Comprehensive Analysis and Quantification of Key Performance Metrices of a SWIPT System

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***Abstract*—This paper presents a comprehensive analysis of Simultaneous Wireless Information and Power Transfer (SWIPT) systems, focusing on the trade-off between energy harvesting (EH) and information decoding (ID). We develop a SWIPT model in SIMULINK, derive mathematical expressions for SNR, BER, and outage probability, and validate them using Monte Carlo simulations. The impact of power splitting ratios on system performance is analyzed, revealing that higher power splitting ratio values improve BER and reduce outage probability, while lower power splitting ratio values enhance energy harvesting. Feasible power quantification from the EH power vs. BER plot identifies the minimum transmit power required to achieve a target BER while ensuring sufficient energy harvesting. The results provide a framework for optimizing SWIPT systems, balancing energy and communication requirements in practical wireless networks.**

Keywords—SWIPT, Energy Harvesting, Information Decoding, SNR, BER, Outage Probability, Power Splitting Ratio, Feasible Power Quantification.

I. INTRODUCTION

Simultaneous Wireless Information and Power Transfer (SWIPT) has emerged as a transformative technology for modern wireless communication systems, enabling devices to simultaneously harvest energy and decode information from the same received signal. This dual functionality is particularly beneficial for energy-constrained applications such as Internet of Things (IoT) devices, wireless sensor networks, and wearable electronics. SWIPT systems achieve this by splitting the received signal into two streams: one for energy harvesting (EH) and the other for information decoding (ID) [1], [2]. The tradeoff between energy transfer and information rate is a key challenge, with foundational principles explored in [5] and [6], while recent advancements in waveform design and system architecture have further enhanced SWIPT efficiency [7], [8].

In this work, we present a comprehensive analysis of SWIPT systems, focusing on key performance metrics such as Signal-to-Noise Ratio (SNR), Bit Error Rate (BER), and outage probability. We develop a SWIPT model in SIMULINK to analyze signal processing and validate our findings using Monte Carlo simulations. Additionally, we derive the minimum transmit power required for reliable information decoding while ensuring sufficient energy harvesting, providing insights into optimizing SWIPT systems for diverse application scenarios [3], [4]. This study bridges theoretical analysis and practical implementation, offering a robust framework for designing efficient SWIPT systems in real-world wireless networks theoretical analysis and practical implementation, offering a robust framework for designing efficient SWIPT systems in real-world wireless networks [3], [4].

II. SYSTEM MODEL

This section provides a detailed description of the SWIPT system architecture, including the transmitter, receiver, and channel model. It also formally defines the problem and introduces the mathematical framework for analyzing key performance metrics such as SNR, BER, and outage probability. The goal is to establish a clear understanding of the system's operation and the trade-offs between energy harvesting (EH) and information decoding (ID).

A. SWIPT System Architecture

The transmitter converts a binary data stream into a wireless RF signal by modulating it using a scheme like BPSK, where binary values map to specific phase shifts (e.g., 0° for '0' and 180° for '1'). The modulated signal is up-converted to a higher frequency, amplified by a power amplifier to ensure sufficient strength, and transmitted via an antenna. This process efficiently encodes and transmits the information over the air.

The receiver splits the incoming signal into two paths using a power splitter: a fraction $\rho\rho$ of the signal power is allocated to information decoding (ID), while the remaining $1-\rho 1-\rho$ is directed to energy harvesting (EH). In the EH path, the signal is rectified to convert AC to DC, filtered to remove high-frequency noise, and stored in a capacitor or battery. In the ID path, the signal is down-converted to baseband, demodulated to recover the original binary data, and processed with noise filtering and error correction to ensure reliable decoding. This dual-path design enables simultaneous energy harvesting and information recovery.

The wireless channel combines Additive White Gaussian Noise (AWGN) and Rayleigh fading, introducing impairments that affect SWIPT system performance. Rayleigh fading models random signal amplitude variations due to multipath propagation, while AWGN, with zero mean and variance *N0B*, adds noise that degrades signal quality. These effects impact both energy harvesting and information decoding, influencing key metrics like SNR, BER, and outage probability, which are critical for system analysis and optimization.

III. Performance analysis

The performance of a SWIPT system is governed by the interplay between energy harvesting (EH) and information decoding (ID), which are influenced by key parameters such as the power splitting ratio (ρ), channel conditions, and system design. To analyze and optimize the system, it is essential to develop a mathematical framework that quantifies the trade-offs between EH and ID. This section presents the derivation of critical performance metrics, including Signal-to-Noise Ratio (SNR), Bit Error Rate (BER), Outage Probability, and Harvested Power. These derivations provide the theoretical foundation for understanding the system's behavior under varying conditions and enable the design of efficient SWIPT systems that balance energy efficiency and communication reliability. The mathematical models developed here will be used in subsequent sections to simulate and evaluate the system's performance. First the SWIPT model is mathematically expressed in order to derive the performance matrices.

A. Mathematical Model of SWIPT system

Firstly, the transmitter is being modelled as per the block Diagram including the following steps.

$$\{dn\} \text{ where } dn \in \{0,1\} \tag{1}$$

This equation denotes the binary data that is the information we are sending.

$$dn \in \{0,1\} \rightarrow dn^* \in \{-1,+1\} \tag{2}$$

When the signal is sent through the BPSK modulator it maps binary '0' as '-1' and binary '1' as '+1'.

$$s_{RF}(t) = A.cos(2\pi f_{RF}t + \theta_i) \tag{3}$$

Equation (3) signifies the BPSK modulated signal with carrier.

$$s_{txn}(t) = G.s_{RF}(t) \tag{4}$$

This is the transmitted signal with G as the gain of the power amplifier.

Secondly, the channel is being modelled which is an AWGN and a Rayleigh fading channel

$$r(t) = h(t).s_{txn}(t) + n(t) \tag{5}$$

This equation is the received equation in the channel where $n(t)$ is the noise component of the channel and $h(t)$ is the Rayliegh fading coefficient.

$$r(t) = |h(t)|.G.A.\cos(2\pi f_{RF}t + \theta_i + \emptyset(t) + n(t) \tag{6}$$

Substituting (3) and (4) in (6) we get this equation as the output signal of the channel. Where $h(t) = |h(t)|e^{j\emptyset(t)}$.

Thirdly, the receiver is modelled and the signals are derived based on the above equations .The signal r(t) is first fed into a power splitter, which divides the incoming signal into two paths Energy Harvesting Path: A fraction ρ (where 0< ρ <1) of the signal power is directed here and Information Decoding Path: The remaining fraction (1− ρ) of the signal power is directed here.

$$r_{EH}(t) = \sqrt{\rho}.r(t) \tag{7}$$

$$r_{ID}(t) = \sqrt{1-\rho}.r(t) \tag{8}$$

This equations represents the signal that splits into two paths that is energy harvesting path and information decoding path based on the given power splitting ratios.

$$r_{rect}(t) = \sqrt{\rho}\big||h(t)|.G.A.\cos(2\pi f_{RF}t + \theta_i + \emptyset(t) + n(t)\big| \tag{9}$$

This signal represents the rectified signal which denotes the DC signal harvested from the signal using rectifier.

$$r_{base}(t) = r_{ID}(t).\cos(2\pi f_{RF}t) \tag{10}$$

$$r_{base}(t) \approx \sqrt{1-\rho}.|h(t)|G.A.\cos\big(\theta_i + \emptyset(t)\big) + n_{base}(t) \tag{11}$$

After substituting and simplifying equation (6) and (8) in (11) and (10) represents the baseband signal.

$$r_{BPSK(t)} = sign(r_{base}(t).\cos(\theta_i + \emptyset(t))) \tag{12}$$

Equation (12) is the BPSK demodulated signal that is defined in terms of signum function. The signum function is used to determine the polarity of the resulting product, which corresponds to the original bit transmitted.

This is the overall mathematical model of the SWIPT system these derivations can be used to derive and quantify the system parameters.

B. Signal to Noise ratio of a SWIPT System

From the received signal equation of the information decoding path, we can derive the SNR of the system.
From equation (11).

$$s(t) = \sqrt{1-\rho}.|h(t)|.G.A.\cos(\theta_i + \emptyset(t)) \tag{13}$$

Equation (12) represents the signal component of the information decoding path.

$$P_{Signal} = E[s(t)^2] \tag{14}$$

This equation denotes the power of the signal that is being estimated to the signal squared.

$$P_{Signal} = 1-\rho.|h(t)|^2.G^2.A^2E\big[\cos^2\big(\theta_i + \emptyset(t)\big)\big] \tag{15}$$

$$P_{Signal} = \frac{1-\rho.|h(t)|^2.G^2.A^2}{2} \tag{16}$$

Substituting and simplifying (13) in (14) we get the power of the signal as (16). Since in BPSK, $\cos^2\big(\theta_i + \emptyset(t)\big)$ has average power of $\frac{1}{2}$.

$$P_{noise} = N_0 \tag{17}$$

Equation (17) represents the noise power of the signal which is taken as N_0 because we are considering only positive high frequency components.

$$SNR = \frac{P_{Signal}}{P_{noise}} \tag{18}$$

Equation (18) is the general SNR equation.

$$SNR = \frac{1-\rho.|h(t)|^2.G^2.A^2}{2N_0} \tag{19}$$

After substituting (16) and (17) in (19) we get the SNR of the SWIPT system.

C. Bit Error Rate of a SWIPT System

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

$$BER = Q\left(2.\sqrt{SNR}\right) \tag{20}$$

This is the BER of the AWGN channel which is represented by the q-function of SNR.

$$\bar{P} = \int_0^{\infty} P_s(\gamma)P_{\gamma s}(\gamma)d\gamma \tag{21}$$

Equation (13) denotes the integration of both the channel's error probability, Where $P_s(\gamma)$ is the probability of error of the AWGN channel and $P_{\gamma s}(\gamma)$ is the probability of error under Rayleigh fading channel.

$$P_{\gamma s}(\gamma)d\gamma = \mathrm{P}(r)\, dr \tag{22}$$

For a given distribution of the fading amplitude r, we compute $P_{\gamma s}(\gamma)$ by making the change of variable in (14).

$$p(r)=\frac{r}{\sigma^2}e^{\frac{-r^2}{2\sigma^2}}, r \geq 0 \tag{23}$$

The received signal amplitude r has Rayleigh distribution that is represented in equation (15)

$$\gamma = \frac{r^2 T_s}{2\sigma_n^2} \tag{24}$$

$$P_{\gamma s}(\gamma) = \frac{1}{\bar{\bar{\gamma}}_s}e^{\frac{-\gamma}{\bar{\bar{\gamma}}_s}} \tag{25}$$

equation (16) denotes the SNR per symbol for a given amplitude r. Differentiating and simplifying we get (17).

$$\bar{P}_b = \frac{1}{2}\left[1-\sqrt{\frac{\bar{\gamma}_b}{1+\bar{\gamma}_b}}\right] \approx \frac{1}{4\bar{\gamma}_b} \tag{26}$$

Integrating BER of AWGN over the distribution (17) yields the following average probability of error for BPSK in Rayleigh fading. Where, $\bar{\gamma}_b$ denotes the binary signaling.

Substituting the SNR of the SWIPT into (18) we get the BER of the SWIPT system.

$$\bar{P}_b = \frac{1}{2}\left[1-\sqrt{\frac{\frac{1-\rho.|h(t)|^2.G^2.A^2}{2N_0}}{1+\frac{1-\rho.|h(t)|^2.G^2.A^2}{2N_0}}}\right] \tag{27}$$

This equation is the BER of the SWIPT system.

D. Outage Probability analysis of a SWIPT System

In wireless communication systems, outage probability is a critical metric that quantifies the likelihood of the system failing to achieve a minimum quality of service (QoS), typically defined by a threshold Signal-to-Noise Ratio (SNR). For SWIPT systems, this metric becomes particularly significant due to the inherent trade-off between energy harvesting (EH) and information decoding (ID). Outage occurs when the instantaneous SNR at the ID path falls below a predefined threshold γ_0, rendering the communication link unreliable.

$$P_{out} = p(\gamma_s < \gamma_0) = \int_0^{\gamma_0} p_{\gamma_s}(\gamma)d\gamma \tag{28}$$

Outage probability relative to γ_0 is defined as in (28)

$$P_{out}=\int_0^{\gamma_0}\frac{1}{\bar{\gamma}}e^{\frac{-\gamma_s}{\bar{\bar{\gamma}}_s}}d\gamma_s = 1-e^{\frac{-\gamma_0}{\bar{\bar{\gamma}}_s}} \tag{29}$$

In Rayleigh fading the outage probability becomes (29).

$$P_{out} = 1-e^{\frac{-2\gamma_0 N_0}{(1-\rho).|h(t)|^2.G^2.A^2}} \tag{30}$$

This equation represents the outage probability of the SWIPT system.

E. Power analysis of a SWIPT System

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 $P_{ID} = (1-\rho).P_r$.

$$P_t = G_{PA}.P_{in} \tag{31}$$

This is the transmitted power where, G_{PA} is the gain of the power amplifier and P_{in} is the input power.

$$P_r = |h|^2.P_t.L_p + N_0 \tag{32}$$

Equation (32) is the received power in which, $|h|^2$ is the Rayliegh fading coefficient, N_0 is the noise power and L_p is the path loss model.

$$P_{EH} = \rho.P_r \tag{33}$$

$$P_{ID} = (1-\rho).P_r \tag{34}$$

Equations (33) and (34) denotes the power allocation in both EH and ID paths.

$$\eta_{EH} = \frac{P_{EH}}{P_t} \tag{35}$$

$$\eta_{ID} = \frac{P_{ID}}{P_t} \tag{36}$$

$$\eta_{total} = \frac{P_{EH} + P_{ID}}{P_t} \tag{37}$$

Equations (27) , (28) and (29) specifies the efficiency of the paths and the overall system.

IV. Results and Discussion

This section presents the simulation results and analysis of the SWIPT system, focusing on the trade-offs between energy harvesting (EH) and information decoding (ID). The plots illustrate the system's performance in terms of Bit Error Rate (BER), Outage Probability, and Harvested Power under varying power splitting ratios (ρ) and channel conditions. The results are compared with theoretical predictions to validate the accuracy of the mathematical models. Key insights from the plots are discussed, providing a comprehensive understanding of the system's behavior and guiding the optimization of SWIPT systems for practical applications.

A. SIMULINK Model and Signal processing

This section describes the implementation of the SWIPT system in Simulink and provides a detailed explanation of the signal processing steps. It includes visual representations of the Simulink model and the signal transformations at each stage, from transmission to reception.

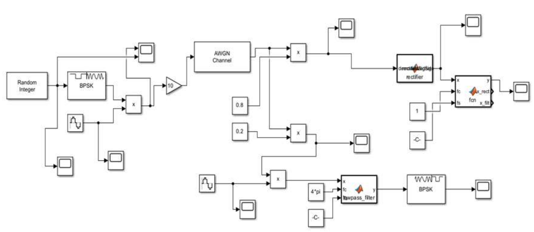


Fig. 1. Simulation setup for the SWIPT system, showing the Random Integer Generator, BPSK modulation, AWGN channel, and power splitting ratios for ID (0.8) and EH (0.2).

The Simulink model for the SWIPT system simulates simultaneous wireless information and power transfer, featuring a transmitter, wireless channel, power splitter, energy harvester (EH), and information decoder (ID). The transmitter generates a binary data stream using a Random Integer Generator and modulates it with BPSK. The signal passes through an AWGN channel, introducing noise. At the receiver, a power splitter divides the signal: the EH path rectifies and filters the signal for energy storage, while the ID path down-converts and demodulates the signal to recover the original data. Each block replicates real-world SWIPT system functionality.

In the transmitter side we have the information that is expressed in terms of binary data and have the carrier signal for up-conversion and BPSK modulated signal.

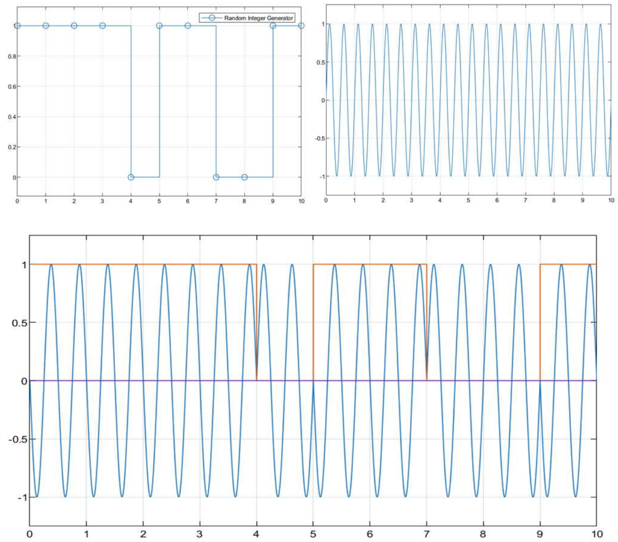


Fig. 2. Binary data stream, carrier signal and BPSK modulated signal processing are being depicted in these plots.

When the BPSK modulated signal is passed via practical channel consisting of AWGN and fading the signal is expressed the BPSK signal with noise components.

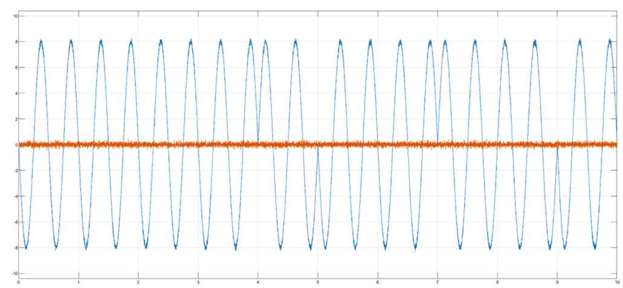
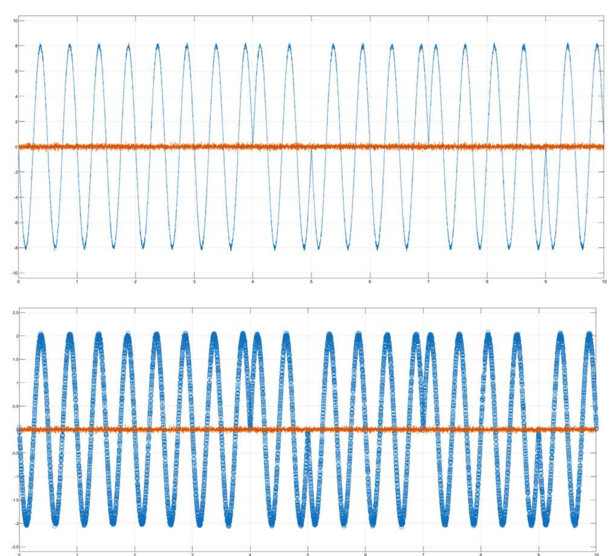


Fig. 3. Signal processing after passing through channel are being depicted in these plots

In the receiver side we have the power splitting relay that splits the power in two paths i.e., EH path and ID path in the EH path we have full wave rectifier and low pass filter and in the ID path we have down conversion and BPSK demodulator.



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

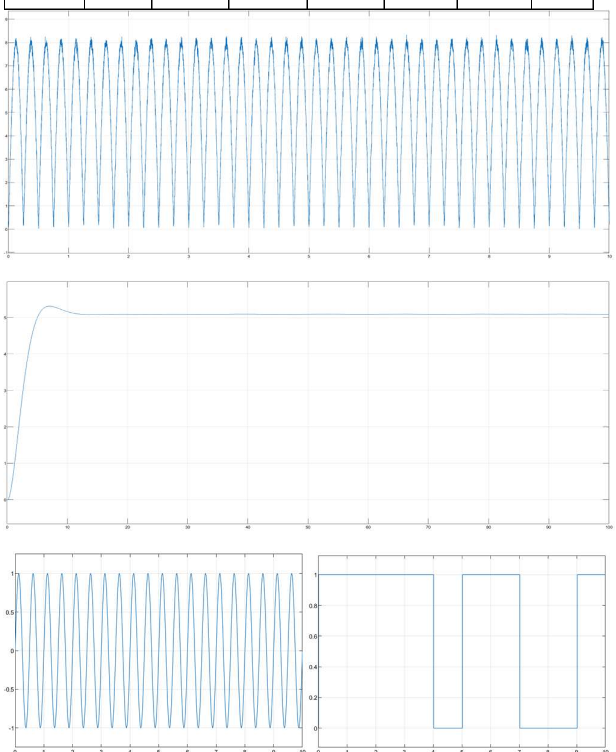


Fig. 4. EH path signal, ID path signal, Rectified signal, DC output, Carrier signal for down conversion and BPSK demodulated signal processing are being depicted in these plots.

In this section, we presented the simulation framework and signal processing steps for the SWIPT system, providing a detailed overview of the Simulink model and the transformation of signals at each stage. The model effectively captures the key components of the system, including the transmitter, wireless channel, power splitter, energy harvester, and information decoder. BER v/s SNR for different power splitting ratios

The BER vs. SNR plot illustrates the impact of the power splitting ratio (ρ) on SWIPT system reliability. As SNR increases, BER decreases, improving communication performance. However, the trade-off between energy harvesting (EH) and information decoding (ID) is evident—lower ρ (e.g., 0.2) results in higher BER due to reduced ID power, while higher ρ (e.g., 0.8) lowers BER but limits harvested energy. The close match between theoretical and simulated results confirms the model's accuracy, providing key insights for optimizing ρ to balance EH and ID based on system need.

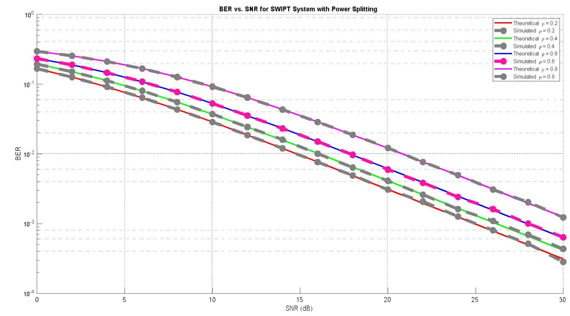


Fig. 5. BER v/s SNR plot for different power splitting ratios

B. *Outage probability v/s SNR for different power splitting ratios*

The Outage Probability vs. SNR plot assesses SWIPT system reliability under different power splitting ratios (ρ). As SNR increases, outage probability decreases, enhancing system performance. However, a trade-off exists—lower ρ (e.g., 0.2) increases outage probability due to reduced ID power, while higher ρ (e.g., 0.8) lowers outage probability but limits harvested energy. The close match between theoretical and simulated results confirms the model's accuracy, offering key insights for optimizing ρ to balance communication reliability and energy harvesting in SWIPT systems.

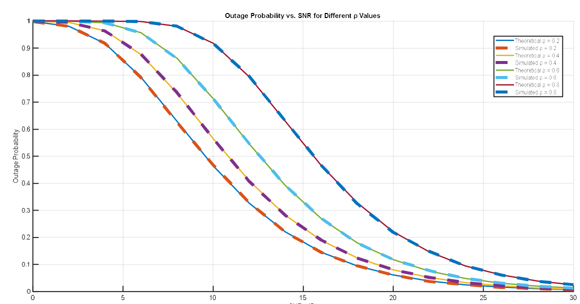


Fig. 6. Outage probability v/s SNR plot for different power splitting ratios

C. *Harvested power v/s power splitting ratios*

The Harvested Power vs. Power Splitting Ratio (ρ) plot illustrates the trade-off between energy harvesting (EH) and information decoding (ID) in SWIPT systems. As ρ increases from 0 to 1, harvested power decreases linearly, while ID power increases. For instance, at ρ = 0.2, 20% of power is harvested, leaving 80% for ID, whereas at ρ = 0.8, 80% is harvested, leaving 20% for ID. The system maintains a constant efficiency (η_total = 12.5%), reinforcing model accuracy. The close match between theoretical and simulated results validates the model and highlights the need to optimize ρ based on energy and communication requirements.

TABLE I

POWER TRADE OFF IN SWIPT SYSTEM

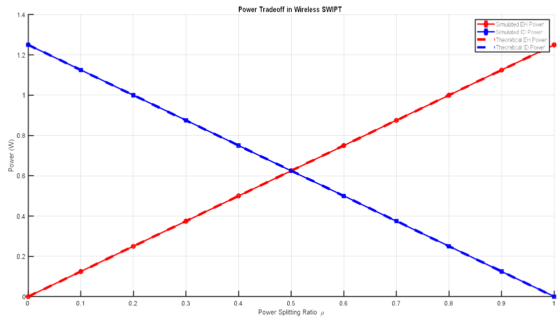


Fig. 7. Harvested power v/s power splitting ratios

This table is crucial for understanding the trade-offs between energy harvesting (EH) and information decoding (ID) in a SWIPT system as the power splitting ratio (ρ) varies. It shows that as ρ increases from 0 to 1, the power allocated to EH (*PEH*) increases linearly, while the power for ID (*PID*) decreases, highlighting the inherent trade-off between the two functions. The total efficiency (ηtotal) remains constant at 12.5%, but the EH efficiency (ηEH) increases with ρ, and the ID efficiency (ηID) decreases. This table serves as a valuable tool for optimizing the system based on specific energy and communication requirements, such as prioritizing EH for energy-constrained devices or ID for reliable communication. It also validates the accuracy of the theoretical models, providing a clear and quantifiable representation of the system's behavior for practical SWIPT applications.

D. Harvested power v/s power splitting ratios

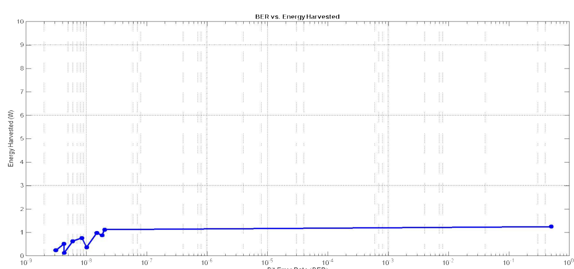


Fig. 8. BER v/s Harvested Power

Fig.8. illustrates the tradeoff between Bit Error Rate (BER) and Energy Harvested (W) in a SWIPT system, highlighting the need to balance energy harvesting (EH) and information decoding (ID). At very low BER (10^{-9}to 10^{-8}), harvested energy fluctuates but stabilizes around 1W as BER increases, indicating minimal EH gains beyond a certain threshold. This suggests an optimal BER range where reliable communication and efficient EH coexist. Optimizing power splitting ratios (ρ) ensures minimal impact on ID, benefiting IoT, remote sensing, and energy-constrained networks.

V. CONCLUSION

This paper presented a comprehensive analysis of a Simultaneous Wireless Information and Power Transfer (SWIPT) system, focusing on the trade-offs between energy harvesting (EH) and information decoding (ID). Through mathematical modeling and simulation, we derived key performance metrics such as Signal-to-Noise Ratio (SNR), Bit Error Rate (BER), Outage Probability, and Harvested Power. The results demonstrated that the power splitting ratio (ρ) plays a critical role in balancing EH and ID, with higher ρ values improving communication reliability but reducing harvested energy, and vice versa. The close alignment between theoretical and simulated results validated the accuracy of the models and provided insights into optimizing the system for various application scenarios. The analysis of BER vs. SNR, outage probability vs. SNR, and harvested power vs. ρ highlighted the system's ability to adapt to different energy and communication requirements. This work contributes to the design of efficient SWIPT systems, offering a framework for achieving optimal performance in practical wireless networks. Future research could explore advanced techniques such as adaptive power splitting, multiple-input multiple-output (MIMO) systems, and nonlinear energy harvesting models to further enhance system performance.

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