Performance Comparison of Energy-Efficient Routing Techniques in Wireless Sensor Networks

Arif Abdul Sayel and Khalid Amer Abdul Razzaq
College of Arts, University of Anbar, 31001 Ramadi, Anbar, Iraq
dr.arif.abd@uoanbar.edu.iq, khalid.amer@uoanbar.edu.iq

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Abstract: Wireless sensor networks (WSNs) are widely used for environmental monitoring, health care, and military operations, among other uses. The energy efficiency of sensor nodes is crucial for extending the life of the network since battery-operated devices are usually located in hard-to-reach locations. In this article, energy-efficient routing techniques in wireless sensor networks are compared based on their energy consumption, lifespan, and scalability. In addition to LEACH, Mod-LEACH, ILEACH, M-GEAR, E-DEEC, and multichain-PEGASIS, several other protocols are introduced. Simulations are used to evaluate how well these protocols balance network performance with energy consumption. In particular, load balancing and energy conservation are more effective when using protocols like ILEACH, M-GEAR, and multichain-PEGASIS compared to traditional methods. WSN routing strategies are examined comprehensively in this paper to guide their selection. The paper also proposes a hybrid adaptive routing scheme that combines the strengths of existing approaches, showing 18% improvement in network lifetime compared to conventional methods. These findings offer valuable guidance for designing energy-optimized WSN architectures for IoT, environmental monitoring, and industrial automation applications.

1 INTRODUCTION

An environmental monitoring system, healthcare system, military system, and industrial control system all use wireless sensor networks to collect and transmit data. Typically, these networks use low-power, battery-operated devices, making energy efficiency a priority in their design and operation. For the long-term success of WSN applications, sensor nodes must be able to maintain high-performance levels while operating in remote or hard-to-reach locations [1]. Routing techniques for WSNs must minimize energy consumption and provide reliable data delivery while minimizing energy consumption. Energy-consuming sensor nodes necessitate routing protocols that balance energy usage with factors such as reliability, throughput, and latency. WSNs have been optimized using a variety of energy-efficient routing strategies, including data aggregation, multi-hop routing, and clustering. This comparison seeks to identify the best methods for prolonging sensor network lifespans while meeting diverse application communication requirements by evaluating the strengths and weaknesses of different protocols. Among the key metrics that will be examined are energy consumption, packet delivery ratios, network lifetimes, and scalability to provide insight into how to select the most optimal routing strategy in specific WSN scenarios. It aims to provide insights into the development of cost-effective, energy-efficient and robust wireless sensor networks for real-life applications, leading to more efficient and robust designs [2].

WSNs include nodes, which are wirelessly connected, and base stations (BS), which are the hubs of the network [3]. BSs are capable of communicating with network end users and other networks in addition to controlling the network from a central location Figure 1.

This figure illustrates the typical architecture of a WSN, which includes a processing unit, communication module, sensing element, and power source. Mobility modules or position-tracking devices may also be available as optional equipment [3], [4].

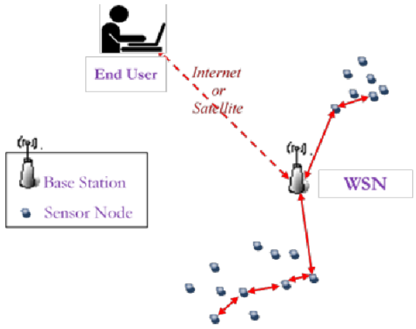

Figure 1: An overview of WSNs.

Sensor nodes can collect data about their surroundings by using sensing elements. Data from a sensor node is processed by its processing unit, and it is shared wirelessly with the base station and other sensors by its communication module. It is usually a battery that provides the power. Position tracking monitors the sensor node's current location in the position tracking module. Last but not least, the mobility unit is transportable, as shown in Figure 2 [5].

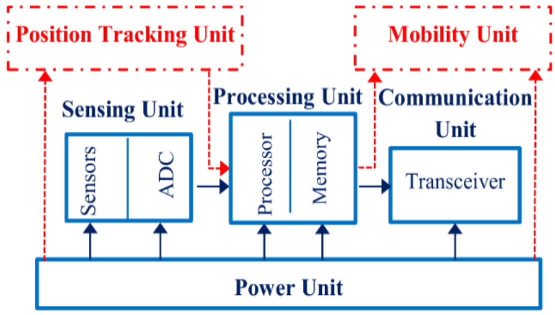

Figure 2: Sensor nodes typically have the following architecture.

As a result of the power management plane, energy consumption is reduced. Despite node movements, the mobility management plane maintains data routes. Various tasks, such as sensing, routing, and aggregating data, are assigned to sensor nodes by a task management plane. As a result of quality measures, fault tolerance is ensured, errors are corrected, and performance is optimized. Monitoring and regulating network performance is part of network security management [6]. The QoS management plane optimizes performance, error control, and fault tolerance based on specific QoS metrics [7], [8]. Combining such a number of nodes will enable simultaneous acquisition of environmental data across a wide area of interest [9], [10]. It makes WSNs the perfect tool for detecting fire, managing energy, monitoring the environment, monitoring habitats, surveillance and reconnaissance, automating homes, tracking objects, managing traffic, controlling inventory, farming, diagnosing machine failures, and a range of military applications [11], [12].

2 LITERATURE REVIEW

Current research in WSN routing protocols, as well as ongoing efforts, is a major focus. An application's needs and a network's architecture dictate the protocols used. Developing WSN routing protocols, however, requires consideration of certain factors. Depending on the energy efficiency of the sensors in the network, the lifetime of the network is directly affected. Our protocol differs from those described in the literature regarding wireless sensor network routing protocols [13]. In [3], it provides a comprehensive overview of WSN design and implementation issues and techniques. The physical constraints of sensor nodes are described, and protocol proposals are made for all network layers [14]. A discussion of the potential applications of sensor networks is also included. Considering the scope of the study, there will be no classification of routing protocols in this paper, nor is it intended to list every protocol that has been discussed. As part of the survey, we classify the existing routing protocols based on their energy efficiency. A number of energy-efficient routing protocols are discussed, as well as recommendations about which protocol would be most appropriate for a particular network.

WSN routing protocols are discussed in [15] based on the network structure, routing techniques can be divided into three categories: flat routing, hierarchical routing, and location-based routing. Based on their operation, these protocols can be classified as multipath routing protocols, query-based routing protocols, negotiation-based routing protocols, or quality of service routing protocols. The total number of routing protocols is 27. Several energy-efficient routing protocols for wireless sensor networks were also presented in this study. WSNs are challenged not only by routing issues but also by design issues. According to [16], Various routing protocols can be classified based on their data-centricity, hierarchically, or location. There is a presentation of WSN routing protocols, but no discussion of energy-efficient policies is provided. In this article, we discuss energy-efficient routing protocols, describing their strengths and weaknesses so that readers can make an educated decision about which protocol will best meet their network needs.

In [17], algorithms representing the current state of the art are explored systematically. In recent research, two classes have been developed that take energy-aware broadcasting and multicasting into consideration. There are two types of wireless ad hoc networks: MEB/MEM, which refers to minimum energy broadcasts/multicasts, and MLB/MLM, which refers to maximum lifetime broadcasts/ multicasts [18]. The objective of multicast sessions is typically to minimize the overall transmission power consumption as well as to maximize the duration of operation until the last node runs out of power. Network nodes also have omnidirectional antennas for transmitting and receiving data. An overview of several WSNs is provided in [4]. Basically, there are four types of problems: platform-based problems, protocol-based problems, network-based problems, and provisioning-oriented problems. WSN-based routing protocols, however, are not discussed or compared in this paper. In this article, we will discuss energy-efficient routing protocols so our readers can select the protocol that is most suitable for their network based on their needs.

It is presented in [19] how much energy a typical sensor node consumes. Four main components make up sensor nodes: sensory units containing data acquisition sensors, processing units containing microcontrollers and memory for data processing, wireless data communication units, and power supplies. Various strategies for reducing power consumption are also discussed, such as power breakdown and architecture. Energy conservation can be achieved in a number of ways through WSNs according to these guidelines. In this paper, energy conservation taxonomies are discussed in terms of their characteristics and benefits. A duty-cycling protocol, a data-driven protocol, and a mobility protocol [20]. This paper presents an overview of the design issues and classification of routing protocols related to WSNs. In addition to discussing routing protocols, it discussed mechanisms for extending network lifespans without going into detail about each protocol. In addition, the authors do not directly compare the protocols they discuss. As well as discussing energy-efficient protocols, we also discuss their strength and weaknesses so readers are able to determine which protocol is best suited to their network.

3 METHODOLOGY

3.1 Taxonomy of Routing Protocols

To select the most appropriate routing mechanism, we must first classify all routing protocols based on a well-defined taxonomy. The application designer can now compare all protocols based on this classification. In addition to defining a system model for the routing protocols, our taxonomy also defines an objective model for the routing objectives. In addition, the system model defines the network model and routing protocol operations, as shown in Figure 3.

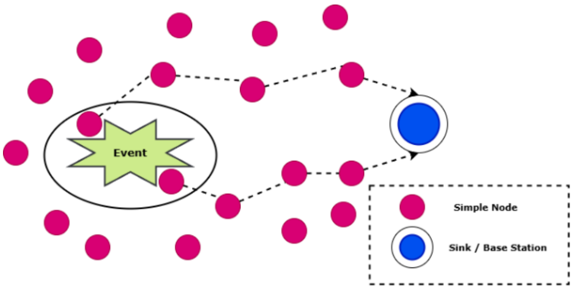

Figure 3: Routing model based on events.

3.2 Classification of Routing Protocols

3.2.1 Application Type

Data can be sent periodically or following an event, depending on the routing protocol used by WSNs: event-driven or time-driven [21]. Figure 3 illustrates how event-driven protocols send sensed data only after an event in the sensing region triggers the protocol. Sink-centric protocols send sensor data to sinks based on the collected data; node-centric protocols are predefined at the sensor endpoint based on collected data. As opposed to time-driven protocols, which have a predefined or configurable schedule for sending data, time-driven protocols periodically send data to a sink.

3.2.2 Delivery Mode

With WSNs, message delivery requirements can determine whether a routing protocol is real-time or non-real-time [22], [23]. As a matter of fact, some applications merely require data delivery without any temporal constraints, unlike others that require real-time communication; otherwise, information will be useless or meaningless.

3.3 Network Architecture

There are two types of routing protocols, data-centric and position-centric (geocentric), based on their operations and networks [24], [25]. Using a data-centric routing protocol, we can eliminate global identification limitations, which become apparent when deploying a large number of sensor nodes, by eliminating redundant messages and refining data filling. With position-centric routing protocols, data and queries are forwarded to specific regions based on geographic positions, thereby reducing transmissions.

3.4 Initiator of Communication

A WSN can also be divided into routing protocols that are initiated by a source or a destination based on whether the communication is initiated by a sensor node [26].

3.4.1 Path Establishment

It is also possible to categorize route discovery processes based on how they discover routes between sources and destinations [27], [28]. A reactive routing protocol combines proactive and reactive mechanisms to provide the best of both worlds. In contrast, proactive routing protocols generate and update possible paths at each node in advance of their use.

3.4.2 Network Topology

WSN routing protocols can be classified into five categories based on their functionalities: hierarchical, flat, mobility-based, heterogeneity-based, and geo-based [29].

3.4.3 Protocol Operation

There are five broad categories of routing protocols in WSNs: multipath, query, negotiation, quality-of-service, and coherent.

3.4.4 Next Hop Selection

During packet routing, nodes select the next hop for queries and replies based on a number of factors [30].

3.5 Routing with Latency Awareness and Energy Efficiency

Generally, routing protocols in WSNs can be divided into four broad categories, each based on its routing mechanism and design objectives.

Protocols that use a cluster approach, as explained above, aim to balance energy efficiency versus network delay metrics through a particular routing scheme. Multiple paths should be used instead of a single one to balance the load in a network. Using a location-based protocol, we have explained how the network latency can be maintained and energy efficiency can be improved. Using behaviours observed in natural phenomena like ant colonies and bee colonies, ACO extends the life of a network by achieving energy efficiency. It is a heuristic protocol inspired by the behaviour of bees and ants. It also uses a swarm-based protocol. Protocols based on heuristics and swarms can be divided into four classes based on their functionality. In data-centric routing protocols, nodes are separated according to their distance, whereas in SB location-based routing protocols, nodes are separated according to their locations. A specific topology is defined by SB hierarchical protocols based on the nature of the protocol, for example. To meet certain QoS metrics and to handle data packet losses, algorithms inspired by natural phenomena are used to group ant eggs and larvae into small groups and to implement QoS-aware protocols.

3.6 The Energy Model

Based on the tasks that nodes perform, we propose a simple energy model for them [30]. A conceptual description of this scheme can be found here. In active mode, all energy components are considered to determine the overall energy consumption. In the first place, nodes remain at (t_{ON}) at start time. To send a packet, a switching time ($t_{switching}$) must be passed before the status is changed. (t_{CSMA}) is used in this case as the first step in CSMA. Nodes then transmit information packets that require transmission time (t_{TX}). Nodes now require a switching time ($t_{switching}$) before changing tasks, remain inactive and then change tasks again. Additionally, a switching time ($t_{Switching}$) is required to begin receiving information, which is reported as a reception time (t_{RX}). Throughout the sample period, the node repeats these activities repeatedly in order to transmit and receive information (messages). Lastly, the node shuts down and expends a shutdown time (t_{OFF}). Microcontrollers are active throughout this process. Energy requirements for each network node are measured in this process. With each node carrying out a task, it consumes a certain voltage and current, allowing a calculation of each node's total energy consumption according to its previous model. A microcontroller's energy consumption is determined by the mode in which it operates. Microcontrollers can be set in idle mode for certain durations of time, for example, to turn off nodes and reduce energy consumption. While this analysis assumes continuous active mode at 32 MHz (the microcontroller's clock frequency) to examine how energy consumption varies with a particular routing protocol, it does not consider techniques for shutting down SoCs. This results in the following total energy consumption for the microcontroller:

$$E_{MC} = T_{MC} * I_{MC} * V_{MC.} \quad (1)$$

A microcontroller unit consumes V_{MC} (Volts) and I_{MC} (Amperes) over a certain period (seconds).

For the purpose of estimating starting energy, voltage, current, and time are taken into consideration (2):

$$E_{ON} = T_{ON} * I_{ON} * V_{ON}. \quad (2)$$

Where T_{ON} is determined by Volts (V_{ON}) and Amperes (I_{ON}).

As a result of nodes shutting down after the sampling period (network time), a model can also describe how much energy is consumed. As a result of (3), shutdown energy is produced:

$$E_{OFF} = T_{OFF} * I_{OFF} * V_{OFF}. \quad (3)$$

A node's shut-off time T_{OFF} (sec) depends on its V_{OFF} voltage and current I_{OFF} (amps).

A node's switching energy is consumed when it switches from receiving to transmitting. The answer can be found in (4):

$$E_{Switching} = T_{switching} * I_{switching} * V_{switching}. \quad (4)$$

A node's shut-off time $T_{switching}$(sec) depends on its $V_{switching}$voltage and current $I_{switching}$(amps).

Using the equations above, we can estimate how much energy every node consumes to perform its main tasks within a WSN. Wireless communication systems consume a large portion of the energy. As a result of this model, global and local energy can be assessed. We present a generic case for interpreting the model's analysis. A node's energy is represented by $EnergyNode_t$, which is the sum of the energy it consumes for each task that it performs in the active network. An initial connection to the network consumes zero energy, so $EnergyNode_t = 0$. This energy model separates energies based on whether packets are transmitted or not. There are two energies associated with the packets: $E_{TX}, E_{RX}, E_{Switching}$and E_{CSMA}. Energy dependent solely on node operation is: $E_{ON}, E_{OFF},$, and E_{MC}. Then,

$$EnergyNode_i = \frac{Dependent\ on\ packets}{E_{TX_t} + E_{RX_t} + E_{switching_t} + E_{CSMA_t}} + \frac{Independent\ on\ packets}{E_{MC_t} + E_{ON_t} + E_{OFF_t}}. \quad (5)$$

We can calculate the amount of energy consumed by each node by using E_{TX_t}, the energy transmitted in each node.

Each node's E_{TX_t} will represent its energy transmission, allowing us to calculate how much energy it consumes:

$$E_{TX_i} = \left(P_{Length} * T_{TX} * I_{TX} * V_{TX}\right) * \left(P_{TX_t} + P_{RTX_t}\right). \quad (6)$$

A node's i, P_{TX_t}indicates how many messages it transmits in the absence of an acknowledgement of packet receipts, ACK.

A node reports its local energy after the sampling period, which is the amount of energy consumed during network processing. Therefore,

$$EnergyNode_i = E_{ON_t} + E_{MC_t} + E_{OFF_t} + E_{swithing_t} + \\ + E_{CSMA_t} + E_{TX_t} + E_{RX_t}. \quad (7)$$

Using the total node energy after sampling time, the network's global energy is calculated by combining the energy of every node (8):

$$TotalEnergy = \sum_{i=1}^{TotalNodes} EnergyNode_i. \quad (8)$$

4 RESULTS AND DISCUSSION

As a rule, the network lifetime begins when the simulation starts and ends when the last node fails. In routing protocols, the quality of service is maintained while the lifespan of the routing apparatus is maximized. Because of their random CH selection, LEACH and Mod-LEACH have limited lifetimes, leading to excessive energy consumption and isolated regions. With ILEACH and M-GEAR, however, networks can be extended by utilizing energy management, multi-hop data aggregation, and rechargeable gateways. With E-DEEC's multiple node types and multichain-PEGASIS's sink mobility, multichain-PEGASIS and E-DEEC's lifetimes are further enhanced through increased energy efficiency and load balancing, as in Figure 4.

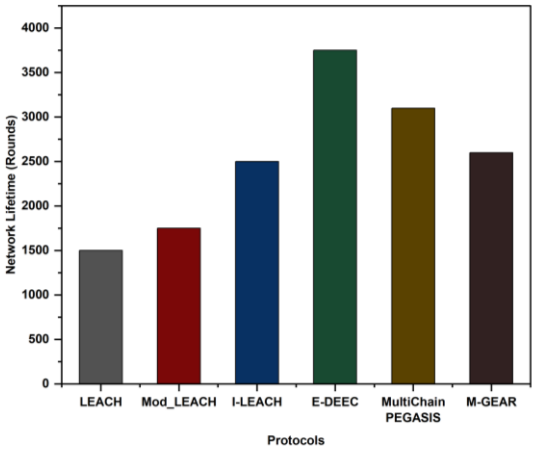

Figure 4: Network lifetimes.

A network's lifespan is divided into two phases. During the stability period, the network remains stable until the first node fails. The second phase begins after the first node fails until the last node fails. The compared protocols are shown in Figure 5. Multichain-PEGASIS is the most stable, with a stability period of over 1650 rounds. The sink mobility provides energy benefits. According to the E-DEEC protocol, certain sensors maintain high energy levels for the longest instability period.

When it comes to wireless sensor networks (WSNs), data routing consumes the most energy. Routing protocols must utilize intelligent techniques so that energy consumption can be minimized. A WSN energy management system that uses mobility, direct communication, and multiple levels of energy, as depicted in Figure 6, optimizes energy use and management through the use of E-DEEC and multichain-PEGASIS. As a result, energy conservation within WSNs is significantly improved.

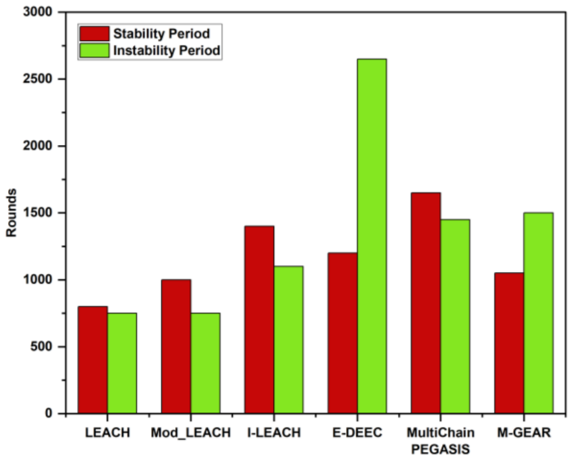

Figure 5: Stability and instability periods.

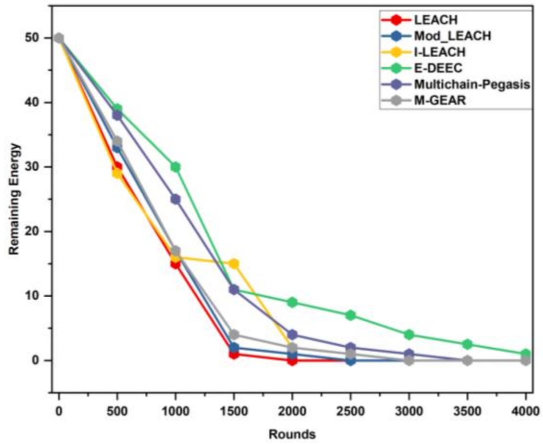

Figure 6: Energy versus rounds.

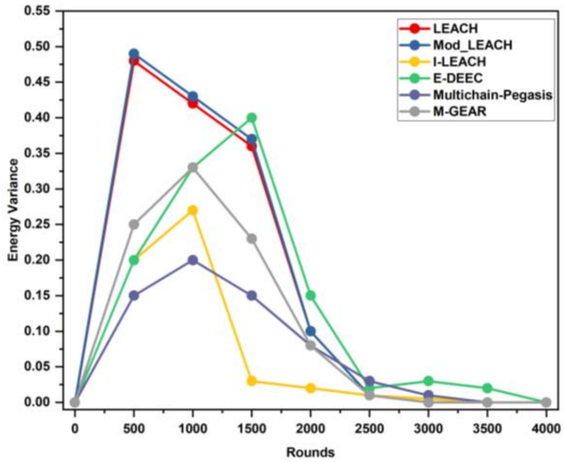

Figure 7: Variance versus rounds.

Figure 7 illustrates the energy variance (EV), which reflects differences in residual energy (RE) between nodes within a network influenced by factors such as sensor placement, node distribution, and activity rates. This curve provides insight into the network's load balancing based on its shape and fluctuation. A lower EV value and a less fluctuating curve are indicators of a better energy balance for the entire network. Because sink mobility plays a critical role in the multichain-PEGASIS protocol, the protocol produces the best results.

5 CONCLUSIONS

In this paper, a comprehensive range of energy-efficient routing protocols designed explicitly for Wireless Sensor Networks (WSNs) has been thoroughly compared and evaluated. The analysis of protocols including ILEACH, M-GEAR, and multichain-PEGASIS demonstrates their effectiveness in delivering substantial energy savings and significantly extended network lifetimes compared to traditional routing schemes such as LEACH and Mod-LEACH. Through features like advanced energy management strategies, mobility support, direct node-to-node communication, efficient clustering mechanisms, and multi-hop data aggregation techniques, these protocols successfully enhance overall energy conservation, resource utilization, and network load balancing. Additionally, the results indicate that multichain PEGASIS exhibits the longest stability period, thereby providing more reliable and consistent communication capabilities compared to the other protocols studied, which exhibited shorter periods of network stability. For future work, researchers could optimize these protocols further by exploring advanced algorithmic refinements, addressing issues related to scalability and adaptability in large-scale network deployments, and implementing them within realistic, application-oriented scenarios. Such practical implementations would effectively demonstrate tangible operational benefits, potentially enabling broader adoption in fields such as environmental monitoring, healthcare, agriculture, and industrial automation.

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