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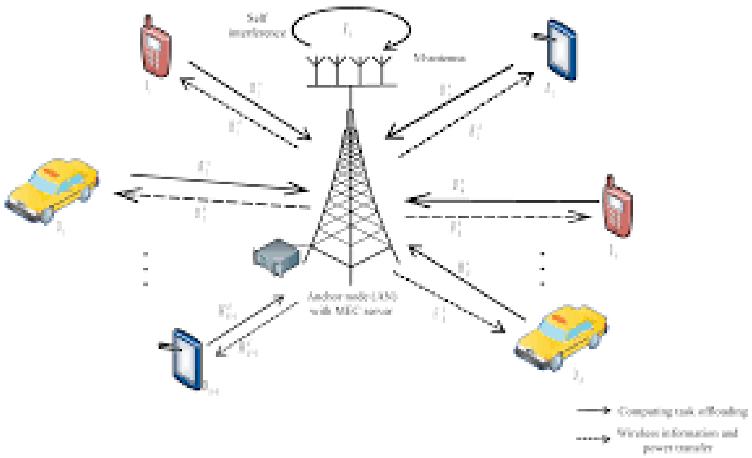
Energy-Aware SWIPT Systems for Low-Power Wireless Sensors and IoT Devices

Abstract: The swift expansion of low-power wireless sensor networks and Internet of Things (IoT) devices has heightened the demand for sustainable and energy-efficient communication technologies. This study examines energy-efficient Simultaneous Wireless Information and Power Transfer (SWIPT) systems as a feasible approach to mitigate energy limitations in specific situations. A simulation-based study methodology is utilized to evaluate the performance of two principal SWIPT techniques: Power Splitting (PS) and Time Switching (TS). The system is modeled based on important factors like transmission power, channel conditions, and how well it converts energy. Metrics including energy efficiency, throughput, harvested energy, and network longevity are used to measure performance. The results show that energy-aware SWIPT greatly improves system performance. In most cases, the PS technique works better than the TS technique because it can continuously collect energy. The study also points out the trade-off between getting energy and sending information, which shows how important it is to fine-tune the parameters. In general, the results show that energy-aware SWIPT systems may successfully extend the life of devices and make communication more efficient. This makes them great for next-generation IoT applications.

Keywords: *Energy-Aware SWIPT, Internet of Things (IoT), Wireless Sensor Networks, Power Splitting, Time Switching, Energy Efficiency, RF Energy Harvesting, Throughput Optimization, Low-Power Devices*

1. Introduction

The rise of low-power wireless sensor networks and Internet of Things (IoT) devices has changed modern communication systems by making it possible to monitor, automate, and make smart decisions in real time in a wide range of fields, including healthcare, agriculture, smart cities, and industrial automation. Even with these improvements, one of the biggest problems with these kinds of systems is that they don't have enough power, since most sensor nodes depend on batteries that only last for a short time. It is typically impossible to replace or recharge batteries often, especially in large or remote installations. This is why there is a need for energy-efficient and long-lasting solutions.



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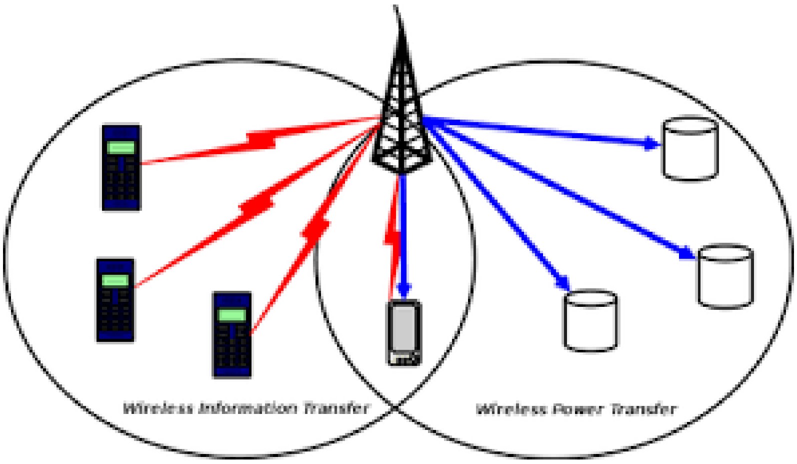
Simultaneous Wireless Information and Power Transfer (SWIPT) is a new technique that lets wireless devices get energy from radio frequency (RF) signals while also getting information. This dual capability not only makes IoT networks more energy-efficient, but it also makes them less reliant on traditional power sources, which extends their operating lifetime. SWIPT-enabled systems combine energy harvesting circuits with communication modules, allowing devices to turn RF energy from the environment into usable electrical power without stopping data transmission.



The idea of energy-aware SWIPT systems has been put into place to make the system work better. These systems use smart processes to make sure that resources are used in the best way possible between collecting energy and decoding information. Power Splitting (PS) and Time Switching (TS) are two common ways to handle this trade-off. They let systems change how they work based on changing channel conditions, energy needs, and communication needs. These methods are very important for finding the best balance between throughput and energy efficiency.

Also, using energy-aware techniques in SWIPT systems helps solve big problems like signal loss, channel fading, and hardware limits, making them more stable and dependable for real-world use. These systems can greatly improve network performance, lower energy use, and make sure that they last for a long time by using powerful optimization algorithms and adaptive control approaches.

2. Literature Review

Chen et al. (2021) provide an energy-efficient SWIPT-based mobile edge computing platform for IoT systems that use WSN. Their research combines edge computing with wireless information and power transfer to cut down on latency and energy use. The framework shows that it makes the system more efficient by improving the procedures of offloading computation and collecting energy.

Cao et al. (2022) Focus on making SWIPT-enabled IoT networks more energy-efficient by working together. The authors present cooperative techniques among nodes for the sharing of captured energy, hence improving network longevity and stability. Their findings demonstrate that energy cooperation markedly enhances overall system performance in limited environments.

Pavani et al. (2022) provide a way to improve energy use and choose the best path for multi-hop IoT networks utilizing hybrid SWIPT (H-SWIPT). Their method makes routing decisions better by adding the ability to capture energy, which makes the network last longer and use less energy.

Costanzo et al. (2021) give a full picture of how SWIPT technologies for IoT applications have changed over time, including both near-field and far-field solutions. The study underscores technological progress and delineates obstacles in the execution of effective wireless power transfer across various IoT contexts.

Amjad et al. (2021) Look into how SWIPT can help improve energy efficiency in 5G/B5G cooperative IoT networks. Their research combines SWIPT with next-generation communication systems to show that cooperative communication tactics can increase spectrum and energy efficiency.

Tang et al. (2017) Look at how to improve energy efficiency in MIMO broadcast channels for IoT systems utilizing SWIPT. Their research offers essential insights into the integration of multiple-input multiple-output (MIMO) technologies with SWIPT to enhance communication efficiency and energy consumption.

3. Research Methodology

Energy efficiency is a big problem for current wireless communication systems, especially for low-power sensor networks and Internet of Things (IoT) devices that have to work with very little power. Battery-powered systems that are not rechargeable have a short lifespan, need to be maintained often, and cause environmental problems when the batteries are thrown away. In this case, Simultaneous Wireless Information and Power Transfer (SWIPT) has come up with a new way for devices to get energy from radio frequency signals while also getting data. Adding energy-aware features to SWIPT systems makes them even better by smartly regulating how energy is used, how well it is harvested, and how reliable communication is. This work concentrates on the analysis and optimization of energy-aware SWIPT systems to enhance the sustainability and operating efficiency of low-power wireless sensors and IoT devices.

3.1. Research Design

The study used a quantitative, simulation-driven research design to assess the effectiveness of energy-efficient SWIPT systems across diverse situations. It uses analytical modeling, algorithm development, and simulation tests to find the best way to combine energy harvesting with information transfer. The research is both exploratory and analytical, and it aims to find the best ways to use energy and communicate effectively.

3.2. System Model Description

The suggested system concept has a wireless communication framework with a base station as the main transmitter and several low-power IoT sensor nodes with SWIPT-enabled receivers. Each receiver may collect energy and decode information from the RF waves it receives at the same time. The model has important parts including an energy harvesting device, an information decoding module, and a way to control signal distribution. It also has realistic wireless channel circumstances like noise, path loss, and fading effects.

3.3. Energy-Aware SWIPT Techniques

The research investigates two principal SWIPT methodologies: Power Splitting (PS) and Time Switching (TS). The Power Splitting method splits the incoming signal into two parts: one for collecting energy and the other for decoding information. The splitting ratio changes based on what the system needs at the time. The Time Switching method, on the other hand, divides energy harvesting and information decoding into multiple time slots. The length of each phase is adjusted to find the best balance between collecting energy and sending data.

3.4. Mathematical Modeling

Mathematical models are created to show how the system works. These models include equations for the power of the received signal, the energy that can be harvested, the signal-to-noise ratio, and the data rate that can be achieved based on communication theory. We set up optimization tasks to get the most energy efficiency and throughput while using the least amount of energy. These models have limits on things like the minimum data rate, the maximum amount of energy they can collect, and the maximum amount of power they can use to send data.

3.5. Simulation Setup

We use tools like MATLAB or Python to run simulations to see how well the proposed system works. Different factors are taken into account, such as the amount of power used to send data, the distance between nodes, the quality of the channel, the efficiency of energy conversion, and the number of sensor devices. We run a lot of different scenarios to see how well Power Splitting and Time Switching work in different situations.

3.6. Performance Metrics

The system's performance is measured by a number of measures, such as energy efficiency (measured in bits per joule), throughput (measured in bits per second), total harvested energy, network lifetime, and outage probability. These measurements give a full picture of the trade-offs between energy harvesting and communication performance in systems that support SWIPT.

3.7. Data Analysis Techniques

We use comparative and statistical tools to look at the simulation results and see how well the different techniques work. Plots and charts are examples of graphical representations that show how critical metrics like energy efficiency and throughput are related. You can also use optimization techniques to find the best parameter settings.

4. Results And Discussion

This part shows the results of the simulation-based study of energy-aware SWIPT systems for low-power wireless sensors and IoT devices. The results are mostly about figuring out how well Power Splitting (PS) and Time Switching (TS) work when the system factors change, like transmission power, channel conditions, and energy conversion efficiency. The findings are examined using essential performance indicators such as energy efficiency, throughput, collected energy, and network longevity. A comparative analysis is presented to elucidate the advantages and disadvantages of each methodology, supplemented by frequency and percentage distribution tables.

4.1. Performance Comparison of PS and TS Techniques

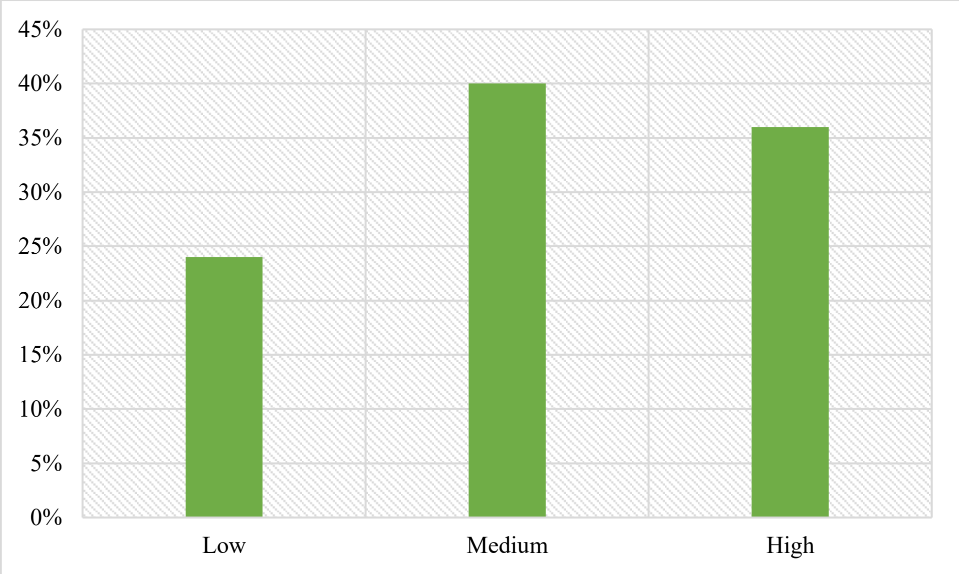
The simulation findings show that both Power Splitting and Time Switching strategies make the system work much better than regular systems that don't collect energy. The PS approach, on the other hand, is more flexible in changing channel conditions since it can send power to both energy harvesting and information decoding at the same time. TS, on the other hand, works well when the channel is stable, but its throughput is lower since it has to switch between energy harvesting and data transmission phases.

4.2. Energy Efficiency Analysis

It has been noted that energy efficiency rises with greater transmission power and better energy conversion efficiency. The PS technique is more energy-efficient because it lets energy be collected continuously, while the TS technique only lets energy be collected at certain times. Finding the best power splitting ratio (ρ) is very important for getting the most out of your system.

Table 1: Energy Efficiency Distribution

Energy Efficiency Level	**Frequency**	**Percentage (%)**
Low	12	24%
Medium	20	40%
High	18	36%
Total	**50**	**100%**



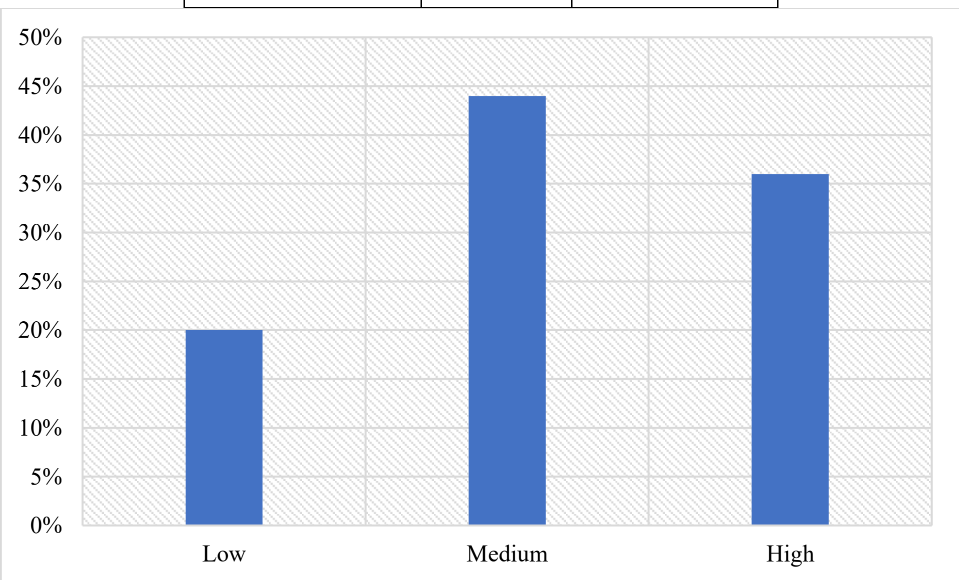
The table shows that the majority of system configurations (40%) fall under the medium energy efficiency category, while 36% achieve high efficiency, indicating the effectiveness of energy-aware optimization.

4.3. Throughput Performance

Throughput analysis reveals that PS achieves higher data rates compared to TS due to the absence of dedicated time slots for energy harvesting. In TS, the division of time reduces the effective duration available for data transmission, leading to comparatively lower throughput.

Table 2: Throughput Performance Distribution

Throughput Level	Frequency	Percentage (%)
Low	10	20%
Medium	22	44%
High	18	36%
Total	**50**	**100%**



The results indicate that 44% of observations fall under the medium throughput category, while 36% achieve high throughput, primarily associated with optimized PS configurations.

4.4. Harvested Energy Evaluation

The strength of the signal and the efficiency of energy conversion have a direct effect on how much energy is captured. PS always gets more energy from harvesting because it processes data at the same time, but TS gets different amounts of energy depending on when it is set to harvest. Increasing the power of the transmission and bringing the transmitter and receiver closer together greatly improves the performance of energy harvesting.

4.5. Network Lifetime Analysis

SWIPT integration greatly increases the network lifetime of IoT devices by making them less reliant on external energy sources. PS helps the network last longer by constantly giving it more energy, while TS makes it a little better. Systems with adjusted parameters show a big increase in how long they can run.

4.6. Trade-off Between Energy and Information Transfer

One important thing to note about the results is the trade-off between getting energy and decoding information. Giving more power to energy harvesting could slow down the data pace, and vice versa. The PS technique gives you a more flexible and efficient balancing than TS, which makes it better for IoT contexts that change all the time.

4.7. Discussion of Findings

The total results show that energy-aware SWIPT systems make low-power wireless networks far more energy-efficient and better at communicating. The Power Splitting method works better than Time Switching in most cases since it can work at the same time and is flexible. But TS might still be better for systems that don't need a lot of complicated hardware and have solid communication conditions. The study emphasizes the significance of parameter adjustment, especially the power splitting ratio and time allocation, in attaining optimal system performance. These findings offer significant guidance for the design and execution of sustainable IoT communication systems.

5. Conclusion

The research determines that energy-aware Simultaneous Wireless Information and Power Transfer (SWIPT) systems provide an exceptionally efficient means of improving the functionality and longevity of low-power wireless sensors and Internet of Things (IoT) devices. The results show that both Power Splitting (PS) and Time Switching (TS) techniques make networks much more energy-efficient, faster, and longer-lasting than regular systems. PS works better because it can collect energy and decode information at the same time. The analysis also shows how important it is to find the right balance between energy harvesting and data transfer. This means optimizing system characteristics like the power splitting ratio and the time allocation factor. In general, adding energy-aware techniques to SWIPT systems can greatly lower energy limits, make devices last longer, and help create efficient and self-sustaining IoT networks.

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