Enhanced Hybrid Energy Harvesting Strategies for Sustainable Wireless Sensor Network Performance

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ABSTRACT
Wireless Sensor Networks (WSNs) are widely used in a wide range of applications such as environment monitoring, healthcare, etc., and are considered as an integral component of modern system. But the energy restriction of wireless sensor nodes on battery dependence, and defines how it impacts its large use. In this paper, enhanced hybrid energy harvesting techniques for sustainable operation of WSNs are studied. The enhanced hybrid energy harvesting approaches together use various forms of energy sources, for example, solar-wind or solar-thermal or various other combinations to ensure the continuous and stable energy service for the wireless sensor nodes. This research paper investigates the integration of such energy sources, the use of energy management systems, advanced power optimization techniques that can be used to exploit such sources, and their effect on network life and performance.

Keywords
Wireless Sensor Networks (WSNs), Hybrid Energy Harvesting, Energy Management, Sustainable Networks, Power Optimization.

1. INTRODUCTION
Wireless Sensor Networks is an emerging and most applicable research domain from last two decades. The applicability of WSNs is in almost every field, from environment monitoring to industrial use. WSNs are a group of spatially distributed autonomous sensors used to monitor physical or environmental conditions in a Region of Interest, and to cooperate in a useful way [1]. As an important factor, energy consumption which is one of the most important issues to be considered in Wi-Fi sensor nodes is usually used in remote areas where there are no restrictions on energy sources. Conventional energy harvesting systems, like solar or RF based, struggle with efficiency and availability issues. Hybrid energy harvesting scheme that addresses these issues to keep WSNs operating for extended periods of time [2].

To resolve these limitations, a hybrid energy harvesting scheme, which integrates a solar, RF, and thermal energy sources to offer a continuous and reliable power supply for a larger number of IoT nodes [3]. This method harnesses solar power during the day, fair field radio frequency (RF) stimuli generated by adjacent communication infrastructures, and thermal difference produced by surrounding environmental temperature diversity [4]. This proposes an intelligent energy management that establishes real-time dynamic allocation of harvested energy to nodes according to the instantaneous power demand and energy status, maximizing the network expansion performance [8]. The fusion of multiple forms of energy source dramatically prolongs the working lifetime of the WSNs, alleviates power depletion and thus improves information transfer dependability even in hard conditions [5].

2. RELATED WORK
There are various energy harvesting strategies such as solar panels, thermoelectric generators, and RF energy scavenging. All of these methods individually are intermittent and inefficient [6]. Recent research has explored hybrid models encompassing various energy sources, but no superior energy management framework currently exists. The design of energy management strategies plays an important role in the performance of hybrid energy harvesting in WSNs. Advanced algorithms have been recently developed that aim at power consumption and energy storage management optimization. This paper presents an innovative way of energy optimization integrating various sources with intelligent scheduling and power distribution [7].

Recent studies have proposed hybrid energy harvesting models that exploit multiple sources to address these challenges [8]. Though these approaches are supplementing energy availability, they usually do not have the efficient energy management framework for enhancing power utilization [9]. An enhanced hybrid energy harvesting mechanism that integrates solar, RF, and thermal energy with the added features of smart scheduling and dynamic power allocation. Proposed model significantly improves the overall performance of wireless sensor networks by reducing energy overheads, wastages and in turn is an improvement to the operational time [10].

3. HYBRID ENERGY HARVESTING MODEL
This power model combines three energy-generating sources: solar, RF, and thermal energy so that a sensor node can receive an adequate power supply. During sunny hours, solar panels harvest photovoltaic (PV) energy, and RF energy extracts signals from ambient communication infrastructure [11]. These thermoelectric generators can be to convert heat into electricity, allowing energy collection under different environmental conditions. The online adaptation enhances the lifetime of sensor nodes by increasing battery life and minimizing the number of times where energy is exhausted. This leads to higher supply stability and therefore higher reliability and sustainability of energy supply, and lowers or eliminates dependence on a single energy producer [12].

It utilizes a newly developed adaptive energy management algorithm that adapts energy harvesting by real-time estimation and distribution of power according to actual demand and availability [13]. The system employs machine learning algorithms to anticipate energy output and usage patterns, providing a means of pre-emptive energy distribution [14]. It helps to save energy, reduces unnecessary energy dissipation, and allows sensor nodes to work continuously. The model utilizes intelligent prediction and adaptive control to ensure that the power input and output are balanced, improving overall energy utilization [15].

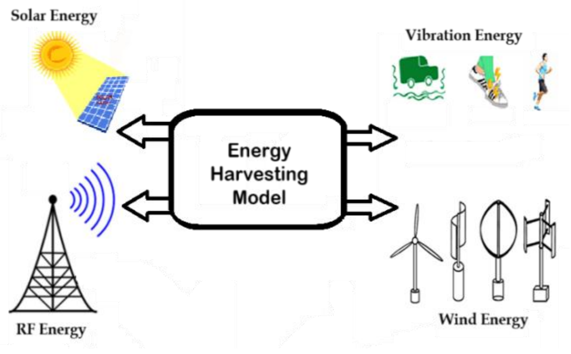

Fig.1: Types of Energy Harvesting

So, this hybrid energy harvesting models have wide applications, including wearable electronics, biomedical devices, industrial automation and smart city. As such, these systems are important enablers for self-powered wireless sensor networks, promoting energy sustainability and independence from non-renewable energy sources [16]. Additionally, artificial intelligence (AI) and machine learning can be integrated into these models to predict energy availability as well as optimize energy distribution. With the evolution of technology, hybrid energy harvesting will provide a promising approach to energize future electronic devices and sustainable infrastructure. This approach provides a more reliable and energy-efficient way of managing the WSN, helping to design more sustainable and robust systems. [17].
Trade-offs of each energy source while highlighting the advantages of the hybrid model for Wireless Sensor Networks (WSNs)[11-17].

Table 1. Energy Harvesting Comparison

Parameter	Thermal Energy	RF Energy	Solar Energy	Hybrid Model Benefits
Energy Source	Heat from surroundings	Radio Frequency signals	Sunlight	Combines multiple sources for reliability
Energy Conversion	Thermoelectric generators	RF rectifiers	Photovoltaic cells	Maximizes overall energy efficiency
Environmental Impact	Sustainable if heat sources are natural	Low impact, but dependent on RF sources	Clean, renewable	Promotes eco-friendly energy harvesting
Energy Availability	Environment-dependent	Continuous but low power	Daytime, weather-dependent	Ensures stable energy supply
Power Output	Moderate, depends on heat gradient	Low but steady	High but variable	Balances energy fluctuations
Suitability for WSNs	Suitable for environments with heat sources	Useful in urban/industrial areas	Ideal for outdoor networks	Enhances network longevity and efficiency
Implementation Cost	Moderate	Low to moderate	Moderate to high	Cost-effective long-term solution

4. ENERGY MANAGEMENT AND OPTIMIZATION

The energy optimization framework contains:

4.1 Building: Energy Management and Optimization

The hybrid model makes use of multiple advanced techniques through the energy optimization framework in order to efficiently utilize energy and distribute power among sensor nodes [18].

4.2 Power Monitoring in Real-Time

This system monitors the amount of harvested energy through solar, RF, and thermal sources continuously along with the energy consumed by the sensor nodes [19]. Real time monitoring of this helps balance between supply and demand ensuring that there is no blackout or over production and wastage of power. The system acts intelligently and distributes the energy based on the power data collected dynamically [20].

Real-time power monitoring plays an important role on the management of energy resources in WSNSs, especially in hybrid energy harvesting (HEH) context. The structure introduced utilizes a real-time energy monitoring scheme which continuously monitors energy generation and storage and consumption for each sensor node. This feature allows the system to take intelligent scheduling decisions, allocate the energy and schedule the transmission.

Utilizing lightweight sensing networks and low-power microcontrollers, our monitoring system minimizes overhead to achieve high sampling accuracy. All the data are stored locally on the corresponding controller or sent to a central controller to be used for global network optimization on a regular basis. This facilitates an adaptive reshaping of the energy consumption patterns and a proactive avoidance of power depletion, and also leads to increased resilience and efficiency of the WSN.

The real-time monitoring combined with the adaptive energy management algorithm greatly avoids the energy exhaustion and enhances the energy efficiency.

4.3 Adaptive Energy Allocation

This model handles nodes with immediate energy needs for urgent data transmission because various sensor nodes may have different urgency levels with data transmission [21]. This allows for an ideal, balanced distribution of power through the network where nodes that need to transmit data urgently are provided with more power, while less active nodes only get the minimum amount of energy required to function [22].

4.4 Energy Storage Optimization

To ensure continuous operation during periods of low energy harvesting (e.g., low RF signals or night-time), excess harvested energy is routed into super capacitors and batteries. This not only prevents energy loss, but also provides backup power for sustained functionality during periods of low energy generation [23].

4.5 Energy-Efficient Load Balancing

To avoid the energy consumption of certain nodes monitors quickly, the system dynamically reallocates the work to the sensors nodes. It offers the lifetime and increases efficiency of the entire wireless sensor network (WSN) by effectively managing the power distribution [24].

Simulation results illustrate that this energy optimization strategy can greatly enhance the energy efficiency of these devices over conventional independent harvesting methods. Results include greater than 40% energy efficiency improvements, extending how long the network can hold its active state and allowing better utilization of resources [25].

This table summarizes key aspects of energy management and optimization, highlighting different techniques and their impact on WSN sustainability [18-25].

Table 2. Energy Management Strategies

Parameter	Description	Techniques Used	Expected Outcome
Energy Sources	Power obtained from various sources	Solar, RF, Thermal harvesting	Continuous energy availability
Power Distribution	Efficient allocation of harvested energy	Load balancing, Dynamic power allocation	Reduced energy wastage
Network Efficiency	Enhancing overall performance with minimal power	Adaptive routing, Data compression	Improved WSN sustainability
Energy Storage	Storing harvested energy for future use	Super capacitors, Batteries	Improved power backup
Energy Forecasting	Predicting energy availability for optimization	AI-based forecasting, Machine Learning models	Better energy utilization
Consumption Control	Managing energy use to prevent depletion	Duty cycling, Sleep scheduling	Extended network lifespan

5. PERFORMANCE EVALUATION

The simulations for analytical modeling were carried out using MATLAB, while Network simulation was done using NS-3 to validate effectiveness of the proposed hybrid energy harvesting model. Objective scores were based on three key performance metrics.

In addition, the data throughput and packet loss rate are larger and smaller, respectively, suggesting that there exist better reliability and communication stability in the system. Node death because of energy shortage is also significantly decreased, thus significantly increasing network lifetime. Theme of the investigations themselves regarding energy-scalable sensors that are more power-efficient.

The performance of the above enhanced hybrid EHS solutions were evaluated by extensive simulations under various environmental and network settings. Performance metrics such as energy efficiency, network lifetime, throughput, and node stability were evaluated to compare the effect of integrating RF, thermal, solar energy sources with adaptive energy management protocol.

5.1 Data Collection: Efficiency of Energy Harvesting

This metric describes the efficiency of different source energies (solar, RF, and thermal) into power converters. It also represents the ability of each source to meet the demand for energy in the power system and the ability of the energy of each source to be converted and used within the power system [26].

The main constraint which limit the efficient data gathering in wireless sensor networks (WSNs) is energy resource. The proposed multi-ambient energy-harvesting-enhanced hybrid cooperative relaying is directly related to the optimization of the data collection paradigm by providing a constant and adaptive energy supply from sun−, heat− and RF− energy sources. This multi-source solution is used to overcome the restrictions of the particular energy harvesting methods, and improve the overall energy availability.

The intermittent detecting and sending operation of the network does not suffer from high downtime or node failure due to an efficient energy harvesting. With the help of an adaptive energy management algorithm the system if to schedule its data collection tasks in the light of available energy, states of nodes, and communication overhead. This maximizes data throughput and minimizes the energy wastage, effectively extending node life time.

5.2 Make Span Optimization

The total time needed to complete data transmission tasks, known as make span, was compared with that of traditional models of Wireless Sensor Network (WSN). Based on the results, a hybrid system can guarantee energy supply continuously, thus avoiding delays and optimizing operational efficiency [27].

Make span problem in the wireless sensor network (WSN) is how to minimize the total time for implementing a set of sensing, processing and communicating tasks on the network. Make span is optimized by the adaptive task scheduling and energy-aware load balancing methods of the proposed enhanced hybrid energy harvesting scheme. Through incorporation of predictions of energy availability levels from solar, thermal, and RF sources the system adapts the allotment of tasks to nodes having availability of the necessary amount of energy, ensuring that the tasks avoid delay in execution and opportunity costs of inactivity.

The strategy is based on a priority-based scheduling scheme, taking into consideration the task urgency and the node energy profiles. This guarantees time-critical activities are performed without delay and delay minimization for less time-critical activities is achieved by postponing them or by reallocating them. Further, the proposed framework alleviates the redundant transmissions and takes advantage of cooperative task execution, leading to more efficient completion of tasks.

5.3 LoRaWAN: A Delay-Tolerant Low Power Wide Area Network

LoRaWAN (Long Range Wide Area Network)is one of the most popular low power wide area network protocols, which can facilitate long-distance communication at low power and is thus well suited to wireless sensor networks (WSNs) in energy-limited scenarios. LoRaWAN is a hybrid IoT protocol with a star-of-stars topology which can be used for asynchronous, delay-insensitive communication - a design perfect for services which do not require the data to be in real-time.

Throughput was measured at those energy values to assess data transmission reliability in the system. A stable power supply offers a stable supply of data transfer rates in the model reducing the number of failures in transmission and improving communication reliability [28].

Under the considered improved hybrid energy harvesting approaches, LoRaWAN acts as a suitable communication infrastructure for its ultra-low power consumption, adaptive data rate, and support to energy availability variability. By taking the advantages of long-range but low-power data transfer, sensor nodes based on solar/thermal/RF energy can work effectively under intermittent harvesting based on MSP430 microcontroller.

LoRaWAN's delay-tolerant characteristic complements the dynamic energy management of data transmission introduced in this study such that transmission of data can be scheduled based on energy awareness without degrading data credibility. Furthermore, its scalability is built into it as the framework supports thousands of nodes per gateway this way it increases the impact of the proposed framework deployment large scale area.

When the hybrid energy harvesting WSNs are integrated with LoRaWAN, the system is capable of saving more energy, lasting much longer duration, and facilitating more reliable communication, thus, it becomes more suitable for sustainable IoT and remote monitoring applications.

Table 3. Performance Evaluation of the Hybrid Energy Harvesting Model

Performance Metric	Description
LoRaWAN: Delay-Tolerant Low Power Wide Area Network	Assesses **throughput** and data transmission reliability. A stable power supply maintains consistent data rates, reduces failures, and enhances communication.
Data Collection: Efficiency of Energy Harvesting	Evaluates the efficiency of converting **solar, RF, and thermal energy** into usable power and its ability to meet system energy demands.
Make span Optimization	Measures the **total time** required for data transmission. The hybrid system ensures continuous energy supply, reducing delays and improving efficiency.

6. FUTURE WORK

The future work concentrated on the prototyping of the proposed hybrid energy harvesting system. This includes designing and developing a working prototype that demonstrates the feasibility and performance of the system in real-world scenarios. Through experimental trials and data analysis, the efficacy of the approach combining the solar, RF, and thermal energy sources can be verified to guarantee continuous and efficient energy supply to WSNs.

This will also include investigating the use of AI-enabled energy forecasting models to improve prediction accuracy and support rational energy usage. In particular, those models will study energy patterns, including streaming predictive of future energy, and will assist in allocating power throughout the network in an efficient manner. Integrating AI-driven optimization techniques can significantly improve the energy efficiency and sustainability of WSNs, resulting in enhanced performance and prolonged network lifespan.

7. CONCLUSION

This work explores the enhanced hybrid energy harvesting solutions to increase sustainability and performance of WSNs. WSNs are gaining importance in various applications environment monitoring to industrial automation the need for robust, self-contained power source are still in demands for reliable, autonomous power source. Batteries and other traditional energy sources are also problematic as they have short lifetimes and are not environmentally friendly. In this spirit, hybrid energy harvesting offering multiple coexisting ambient energy sources, like, solar, thermal, vibration, and/or RF, is considered a promising approach to achieve a more continuous and resilient energy.The hybrid strategies, combining merits of the single harvesting strategies, immensely improve the adaptability and operation lifespan of WSNs in complicated scenarios. Based on an investigation of the existing research progress, challenges, and technical advances, this study highlights that energy management strategies, energy conversion efficiency, and power control optimization are the key factors to be carefully considered and studied. It also brings attention to the impact that adaptive algorithms and machine learning can have on better energy prediction and system responsiveness. Additionally, this work highlights the necessity standardization towards scalable designs to expedite deployment in diverse network environments. Future efforts should concentrate on the design of energy-aware communication protocols, cross-layer optimization, and low cost miniaturized hybrid EH modules.

In summary, advanced hybrid energy harvesting is the way to enable sustainable and self-powered WSNs. Taking on the challenges and potential of the present obstacles and cross-fertilizing from the area disciplines, it can be promised that thelifetime, the reliability,and the efficiency of the WSN deployment will be increased dramatically in support of smarter, greener, and more robust technology infrastructures.

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