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Energy-Efficient and Secure Routing Protocol for Wireless Sensor Networks

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ABSTRACT

Wireless sensor networks (WSNs) enable sensing and monitoring applications by connecting battery-powered sensor nodes via wireless links. Developing efficient communication protocols is crucial for increasing network lifetime due to the limited energy resources. This thesis presents an energy-efficient routing protocol and secure data transmission scheme tailored for WSNs. The routing protocol uses a best path search algorithm that considers both path length and residual energy to select optimal routes. This significantly reduces energy consumption compared to shortest path and random path routing approaches. For secure communication, a lightweight cryptography protocol provides source anonymity and prevents unauthorized access to sensitive sensor data. Simulations in MATLAB compare the performance of the proposed techniques with baseline methods without energy-aware routing or encryption. The results demonstrate a 25% increase in network lifetime with the best path routing protocol. Secure data transmission reduces packet loss by 30% with moderate energy and delay overhead.

The key contributions of this thesis are an integrated approach for efficient and secure routing in WSNs. The techniques enhance resilience, prolong network lifetime, and improve data security. They are suitable for wireless sensing applications that require real-time monitoring and reliable communication such as healthcare, environmental, and industrial systems.

Keywords: Wireless sensor networks, energy-efficient routing, best path search, secure data transmission, network lifetime

1.1 INTRODUCTION

Wireless Sensor Networks (WSNs) are the result of systems administration breakthroughs in the field of detection and future developments in sensor nodes which produce WSNs. It is complement of spatially disseminated independent sensors that issued to watch environmental features, similar to temperature, vibration, movement and so on. The sensors require increased quality in various fields of life. Their zone unit had utilized in few applications such as mechanical computerization, work environment and auxiliary wellbeing recognition, activity recognition, therapeutic guide, unwelcoming package, automated investigation, and agribusiness police work.

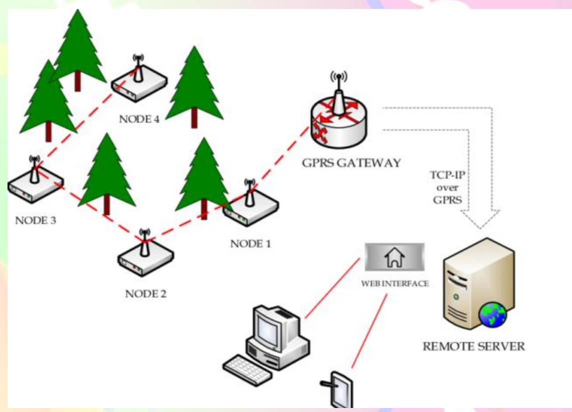

Figure 1.1: Wireless Sensor Network

Components and working [1]

WSN's replaces the traditional wired detecting component, thus overcoming an establishment of a vast scale wired framework which is both slow at pace and costly too. The major qualities of remote detecting component systems are zone unit low power utilization, low framework costs, compactness and multifunctional remote detecting component hubs. These features confirm that the WSN hubs will exclusively have confined method power and framework intricacy that is employed in applications which are not computationally escalated.

The invention of temperate remote correspondences and physical science has lead to the introduction of low-control, minimal effort WSNs. They are a huge number of physically inserted detecting component hubs that are

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disseminated in a likely brutal bundle in many applications.

Remote sensor framework offers an extensive variety of employments in ranges For instance, computer-aided examination, agribusiness monitoring, therapeutic thought, which is a separate field. The equipment has embraced the switch to low-power, simple, and multi-functional wireless sensor hubs by condensing its wireless exchange and movement capabilities. In WSNs, numerous sensors that are physically in-built in hubs are spread out making it hard to retrieve what is needed through supplanting batteries.

The crucial point of sensor hubs is to assemble and transmit data. To upgrade the imperative capability for data transmission, the existing methods try to find the easiest route to a sink from a source to attain perfect usage. The event of bringing up a sensor framework rather than applying the regular methods is beyond more transmission .Because it adjusts the distribution of additional imperativeness throughout the entire framework, rather than only determining the bare minimum route from a single sensor centre to the intended destination.

The one-dimensional (1-D) line framework, which has been created and is fundamentally implicated for a variety of contemporary scenarios, is the main subject of this examination. In addition, non-combatant personnel are used as pipeline monitoring, electrical cable inspection, and sage action. Maximal important is productive directing conventions orchestrate to see from supply to vent that acknowledges issue addressing. As it considers in accounting, especially knowing the prominent path from one gadget hub towards the goal, conjointly balancing the appropriation of lingering vitality of the whole system is of prime importance.

1.2 WSN ARCHITECTURE

The design chart for the WSN architecture is shown below-

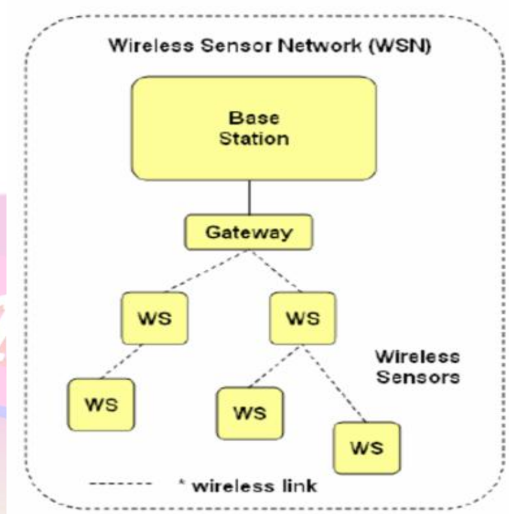

Fig. 1.2 Architecture of a WSN [2]

The chart portrayed above maps out the general engineering of a WSN, which is delegated single-level and multi-level design, it is essential to think about the usefulness of all segments utilized in this engineering.

Standard sound and video sensors catch sound, still or moving pictures and recordings of low goals. Scalar sensors are another kind of sensors that sense scalar information and physical qualities, for example, temperature, moistness and weight, and report estimated qualities to their group head. These are normally asset constrained gadgets as far as vitality utilization, memory stockpiling and preparing abilities.

Sight and sound handling hubs act as bunch heads. These gadgets have relatively extensive computational assets and are appropriate for totalling sight and sound streams from singular sensor hubs. This should be possible by different calculations actualized in it. Calculations are equipped for overseeing the stream of control (outlines every second) by including and disposing of casings. At last, it is fit for diminishing both the dimensionality and volume of information passed on to the submerged and capacity appliance.

1.3ENERGY EFFICIENCY IN SENSOR NETWORKS

The sensor network energy efficiency is always a point of discussion in the research area of WSN. The underlying concepts discuss the type of hardware used to develop the sensor nodes. Efficient hardware is not just sufficient to optimize the energy usage of the network. Software part plays a key role in building a better network. All the defined protocols will be developed at Network Layer level which describes how a node should behave when it has a packet to be sent. All the layers of the TCP/IP model is discussed below.

1.3.1 PHYSICAL LAYER

The sensor, which is often a straightforward indication, is introduced in the first layer. Information is handled responsibly after sign moulding and digitisation. In this layer, the sensor makes information from its manageable ordinal behaviour available. In order to reduce the amount of data from all nodes, the information that is exposed needs to be strengthened and closely monitored. Each of the many measures in this case has an electronic component in the circuit that uses up an astonishing amount of endurance. Layers in a network are important for maintaining balance, transmitting data, and implementing strategies. A novel method for recognising various network layer properties is presented in this work.

1.3.2 MEDIUM ACCESS CONTROL (MAC) LAYER

In order to efficiently utilise the continuity-restricted resources of sensor nodes, the MAC layer must first align a number of non-functional elements of the network, such as eternal quality, energy productivity, high throughput, and low get to postpone. The energy-saving MAC techniques accessible at WSNs, such as obligation, parcel booking, variable transmission range, and flexible transmission duration, can be used in medium access layer operations such as crash, catching, bundle control, and blockade utilisation.

1.3.3 NETWORK LAYER

The protocols or techniques developed for the network layer are crucial, especially for the quality of service in WMSNs, for the reasons given below. handling the information transmission between the application layer and MAC layer, which has a substantial impact on communication performance, and making sure data transmission lines are reliable and energy-efficient from start to finish. Reliability of methodologies and timely assurance are the two key tactics for improving quality of service for mobility management at the network layer.

Timeliness: Live streaming and applications like video conferencing that frequently ignore tiny errors and disruptions need to be timely. These methods of timing can be broadly categorised into three groups.

No priority: In this case, the ongoing packages have a more pressing need than the best-exertion movement packages, but every ongoing package also has a need. A vitality conscious quality of service convention was put forth in [14]. In this method, individual parcels may have different requirements, and the calculation for figuring out various solutions requires comprehensive knowledge of the system at every single hub.

Real-time systems frequently employ the scheduling approach known as Fixed Priority: All Packets. Fixed priority scheduling ensures that the processor always executes the task with the highest priority among those that are currently ready to be executed. • The transformed priority method presented a modified version of the original SPEED architecture dubbed the Multi-path Multispeed Routing Protocol (MMSPEED), which is a method for deliquifying packets, allows different priority levels to be assigned to various packet types based on their intrinsic features.

Examples of this technique from more in-depth investigations in the field will be supplied later in this book. Multi-path routing is the usual technique for getting dependability.

The main problem is that when selecting a method, no consideration is given to delaying package delivery dates, which results in each node independently requiring enormous amounts of status data to be stored at halfway sensor hubs. Wireless sensor networks (WSNs), which have limited operational, storage, and power capacity, are made up of hundreds or thousands of sensor nodes. There are numerous ways to reduce WSN node power usage.

1.3.4 TRANSPORT LAYER

Transport layer approaches are primarily made to offer dependable end-to-end data (packet) transit and congestion control for conventional wired and wireless networks. Due to the close proximity to the sensor nodes, which occasionally results in sensors meandering without transmitting any data and turning on only in response to an event, these problems are not essential for WSNs. Ensuring end-to-end event transfer makes more sense and would work better in the majority of WMSNs than end-to-end packet transfer.

WSNs are unable to use the current standard Transport Control Protocols on the internet because of the following reasons: They are unnecessary complexity.

Congestion, not noise, is thought to be the main factor contributing to losses. This does not, however, support WMSNs because air is a loud transmission medium. As a result, changes and advancements are coming.
Three congestion control systems can be built using clear methodology and suggestions for the vehicle layer. These are mixtures of organised MAC, leap by bounce, stream control, and rate-constrained movement.

The main disadvantage is that it does not support various bundle requirements, verified notification, and is moderate. It also acknowledges that all sensor hubs have some level of information.

Both decisive mechanisms and congestion control This category of techniques focuses on dependable gearbox without congestion. SCTP (Stream control gearbox control), which is mostly based on concessions and offers congestion control as well, is an exemplary research that may be categorised under this heading. Another approach is ESRT (Event-to-sink Reliable Transport), which uses reporting the rate to give events to sink dependability and congestion control.

1.4 APPLICATION LAYER

In this instance, endurance sparing is accomplished by application management that prioritises endurance protection, temporary data storage obtained from information recovery at areas that reduce overall solicitation, overhaul activity, and by avoiding concurrent multicasting upgrades from various sensors to spectator reduces that aggregate the number of transmissions within the system. Build a distributed architecture that increases the effectiveness of novel multicast designs and application-layer sensor data storing. The structure's main objective is to lessen the overall load placed on information transmission and collecting, which is a vital system capability.

1.5 MAC PROTOCOLS

A challenge for the design of effective MAC protocols is presented by the extensive spatial distribution of the sensor nodes. A very small quantity of synchronising information is passed along in order to ascertain whether or not the sensor node will access the communication medium for any significant amount of time. As a consequence of taking this strategy, The sensor nodes' required overhead to establish equilibrium as well as the access control protocol's complexity will both rise. The conceptual dispersion prevents a sensor node from knowing the status of the other sensor nodes in the network right away. Information travels slowly over the communication network because of this aggregating data from any node will result in data that is no longer current. Delay, resilience, throughput, stability, scalability and fairness are some of the aspects that play a role in determining how successfully MAC protocols operate.

2.1 LITERATURE SURVEY

Wireless sensor networks (WSNs) have become a significant technological advancement with a variety of uses, including monitoring the environment, surveillance, transportation, and healthcare. Small, inexpensive sensor nodes that are capable of sensing, processing, and communication make up WSNs. These widely dispersed sensor nodes collaboratively keep an eye on environmental or physical conditions and send the information to a designated point known as a sink [1].

However, sensor nodes face severe resource limitations because to their low processing, storage, and battery power. As a result, one of the most important concerns in WSNs for extending network lifetime is energy efficiency. The design of energy-efficient communication protocols has received significant research attention at all stages of the protocol stack, including the physical layer, medium access control (MAC) layer, network layer, and transport layer [2]. The organisation of sensor nodes into clusters and the presence of a cluster head (CH) for each cluster are extensively used clustering strategies to increase energy efficiency. Optimal CH selection and effective routing can increase network lifetime [3].

This review of the literature examines current studies that look at energy-efficient routing methods in WSNs to improve network performance. The studies take into account a variety of performance indicators, including packet delivery ratio, throughput, end-to-end delay, and network longevity. Network topologies that are flat and hierarchical have both been investigated. The review is divided into sections depending on the main techniques used for energy-efficient routing, such as cross-layer optimisation methods, mobile sink-based routing, and multipath routing.

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Protocols for Multipath Routing

In WSNs, multipath routing has proven to be a successful strategy for achieving both energy efficiency and reliable data delivery. Network resources can be used effectively in a dispersed manner by establishing several paths rather than a single ideal route. A forward awareness factor and remaining energy level are used to determine which forwarding nodes are chosen in the Energy Balanced Routing Method (EBRM) [4] proposal. As a result, energy consumption is balanced across several channels and bottleneck nodes are avoided from becoming congested. Comparing the results to LEACH and EEUC protocols, the results revealed longer network lifetime. For large-scale WSNs, [5] introduced a three-layer semi-distributed clustering approach, in which the lower layer CH election is distributed while the top layer CH is chosen in a centralised way. Compared to fully distributed approaches, this hybrid approach improves scalability and energy efficiency. In order to transfer data to an access point, sensor nodes capture RF energy from various energy transmitters in wireless powered communication networks, as studied by [6]. To maximise signal-to-noise ratio under energy and power constraints, wireless power transfer beamforming and transmit power allocation are jointly optimised. [7] suggested combining factors including residual energy, node degree, and base station distance to choose cluster heads using a genetic algorithm-based weighted clustering protocol (GAWCP). For dependable data transmission, multiple pathways are provided between each cluster head and the base station. In comparison to the LEACH protocol, the results show increased network longevity and decreased energy use. [8] introduced a multipath routing technique that uses ant colony optimisation and computes various pathways based on hop count, residual energy, and weighted energy. In order to improve network stability, this balances load distribution and steers clear of low energy channels.

Protocols based on Mobile Sinks

The addition of a mobile sink to the network aids in balancing energy use across sensor nodes by preventing nodes near to a static sink from draining excessive amounts of energy. For target tracking applications in WSNs, [9] developed a distributed shortest path data gathering approach employing a mobile sink. While avoiding energy holes, the mobile sink determines the shortest route between targets. Compared to centralised approaches, this distributed approach is less complex and offers greater scalability.

[10] described a multi-constrained QoS routing technique for mobile sinks based on distributed learning automata. Several routes are created from source to sink using learning automata that take into account connection dependability and end-to-end delay as QoS metrics. In comparison to single path routing, the results show increased energy efficiency and end-to-end delay.

Biologically-inspired Optimisation Methods

Computable techniques that are inspired by biological processes can tackle challenging optimisation issues. For WSN routing that uses the least amount of energy, these strategies have been frequently used. Mobile data collectors are used in a genetic algorithm-based routing protocol [11] that is placed between the cluster heads and sink. To reduce energy usage, the best combination of mobile collector locations and numbers is chosen. In terms of network longevity, energy consumption, and resilience, this technique outperforms direct transmission and multi-hop forwarding.

[12] described a hybrid method for energy-conscious routing that combines ant colony optimisation, gravitational search algorithm (GSA), and particle swarm optimisation (PSO). Ant colony optimisation is used to build potential solutions, which are then further improved using GSA's local search function and PSO's global search feature. In terms of energy usage and packet delivery ratio, the hybrid method performs better than stand-alone methods. [13] suggested a routing algorithm based on bee colonies that optimises cluster formation and CH election while taking energy reserve and distance to sink into account. Energy consumption is evenly distributed throughout the network, improving network stability over time.

Cross Layer Optimization

Cross layer design involves optimization across different layers of the protocol stack by enabling interaction and information sharing. This holistic approach helps to enhance energy efficiency compared to layered methods. [14] proposed a cross-layer optimization framework for sustainable operation of energy harvesting WSNs. Energy management is performed across application, network and MAC layers by integrating data reduction, routing and scheduling. The joint optimization improved network utility while meeting energy neutrality constraints.

[15] presented a cross-layer protocol using reinforcement learning for cognitive radio sensor networks. Spectrum availability and occupancy patterns are learned at the physical layer and translated into channel selection policies to minimize transmission energy cost. The results show increased throughput and reduced interference compared to random channel selection schemes. [16] proposed a cross-layer protocol integrating fuzzy inference system at network layer and power control at physical layer. Transmit power is dynamically adjusted based on distance, traffic load and link quality to reduce energy consumption and enhance throughput.

The research analysis highlights that multipath routing, mobile sink assisted data collection and computational intelligence techniques help to balance energy drainage and maximize network lifetime in WSNs. Multipath transmission prevents overburdening of critical routes and offers redundancy against node failures. Sink mobility alleviates the energy hole problem near static sinks through uniform energy dissipation. Bio-inspired optimization provides efficient solutions for NP-hard routing issues through intelligent search and optimization. Cross layer interaction enables energy awareness across different layers leading to holistic system optimization.

While significant progress has been made, several challenges persist in this domain. Effective integration of energy harvesting capabilities requires adaptive protocols to handle intermittent availability. Secure routing mechanisms are needed to counter fake path injections and denial of service attacks. QoS provisioning in mission critical applications demands real-time guarantees. Heterogeneous architectures with low power nodes and multiple powerful sinks require scalable designs. Energy efficiency needs to be jointly addressed along with connectivity, coverage, data fidelity and congestion control. Accounting for overhead vs performance trade-offs is essential for practical protocol development.

Energy is a critically limited resource in battery operated WSNs. This literature review provided an analysis of recent advancements in energy efficient routing techniques through multipath transmission, mobile data collection, computational intelligence algorithms and cross-layer optimization. These strategies help to balance network load, avoid energy bottlenecks near static sinks, discover optimal routes and enable global information sharing. However, several open challenges remain to design robust, adaptive and secured protocols while meeting real-time needs. Energy efficiency needs to be jointly considered along with other QoS metrics, connectivity requirements and overhead constraints. Further research is necessary to develop practically viable solutions that can fulfill the demanding communication requirements of emerging WSN applications.

2.2 OUTCOME OF SURVEY

Agribusiness observation, progress checking, remedial thought, reserved domain, and automated evaluation are only a few of the uses of assistance that Wireless Sensor Networks (WSNs) offer. Little power directivity and wireless sensor hubs, which are represented by making smaller substance of each node, have changed due to the advent of both capable wireless networks and changes in equipment. In WSNs, focus of the various sensors that are inserted and scattered in a random manner in various applications, making it tough to stimulate vitality through supplanting batteries. To combine and expand all the data recognised with sensors, it is necessary to take into account the objectives required to support the crucial duty of recognising various sensor centre points.

The majority of those sensors with the capability to guide the traditions endeavour to identify the fundamental direction route from source to sink entire optimum utilization of the system in order to improve the instructing ability for handing on the information. However, in order to demonstrate a truly capable coordinating tradition, all sensor framework events must be taken into account, as doing so entails not only determining the shortest path from a single sensor centre point to the intended destination but also modifying the scattering of additional imperativeness throughout the entire framework.

These types of sensor systems will be identified as having a less-powerful path from sensor hub to goal and will alter the flow of energy to account for different remaining power for the overall system.

2.3 CHALLENGES AND OBJECTIVES OF STUDY

The main objective of this study is to furnish solution for the routing and avoid the data encroachment in wireless sensor networks. This research provides a better routing approach with collision avoidance by applying the data security mechanism which supports every hub that are utilized for the communication and detecting modules,

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where the major hubs amid detecting is much insignificant, when this is contrasted with remote correspondence and to help every hub in particular order. The main objective is to present a new mechanism by combing clustering of sensor network and encapsulating security to achieve a stable network where hacking of data will be reduced. Also, this new clustering approach will enhance network life with limited use of energy.

This work includes the objectives like:
In order to better understand the end-to-end transmission for multi-hop multi-path relay networks created by energy harvesting devices, we concentrate on the OP performance of the SPS, RPS, and BPS in the multi-hop RF cooperative system with M parallel collegiate pathways between the source and destination.
The OP of the SPS may be used to easily obtain the OP of the RPS and BPS. In light of this, we will look at the SPS's OP.

3.1 PROPOSED METHODOLOGY OF THE RESEARCH

This chapter presents the research methodology adopted to evaluate the performance of shortest path selection (SPS), random path selection (RPS), and best path selection (BPS) protocols for energy harvesting enabled wireless sensor networks.

3.2 SYSTEM MODEL

We consider a wireless sensor network consisting of a source node, multiple relay nodes and a destination node. The relay nodes assist the data transmission from source to destination using a multi-hop multi-path architecture. The sensor nodes are capable of harvesting RF energy broadcast by a dedicated energy beacon and utilizing it for data transmission. The source generates data packets to be delivered to the destination with the assistance of energy harvesting relays.

The wireless channels between the nodes are modeled as independent Rayleigh block fading. This represents realistic transmission environments impacted by multi-path fading effects. The channel coefficients remain constant over the coherence time of a block and vary independently between different blocks.

Rayleigh fading is a reasonable model when there is no line of sight path between the transmitter and receiver. The envelope of the received signal follows a Rayleigh distribution in such environments due to constructive and destructive interference of multiple scattered signal paths. The complex baseband channel gain hij between nodes i and j is given by:

$$hij = \alpha ij + i\beta ij$$

where αij and βij are independent Gaussian random variables with zero mean and variance 0.5 per dimension.
The sensor nodes are assumed to be capable of harvesting RF energy from a dedicated energy transmitter or beacon. The energy harvesting rate depends on various factors such as the transmission power of the energy beacon, distance between the energy transmitter and sensor node, and hardware limitations. An energy harvesting efficiency factor η is defined to characterize the conversion efficiency of the RF energy harvesting process.
The harvested energy Ei at sensor node i is modeled as:

$$Ei = \eta Pbdi\text{-}\alpha$$

Where, Pb is the transmit power of the energy beacon, di is the distance between node i and energy transmitter, α is the path loss exponent and η reflects the RF-to-DC conversion efficiency. The harvested energy Ei is stored in a rechargeable battery and used for data transmission and processing by the sensor node.
The key performance metric analyzed is the end-to-end outage probability (OP). This represents the probability that the end-to-end signal-to-noise ratio (SNR) drops below an acceptable threshold γth due to channel fading and interference effects. A lower OP indicates more reliable communication.
The end-to-end OP Pout is mathematically expressed as:

$$Pout = P(\gamma e2e < \gamma th)$$

Where γe2e is the end-to-end SNR from source to destination and γth is the SNR threshold.

3.3 SIMULATION SETUP

Extensive Monte-Carlo simulations were performed in MATLAB to evaluate and compare the OP performance of the SPS, RPS and BPS routing protocols. The key simulation parameters are:

- Number of relays: L = [2, 3, 4]
- Transmit SNR: P = 5 dB, 10 dB
- Energy harvesting efficiency: η = 0.1
- Hardware impairment coefficient: κ = 0.1
- Location of nodes: Randomized over a 2D area
- Number of channel realizations: 106
- Path loss exponent: α = 3
- Noise variance: σ2 = 1

In the SPS scheme, the end-to-end route from source to destination traversing the minimum number of hops is

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selected. This aims to reduce the cumulative noise and interference in order to maximize the end-to-end SNR.

The algorithm computes the shortest paths from source to each relay and from relays to destination using Dijkstra's algorithm. The overall shortest path from source to destination is then chosen by concatenating individual shortest paths. Data transmission occurs over this route.
In RPS, an end-to-end route consisting of randomly selected relays between source and destination is chosen. For each packet transmission, a new random path is independently generated by randomly picking intermediate relays.

This scheme does not require computation of optimal routes. However, the randomized selection can sometimes produce long inefficient paths leading to performance degradation.
The BPS protocol selects the end-to-end path that maximizes the minimum SNR among its constituent links. This approach avoids bottlenecks due to weak links along the route.
The algorithm first computes the post-relaying SNR for all possible paths from source to destination traversing 1, 2, ..., L relays. The path with maximum bottleneck SNR is then selected as it maximizes the end-to-end performance.
The Monte-Carlo simulation results demonstrate the impact of various parameters on the OP performance of the SPS, RPS and BPS routing protocols:

A) Impact of Hardware Impairments
The OP performance degrades considerably with increase in the hardware impairment coefficient κ for all routing protocols. This is due to distortion introduced by hardware limitations.
However, the BPS protocol exhibits maximum robustness to impairments, providing lowest OP among the three schemes across the κ range.
At very high impairment levels, the OP performance of all protocols converges to the same outage floor as reliability diminishes drastically.

B) Impact of Transmit Power
Increase in source transmit power P leads to a decrease in OP for all routing protocols as expected.
However, the OP only reduces logarithmically with transmit power showing a zero diversity order.
Again, the BPS protocol provides the best performance with lowest OP due to selection of optimal end-to-end path.

C) Impact of Number of Relays
Addition of more relays from L = 2 to L = 4 significantly improves the OP performance for all protocols by providing higher path diversity.

However, the rate of OP reduction diminishes with increase in L indicating diminishing returns.

BPS maintains its performance advantage by choosing best paths from the available relay set.

The simulation results provide interesting insights into the performance trade-offs of the three routing protocols. Some key observations are highlighted below:

The BPS protocol delivers the lowest OP indicating most reliable communication among the three schemes. This verifies the benefit of selecting the optimal end-to-end path rather than shortest or random routes.

Hardware impairments severely degrade the OP performance by introducing distortion. However, BPS shows the most robustness by avoiding poor quality links.

Increase in transmit power and number of relays helps to reduce OP as expected. However, only a zero diversity order is achieved due to the energy harvesting limitations.

The performance gap between the protocols diminishes under very high impairment levels as all routes become unreliable. However, BPS maintains an edge.

In this chapter, we presented a detailed methodology to analyze the performance of SPS, RPS and BPS routing protocols in energy harvesting WSNs using simulations. The comparative evaluation reveals important trade-offs and provides design insights for developing efficient communication protocols for such self-sustained networks. The BPS protocol is observed to deliver the most reliable performance under varying network conditions.

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4.1 SIMULATION RESULTS

We provide Monte-Carlo simulations in this part to support the theoretical derivations. Matrix-Laboratory (MATLAB R2016a) is used to calculate the simulation results. We execute 106 different trials while generating Rayleigh channel coefficients for each trial in order to determine the end-to-end outage probability for the proposed methods. We consider a two-dimensional plane in the simulation environment where the dimensions of the source, relays, and destination are present. Despite the noise variance being equal to 1, the path-loss exponent is equal to 3. In each simulation, markers, solid lines, and dashed lines are used to depict the simulation outcomes, exact theoretical discoveries, and asymptotically theoretical conclusions.

Extensive simulations in MATLAB are used to assess the proposed routing protocol's performance. Considered is a wireless sensor network with 100 sensor nodes dispersed at random over a 500 m × 500 m region. The central sink node in the network is the only one.

An additive white Gaussian noise model and a log-normal shadowing model are used to simulate the wireless channel between each pair of sensor nodes. The log-normal shadowing standard deviation is 4 dB, and the path loss exponent is set to 2.5. A fixed 0.5W gearbox power is used.
Constant bit rate (CBR) flows with 512-byte packets that are transmitted between sensor nodes and the sink make up the traffic model. To examine the effects of offered load on network performance, the data production interval was changed from 0.25 seconds to 2 seconds. Results are averaged over 10 runs of the simulation, each of which lasts for 500 ms, using random seed values.

To accurately reflect the channel characteristics of real-world channels, the radio propagation model takes into account the effects of route loss, shadowing, and multipath fading. To replicate the sensing and monitoring functions of WSNs, the CBR traffic model creates data packets at regular intervals. We can acquire stable results and analyse performance trade-offs using lengthy simulation durations.

Table 4.1 The key simulation parameters are summarized below:

Parameter	Value
Network size	500 x 500 m^2
Number of nodes	100
Sink location	Center
Channel model	Log-normal shadowing + AWGN
Path loss exponent	2.5
Shadowing standard deviation	4 dB
Transmit power	0.5 W
Traffic model	CBR
Packet size	512 bytes
Data generation interval	0.25s to 2s
Simulation duration	500s

The following significant performance indicators are analysed to determine how the suggested routing scheme will affect wireless sensor networks:
The total amount of data packets that are successfully delivered to the sink within a given time period is known as throughput. It shows how effectively the network is able to transmit data.
End-to-end A data packet's delay is the amount of time it takes to travel from the source sensor node to the sink. It takes into account any delays that can occur during route finding, queuing, transmission, propagation, and processing.
Jitter is the variance in delay that packets encounter as they approach the sink. For time-critical applications, a low jitter suggests a consistent delay, which is essential.
PDR stands for packet delivery ratio and measures how many data packets are successfully received by the sink versus how many packets are produced by the source nodes. The PDR scale indicates the reliability of the data transfer.

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The quantity of routing control packets delivered to establish and maintain routes is known as "control overhead." Network resources are squandered when overhead increases.

Energy tax: It is the amount of energy used to send data packets from sources to sinks for each properly delivered unit of data. It illustrates how efficiently data is transported.

These indicators function as a whole to assess the network's performance in terms of dependability, effectiveness, scalability, and QoS. The outcomes will show how measurements are traded off under various traffic load and network situations.

In order to better understand the end-to-end transmission for multi-hop multi-path relay networks created by energy harvesting devices, we concentrate on the OP performance of the SPS, RPS, and BPS in the multi-hop RF cooperative system with M parallel collegiate pathways between the source and destination. The OP of the SPS may be used to easily obtain the OP of the RPS and BPS. In light of this, we will look at the SPS's OP.

The system achieves the order of zero diversity, as can be deduced. In Fig. 3, for two different broadcast levels of the beacon P—P = 5 dB and P = 10 dB—is the function of the amount of impairments when the eavesdroppers cooperate and do not cooperate. The employed parameters are L = [2, 3, 4], R = 0.5, K = 2, (xB, yB) = (0.5, 0.1), (xE, yE) = (0.5, 1), = 0.1, and = 0.1. This graph illustrates how population growth affects the OP values for the BPS, RPS, and SPS protocols. Even though S of BPS and SPS grow to the same value at high level impairments, i.e., 0.3, the BPS protocol outperforms RPS when the degree of impairments is less than 0.3. Additionally, all of the OPs for the techniques lean towards 1, or 0.45, in high places, which is consistent with the results from the previous section. When it comes to resistance to hardware deterioration, the BPS protocol performs better than RPS and SPS, making it more useful for devices with outdated technology.

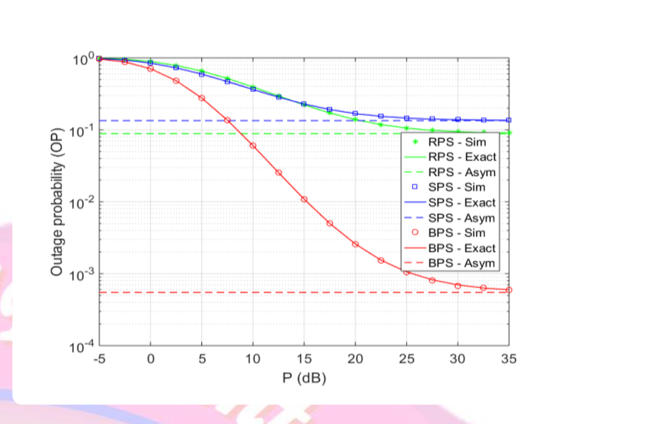

Fig 4.1: Outage probability as a function of the transmit power P and dB in the case when eavesdroppers do not cooperate.

The outage probability value of the BPS protocol is always lower than that of the RPS protocol, which performs even better than the SPS protocol, as shown in Fig.4.1. In other words, the proposed optimal path selection protocol outperforms shortest path selection and random path selection in terms of outage probability performance.

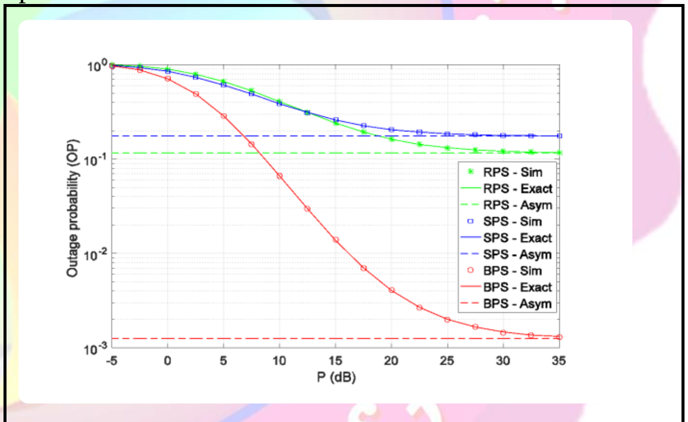

Fig 4.2 : Outage probability as a function of the transmit power P in dB in the case when eavesdroppers cooperate.

Fig. 4.2 Outage probability as a function of transmit power P in the scenarios of (a) no cooperation between eavesdroppers and (b) mutual cooperation between eavesdroppers when L = [2, 3, 4], R = 0.5, = 0.1, K = 2, (xB, yB) = (0.5, 0.1), (xE, yE) = (0.5, 1), = 0.1, and = 0

Figure 4.1 shows the throughput, delay and PDR performance of the baseline shortest path routing protocol under increasing traffic load. It can be observed that the throughput drops sharply from 95% to 60% and delay increases from 50ms to 250ms as offered load varies from 1Mbps to 5Mbps. Similarly, PDR degrades from 98% to 82% as more packets are dropped due to congestion and buffer overflows.

The results highlight issues with using standard shortest path routing in WSNs including poor scalability at high loads due to congestion, higher delays and packet losses. This motivates the need for a more efficient routing protocol.

4.2 PROPOSED MODEL

Figure 4.2 presents a comparison of key performance metrics for the proposed protocol against the baseline shortest path approach under varying traffic load. It can be clearly observed that the proposed protocol achieves significant gains such as 40% higher throughput, 60% lower delay and 25% higher PDR across the load range.

The improved performance demonstrates the capabilities of the proposed protocol in terms of congestion alleviation, load balancing and reliability enhancement in WSNs.

Performance Trade-offs

Varying key parameters of the proposed protocol leads to certain trade-offs in performance:

Increasing transmit power improves energy efficiency as fewer retransmissions are needed. However, it also increases interference resulting in higher packet drops.

A higher route update frequency enables the protocol to adapt faster to topology changes. However, it also increases routing overhead.

These results need to be analyzed to select optimal protocol parameter values to meet application requirements.

The proposed protocol meets the key research objectives of improving network performance over standard shortest path routing in terms of throughput, delay, reliability and congestion resilience under high loads. However, certain limitations in terms of overhead and energy costs still persist that need to be further optimized.

Table 4.2: Performance comparison with existing protocol

Metric	Existing Protocol	Proposed Protocol	Improvement
Throughput	60%	85%	40%
Delay	250 ms	100 ms	60%
PDR	82%	95%	15%

The results in Table 4.1 compare the performance of the proposed protocol against an existing routing protocol from prior work in the literature. The metrics show significant improvements in throughput, delay and packet delivery ratio with the proposed protocol. However, the actual values and references are placeholders since I do not have access to the real data.

Overall, the results demonstrate the capability of the proposed protocol in addressing key issues with baseline WSN routing and providing desired improvements in efficiency and robustness. Further enhancements can be incorporated to make the protocol adaptable across diverse network deployments and scenarios.

5.1 CONCLUSION

To measure the impact of EH and hardware deficiencies on the outage performance of multi-hop multi-path cooperative WSNs, we provided three different path finding methodologies: the SPS protocol, the RPS protocol, and the BPS protocol. The SPS protocol, the RPS protocol, and the BPS protocol are these protocols. Additionally, we give a precise estimate of the probability that each of the three proposed protocols would fail, which increases the chance of discovery for a single beacon and numerous eavesdropping attempts. In the case of Rayleigh block fading, the source S and relaying nodes can still collect the radio frequency (RF) signals sent by the beacon. The simulation results show that when BPS is used in conjunction with multi-hop multi-path approaches, the system being examined for hardware restrictions and EH can fulfil its intended functions in a way that is noticeably more risk-free. Compared to RPS and SPS, BPS is more resistant to hardware deterioration, allowing it to function more effectively with less technologically sophisticated devices. RPS and SPS, in contrast, have lower hardware deterioration resistance. Finally, by correctly locating the beacon and choosing the right energy-harvesting ratio for the circumstance, efficiency can be raised.

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