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PERFORMANCE ANALYSIS OF HYBRID ENERGY HARVESTING TECHNIQUES FOR WBAN APPLICATIONS

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Abstract:
Wireless Body Area Networks (WBANs) are widely used in healthcare and wearable monitoring applications, where continuous power supply is a major challenge due to limited battery life. Conventional Radio Frequency (RF) energy harvesting methods provide low and unstable energy, especially at longer distances. To overcome this limitation, this paper proposes a hybrid energy harvesting system that combines RF, motion, and thermal energy sources for long-term WBAN operation. The proposed system improves power availability and reliability by utilizing body movement and body heat along with RF signals. MATLAB simulation is used to analyze the performance of both the existing RF-only method and the proposed hybrid method. The results show that the hybrid system provides better energy efficiency, stable power generation, and improved operational lifetime compared to the conventional approach. The proposed method is suitable for low-power wearable healthcare devices and sustainable WBAN applications.

Keywords: Wireless Body Area Network (WBAN), RF Energy Harvesting, Hybrid Energy Harvesting, Thermal Energy, Motion Energy, MATLAB Simulation, Wearable Devices

1. Introduction

Wireless Body Area Networks (WBANs) play an important role in modern healthcare, wearable electronics, fitness monitoring, and medical diagnosis systems. WBAN consists of small sensor devices placed on or inside the human body to continuously monitor physiological parameters such as heart rate, body temperature, blood pressure, and other health-related data. These sensors require a continuous and reliable power supply for long-term operation.

Conventional WBAN devices mainly depend on batteries, which have limited lifetime and require frequent replacement or recharging. This creates difficulties in continuous monitoring applications, especially for implantable and wearable medical devices. To overcome this limitation, energy harvesting techniques have gained significant attention in recent years.

Among various energy harvesting methods, Radio Frequency (RF) energy harvesting is widely used because ambient RF signals from WiFi, mobile networks, and communication devices are easily available in the environment. However, RF energy alone provides limited and unstable power, especially when the distance from the RF source increases. This reduces the efficiency and reliability of the system.

To improve energy availability and system performance, this paper proposes a hybrid energy harvesting approach that combines RF energy with motion and thermal energy sources. Motion energy is generated from body movements such as walking and hand movement, while thermal energy is obtained from the temperature difference between the human body and surroundings. By combining multiple energy sources, the proposed system provides better energy stability, improved efficiency, and longer operational lifetime.

The proposed hybrid model is implemented and analyzed using MATLAB simulation. The performance of the existing RF-only method and the proposed hybrid method are compared in terms of harvested power and energy efficiency.

The simulation results demonstrate that the hybrid approach significantly improves the overall performance of WBAN systems for long-term healthcare and wearable applications.

2. Objective

The main objective of this work is to develop an efficient and reliable hybrid energy harvesting system for Wireless Body Area Networks (WBANs) used in healthcare and wearable monitoring applications. Conventional RF energy harvesting systems depend only on ambient radio frequency signals, which provide limited and unstable power, especially when the distance from the RF source increases. This limitation reduces the operational lifetime and reliability of wearable devices. To overcome this problem, the proposed method combines RF energy with motion and thermal energy sources to improve overall energy generation and system stability.

Another important objective is to reduce battery dependency in WBAN devices by utilizing human body movement and body heat as additional renewable energy sources. Motion energy is generated from activities such as walking and hand movement, while thermal energy is produced from the temperature difference between the human body and the surrounding environment. By integrating these multiple energy sources, the proposed system ensures continuous power availability for low-power wearable sensors.

The proposed work also aims to analyze and compare the performance of the existing RF-only method and the proposed hybrid method using MATLAB simulation. The comparison is carried out in terms of harvested power, energy efficiency, operational stability, and long-term device performance. The final objective is to design a sustainable and energy-efficient WBAN system suitable for continuous healthcare monitoring and wearable electronic applications.

3. Literature Review

Wireless Body Area Networks (WBANs) have become an important research area in healthcare monitoring, wearable electronics, and biomedical applications due to their ability to continuously monitor human physiological parameters. However, one of the major challenges in WBAN systems is the limited lifetime of batteries used in wearable and implantable sensor devices. Researchers have proposed various energy harvesting techniques to overcome this limitation and achieve long-term operation of WBAN devices.

In conventional WBAN systems, battery-powered sensor nodes are widely used for data collection and wireless communication. Although batteries provide stable power, frequent charging and replacement increase maintenance cost and reduce user convenience. To address this issue, several studies focused on ambient energy harvesting techniques such as solar, thermal, vibration, and Radio Frequency (RF) energy harvesting.

Among these methods, RF energy harvesting has gained significant attention because RF signals from WiFi routers, mobile communication systems, and Bluetooth devices are continuously available in the environment. RF energy harvesting systems generally consist of an antenna, matching circuit, rectifier, and energy storage unit. The antenna receives ambient RF signals, and the rectifier converts RF energy into usable DC power. Previous studies showed that RF harvesting can support low-power WBAN devices and reduce battery dependency. However, the harvested RF power is very small and decreases rapidly with distance from the RF source. As a result, RF-only systems suffer from low efficiency and unstable operation.

Researchers also investigated biomechanical energy harvesting techniques, where energy is generated from body movements such as walking, arm movement, heartbeat, and joint motion. Piezoelectric and electromagnetic transducers are commonly used to convert mechanical movement into electrical energy. Motion-based harvesting provides higher energy during physical activity, but power generation becomes low when the user remains inactive.

Thermal energy harvesting is another promising technique used in wearable devices. It utilizes the temperature difference between the human body and the surrounding environment through thermoelectric generators based on the Seebeck effect. Thermal harvesting provides continuous low-power generation even during rest conditions. However, the generated power is usually limited and depends on environmental temperature conditions.

Several recent studies proposed hybrid energy harvesting approaches by combining multiple energy sources to improve overall system efficiency and reliability. Hybrid systems can provide continuous power availability because when one energy source becomes weak, other sources can compensate for the power deficiency. Researchers reported that combining RF, motion, and thermal energy sources significantly improves harvested power, operational lifetime, and stability of WBAN devices.

Although many existing works focused on individual harvesting techniques, there is still a need for an efficient and reliable hybrid energy harvesting model suitable for long-term WBAN applications. Therefore, this work proposes a hybrid RF, motion, and thermal energy harvesting system and analyzes its performance using MATLAB simulation. The proposed system aims to improve energy efficiency, reduce battery dependency, and support sustainable operation of wearable healthcare devices.

4. Proposed system

The proposed system presents a Hybrid Energy Harvesting Model for Wireless Body Area Networks (WBANs) by integrating Radio Frequency (RF), motion, and thermal energy sources to provide continuous and reliable power for wearable healthcare devices. The main objective of the proposed system is to overcome the limitations of conventional RF-only energy harvesting methods, which suffer from low power generation and reduced efficiency at longer distances.

In the proposed model, RF energy is harvested from ambient wireless communication sources such as WiFi routers, mobile networks, and Bluetooth signals. An antenna receives the RF signals, and a rectifier circuit converts the received RF energy into usable DC power. However, since RF energy alone is insufficient for continuous WBAN operation, additional renewable energy sources are integrated into the system.

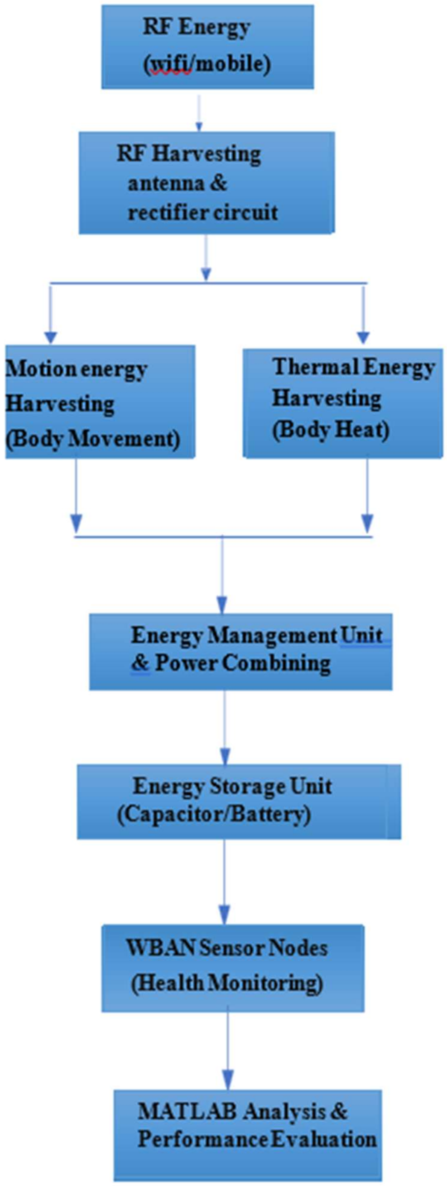
Motion energy harvesting is achieved by converting human body movements such as walking, running, and hand motion into electrical energy using piezoelectric or electromagnetic transducers. This source provides additional power during body activity and improves the overall harvested energy. Thermal energy harvesting is performed using thermoelectric generators, which utilize the temperature difference between the human body and the surrounding environment to generate electrical power continuously.

The energies harvested from RF, motion, and thermal sources are combined through an energy management unit to obtain total usable power for WBAN sensor nodes. The proposed system also includes an intelligent energy utilization mechanism that distributes energy efficiently to wearable sensors for stable and long-term operation.

MATLAB simulation is used to model and analyze the performance of the proposed hybrid system. The proposed method is compared with the conventional RF-only method in terms of harvested power, energy efficiency, stability, and operational lifetime. Simulation results demonstrate that the hybrid system provides improved power availability and better reliability compared to the existing system.

The proposed hybrid energy harvesting system is highly suitable for wearable healthcare monitoring applications, low-power biomedical devices, and sustainable WBAN systems requiring continuous and battery-free operation.

4.1..Block Diagram



1.

5. Results and discussion

The performance of the proposed Hybrid Energy Harvesting System for Wireless Body Area Networks (WBANs) is analyzed using MATLAB simulation. The analysis evaluates the efficiency of the proposed system under different operating conditions by comparing the existing RF-only method with the proposed hybrid method. The performance is analyzed based on three important factors: harvested energy behavior, energy stability, and power management efficiency.

The proposed hybrid model combines RF, motion, and thermal energy sources to improve continuous power availability for wearable healthcare sensor devices. MATLAB simulations are used to evaluate the harvested power under varying distance and activity conditions.

Normal data range

parameters	Normal Range	Low energy condition
RF Harvested Power	0.00005 – 0.0001 W	< 0.00001 W
Motion Energy	Normal body movement	No movement
Thermal Energy	Stable body temperature	Low thermal variation
Total Harvested Power	Sufficient for operation	Insufficient power
Operating Distance	1 – 20 m	> 30 m

Table 5.1 Data Range

5. 1 Hybrid Energy Harvesting Result

Scenario:

Weak RF Signal / Long Distance Condition

Dataset:

"Hybrid_Energy_Harvesting_Dataset_200_Samples.csv"

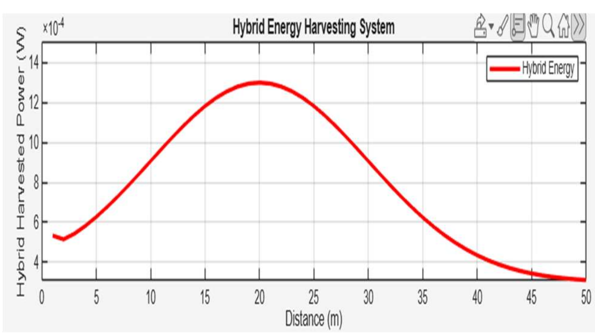
Software Used:

MATLAB

1. Dataset Generation Using MATLAB

For this work, a dataset is generated using MATLAB by modeling different WBAN energy harvesting conditions. The dataset contains parameters such as RF harvested power, motion energy, thermal energy, total harvested power, and operating distance.

Random data values are generated based on normal and low-energy conditions representing different environmental and body activity situations. Logical conditions are applied to simulate weak RF signals, low movement conditions, and thermal variations.



2. Hybrid Energy Harvesting Model

The proposed framework utilizes a Hybrid Energy Harvesting Model that combines:

1. RF energy harvesting

2. Motion energy harvesting
3. Thermal energy harvesting

RF power is calculated using the Friis transmission equation, while motion and thermal energies are modeled as additional renewable power sources. The total harvested energy is obtained by combining all three energy sources.

3. Energy Classification

The harvested energy data is processed at the edge node using the proposed hybrid model. Based on the available total harvested energy, the system classifies the operating condition into:

1. Normal Energy Condition
2. Low Energy Condition

If sufficient power is available, WBAN sensors continue normal monitoring and transmission operation. Otherwise, the system detects a low-energy condition.

4. Edge Energy Management Function

The edge energy management function controls sensor node activity based on the harvested energy level. When sufficient hybrid energy is available, the sensor nodes continue data transmission and monitoring.
If the harvested energy becomes lower than the threshold value, the system minimizes power consumption by reducing communication activity and switching the WBAN sensor node into low-power mode. This improves energy efficiency and increases the operational lifetime of wearable healthcare devices.
The proposed hybrid model demonstrates improved stability, reliability, and power efficiency compared to the conventional RF-only energy harvesting system.

5.2.Comparison Table

Distance (m)	RF Power (W)	Hybrid Power (W)

1	0.0001	0.0005
5	0.0000	0.0006
10	0.0000	0.0009
15	0.0000	0.0012
20	0.0000	0.0013
25	0.0000	0.0012
30	0.0000	0.0009
35	0.0000	0.0006
40	0.0000	0.0004
45	0.0000	0.0003
50	0.0000	0.0003

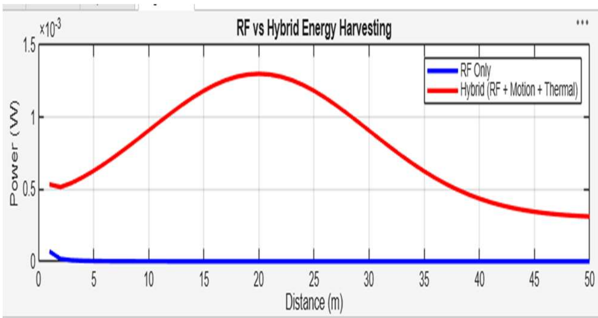
Table 5.2. Comparison of RF-Only and Hybrid Energy Harvesting Results

5.3.Compare Normal (RF only) and Hybrid method

In the case of the conventional RF energy harvesting system for Wireless Body Area Networks (WBANs), the wearable sensor nodes depend only on ambient RF signals obtained from WiFi routers, mobile networks, and other wireless communication devices. Since RF energy decreases rapidly with increasing distance, the harvested power becomes very low and unstable. As a result, the sensor nodes may experience insufficient power for continuous monitoring operation, reducing the efficiency and operational lifetime of the WBAN system. Furthermore, the existing RF-only method lacks additional backup energy sources, making the system unreliable in low RF signal conditions.

However, the proposed hybrid energy harvesting system improves the overall performance of WBANs by ntegrating RF, motion, and thermal energy sources. In addition to RF energy, the system harvests motion energy generated from body movement and thermal energy generated from body heat. The harvested energies are combined through an energy management unit to provide continuous and stable power for wearable healthcare devices.

Instead of depending on a single energy source, the proposed hybrid method utilizes multiple renewable energy sources to maintain sensor operation even when RF energy becomes weak. Therefore, the proposed system provides better energy efficiency, improved power stability, reduced battery dependency, and longer operational lifetime compared to the conventional RF-only system. Conclusively, the performance of the hybrid energy harvesting-based WBAN is superior to the traditional RF harvesting method because it ensures continuous power availability, improved reliability, lower power interruption, and sustainable long-term healthcare monitoring operation.



6.Conclusion

This paper presented a Hybrid Energy Harvesting System for Wireless Body Area Networks (WBANs) by integrating RF, motion, and thermal energy sources to improve the power efficiency and reliability of wearable healthcare devices. The conventional RF-only energy harvesting method suffers from low power generation and unstable performance, especially at larger distances from the RF source. To overcome these limitations, the proposed hybrid method utilizes additional renewable energy generated from body movement and body heat.

The performance of the proposed system was analyzed using MATLAB simulation. The simulation results demonstrated that the proposed hybrid method provides higher harvested power, improved energy stability, reduced power interruption, and longer operational lifetime compared to the existing RF-only method. The integration of multiple energy sources ensures continuous power availability even under weak RF signal conditions.

The proposed hybrid energy harvesting system significantly reduces battery dependency and improves the sustainability of WBAN sensor nodes. Therefore, the developed system is highly suitable for long-term wearable healthcare monitoring, biomedical applications, and low-power wireless sensor systems. Future work can focus on integrating intelligent energy management algorithms and real-time hardware implementation for further performance enhancement.

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