implementation challenges.
    - Provide insights into optimizing SWIPT system design for improved wireless energy transfer and communication efficiency.

These objectives aim to establish a comprehensive understanding of SWIPT systems, helping to enhance their efficiency for practical applications such as IoT networks and wireless sensor systems.

CHAPTER 4

PERFORMANCE MATRICES ANALYSIS

In this project the performance matrices like Signal to noise ratio, Bit error rate, outage probability is being derived and analyzed under theoretical and experimental scenarios.

4.1 Signal-to-Noise Ratio (SNR) Analysis

In a Simultaneous Wireless Information and Power Transfer (SWIPT) system, the received signal is used for both information decoding (ID) and energy harvesting (EH). The SNR (Signal-to-Noise Ratio) is a crucial parameter that determines the quality of the received signal for information processing.

Since the received power is split between energy harvesting and information decoding using a power splitting ratio ρ, the available power for decoding is reduced, which directly impacts the SNR at the receiver. The SNR in a SWIPT system depends on various system parameters.

Derivation of SNR of the SWIPT system model

In phase 1 of the project the transmitter, channel and receiver is being modelled for deriving the SNR we have to consider the following equations:

- Transmitted signal

$$s_{txn}(t) = G.s_{RF}(t) = A.cos(2\pi f_{RF}t + \theta_i) \ldots\ldots\ldots\ldots..(1)$$

- Channel model

$$r(t) = |h(t)|.G.A.\cos(2\pi f_{RF}t + \theta_i + \emptyset(t)) + n(t) \ldots\ldots\ldots (2)$$

- Received signal

At energy harvesting path:

$$r_{rect}(t) = \sqrt{\rho}\left||h(t)|.G.A.\cos(2\pi f_{RF}t + \theta_i + \emptyset(t) + n(t)\right|\ldots\ldots\ldots (3)$$

At information decoding path:

$$r_{base}(t) = \sqrt{1-\rho}.\,(|h(t)|.\,G.\,A.\cos(2\pi f_{RF}t + \theta_i + \emptyset(t) + n(t)).$$
$$\cos(\,2\pi f_{RF}t) \text{ ………………... (4)}$$

From the received signal equation, we can derive the equations for the SNR.

From equation (4)

The **signal component** is:

$$s(t) = \sqrt{1-\rho}.\,|h(t)|.\,G.\,A.\cos(\theta_i + \emptyset(t)) \text{………… (5)}$$

The **power** of the signal is calculated as:

$$P_{Signal} = E[s(t)^2] \text{……………………………………… (6)}$$

Substituting (5) in (6) and simplifying:

$$P_{Signal} = \; 1-\rho.\,|h(t)|^2.\,G^2.\,A^2.\,E\left[\cos^2\left(\theta_i + \emptyset(t)\right)\right] \text{…….. (7)}$$

For BPSK, $\cos^2\left(\theta_i + \emptyset(t)\right)$ has an average power $\frac{1}{2}$

$$P_{Signal} = \frac{1-\rho.|h(t)|^2.G^2.A^2}{2} \text{…………….. (8)}$$

The **noise component** is: $n_{base}(t)$

Since $n_{base}(t)$ is AWGN, its power spectral density N_0.

The **noise power** is:

$$P_{noise} = N_0 \text{………………….(9)}$$

N_0 *is taken because we are only considering high frequency*

The **SNR** is defined as the ratio of signal power to noise power:

$$SNR = \frac{P_{Signal}}{P_{noise}} \text{……………… (10)}$$

Substituting (8) and (9) in (10)

$$SNR = \frac{1-\rho.|h(t)|^2.G^2.A^2}{2N_0} \text{………………………….. (11)}$$

Equation (11) is the SNR of the SWIPT model the SNR depends on the

- Power splitting ratio (ρ)
- h(t) fading channel coefficient
- G – gain of the power amplifier
- A – amplitude of the signal
- N_0 – Power spectral density of noise

4.2 Bit Error Rate (BER) Analysis

The **Bit Error Rate (BER)** for BPSK under AWGN is given by

$BER = Q(2.\sqrt{SNR})$…………….. (12)

The average probability of error is computed by integrating the error probability in AWGN over the fading distribution.

$\bar{P} = \int_0^{\infty} P_s(\gamma) P_{\gamma s}(\gamma) d\gamma$……….. (13)

Were, $P_s(\gamma)$ *is the probabilty of error of under AWGN channel.*

$P_{\gamma s}(\gamma)$ is the probabilty of error under Rayliegh fading channel.

For a given distribution of the fading amplitude r, we compute $P_{\gamma s}(\gamma)$ by making the change of variable

$P_{\gamma s}(\gamma) d\gamma$= P$(r)\ dr$………….. (14)

The received signal amplitude r has Rayleigh distribution

$p(r)$=$\frac{r}{\sigma^2} e^{\frac{-r^2}{2\sigma^2}}, r \geq 0$…………….. (15)

The SNR per symbol for a given amplitude r is

$\gamma = \frac{r^2 T_s}{2\sigma_n^2}$……….. (16)

Differentiating both sides of this expression yields

Substituting 16 and 17 into 15 and then 14 yields

$P_{\gamma s}(\gamma)$= $\frac{\sigma_n^2}{\sigma^2 T^s} e^{-\gamma\sigma_n^2 / \sigma^2 T_s}$……………………… (18)

Since the average SNR per symbol $\bar{\gamma}$ is just $\frac{\sigma^2 T^s}{\sigma_n^2}$ we can rewrite 18 as

$P_{\gamma s}(\gamma)$ = $\frac{1}{\bar{\gamma}_s} e^{\frac{-\gamma}{\bar{\gamma}_s}}$…………………… (19)

For binary signaling this reduces to

$P_{\gamma_s} = \frac{1}{\bar{\gamma}_b} e^{\frac{-\gamma}{\bar{\gamma}_b}}$…………… (20)

Integrating BER of AWGN over the distribution (20) yields the following average probability of error for BPSK in Rayleigh fading:

$\bar{P}_b = \frac{1}{2}\left[1 - \sqrt{\frac{\bar{\gamma}_b}{1+\bar{\gamma}_b}}\right] \approx \frac{1}{4\bar{\gamma}_b}$……….. (21)

Were, $\bar{\gamma}_b$ is the SNR of the SWIPT system model i.e. equation (11)

Substituting (11) in (21)

$\bar{P}_b = \frac{1}{2}\left[1 - \sqrt{\frac{\frac{1-\rho.|h(t)|^2.G^2.A^2}{2N_0}}{1+\frac{1-\rho.|h(t)|^2.G^2.A^2}{2N_0}}}\right]$……… (22)

$\bar{P}_b$ is the Bit error rate of the SWIPT system

Bit Error Rate (BER) analysis in SWIPT systems evaluates how reliably information is decoded while considering the trade-off between energy harvesting (EH) and information decoding (ID). Since a fraction (ρ) of the received power is allocated to EH, the remaining power (1−ρ) is used for decoding, affecting the Signal-to-Noise Ratio (SNR) and, consequently, the BER. The BER is typically derived as a function of SNR using modulation schemes like BPSK or QPSK, where a higher SNR leads to lower BER, ensuring better communication reliability. The general BER expression for a SWIPT system in a Rayleigh fading channel is given by

$$\bar{P}_b = \frac{1}{2}\left[1 - \sqrt{\frac{\frac{1-\rho.|h(t)|^2.G^2.A^2}{2N_0}}{1+\frac{1-\rho.|h(t)|^2.G^2.A^2}{2N_0}}}\right]$$

This equation shows that as ρ increases, more power is harvested, but BER worsens due to reduced SNR. Conversely, a lower ρ improves BER at the cost of reduced energy harvesting. Thus, selecting an optimal ρ is crucial to achieving a balance between reliable data transmission and efficient energy harvesting in SWIPT systems.

4.3 Outage Probability Analysis

Outage probability is a crucial performance metric in Simultaneous Wireless Information and Power Transfer (SWIPT) systems. It quantifies the probability that the received Signal-to-Noise Ratio (SNR) falls below a certain threshold, leading to a failure in reliable communication.

Outage probability relative to γ_0 is defined as

$P_{out} = p(\gamma_s < \gamma_0) = \int_0^{\gamma_0} p_{\gamma_s}(\gamma)d\gamma$........... (23)

In Rayleigh fading the outage probability becomes

$P_{out}=\int_0^{\gamma_0} \frac{1}{\bar{\gamma}} e^{\frac{-\gamma_s}{\bar{\gamma}_s}} d\gamma_s = 1 - e^{\frac{-\gamma_0}{\bar{\gamma}_s}}$............... (24)

Substituting γ_s in (24)

$P_{out} = 1 - e^{\frac{-2\gamma_0 N_0}{(1-\rho).|h(t)|^2.G^2.A^2}}$............... (25)

The power splitting ratio (ρ) in a SWIPT system directly impacts the outage probability, as it determines how much of the received power is allocated to energy harvesting (EH) versus information decoding (ID). When ρ increases, more power is diverted toward EH, leaving less power available for signal detection and increasing the likelihood of the received SNR falling below the threshold (γ_0). This results in a higher outage probability, meaning the system experiences more frequent communication failures. Mathematically, the outage probability follows the exponential relation

$$P_{out} = 1 - e^{\frac{-2\gamma_0 N_0}{(1-\rho).|h(t)|^2.G^2.A^2}}$$

which shows that as ρ approaches 1, as $1 - \rho.|h(t)|^2.G^2.A^2$ decreases, causing P_{out} to increase significantly. Conversely, when ρ is low, more power is allocated to ID, improving the SNR and reducing outage probability, ensuring more reliable communication. However, reducing ρ too much limits the harvested energy, making it unsuitable for applications requiring significant wireless power transfer. Therefore, an optimal ρ must be selected to balance energy efficiency and communication reliability, depending on the system's quality of service (QoS) requirements.

4.4 Power Trade off Analysis

Simultaneous Wireless Information and Power Transfer (SWIPT) enables the concurrent transmission of energy and data over the same wireless channel, where the received power is split between energy harvesting (EH) and information decoding (ID) using a power splitting ratio ρ. The received power P_r is influenced by Rayleigh fading, path loss, and noise, and is modelled as $P_r = |h|^2 . P_t . L_p + N_0$. The energy harvested is given by $P_{EH} = \rho . P_r$, while the power available for decoding is $P_{ID} = (1 - \rho) . P_r$. Monte Carlo simulations analyse the system's efficiency by averaging multiple wireless channel realizations, showing a fundamental trade-off: increasing ρ enhances energy harvesting but reduces information decoding capability. Efficiency metrics, including EH efficiency, ID efficiency, and overall system efficiency, help evaluate performance. Theoretical and simulated results confirm that optimizing ρ\rhoρ is crucial for balancing energy harvesting and reliable data transmission in SWIPT systems.

Transmitted power is expressed as the equations as

$P_t = G_{PA} . P_{in}$………. (26)

Were, P_t is the transmitted power

G_{PA} is the Gain of the power amplifier

P_{in} is the input power

Received power is expressed as the equations as

$P_r = |h|^2 . P_t . L_p + N_0$……… (27)

Were, $|h|^2$ is the Rayliegh fading coefficient

N_0 is the noise power

L_p is the path loss model that has been incorporated in order to measure the changes in the power received due to increase in the distance between transmitter and receiver.

Were, $L_p = \left(\frac{d_0}{d}\right)^n$

d_0 is the reference distance

d is the receiver distance

n is the path loss exponent.

Power allocation for energy Harvesting and Information Decoding paths

Using the power splitting ratio ρ the received signal power is split into EH and ID paths

Energy harvesting power

$P_{EH} = \rho . P_r$………. (28)

Information decoding power

$P_{ID} = (1 - \rho) . P_r$……… (29)

System efficiency can be expressed as

$\eta_{EH} = \frac{P_{EH}}{P_t}$ ………… (30) is the efficiency of EH path

$\eta_{ID} = \frac{P_{ID}}{P_t}$ ………….. (31) is the efficiency of ID path

Total system efficiency is

$\eta_{total} = \frac{P_{EH}+P_{ID}}{P_t}$ ………. (32)

The derived equations provide a mathematical framework for analysing Simultaneous Wireless Information and Power Transfer (SWIPT), demonstrating how the received power is distributed between energy harvesting (EH) and information decoding (ID). The expressions for transmitted power (Pt), received power (Pr), and path loss (Lp) help quantify the impact of channel fading and propagation effects on power distribution. The power splitting ratio ρ determines the trade-off between EH and ID, with higher ρ favouring energy harvesting but reducing the power available for decoding. Efficiency metrics η_{EH} , η_{ID} and η_{total} provide insight into system performance and optimization strategies. These derivations are crucial for designing and optimizing SWIPT-based wireless networks, ensuring efficient power allocation for IoT applications, wireless sensor networks, and energy-constrained communication systems, where balancing power efficiency and reliable data transmission is essential.

CHAPTER 5

SIMULATION AND RESULTS

The derived equations for the performance matrices are codded and plotted in MATLAB in order to analyze the signal quality and efficiency based on the power splitting ratio. The simulation is carried out in theoretical and experimental analysis of the system in order to compare the results. For experimental analysis we use Monte Carlo simulation setup. Monte Carlo Simulation is a computational technique used to model and analyse complex systems by performing random sampling to obtain numerical results. It is widely used in engineering, finance, physics, and communication systems to evaluate the performance of probabilistic models that are difficult to solve analytically.

In wireless communication, Monte Carlo simulations are commonly used to analyse the performance of systems under different fading conditions, noise levels, and signal processing techniques. The key idea is to generate a large number of random channel realizations and compute the system's performance metrics, such as Bit Error Rate (BER), Outage Probability, and Signal-to-Noise Ratio (SNR), over these realizations. The results are then averaged to estimate the system's overall behaviour.

5.1 BER v/s SNR Analysis

Bit Error Rate (BER) vs. Signal-to-Noise Ratio (SNR) analysis is a fundamental performance evaluation method in wireless communication systems. BER represents the probability of bit errors occurring during transmission, while SNR quantifies the signal strength relative to noise power. This analysis is crucial in understanding how efficiently a communication system can transmit data under varying channel conditions.

In Simultaneous Wireless Information and Power Transfer (SWIPT) systems, the BER is influenced by factors such as power splitting ratio (ρ), channel fading (Rayleigh or Rician), and noise levels. Higher SNR typically results in a lower BER, indicating better signal quality and improved data transmission reliability. However, in SWIPT systems, increasing ρ for energy harvesting reduces the available power for information decoding, which affects BER performance.

By plotting BER against SNR, we can analyze the impact of different system parameters on communication performance. Monte Carlo simulations are often employed to validate theoretical BER expressions, providing insights into system optimization for practical applications.

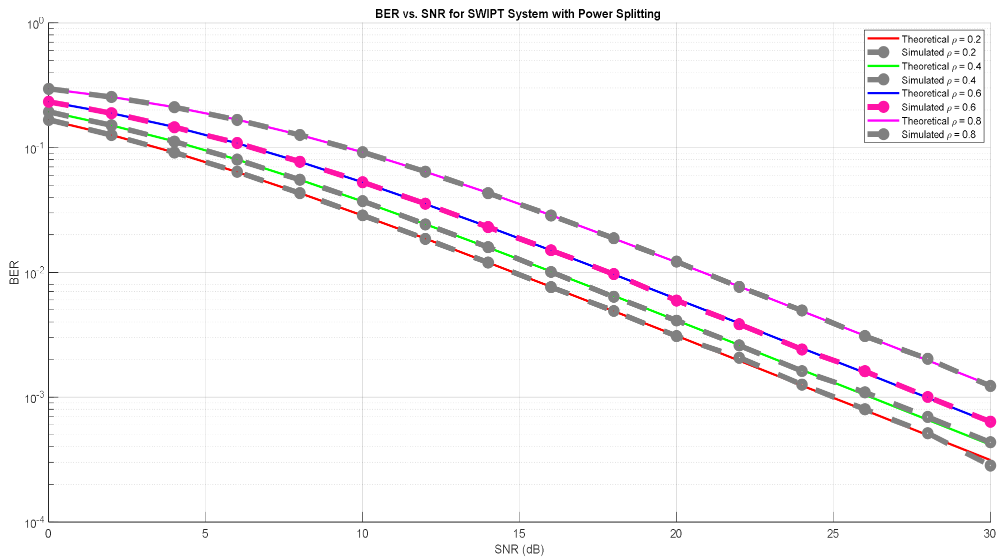

Fig. 5.1 BER v/s SNR plot

The plot illustrates the relationship between the Bit Error Rate (BER) and Signal-to-Noise Ratio (SNR) for a Simultaneous Wireless Information and Power Transfer (SWIPT) system under Rayleigh fading conditions. The analysis is conducted for different power splitting ratios (ρ), which determine the fraction of received power used for energy harvesting. The theoretical values (solid lines) are compared with simulated values (marked points) for validation. The BER is plotted on a logarithmic scale against the SNR (dB), demonstrating the system's performance across varying noise and power allocation conditions. As expected, BER decreases with increasing SNR, confirming improved transmission reliability at higher power levels.

Effect of Power Splitting Ratio (ρ) on BER Performance

The plot contains multiple curves corresponding to different values of ρ (0.2, 0.4, 0.6, and 0.8). A clear trend is observed where higher values of ρ result in a higher BER across all SNR levels. This is because a larger fraction of the received power is allocated to energy harvesting, reducing the power available for information decoding. For instance, at SNR = 10 dB, the BER for $\rho=0.2$ is significantly lower compared to $\rho=0.8$, indicating better reliability when more power is used for signal processing. The gap between the theoretical and simulated curves is minimal, validating the accuracy of the mathematical models used for BER estimation.

Key Observations and Trade-offs

From the analysis, an important trade-off is highlighted, higher energy harvesting (ρ) degrades BER performance, while lower ρ ensures better communication reliability. This trade-off is crucial in SWIPT applications, where balancing power for energy harvesting and information processing is essential. The results suggest that optimal performance can be achieved for moderate values of ρ (e.g., 0.4 to 0.6), ensuring a balance between reliable data transmission and sufficient energy harvesting. The overall trend of the BER vs. SNR plot aligns with theoretical expectations, confirming that an increase in SNR improves system performance. These insights are critical for designing energy-efficient wireless communication systems where both data transmission and power transfer must be optimized.

- The SNR vs. BER analysis confirmed that increasing ρ increases BER, highlighting the need for an optimal power splitting ratio to balance energy harvesting and communication reliability.
- The outage probability analysis showed that at higher SNR values, outage probability decreases, ensuring better system performance.
- The results confirm the fundamental SWIPT trade-off, where excessive power allocation to energy harvesting (ρ) degrades data transmission quality.
- The optimal ρ range should be chosen based on the application requirements:
    - Low ρ (0.1 - 0.3): Better BER, low outage, but less energy harvested.
    - Moderate ρ (0.4 - 0.5): Balanced trade-off for IoT applications.
    - High ρ (0.6 - 0.9): More energy harvested but unreliable communication.

5.2 Outage Probability Analysis

Outage probability is a key performance metric in wireless communication systems that measures the probability that the received signal-to-noise ratio (SNR) falls below a predefined threshold, leading to unreliable communication. In Simultaneous Wireless Information and Power Transfer (SWIPT) systems, the outage probability is influenced by multiple factors such as channel fading, noise power, and power splitting ratio (ρ). A lower outage probability indicates better system performance, ensuring reliable data transmission.

The power splitting ratio (ρ) determines how much of the received power is allocated for energy harvesting versus information decoding. A higher ρ means more power is diverted to energy harvesting, leaving less power for decoding, which increases outage probability. Conversely, a lower ρ prioritizes information decoding, leading to lower outage probability. However, reducing ρ too much may impact the sustainability of the system, as insufficient energy harvesting can hinder the operation of wireless devices. Therefore, an optimal ρ needs to be selected based on the trade-off between energy harvesting and reliable communication.

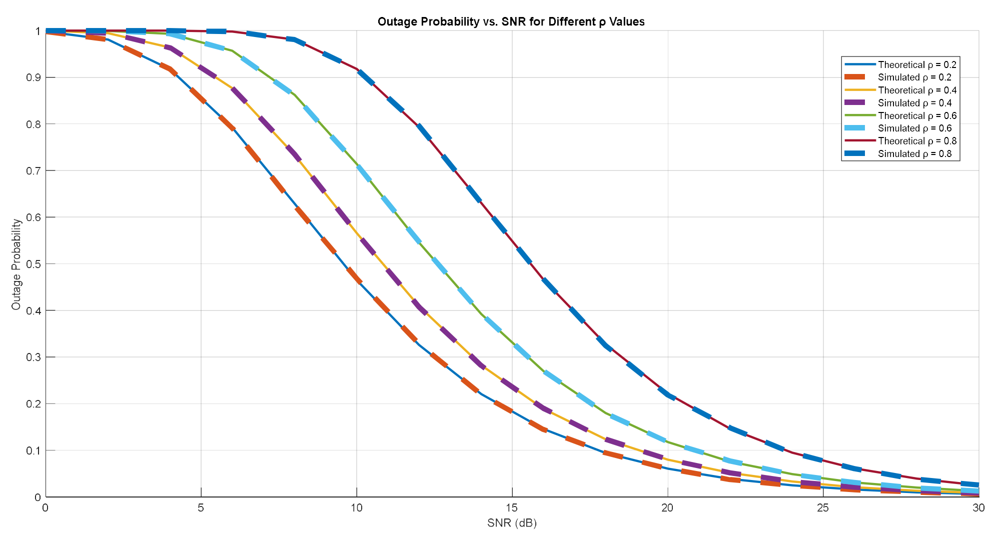

Fig. 5.2 Outage probability plot

From the outage probability plot, several key trends are observed

1. **Higher SNR Reduces Outage Probability**: As SNR increases, outage probability decreases for all values of ρ. This is because stronger received

signals improve decoding performance, reducing the likelihood of outage events.

2. **Impact of ρ on Outage Performance**: At any given SNR, higher values of ρ (e.g., 0.8) result in a higher outage probability, whereas lower values of ρ (e.g., 0.2) exhibit better reliability with lower outage probability.

3. **Theoretical vs. Simulated Results**: The theoretical and simulated curves show a strong correlation, validating the accuracy of the analytical outage probability model. The minor deviations can be attributed to Monte Carlo simulation variations and approximations in the theoretical model.

4. **Sharp Drop in Outage Probability**: There is a steep decline in outage probability as SNR increases from low to moderate values. Beyond a certain SNR (~20 dB), the curves start to flatten, indicating diminishing improvements in outage probability with further SNR increases.

Overall, the analysis demonstrates that optimizing ρ is essential for balancing energy harvesting and communication reliability. This trade-off must be carefully considered in SWIPT-based IoT and wireless power transfer applications.

5.3 Power Trade-off Analysis

Power trade-off analysis in Simultaneous Wireless Information and Power Transfer (SWIPT) is essential for optimizing the balance between energy harvesting (EH) and information decoding (ID) in wireless communication systems. Since the received signal power is split between these two functions, an efficient allocation strategy is required to ensure both reliable data transmission and sufficient energy harvesting. By analysing power allocation using different power splitting ratios (ρ), we can evaluate the trade-off between maximizing harvested energy and maintaining signal quality for decoding. This analysis is crucial for the design of energy-efficient IoT networks, wireless sensor systems, and next-generation communication protocols, where energy constraints play a significant role in system performance.

Power Splitting Ratio	$P_t(W)$	$P_r(W)$	$P_{EH}(W)$	$P_{ID}(w)$	$\eta_{EH}(\%)$	$\eta_{ID}(\%)$	η_{total} (%)
0.0	10.0	1.24999	0.00000	1.24999	0	100	12.50
0.1	10.0	1.24999	0.12500	1.12499	10	90	12.50
0.2	10.0	1.24999	0.25000	0.99999	20	80	12.50
0.3	10.0	1.24999	0.37500	0.87499	30	70	12.50
0.4	10.0	1.24999	0.49999	0.74999	40	60	12.50
0.5	10.0	1.24999	0.62499	0.62499	50	50	12.50
0.6	10.0	1.24999	0.74999	0.49999	60	40	12.50
0.7	10.0	1.24999	0.87499	0.37500	70	30	12.50
0.8	10.0	1.24999	0.99999	0.25000	80	20	12.50
0.9	10.0	1.24999	1.12499	0.12500	90	10	12.50
1.0	10.0	1.24999	1.24999	0.00000	100	0	12.50

Table 5.3 Power Trade-Off Table

The table presents the power trade-off analysis in a Simultaneous Wireless Information and Power Transfer (SWIPT) system, showcasing how the power splitting ratio (ρ) affects energy harvesting (EH) and information decoding (ID) performance. As ρ increases from 0 to 1, more power is allocated to energy harvesting (P_EH), while the power available for information decoding (P_ID) decreases accordingly. The system maintains a constant transmitted power (Pt = 10 W) and received power (Pr ≈ 1.25 W) due to Rayleigh fading and path loss effects. The efficiency of EH path increases with ρ, while the efficiency of ID path decreases proportionally. Notably, the total system efficiency remains constant at 12.5%, indicating that the received power is fully utilized, but its distribution between EH and ID varies. This analysis is crucial for designing SWIPT-based wireless networks, where optimizing ρ allows balancing energy harvesting for powering IoT devices while ensuring reliable communication for data transmission.

This tradeoff is essential in practical SWIPT system design, particularly in wireless sensor networks (WSNs), IoT applications, and energy-constrained communication systems, where optimizing power allocation can enhance both system performance and energy sustainability. Depending on the application, a lower ρ can be chosen when reliable data transmission is a priority, whereas a higher ρ is beneficial when maximizing energy harvesting is the main objective. The insights gained from this analysis help in designing adaptive power splitting strategies, where the ratio ρ can be dynamically adjusted based on channel conditions, network demands, and energy availability. Ultimately, this ensures an efficient and self-sustainable communication network, where devices can operate with minimal external power sources while maintaining reliable data exchange.

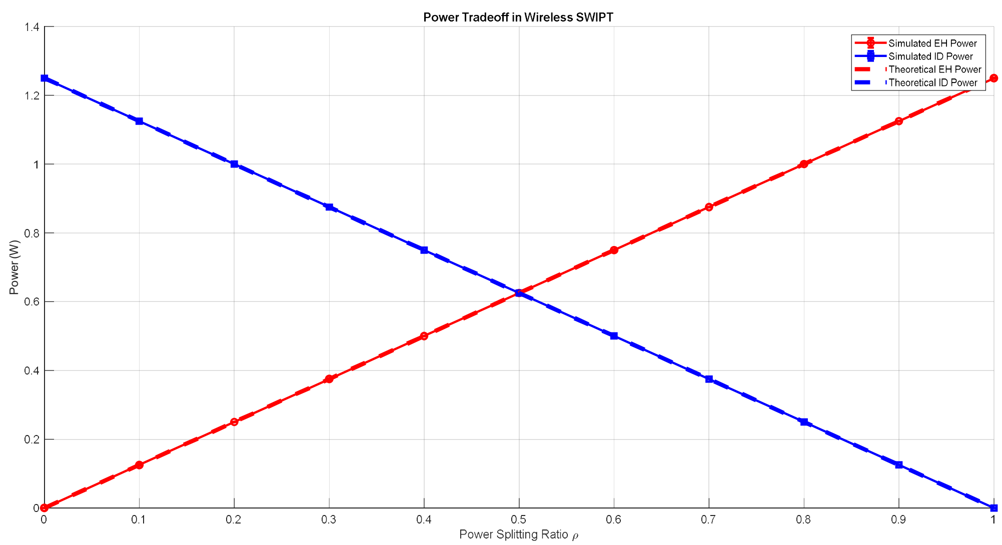

Fig 5.3 Power Trade-off in SWIPT

The graph presents the power tradeoff between Energy Harvesting (EH) and Information Decoding (ID) as a function of the Power Splitting Ratio (ρ) in a Simultaneous Wireless Information and Power Transfer (SWIPT) system. The red curve represents the simulated EH power, which increases with ρ, while the blue curve represents the simulated ID power, which decreases as ρ increases. The theoretical curves (dashed lines) follow the same trend, confirming that the simulation results align well with analytical expectations.

This behavior follows directly from the power splitting model, where the received power is divided into two components—one used for energy harvesting (ρPr) and the other for information decoding ((1 - ρ)Pr). As more power is allocated to EH (higher ρ values), less remains for ID, and vice versa. The intersection points at ρ = 0.5 signifies a balanced distribution of power, meaning that equal portions of the received power are utilized for energy harvesting and information decoding.

This tradeoff is crucial in the design of SWIPT-enabled IoT systems, wireless sensor networks, and self-sustaining devices, where an optimal choice of ρ must be made based on the system's operational requirements. If the primary goal is to maximize energy harvesting for self-powered devices, a higher ρ is desirable. Conversely, for high data reliability and throughput, a lower ρ is preferred to allocate more power to information decoding. The results of this analysis provide insights into optimizing power allocation strategies in SWIPT systems, ensuring efficient energy utilization and communication reliability.

5.4 Feasibility Analysis of Maximum Power Harvesting with Low BER

Simultaneous Wireless Information and Power Transfer (SWIPT) is a promising technology that enables wireless devices to harvest energy and decode information from the same received signal. However, there exists a fundamental tradeoff between energy harvesting (EH) and information decoding (ID) since a portion of the received signal must be allocated for each function. The efficiency of a SWIPT system depends on the power splitting ratio (ρ), which determines how much of the received power is used for energy harvesting and how much is utilized for information decoding.

A key challenge in SWIPT system design is to maximize power harvesting while maintaining an acceptable Bit Error Rate (BER) to ensure reliable communication. The power tradeoff analysis helps in identifying the optimal power allocation that balances energy efficiency and communication reliability. This report explores the mathematical modeling, simulations, and graphical analysis of power tradeoffs in a SWIPT-enabled system, focusing on system efficiency, path loss effects, and the impact of BER on power harvesting.

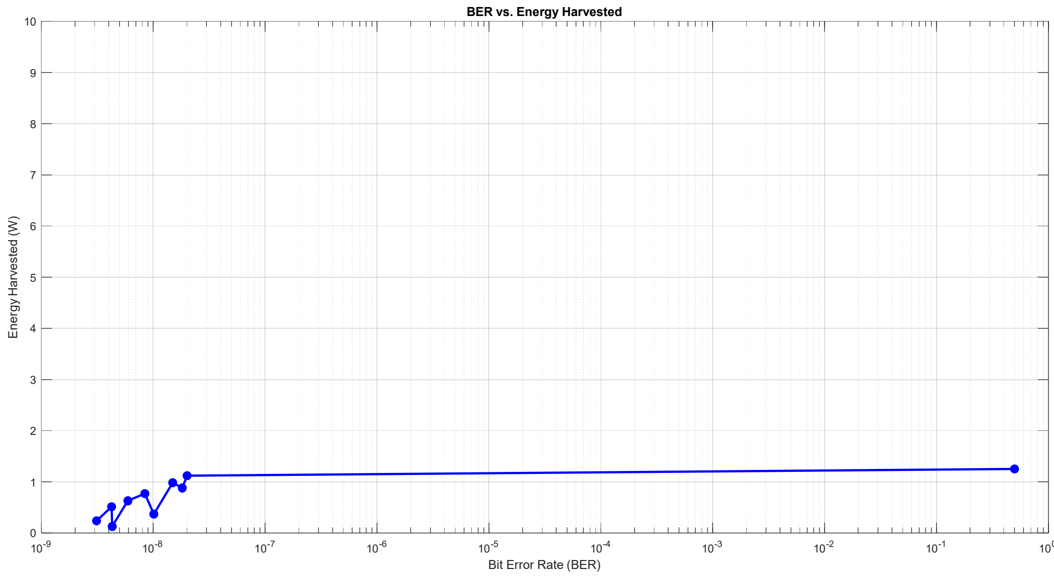

Fig.5.4 BER v/s Energy harvesting plot

The graph illustrates the tradeoff between Bit Error Rate (BER) and Energy Harvested (W) in a Simultaneous Wireless Information and Power Transfer (SWIPT) system. The primary goal of this analysis is to identify an optimal operational point where the system can maximize energy harvesting without compromising communication reliability. Since both information decoding (ID) and energy harvesting (EH) rely on the received signal, a balance must be maintained between these two functions.

From the plotted results, it is evident that at very low BER values (approximately 10^{-9} to 10^{-8}), the harvested energy fluctuates slightly but eventually stabilizes around 1W as BER increases. This suggests that, in the initial phase, the system experiences some variations in power reception due to signal fluctuations or noise effects. However, beyond a certain BER threshold, the energy harvesting efficiency becomes relatively stable, indicating that further degradation in BER does not contribute significantly to energy harvesting gains.

This behavior is crucial for power allocation strategies in SWIPT-enabled wireless networks. The results indicate that there exists a feasible BER range where the system can achieve both low error rates for reliable communication and sufficient energy harvesting for system sustainability. Beyond this point, an excessive increase in BER may severely degrade data transmission quality without any substantial gain in harvested power.

These insights play a vital role in optimizing power splitting ratios (ρ) in SWIPT-based systems. By carefully selecting an appropriate BER operating point, network designers can ensure that the power allocated for energy harvesting does not excessively degrade the information decoding process. This is especially beneficial for IoT applications, remote sensing devices, and energy-constrained wireless networks where both power efficiency and communication reliability are critical factors.

CHAPTER 6

RESULTS AND DISCUSSION

The analysis of a Simultaneous Wireless Information and Power Transfer (SWIPT) system involves evaluating the trade-offs between energy harvesting (EH) and information decoding (ID). The following plots illustrate key performance metrics, highlighting the impact of different power splitting ratios (ρ) on Bit Error Rate (BER), outage probability, harvested energy, and information decoding power. Understanding these relationships is crucial for optimizing SWIPT-based IoT applications.

6.1 BER vs. SNR for Different Power Splitting Ratios

The SNR vs BER plot (Fig.5.1) depicts the variation of BER with respect to SNR for different values of the power splitting ratio (ρ). Theoretical and simulated curves show a consistent trend, validating the model's accuracy.

- As SNR increases, BER decreases for all values of ρ, indicating improved signal quality.
- Impact of ρ:
    - A lower ρ (e.g., 0.2) dedicates more power to information decoding, reducing BER significantly.
    - A higher ρ (e.g., 0.8) means more power is allocated to energy harvesting, leaving less power for information decoding, thereby increasing BER.
- An optimal ρ must be chosen to minimize BER while still allowing sufficient energy harvesting.

6.2 Outage Probability vs. SNR

The plot of Outage probability v/s SNR (Fig. 5.2) examines how the probability of system outage varies with increasing SNR under different power splitting ratios.

- Outage probability decreases as SNR increases, meaning that at higher SNR values, the system operates more reliably.
- Impact of ρ:

    - For low ρ, more power is allocated to information decoding, reducing outage probability.
    - Higher ρ values increase the probability of outage, especially at low SNR, since more power is diverted to energy harvesting.
- A balance is required to ensure that the system maintains reliable transmission while still harvesting adequate energy.

6.3 Harvested and Information Decoding Power vs. Power Splitting Ratio

The plot of Harvested and Information Decoding Power vs. Power Splitting Ratio (Fig. 5.3) visualizes the power allocated to energy harvesting (EH) and information decoding (ID) as a function of the power splitting ratio.

- Observation:
    - As ρ increases, the energy harvested increases linearly.
    - Simultaneously, the power available for information decoding decreases, which can degrade communication reliability.
- Trade-off Analysis:
    - For a high EH power, the system sacrifices ID power, leading to a higher BER.
    - For low EH power, the ID power increases, improving BER performance but reducing the available energy for the IoT sensor.
- The system designer must find an optimal ρ that ensures sufficient harvested energy while maintaining reliable data transmission.

6.4 Energy Harvested vs. BER

The plot of Energy Harvested vs. BER (Fig. 5.4) investigates how the energy harvested varies with BER.

- Observation:
    - At high BER, energy harvesting remains unaffected since errors in data transmission do not influence power collection.

- At extremely low BER, a slight decrease in energy harvested is observed, indicating that prioritizing data transmission can slightly affect energy collection.
- There exists a fundamental trade-off between reliable communication (low BER) and energy harvesting efficiency.
- The SWIPT system must be optimized such that BER is minimized while ensuring sufficient energy is collected for continuous operation.

The results from these plots are crucial for optimizing a SWIPT system where both efficient energy harvesting and reliable data transmission are needed. To minimize BER, more power must be allocated to information decoding, which means using a lower power splitting ratio (ρ). However, maximizing harvested energy requires increasing ρ, but this leads to a higher BER, potentially degrading system performance. This fundamental trade-off between BER and energy harvesting highlights the need for an optimal balance. The results suggest that selecting a moderate value of ρ allows the system to achieve both efficient power transfer and reliable communication, ensuring that IoT devices in SWIPT-enabled applications operate effectively without compromising data accuracy or power availability.

The study highlights the fundamental trade-off between BER, outage probability, energy harvesting, and power allocation in a SWIPT system. By carefully selecting the power splitting ratio, it is possible to design an energy-efficient and reliable IoT communication system that supports long-term operation, making it suitable for applications like precision agriculture, remote sensing, and smart cities.

CHAPTER 7

CONCLUSION AND FUTURE SCOPE

7.1 Conclusion

This study analyzed the performance trade-offs in a Simultaneous Wireless Information and Power Transfer (SWIPT) system, focusing on BER, outage probability, harvested energy, and power allocation under different power splitting ratios (ρ). The results demonstrate that minimizing BER requires allocating more power to information decoding, whereas maximizing harvested energy demands a higher ρ, leading to increased BER. This highlights a fundamental trade-off between efficient energy harvesting and reliable data transmission, crucial for designing energy-autonomous IoT systems.

The findings emphasize the need for an optimal power splitting ratio, ensuring both sufficient harvested energy and acceptable BER levels. A moderate ρ value is recommended to maintain low BER while supplying adequate power to sensors and devices. Such optimization is particularly important for IoT applications in smart agriculture, remote sensing, and low-power wireless networks, where continuous operation without frequent battery replacements is necessary.

Overall, this analysis provides insights into designing a SWIPT system that balances energy efficiency and communication reliability, making it a viable solution for sustainable and autonomous wireless networks.

7.2 Future Scope

Future research in Simultaneous Wireless Information and Power Transfer (SWIPT) systems can explore multiple avenues to enhance both energy harvesting efficiency and communication reliability. One key area is the development of advanced power splitting techniques, such as adaptive or dynamic algorithms that optimize energy allocation based on real-time network conditions, ensuring minimal BER while maximizing harvested energy. The integration of machine learning (ML) and artificial intelligence (AI) can further improve SWIPT performance by dynamically predicting and adjusting power splitting ratios, optimizing energy utilization without compromising data transmission. Additionally, SWIPT in next-generation wireless networks such as 5G, 6G, and large-scale IoT deployments can enable self-sustaining sensor networks, reducing reliance on traditional battery-powered devices.

Further advancements can be made by leveraging metamaterials and GRIN lenses to enhance wireless power transfer efficiency, enabling better signal focusing and energy reception. A hybrid energy harvesting approach that combines SWIPT with RF, solar, and vibrational energy sources can create multi-source energy harvesting systems, making IoT devices more sustainable and reducing dependence on a single power source. Security and reliability enhancements are also critical, requiring the development of secure SWIPT protocols that mitigate risks such as eavesdropping, interference, and power jamming, ensuring stable data transmission and efficient energy utilization.

In addition to theoretical advancements, real-world implementation and testing of SWIPT-based IoT systems in applications such as precision agriculture, remote healthcare, industrial automation, and smart cities will help validate these technologies under practical conditions. Developing prototype systems and conducting field trials will allow researchers to refine theoretical models and adapt SWIPT to diverse real-world environments. By addressing these aspects, future research can significantly enhance the efficiency, scalability, security, and practicality of SWIPT systems, making them a cornerstone technology for next-generation energy-autonomous wireless networks.

REFERENCES

[1] J. Huang and V. K. N. Lau, "Enabling wireless power transfer in cellular networks: Architecture, modeling and deployment," *IEEE Transactions on Wireless Communications*, vol. 13, no. 2, pp. 902-912, Feb. 2014.

[2] L. R. Varshney, "Transporting information and energy simultaneously," *IEEE International Symposium on Information Theory (ISIT)*, Toronto, ON, Canada, 2008, pp. 1612-1616.

[3] S. Bi, C. K. Ho, and R. Zhang, "Wireless powered communication: Opportunities and challenges," *IEEE Communications Magazine*, vol. 53, no. 4, pp. 117-125, Apr. 2015.

[4] D. W. K. Ng, E. S. Lo, and R. Schober, "Wireless information and power transfer: Energy efficiency optimization in OFDMA systems," *IEEE Transactions on Wireless Communications*, vol. 12, no. 12, pp. 6352-6370, Dec. 2013.

[5] X. Zhou, R. Zhang, and C. K. Ho, "Wireless information and power transfer: Architecture design and rate-energy tradeoff," *IEEE Transactions on Communications*, vol. 61, no. 11, pp. 4757-4767, Nov. 2013.

[6] K. Huang and V. K. N. Lau, "Enabling wireless power transfer in cellular networks: Architecture, modeling and deployment," *IEEE Transactions on Wireless Communications*, vol. 13, no. 2, pp. 902-912, Feb. 2014.

[7] H. Ju and R. Zhang, "Throughput maximization in wireless powered communication networks," *IEEE Transactions on Wireless Communications*, vol. 13, no. 1, pp. 418-428, Jan. 2014.

[8] A. Nasir, X. Zhou, S. Durrani, and R. A. Kennedy, "Relaying protocols for wireless energy harvesting and information processing," *IEEE Transactions on Wireless Communications*, vol. 12, no. 7, pp. 3622-3636, Jul. 2013.