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Performance Evaluation of Simultaneous Wireless Information and Power Transfer (SWIPT) In Wireless Sensor Networks Using Matlab-Based RF Energy Harvesting Simulation

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ABSTRACT
Simultaneous Wireless Information and Power Transfer (SWIPT) offers a promising approach to enhance the sustainability of Wireless Sensor Networks (WSNs) by enabling simultaneous energy harvesting and communication. This study uses MATLAB-based RF energy harvesting simulations to evaluate SWIPT performance across key parameters including harvested energy, throughput, power splitting ratio, signal-to-noise ratio (SNR), bit error rate (BER), network lifetime, node density, and latency.Results shows that a power splitting ratio of 0.5 yields the best balance, achieving a peak throughput of 5.2 Mbps and 0.85 mW of harvested energy. Increasing the harvesting ratio to 0.8 boosts harvested energy to 1.3 mW, but throughput declines to 4.1 Mbps, illustrating a trade-off between energy efficiency and communication. Time splitting (TS) harvesting extends network lifetime to 52 hours, outperforming power splitting (36 hours). Higher node density (25 nodes/unit area) reduces energy efficiency by 18% and increases latency to 200 ms, compared to 150 ms at lower densities.Throughput drops by 50% at 200 meters due to reduced SNR (from 12 dB to 4 dB), resulting in a BER increase from 10^{-6} to 10^{-2}. These findings emphasize the need to optimize system parameters for efficient, sustainable SWIPT-enabled WSN deployment.

KEYWORDS: *SWIPT, WSN, RF Energy Harvesting, Performance Evaluation, MATLAB*

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I. INTRODUCTION

Wireless Sensor Networks (WSNs) have become a foundational technology across multiple fields, ranging from environmental monitoring and industrial automation to healthcare, smart cities, and military operations. These networks are composed of numerous spatially distributed and autonomous sensor nodes that are designed to sense physical or environmental conditions such as temperature, humidity, or motion and transmit the collected data collaboratively to a central base station or sink node for processing and analysis [1]. A significant challenge for the long-term operation of Wireless Sensor Networks (WSNs) is the limited energy supply of the sensor nodes. These nodes are typically battery-powered and often placed in remote or harsh environments, making regular battery replacement not only difficult but sometimes entirely unfeasible [2].

To overcome the energy limitations of sensor nodes, energy harvesting (EH) techniques have gained considerable attention. These methods allow sensor nodes to capture and utilize ambient energy from sources such as solar power, thermal gradients, wind, or even Radio Frequency (RF) signals, helping to extend the operational lifespan of the networks [3]. Among these techniques, RF Energy Harvesting (RFEH) stands out as especially appealing because of its controllability, widespread availability, and unique ability to serve a dual purpose. The same Radio Frequency (RF) signal can simultaneously deliver both energy and data, a concept known as Simultaneous Wireless Information and Power Transfer (SWIPT) [4].The core idea behind SWIPT (Simultaneous Wireless Information and Power Transfer) is based on the fundamental balance between two key tasks: information decoding (ID) and energy harvesting (EH). Since the same signal is used for both purposes, a sensor has to carefully manage how much of the signal's power is dedicated to decoding the information and how much is allocated for energy harvesting [5].

This research presents a comprehensive MATLAB framework to simulate and evaluate the performance of SWIPT-enabled WSNs under realistic RF harvesting conditions.

II. LITERATURE REVIEW

Wireless Sensor Networks and Energy Constraints: Wireless Sensor Networks (WSNs) consist of a large number of small, low-power sensor nodes that are strategically deployed to monitor and collect data on various environmental parameters, such as temperature, humidity, or air quality. [6]. However, a significant challenge they face is their limited energy supply. Since most of these sensor nodes are battery-powered and often placed in remote or difficult-to-reach locations, their operational lifespan is constrained by the available energy, making it difficult to maintain the network over long periods without frequent maintenance or battery replacements [7].

Figure1: Block diagram of Wireless Sensor Network

SWIPT in Wireless Sensor Networks: The concept of Simultaneous Wireless Information and Power Transfer (SWIPT) was first introduced by Varshney, who proposed using Radio Frequency (RF) signals for both energy and data transmission. Since then,several architectures have been developed to implement SWIPT, including Time Switching (TS) and Power Splitting (PS) methods, each offering unique ways to balance the dual functions of energy and data transfer [8].

Implementing SWIPT in Wireless Sensor Networks (WSNs) involves striking a delicate balance between harvesting energy and decoding data, as both processes need to occur simultaneously without interfering with each other [9].

Figure 2: Pictorial illustration of SWIPT

Previous Research and Constrains: Extensive researchon energy harvesting in wireless sensor networks exists, few studies truly dive into optimizing both energy harvesting and information transfer (SWIPT) simultaneously, especially when considering how these two factors impact overall network performance. Most existing studies tend to look at either energy harvesting or communication separately, without really examining how they interact and the trade-offs involved. Moreover, there’s a lack of real-world numerical simulations that assess SWIPT systems and compare various energy harvesting techniques, such as time splitting (TS) and power splitting (PS). This study aims to fill that gap by offering a detailed, quantitative analysis of key SWIPT performance metrics like throughput, harvested energy, signal-to-noise ratio (SNR), bit error rate (BER), network lifetime, node density, and latency across different power splitting and harvesting methods.

III. METHODOLOGY

The complete system of Simultaneous Wireless Information and Power Transfer (SWIPT) in Wireless Sensor Networks was modeled and simulated in MATLAB environment. For convenient digital computer implementation of the analysis, the mathematical models of the various component of the system were developed.

i.RF Harvesting Model

The energy harvested E_h at a sensor node from an RF source can be modeled as: [10].

$$E_h = \eta \cdot P_r \cdot T \quad (1)$$

Where;

η = is the energy harvesting efficiency

P_r = is the received RF power (Watts)

T = is the harvesting duration (seconds)

The received RF power P_r is calculated using the Friis transmission equation

$$P_r = P_t \cdot G_t \cdot G_r \cdot \left(\frac{\lambda}{4\pi d}\right)^2 \quad (2)$$

Where;

P_t = is the transmit power (Watts)

G_t and G_r = are the transmit and received antenna gains

λ = is the wavelength (Meters)

d = is the distance between transmitter and receiver (Meters)

ii.Power Splitting Ratio Model

In power splitting (PS) based SWIPT, the received signal y at the receiver is split into two streams for energy harvesting and information decoding: [11].

$$y = \sqrt{1-p} \cdot yID + \sqrt{p} \cdot yEH \quad (3)$$

Where;

$p \in [0, 1]$ = is the power splitting ratio

yID = is used for information decoding

yEH = is used for energy harvesting

The energy harvested under PS is;

$$E_{PS} = \eta \cdot p \cdot P_r \cdot T \quad (4)$$

iii.Signal -To -Noise- Ration (SNR) Model

The SNR at the receiver s given by; [12].

$$\text{SNR} = \frac{(1-p) \cdot P_r}{N_0} \quad (5)$$

Where;

N_0 = is the Noise power (Watts)

iv.Bit Error Rate (BER) Model

For binary phase shift keying (BPSK), the BER as a function of SNR is given by;[13].

$$\text{BER} = Q\left(\sqrt{2 \cdot SNR}\right) \quad (6)$$

Where $Q(\cdot)$ is the Q- function

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-t^2/2dt} \quad (7)$$

v.Throughput Model

Throughput is calculated based on Shannon under AWGN

$$\text{Throughput} = B \cdot \log_2(1 + SNR) \quad (8)$$

Where;

B = is the channel bandwidth (Hz)

SNR = is signal-to-Noise Ratio (linear Scale)

vi.Network Lifetime Model

Assuming a node consume energy E_c per cycle and has harvested energy E_h , the network lifetime L in cycles is given by;

$$L = \frac{E_{total} + \sum_{i=1}^{n} E_{hi}}{E_c} \quad (9)$$

Where;

E_{total} = is initial battery energy

E_{hi} = is the energy harvested in the i^{th} cycle

n = is the number of harvest intervals

vii.Latency Model

Total delay or latency D in SWIPT enable WSNs is affected by transmission time and harvesting delay

$$D = \frac{L}{R} + T_{harvest} \tag{10}$$

Where;
L = is the message size (bits)
R = is the data rate (bits)
$T_{harvest}$ =is the energy harvesting time delay

viii.Energy Efficiency Model

Energy efficiency η_e is calculated as;

$$\eta_e = \frac{\text{Throughput}}{\text{Total Power Consumption}} \tag{11}$$

Where throughput is in bits/sec and power consumption is in Watts.

ix.Node Density and Power Efficiency

Node density δ affects path loss and interference power efficiency η_p is evaluated as; [14].

$$\eta_p = \frac{Total\ Useful\ Energy}{Total\ energy\ consumed} \times 100\% \tag{12}$$

IV. RESULTS AND DISCUSSION

Table: 1: Parameters used for SWIPT Analysis in Wireless Sensor Networks

PARAMETER / SYMBOL	**VALUE/ UNIT**
Transmit Power(P_t)	1 Watts
Transmit Antenna Gain(G_t)	2
Receive Antenna Gain(G_r)	2
Wavelength (λ)	0.125 Meters
Distance (d)	10
Energy Harvesting Efficiency (η)	0.5
Harvesting Time (T)	1 second
Power Splitting Ratio (ρ)	0.3
Noise Power(N_0)	10e-9 Watt
Channel Bandwidth (B)	1e6 Hz
Initial Battery Energy(E_{total})	0.5 Joules
Energy Consumption per Cycle(E_c)	0.02 Joules
Message Size (L)	1000 Bits
Data Rate (R)	50000 bps
Harvesting Delay($T_{harvest}$)	0.05 seconds
Node Density (δ)	0.01 Nodes per m^2

Figure 2: Energy Harvest Against Distance

Figure 4: Throughput against Power Splitting Ratio

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Figure 5: Harvested Energy against Power Splitting Ratio

Figure 6: SNR against Distance

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Figure 7: BER Against SNR

Figure 8: Network Lifetime against Harvesting Techniques

Figure 9: Power Efficiency against Node Density

Figure 10: Energy Efficiency Against Data Rate

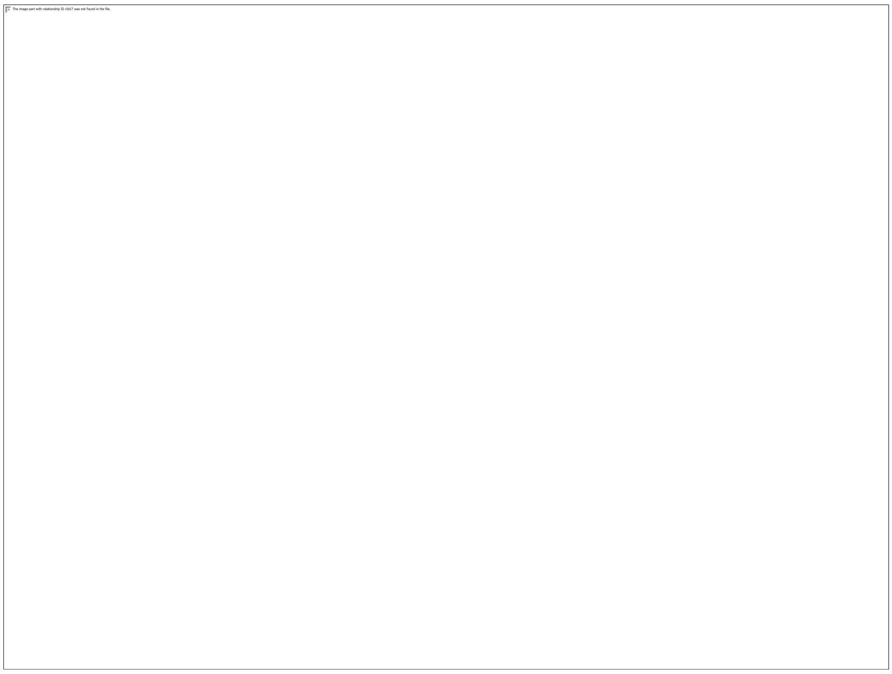

Figure 11: Latency against Harvesting Ration

V. DISCUSSION

In fig. 3. As the distance (d) increases, the harvested energy (EH) decreases significantly. This is due to the increasing path loss PLPLPL, which causes a reduction in the received signal strength as the distance grows. In fie. 4. The throughput increases as the power splitting ratio (ρ) moves towards 0.5 and then levels off. At ρ = 0, In fig. 5. As the power splitting ratio (ρ) increases, more power is allocated to energy harvesting, which directly increases the harvested energy. In fig 6, As the distance increases, the SNR decreases. This is due to the increased path loss (PL) at larger distances, which leads to a lower received signal power and a higher noise-to-signal ratio. In fig. 7. As the SNR increases, the BER decreases sharply, showing that a higher SNR leads to a lower likelihood of errors in the received bits. In fig. 8. The network lifetime is longest when the ideal harvesting technique is used, followed by time splitting, and shortest with power splitting. This shows that in practical terms, dedicating more time to energy harvesting leads to longer network operation. In fig. 9. As the number of nodes increases, the average harvested power per node decreases. This could be due to the higher power sharing among more nodes in the network, leading to lower efficiency for each individual node. In fig. 10. As the data rate increases, energy per bit decreases. This suggests that higher data rates lead to more efficient use of energy. In fig. 11. The latency increases as the harvesting ratio approaches 1 because more power is dedicated to energy harvesting, leaving less power for data transmission, which can lead to slower response times.

VI. CONCLUSION

SWIPT plays a crucial role in enhancing both energy sustainability and communication quality in wireless sensor networks (WSNs). This study stands out by presenting a detailed performance evaluation framework tailored for SWIPT in WSNs, offering valuable insights into how system parameters can be fine-tuned for optimal energy harvesting and data transmission. Through MATLAB-based simulations, the research identifies the ideal parameter ranges for practical and efficient deployment. Overall, the findings lay a solid foundation for integrating SWIPT into energy-limited wireless systems, emphasizing the importance of carefully optimizing factors such as the power splitting ratio, node density, and energy harvesting techniques to ensure smooth and efficient network operation.

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