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Review

Advances in Energy Harvesting for Sustainable Wireless Sensor Networks: Challenges and Opportunities

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Abstract: Energy harvesting wireless sensor networks (EH-WSNs) appear as the fundamental backbone of research that attempts to expand the lifespan and efficiency of sensor networks positioned in resource-constrained environments. This review paper provides a in-depth examination of latest developments in this area, highlighting the important components comprising routing protocols, energy management plans, cognitive radio applications, physical layer security (PLS), and EH approaches. Across a well-ordered investigation of these features, the article clarifies the notable developments in technology, highlights recent barriers, and inquires avenues for future revolution. The article starts by furnishing a detailed analysis of different energy harvesting methodologies, incorporating solar, thermal, kinetic, and radio frequency (RF) energy, and their respective efficacy in non-identical operational circumstances. It also inspects state-of-the-art energy management techniques aimed at optimizing energy consumption and storage to guarantee network operability. Moreover, the integration of cognitive radio into EH-WSNs is acutely assessed, highlighting its capacity to improve spectrum efficiency and tackle associated technological problems. The present work investigates ground-breaking methodologies in Physical Layer Security (PLS) that uses energy harvesting measures to improve the data security. In this review article, these techniques are explored with respect to classical encryption and discussed its as well the network security points of view. The assessment furthers criticizes traditional routing protocols and their significance in Energy Harvesting Wireless Sensor Networks (EH-WSNs) as well as the balance that has long been sought between energy efficiency and security in this space. The paper closes with the importance of continuous research to tackle existing challenges and to leverage newly available means as highlighted in this document. In order to adequately serve the increasingly changing requirements of EH-WSNs, future research will and should, be geared towards incorporating AI techniques with some advanced energy storage solutions. This paper discusses the integration of novel methodologies and interdisciplinary advancements for better performance, security and sustainability for WSNs.

Keywords: energy harvesting; Wireless Sensor Networks; cognitive radio; physical layer security; routing protocols; energy management strategies

1. Introduction

Development of wireless sensor networks (WSN) has revolutionized several applications like smart cities, healthcare and environmental monitoring for real time data acquisition [1]. One of the key challenges for Wireless Sensor Networks (WSNs) is to operate sustainably in energy-constrained environments. The lifetime of the common battery-powered WSNs could be short-living, which causes higher maintenance and operation costs [2]. To make the system more prominent, and to achieve fully monitored wireless sensors for a long time; energy harvesting has been identified as useful technique to harnessing environmental forces (e.g. sunlight, wind, vibrations, RF signal) in order to harvest unlimited energy source into Wireless Sensor Networks (WSNs) [3,4]. When we speak on energy harvesting (EH) for wireless sensor nodes, we not only refer to addressing the issues related to

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power consumption in a WSN but introduce an additional era of self-sustainable/ green networking. Research work in this area is going on as fast as possible because energy harvesting system enable wireless sensor nodes to increase their lifetime and minimise dependence on finite energy resources [5]. The hybrid EH-WSNs/CR-WSNs have attracted much attention, as they not only improve network security but also increase the spectrum efficiency in wireless sensor networks. [6]. Despite significant advancements in energy harvesting (EH) for wireless sensor networks (WSNs), a number of challenges remain. However, these also bring us to a few of the challenges, i.e., harvested energy is variable and requirements for optimization of protocols for energy management as well as building strong security mechanisms to combat potential threats are primary in such kind of energy limited environment. Integrating EH mechanisms with cognitive and cooperative communication schemes, however, makes things even worse and calls for promising remedies to maintain continuity during different network operation levels.

The goal of this review is to offer a comprehensive review of the state-of-the-art EH solutions for long lifetime WSNs. Next we will present some of the important challenges faced in designing and implementation energy harvesting wireless sensor networks, Scalability, Energy efficiency and network security. Furthermore, we will discuss the way forward in this field with emphasis on cutting-edge innovative methodologies and technologies that started to bypass current bottlenecks as well. Additionally, this article highlights the role of physical layer security (PLS) [6] in EH-WSNs and argues for adopting complex routing protocols that offer better network performance under various situations. In this paper a comprehensive review of the cutting edge in the field of EH for WSNs is presented with an objective to provide scholars and practitioners in-depth understanding of the existing scenario as well as future directions on this emerging subject. While its application in a WSN may appear new, the concept of EH is far from being so. This is mostly because large amount of sensors are being deployed, often too far from any maintenance center and some sort of power network making battery replacement not feasible or unduly expensive. Conventional power sources have limited lifetime and dependability for WSN's [7], which makes them less viable for many critical deployments over a long term such as infrastructure management, security systems and environmental monitoring. These trends have driven the research toward energy harvesting and an improvement of network security to cope with increase demands for self-sufficient and long time sustainable networks.

Sensor nodes in EH-WSNs are built to absorb and transform ambient energy from their surroundings into electrical power [8,9], allowing for perpetual operation. One can take advantage of solar, thermal, vibrational, and radio frequency (RF) energy, among other energy sources. Because solar EH is dependable and useful in a variety of outdoor applications, it is arguably the most studied of these [10–12]. Nevertheless, the use of ambient sources of energy such as kinetic or thermal are increasingly becoming possible to support large deployment and varied sets of sensing applications. Both the processing and management of the harvested energy are mostly what drives EH-WSN research [13]. The amount of energy that can be harvested is often unpredictable and variable; thus, energy management solutions are needed for ensuring the best functioning of sensor nodes [14]. To ensure that the network continues to function even in situations where energy is scarce, sophisticated energy allocation algorithms [15], dynamic power management strategies [16], and intelligent scheduling mechanisms [17] are required to balance energy use with the availability of captured energy. In addition, the appearance of CR-WSNs has refreshed our view about spectrum management and power conservation. Dynamic access to the available spectrum bands by CR-WSNs improves communication efficiency and reduces interference for sensor nodes. Nevertheless, the higher energy consumption of nodes resulting from this added functionality reinforces the importance of suitable EH solutions.

Another significant problem that EH-WSNs must address is security, given their increasing integration within critical infrastructure and other sensitive applications. They are computationally expensive, hence not feasible in energy limited systems like IoT. Among various secure communication approaches in EH-WSNs, physical layer security (PLS) has found to be more suitable with low-power consumption within this context. Without depending on upper-layer encryption algorithms, PLS uses

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the natural characteristics of the communication channel [18], such as noise and interference, to secure data transfer. But integrating PLS into EH-WSNs comes with its own set of difficulties, especially when eavesdroppers and hostile attacks are involved [6]. In EH-WSNs, the development of multi-hop and multipath routing protocols is also essential for improving network performance and resilience [19]. These protocols are intended to increase network longevity, reduce energy consumption, and prevent eavesdropping. Sensor nodes can cooperate to enhance data transmission and energy usage by utilizing cooperative communication strategies [20]. However, there are still difficulties in creating protocols that can adjust to changing network circumstances and guarantee reliable operation in a range of attack scenarios. Visualizing the underlying architecture and fundamental components of EH-WSNs is crucial, especially considering the variety and complexity of energy harvesting approaches [21,22]. The major building blocks of an EH-WSN is shown in Figure 1, which also includes the wide variety of energy sources, power managing policies and multiple protection levels ensuring a safe and efficient infrastructure for the network. It demonstrates that sensor nodes capture energy from several types of ambient sources, like solar, thermal, vibrational, and RF energy. It also demonstrates the relevance of network actors (e.g., PLS for secure data transmission, cognitive radio techniques for managing a spectrum, and routing protocols) to energize harvesting modules.

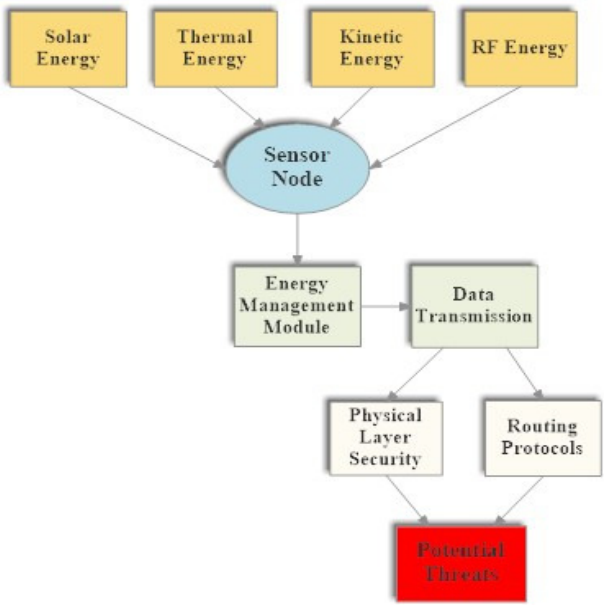

Figure 1. Conceptual Architecture of Energy Harvesting Wireless Sensor Networks

The integration of energy harvesting with cognitive radio wireless sensor networks (CR-WSNs) is especially important for overcoming the constraints of standard WSNs [23,24]. CR-WSNs allow sensor nodes to dynamically access under-utilized spectrum bands, hence increasing spectrum efficiency. However, dynamic spectrum access adds additional energy overhead that must be carefully handled with efficient energy harvesting strategies [25,26]. In this review, we will briefly discuss not fundamental but essential improvements in energy harvesting for sustainable WSNs. We will also discuss energy management protocols, security means and routing methods developed for wireless sensor networks; thus providing a deep understanding of the challenges and opportunities in this fast emerging field. This study intends to investigate the ways that emerging technologies like machine learning and artificial intelligence can enhance energy efficiency and network security, offering directions for future research.

2. Background and Motivation

The Wireless Sensor Networks (WSNs) that have revolutionized the way we sense and interact with our environment. WSNs allow data collection from different areas, such as smart cities, health monitoring and environmental conditions by deploying a network of small-scale battery-powered

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sensor nodes. Regardless of this, a significant obstruction remains because these sensor nodes lack an appropriate source of energy [27]. Traditional WSNs operate on battery power, which is both expensive and bad for the environment as they need frequent replacement. The major advantage of EH Technologies is that they provide a continuous and perpetual power supply for sensor nodes, harvesting renewable ambient energy from the environment (e.g., solar energy, thermal energy, kinetic energy and RF energy). This way allows a WSN longer life to live and less need of battery replacement, reduce price costs and is more environmentally friendly.

- Solar Energy: This energy is derived from sunlight and the solar panels are used to convert it into electrical energy.
- Thermal Energy: Manufactured from temperature via thermoelectric generators that transform warmth electricity into electric power.
- Kinetic Energy: generated through vibrations or motion, and piezoelectric materials are employed to transmute in an electric power.
- RF Energy: RF harvesting modules are used to Harvest energy from radio frequency signals.

These energy sources are combined into WSNs by linking them to the sensor nodes via an Energy Management Module [28], which controls and optimizes the consumption of collected energy. This component ensures that the energy acquired is efficiently utilized for the network functionalities such as data gathering, transmission, and security. The inspiration for creating EH methods in WSNs derives from the desire to setting-up self-sustaining networks that can run eternally without human participation [29]. By reducing trust on the standard batteries [30,31], EH-WSNs give a long-term solution that can assist a wide range of applications, from environmental monitoring to industrial automation and elegant infrastructure [5,8,32].

Rest of the paper includes section II that puts light upon different methodologies of energy harvesting that are employed in wireless sensor networks, including solar, thermal, kinetic, and RF energy. Section III explains the strategies for managing the harvested energy within sensor networks. Section IV inspects the integration of cognitive radio technology into wireless sensor networks. The section also explains spectrum sensing and management, energy-efficient spectrum usage, and the challenges linked with deploying cognitive radio in these kinds of networks. Section V defines and explains in detail the application of physical layer security techniques in EH-WSNs. Section VI elaborates various routing protocols that are designed for energy harvesting wireless sensor networks. Key challenges faced by EH-WSNs and chances for future developments are discussed in Section VII. Section VIII sums-up the key discoveries of the paper, reflects on the applications of these discoveries for future research, and puts forward the final thoughts on improving the field of energy harvesting for wireless sensor networks. Section IX is the conclusion section.

3. Energy Harvesting Techniques

Because EH captures ambient energy, it is essential to the sustainability of WSNs because it allows sensor nodes to function independently. This section examines different methods of EH, describing how they transform solar energy into electrical power and weighing the benefits and drawbacks of each.

3.1. Solar Energy Harvesting

Solar energy harvesting leverages sunlight to generate electrical power using photovoltaic (PV) cells [33,34]. These cells convert light into electricity through the photovoltaic effect. The power generated by a PV cell can be expressed as:

$$P = \eta \cdot A \cdot G \cdot \cos(\theta) \tag{1}$$

Where, P is the electrical power output (watts), η is the efficiency of the PV cell, A is the surface area of the PV cell, G is the solar irradiance and θ is the angle of incidence of sunlight on the PV cell. Solar

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energy is one of the most commonly used methods in energy harvesting due to its abundance and reliability. The **advantages** of solar energy harvesting are:

- High Power Output: Solar panels can generate substantial amounts of energy, suitable for various applications.
- Mature Technology: Well-established technology with extensive research and development.
- Environmentally Friendly: Solar energy is renewable and does not produce emissions.

The **limitations** of the solar energy harvesting are:

- Intermittent Availability: Solar energy depends on weather conditions and time of day.
- Space Requirement: Efficient solar panels require adequate surface area, which might be challenging in some applications.

The Figure 2 illustrates a typical solar energy harvesting system, including the solar panel, energy storage (battery or supercapacitor), and the sensor node.

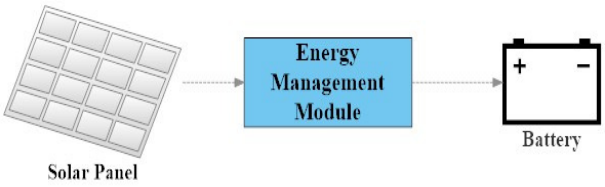

Figure 2. Solar Energy Harvesting System.

3.2. Thermal Energy Harvesting

Thermal energy harvesting converts heat gradients into electrical power using thermoelectric generators (TEGs)[35,36]. These generators exploit the Seebeck effect, where a temperature difference across a material generates a voltage. The electrical power generated by a TEG can be expressed as:

$$P = \frac{S^2 \cdot \Delta T^2}{R_{\text{load}} + R_{\text{int}}} \tag{2}$$

Where, P is the electrical power output (in watts), S is the Seebeck coefficient of the material (in volts per kelvin), ΔT is the temperature gradient across the TEG (in kelvin), R_{load} is the load resistance (in ohms), R_{int} is the internal resistance of the TEG (in ohms). The **advantages** of thermal energy harvesting are:

- Continuous Operation: Can operate as long as there is a temperature gradient, which can be constant in many environments.
- Compact Design: TEGs are generally small and can be integrated into various devices.

The **limitations** of thermal energy harvesting are:

- Low Efficiency: TEGs typically have low conversion efficiency, making them suitable for low-power applications.
- Temperature Gradient Requirement: Requires a consistent temperature difference to generate power effectively.

Figure 3 depicts a thermal energy harvesting setup, including the thermoelectric generator, heat source, and energy storage unit.

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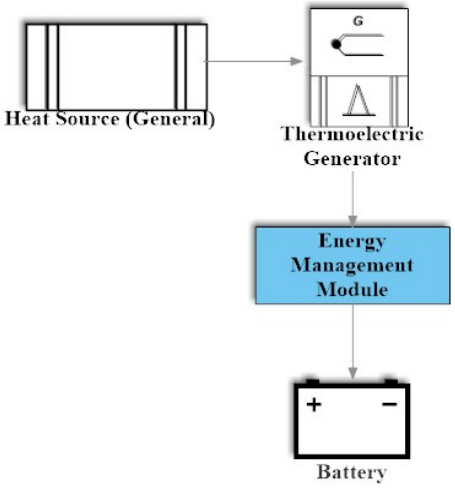

Figure 3. Thermal Energy Harvesting System.

3.3. Kinetic Energy Harvesting

Kinetic energy harvesting captures mechanical motion, such as vibrations or movements, and converts it into electrical energy using piezoelectric materials or electromagnetic generators [37–39]. This technique is particularly useful in environments with constant vibrations or movement. The power generated from vibrations can be expressed as:

$$P = \frac{1}{2} m \cdot A^2 \cdot \omega^3 \cdot Q \tag{3}$$

Where, P is the electrical power output (in watts), m is the mass of the vibrating object (in kilograms), A is the amplitude of the vibration (in meters), ω is the angular frequency of the vibration (in radians per second) and Q is the quality factor of the system. The **advantages** of kinetic energy harvesting are:

- Versatility: Can be used in various settings, including wearable devices and industrial equipment.
- Low Maintenance: Passive energy harvesting requires minimal maintenance compared to battery-powered systems.

The **limitations** of kinetic energy harvesting are:

- Variable Power Output: Power generation depends on the intensity and frequency of mechanical motion.
- Complex Integration: Integrating kinetic energy harvesters into existing systems can be challenging.

Figure 4 shows a kinetic energy harvesting system, including the piezoelectric materials or electromagnetic generator and the sensor node.

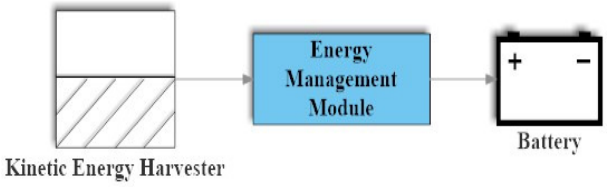

Figure 4. Kinetic Energy Harvesting System.

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3.4. RF Energy Harvesting

RF energy harvesting captures energy from radio frequency signals, such as those emitted by cellular towers [40–42], Wi-Fi routers [41,43,44], or other RF sources. This technique uses RF antennas and rectifiers to convert electromagnetic waves into electrical power. The power harvested from RF signals can be expressed as:

$$P = \eta \cdot P_{\text{RF}} \cdot G \cdot \left(\frac{\lambda}{4\pi d}\right)^2 \tag{4}$$

Where, P is the electrical power output (in watts), η is the conversion efficiency of the rectifier, P_{RF} is the transmitted RF power (in watts), G is the antenna gain (dimensionless), λ is the wavelength of the RF signal (in meters) and d is the distance between the RF source and the antenna (in meters). The **advantages** of RF energy harvesting are:

- Non-Intrusive: Can capture energy from existing RF sources without additional infrastructure.
- Can be deployed in various environments with prevalent RF signals.

The **limitations** of RF energy harvesting are:

- Low Power Density: RF energy is typically low in power density, making it suitable for low-power applications.
- Distance Dependent: Efficiency decreases with increasing distance from the RF source.

Figure 5 illustrates an RF energy harvesting system, showing the RF antenna, rectifier circuit, and energy storage component.

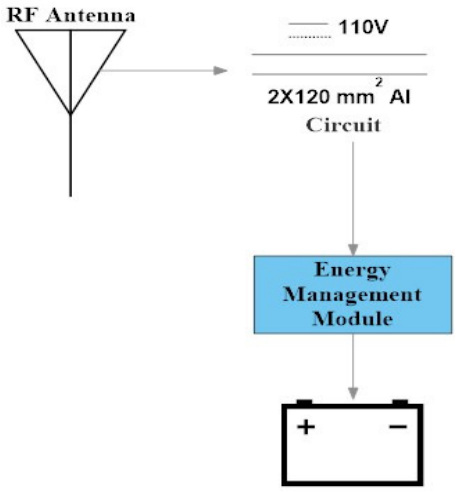

Figure 5. RF Energy Harvesting System.

3.5. Comparative Analysis of Energy Sources

Each energy collecting approach has distinct advantages and limits, making it appropriate for a variety of applications [45,46]. The choice of energy harvesting technology is determined by factors such as energy demand, ambient conditions, and deployment limits. Table 1 outlines the major characteristics of each technique: restrictions and solutions, respectively.

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Table 1. Comparative Analysis of Energy Harvesting Techniques.

Technique	Advantages	Limitations
Solar Energy	High Power Output, Mature Technology	Intermittent Availability, Space Requirement
Thermal Energy	Continuous Operation, Compact Design	Low Efficiency, Temperature gradient requirement
Kinetic Energy	Versatility, Low Maintenance	Variable Power Output, Complex Integration
RF Energy	Non-Intrusive, Scalable	Low Power Density, Distance Dependant

4. Energy Management Strategies

Optimizing the performance and longevity of WSNs that use EH methods requires effective energy management. This section examines a number of energy management techniques, including as integration with WSNs, consumption optimization, energy storage, and management protocols.

4.1. Energy Storage Solutions

Energy storage solutions are essential for ensuring a stable power supply in WSNs [47]. These solutions store harvested energy and provide power during periods when energy generation is insufficient.

- **Batteries:** Because of their ability to store large amounts of energy, batteries can be recharged and are extensively utilized in WSN. There are several varieties of batteries, including lithium-ion, nickel-metal hydride (NiMH), and lead-acid. The positives are high energy density and known technology, while the disadvantages are limited cycle life, temperature sensitivity, and a relatively expensive cost.
- **Supercapacitor:** Has a high power density and the ability to deliver energy in short bursts. Greater cycle life and quicker charge/discharge rates in comparison to batteries are the benefits. The drawbacks are more expensive than standard batteries and a lower energy density.
- **Hybrid System:** Combines batteries and supercapacitors to maximize the benefits of both technologies. Its advantages include balancing energy and power density, which improves total system efficiency. The restrictions include design complexity and cost.

4.2. Energy Consumption Optimization

Optimizing energy consumption is critical for extending the operational life of sensor nodes [26,48]. Various strategies and techniques are employed to minimize energy usage during different operational phases.

- Adaptive Sampling: Adjusts the frequency of data collection based on environmental conditions or application needs.
- Compression Techniques: Reduces the amount of data transmitted by compressing sensor data before transmission.
- Duty Cycling: Alternates between active and sleep modes to reduce energy consumption during idle periods.
- Low-Power Communication Protocols: Utilizes energy-efficient communication protocols that minimize power usage during data transmission.

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- Efficient Algorithms: Implements algorithms that minimize computational complexity and energy consumption.
- Edge Computing: Processes data locally on the sensor node to reduce the amount of data transmitted and save energy.

Figure 6 illustrates various energy consumption optimization techniques, including adaptive sampling, compression, duty cycling, and low-power communication protocols.

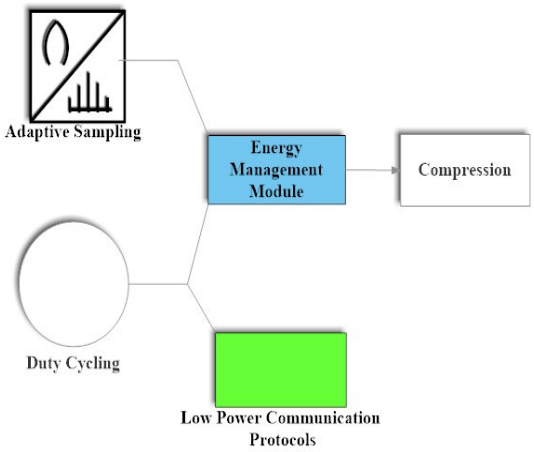

Figure 6. Energy Consumption Optimization Techniques.

4.3. Energy Management Protocols

Energy management protocols are algorithms designed to effectively manage and allocate energy resources within WSNs [49,50]. These protocols ensure efficient energy use and prolong the network's operational life.

4.3.1. Energy-Efficient Routing Protocols

- **Objective:** Optimize the path for data transmission to minimize energy consumption.
- **Examples:** Energy-efficient variants of routing protocols like LEACH (Low-Energy Adaptive Clustering Hierarchy) and TEEN (Threshold-sensitive Energy Efficient Network).

4.3.2. Energy Harvesting Aware Protocols

- **Objective:** Incorporate energy harvesting capabilities into routing and data management strategies.
- **Examples:** Protocols that adjust energy consumption based on the availability of harvested energy.

4.3.3. Load Balancing Protocols

- **Objective:**Distribute energy consumption evenly across the network to prevent early depletion of energy in specific nodes.
- **Examples:** Load-balancing mechanisms that dynamically adjust node roles based on energy levels.

4.4. Integration with Wireless Sensor Networks

Integrating energy management strategies into WSNs involves aligning energy harvesting and management techniques with the network's operational requirements.

4.4.1. System Design Considerations

- **Compatibility:**Ensuring that energy harvesting components are compatible with the sensor node and network architecture.

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- **Scalability:** Designing energy management systems that can scale with the network size and application demands.

4.4.2. Implementation Challenges

- **Cost:**Balancing the cost of advanced energy management solutions with the benefits they provide.
- **Complexity:** Addressing the complexity of integrating diverse energy harvesting methods and management protocols into a cohesive system.

5. Cognitive Radio for Wireless Sensor Networks

Cognitive Radio (CR) technology dynamically manages the usage of available spectrum to improve the flexibility and efficiency of WSNs [51,52]. This section discusses the fundamentals of Cognitive Radio, its application in WSNs, spectrum sensing and management, energy-efficient spectrum usage, and associated challenges.

5.1. Overview of Cognitive Radio

Cognitive Radio is an innovative communication technology that enables radios to automatically and dynamically access and utilize available spectrum bands [51,53]. The primary goals of CR are to increase spectrum utilization and reduce interference by allowing radios to adapt to their present spectrum environment. The primary characteristics of cognitive radio are:

- Spectrum Sensing: Detects the presence of primary users (licensed users) and identifies unused spectrum bands.
- Dynamic Spectrum Access: Allows secondary users (unlicensed users) to access spectrum bands when primary users are not active.
- Adaptive Transmission: Adjusts transmission parameters based on the spectrum environment.

5.2. Spectrum Sensing and Management

Finding and classifying available spectrum bands that secondary users can use is known as "spectrum sensing." Maximizing spectrum use and avoiding interference with primary users depend on effective spectrum sensing. The essential methods are:

- Energy Detection: Measures the energy of the received signal to determine the presence of primary users.
- Matched Filtering: Uses known characteristics of primary user's signals to detect their presence.
- Cyclo-stationary Feature Detection: Exploits the periodicity of signals to detect primary users.
- Spectrum Allocation: Assigning spectrum bands to users based on their requirements and availability.
- Spectrum Sharing: Allowing multiple users to share the same spectrum band using different access strategies.

5.3. Energy-Efficient Spectrum Usage

In WSNs, energy efficiency is a critical concern [54,55]. CR technique can come-up with energy savings by optimizing spectrum consumption and decreasing unwanted transmissions.

- Spectrum Optimization: By keeping-away congested or under-utilized bands, it uses spectrum bands more intelligently.
- Adaptive Power Control: Modifies the transmission power based upon the observed spectrum environment in order to reserve the energy.

5.4. Challenges and Solutions

As Cognitive Radio provides notable advantages, various obstacles are necessary to be addressed:

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- Interference Management: Making sure that the secondary users (SUs) do not obstruct primary users (PUs) or other secondary users.
- Security Concerns: Keeping CR systems safe from malicious attacks and certifying steady spectrum access.
- Complexity in Implementation: It would be complex and costly to Integrate the CR technology into existing WSN infrastructure.

6. Physical Layer Security

Physical Layer Security (PLS) is a security strategy that uses the physical qualities of the communication channel to improve data security, rather than depending exclusively on cryptographic approaches [56–58]. This section delves into the principles of PLS, its use in EH-WSNs, a comparison with existing encryption methods, and the obstacles connected with PLS implementation. PLS uses the inherent properties of the communication medium to assure secure transmission. In contrast to classical encryption systems, which operate with complex algorithms and key management on the basis of conventional security technologies, PLS is based on the physical properties of the channel. The basic concepts of PLS are:

- Secrecy Capacity: The maximum amount of information that can be safely transmitted over a communication channel.
- The Signal-to-Noise Ratio (SNR): This ratio is a comparison of the level of the desired signal to the level of background noise.
- Channel State Information (CSI): It states that knowledge of the channel conditions is crucial for optimal scheduling and allocation of radio resources.

PLS can be included into EH-WSNs to further enhance the data security when data is shifted across energy-harvesting networks [8,59]. Data protection and energy efficiency are the objectives of PLS integration in EH-WSNs. PLS techniques that are applied in EH-WSNs include:

- Energy-Harvesting-Based Security: Employing the energy harvesting abilities of the network, in order to assist secure communication.
- Secure Data Transmission: Making sure that data is transmitted securely using PLS methods, even with less energy resources.

PLS provide a number of advantages over conventional encryption methods that include:

- Reduced Computational Overhead: PLS does not need complex cryptographic algorithms, bringing down the computational burden.
- Enhanced Security in Adverse Conditions: PLS can preserve security even in demanding environments with excessive levels of interference.

Table 2 portrays a difference between PLS and traditional encryption methods.

Table 2. Comparison of PLS and Traditional Encryption Methods.

Feature	Physical Layer Security (PLS)	Traditional Encryption
Computational Overhead	Low	High
Security Level	High in adverse Conditions	High with proper key management
Implementation Complexity	Low	High

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7. Routing Protocols in EH-WSNs

In order to effectively manage data transfer in EH-WSNs, routing protocols are necessary [60,61]. Routing protocols in EH-WSNs must handle the particular difficulties brought forth by fluctuating network circumstances, dynamic network topologies [62], and energy limitations [63]. The main routing protocols used in EH-WSNs are examined in this part with an emphasis on their effectiveness, energy management, and security implications. EH-WSN routing protocols are developed to maximize data transfer while preserving energy and guaranteeing dependable connection. Among the primary categories of routing protocols are:

- Direct Routing Protocols: Send data directly from the source to the destination without intermediate nodes.
- Hierarchical Routing Protocols: Use a tiered structure where nodes are grouped into clusters, and data is routed through cluster heads.
- Geographic Routing Protocols: Utilize the geographic location of nodes to determine the routing path.

In addition, the Energy-efficient routing protocols aim to minimize energy consumption while ensuring reliable data transmission. Key strategies include:

- Energy-Aware Routing: Select routes based on the energy levels of nodes to extend the network's lifetime.
- Load Balancing: Distribute the data transmission load evenly across the network to avoid energy depletion in specific nodes.
- Sleep Scheduling: Implement sleep-wake cycles to conserve energy by putting nodes into low-power modes when not actively transmitting data.

Furthermore, the Multi-hop and multi-path routing protocols improve reliability and robustness in EH-WSNs by:

- Multi-hop Routing: Data is transmitted through multiple intermediate nodes before reaching the destination, which helps in overcoming long-distance transmission challenges.
- Multi-path Routing: Multiple paths are used for data transmission, providing redundancy and load balancing to improve reliability and fault tolerance.

Security is crucial in EH-WSNs to protect against various attacks, such as eavesdropping, data tampering, and denial of service. Key security considerations include:

- Data Encryption: Encrypt data during transmission to prevent unauthorized access.
- Authentication: Verify the identity of nodes to prevent malicious nodes from participating in the network.
- Secure Routing Protocols: Implement routing protocols designed to resist security threats and ensure data integrity.

8. Challenges, Opportunities and Future Trends

We present here the major challenges EH-WSNs face and what we expect to be improved or innovated in order to overcome them, as well as some of the emerging directions in research on energy harvesting and cyber security. These ideas are important for practical EH-WSN technology and applications.

8.1. Challenges Faced by EH-WSNs

Table 3 presents challenges faced by EH-WSNs. The information in the table gives an up-to-date summary of the challenges to be faced EH-WSNs, including energy related issues, resource management and security in concern with network. Different challenges defined with respective

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results and its likely impact on the quality of service (QoS) and lifetime performance of EH-WSNs, which describe a clear view to focus each significant areas for implementing future research.

Table 3. Key Challenges in EH-WSNs.

Challenge	Description
Energy Efficiency	Manage limited energy resources while ensuring reliable data transmission and network functionality
Network Scalability	Addressing issues related to performance and lifetime as the network grows in size
Data Security	Ensuring secure data transmission and protection against unauthorized access
Dynamic Topologies	Handling changes in node availability and network structure
Integration with Existing Technologies	Ensuring compatibility and interpretability with existing systems

8.2. Opportunities for Improvement and Innovation

The chances for enhancement and innovation in EH-WSNs are presented in Table 4. This table summarizes potential advancements and innovative approaches that could enhance the efficiency, sustainability, and performance of energy harvesting wireless sensor networks. It highlights key areas for future research and development.

Table 4. The opportunities for improvement and innovation.

Opportunity	Description
Advanced Energy Harvesting Technologies	Innovations in harvesting technologies for better energy capture
Smart Energy Management Systems	Systems that dynamically manage energy based on availability and network needs
Enhanced Routing Protocols	Development of routing protocols that optimize data transmission and network performance
Integration of AI and Machine Learning	Use of AI and ML for adaptive energy management and routing
Improved Security Mechanisms	Enhancing security protocols to protect data and resist attacks

8.3. Future Trends in Energy Harvesting and Security

8.3.1. Emerging Technologies

The emerging technologies in EH-WSNs are:

- Advanced Energy Harvesting Materials: Research into novel materials, such as nano-materials and meta-materials, has the potential to improve the efficiency and scope of energy harvesting technology. These compounds can enhance the performance of solar cells, thermoelectric generators, and other energy harvesting systems.

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- Integration of IoT and EH-WSNs: Innovation in EH is anticipated to be fueled by the expanding Internet of Things (IoT). Improved network efficiency and innovative energy management techniques are expected outcomes of integration with IoT devices.
- Smart Grids and EH-WSNs: The combination of EH-WSNs and smart grid technologies can improve energy distribution and utilization. Smart grids will provide EH-WSNs more control over energy supplies, allowing them to adjust to fluctuating energy availability.

8.3.2. Innovations in Energy Management

The recent innovations in energy management include:

- Enhanced Energy Storage Solutions: Advanced supercapacitors and solid-state batteries are two examples of energy storage innovations that will offer more dependable and effective energy storage options for EH-WSNs.
- Adaptive Energy Management Systems: Future energy management systems are predicted to be more flexible and intelligent, leveraging AI and machine learning to optimize energy consumption in real time based on network circumstances and energy availability.
- Blockchain for Energy Transactions: Energy transactions in EH-WSNs might be managed and verified using blockchain technology, guaranteeing security and openness in the distribution and consumption of energy.

8.3.3. Advances in Security Mechanisms

The recent advances in security mechanism related to EH-WSNs are:

- Quantum Cryptography: Quantum cryptography provides a new level of security by enforcing quantum mechanics rules during data transmission. This technology could be built into EH-WSNs to improve data security.
- Bio-Inspired Security Approaches: Investigations into bio-inspired security mechanisms—that is, security based on biological processes—may yield novel approaches to protecting EH-WSNs from cyber attacks.
- Adaptive Security Protocols: Future security protocols are predicted to be more adaptable, able to change their protection methods in response to real-time threat analysis and network conditions.

9. Summary of Key Findings

The review paper provides a complete overview of advancements in energy harvesting wireless sensor networks (EH-WSNs). The important findings from each area are given below in table form:

9.1. Comparison of Energy Harvesting Techniques

Comparison of Energy Harvesting Techniques in Table 5 presents a summary of various energy harvesting methods, including solar, thermal, kinetic, and RF, highlighting their relative effectiveness and suitability for different applications.

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Table 5. Comparison of Energy Harvesting Techniques.

Technique	Advantages	Limitations
Solar Energy	High energy yield in sunny conditions	Dependent on sunlight availability
Thermal Energy	Can be harvested from waste heat	Low efficiency compared to other methods
Kinetic Energy	Suitable for dynamic environments	Limited energy output and efficiency
RF Energy	Can be harvested from ambient RF signals	Low energy density and range

9.2. Energy Management Strategies

Energy management strategies in Table 6 outline various approaches to optimizing energy use and storage in wireless sensor networks, detailing methods for enhancing efficiency and extending operational lifespan.

Table 6. TEnergy Management Strategies.

Strategy	Description	Impact
Energy Storage	Utilization of batteries and supercapacitors to store the energy	Increases reliability and operatiional lifespan
Energy-Aware Routing	Routing decisions based on current energy levels	Enhances energy efficiency and network performance
Load Balancing	Distributing data trans--mission to prevent node overuse	Balances energy consump--tion across the network

9.3. Cognitive Radio Benefits and Challenges

In this section, we list the benefits of and challenges in applying CR technology to WSNs (Table 7), as well as its influence on spectrum efficiency and network performance.

Table 7. Cognitive Radio Benefits and Challenges.

Aspects	Benefits	Challenges
Spectrum Efficiency	Improved utilization of available spectrum	Requires sophiticated spectrum management
Dynamic Access	Ability to access unused spectrum bands	Complexity in spectrum sensing and adaptation
Integration Issues	Compatibility with existing systems and technologies	Integration with current network infrastructure

9.4. Physical Layer Security Techniques

Table 8 tabulates the related methods and techniques, as well as approaches that have been presented previously to ensure data transmission security in wireless sensor networks at the physical layer, shedding light on their efficiency and providing arguments (instance for some key) against safety threats.

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Table 8. Physical Layer Security Techniques.

Techniques	Description	Challenges
Energy Harvesting Based Security	Security using harvested energy for data protection	Effectiveness in various environmental conditions
Encryption Alternatives	Reduces need for traditional encryption methods	Requires robust physical layer security mechanisms

9.5. Routing Protocols Overview

The Table 9 given below shows a summary of various routing techniques used in wireless sensor networks with the key features, advantages or limitations.

Table 9. Routing Protocols Overview.

Protocol	Description	Key Considerations
Direct Routing	Direct path from source to destination	Effectiveness in various environmental conditions
Hierarchical Routing	Data passed through cluster heads in a tiered structure	Efficient for large networks but adds complexity
Geographic Routing	Routing based on geographic location of nodes	Requires accurate location data and may not scale well

10. Conclusion

The energy harvesting wireless sensor networks (EH-WSNs) is an important category in the scope of WSNs, and this paper extensively reviews a variety of aspects with respect to EH-WSNs, including energy harvesting (EH) techniques, energy management strategies, cognitive radio (CR) applications, physical layer security (PLS), and routing protocols. The identification of individual element showed significant progresses in the area which underline importance of employing EH systems other than conventional energy resources towards sustainable and efficient WSNs, especially for low-power context. While the industry has come a long way, major obstacles remain. It is a research direction to, for example, optimize across EH coming from multiple sources such as solar, thermal, kinetic and RF maximizing in-order also a balance on energy consumption and storage efficiency. Besides, the combination of CR and WSNs appears very appealing for performance-oriented spectrum access despite plenty of technical challenges such as spectrum management and energy efficiency waiting to be addressed.

Future challenge is PLS in EH-WSNs, which provides a great opportunity to embed the security in the process of energy harvesting itself and therefore it replaces classical encryption techniques. Before PLS becomes a broad technology, more dangers and challenges are required to be addressed for the deployment of solution. In this line, EH-WSN routing protocols are required to be further developed such that they can provide proper security mechanisms against hostile attacks and cyber threats in addition to energy saving. Future work should focus on a number of key areas in order to advance EH-WSNs. Top-notch technologies such as artificial intelligence (AI) and machine learning (ML) can transform energy management allowing it to change and react according to the levels of energy every stage. Similarly, advancements in powers storage technology such as hybrid powers storage systems & super capacitor might help reduce the existing constraints. Second, blockchain could be considered as a turning point in the security of EH-WSN, realizing energy transactions and creating data integrity.

This highlights the importance of interdisciplinary work given the proliferation of Internet of Things (IoT) devices and requirement for high performance, long-lasting deployments. In modern time the researchers must look towards development of complete systems comprising of energy harvesting, secure and optimal operation of network in one scalable manner. By addressing these difficulties and capitalizing on the potential identified, future EH-WSNs will be better able to enable the development of applications in smart cities, environmental monitoring, and other areas.

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