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https://doi.org/10.1007/s11277-018-5747-9

Survey on Wireless Sensor Network Applications and Energy Efficient Routing Protocols

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Abstract Wireless sensor network (WSN) is a group of small power-constrained nodes that sense data and communicate it to the base station (BS). These nodes cover a vast region of interest (ROI) for several purposes according to the application need. The first challenge encountered in WSNs is how to cover the ROI perfectly and send the monitored data to the BS. Although the energy introduced during setup phase and the violation of energy fairness constraint of dynamic routing topologies, they achieve high network performance in terms of coverage and connectivity. In this paper, we categorize the applications of WSN based on different aspects to show the major protocol design issues. Thus, the energy efficiency of the recent proactive routing protocols is studied from different angles. The energy overhead and energy fairness of each protocol were carefully analyzed. The most energy efficient routing protocols for homogeneous proactive networks were studied and compared to highlight the research challenges and existing problems in this area. The results proved that energy overhead and route selection are the most effective aspects of network lifetime and network efficiency.

Keywords Energy efficient routing · Proactive routing protocols · Network lifetime

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Published online: 22 May 2018

1 Introduction

Wireless sensor network WSN is a hot research area with a rapidly growing set of applications. Given the benefits offered by wireless sensor networks (WSNs) with respect to that of wired networks, for example, simple deployment, low installation cost, high mobility, and lack of cabling. WSNs are appealing technology for smart infrastructure; for example, building, factory automation, and process control applications [1]. WSN is well established for low-cost systems, it brings IoT applications richer sensing and actuation capabilities. A sensor network is a number of tiny sensor nodes of low costs that cover a certain region of interest ROI to measure data using different sensing capabilities and transmit it to the base station BS as in Fig. 1. The data transmission process requires radio communication system that mainly consists of the following: (1) A processing unit contains Digital to Analog Converter (DAC), (2) memory, and (3) Digital Signal Processing (DSP) unit that helps the node to choose the suitable protocols to accomplish the data transmission task according to the system requirement. Moreover, such protocols handle the limited battery size and control the additional node capabilities that include mobility and location discovery mechanism that are essential in many applications.

Therefore, sensor nodes have very high adaptability in their physical features and protocols to suit different types of application environments and requirements, as described in [2].The communication performed between nodes using multi-hop or direct transmission, as studied in [3]. In multi-hop data transmission fashion, the nodes communicate with each other using minimal transmission power. The data sent by a source node travels through the nodes in-between to reach the destination node which is typically the base station BS. To minimize power consumption in data transmission, it is preferable to use the multi-hop transmission to reach the BS instead of direct transmission, especially in large ROIs and if only one BS is used. Consequently, the computational and communication task of sensor nodes may divide them into three main types according to their role in ROI.

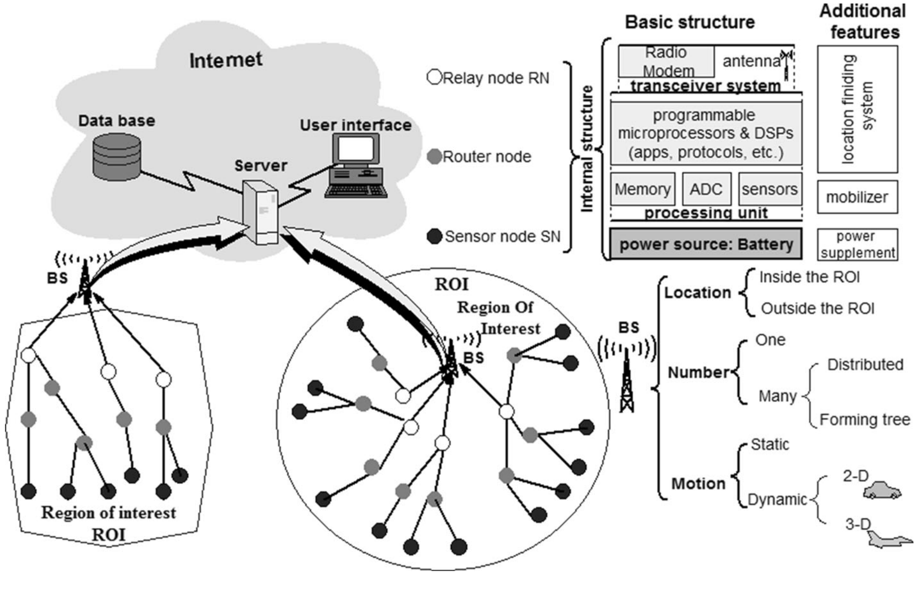

Fig. 1 Different aspects of WSN system

These three main types may vary physically as in the heterogeneous networks are not as in homogeneous networks, as discussed in [4].

These types are the sensor nodes *SN* that are responsible for sensing data and transmitting it according to the routing protocol used to the router nodes which is the second type. Router nodes have three roles, the first is similar to *SN*s which is sensing the environment, the second is aggregating the data received from *SN*s with the sensed data to limit the number of transmissions and the third is transmitting the aggregated data to higher level nodes. The third type is the relay nodes *RN*s that perform the same operations as router nodes but they transmit the aggregated data to the BS directly. The BS then transmits the sensed data to the server that is connected to data base that stores data and user interface that monitors the network task. This BS may be inside the ROI of far from the ROI according to the application environment. There may be several stationary or mobile BS, as in [5–7]. These BSs may connect directly to the server, or form a multi-hop data aggregation tree to limit connection to the server, as in [8]. The mobile BS may be moving on the ground that can be controllable or uncontrollable, as in [7, 9], or be an overflying unmanned aerial vehicle as in distributed antenna array systems [10].

Accordingly, the computational and communication load on *RN*s are higher than router nodes which are higher than that of the *SN*s. On the other hand, *ROI*s are hardly reached in many applications, which prevent the availability of network maintenance; thus, the loss of nodes can't be handled manually. As a result, the lack of energy fairness in multi-hop routing applications, especially when BS is far from the ROI, and the need for self-organized networks encourage researchers to introduce different solutions to maintain higher energy fairness and achieve WSN survivability by extending its lifetime.

In this paper, we study WSN lifetime primarily based on energy consumption. The main contributions of our work can be summarized as follows:

- First, we introduce a detailed taxonomy of WSN applications considering all the main design aspects and related network features. Since WSN cover nearly all aspects of life nowadays, especially after the extension of IoT technology, such a taxonomy will provide readers with all the required information to start any real life application considering all the application physical and logical requirements.
- Second, a detailed analytical study is performed on the most energy efficient proactive routing protocols, defined in [6], showing their strengths and weaknesses. It covers the network setup and data transmission process. To the best of our knowledge, this is the only analytical study performed on network lifetime and stability period, as defined in [11].
- Third, a comparison of the covered energy efficient protocols is provided on a periodic monitoring application to show the network lifetime and stability period using simulation results. This may help network designers to select suitable routing protocols for their applications according to their system parameters.

The rest of this work is organized as follows; in Sect. 2, the related work is shown including a summary of the previous surveys, reviews and comparative studies performed through the last 6 years on WSN applications and lifetime maximization. In Sect. 3 a detailed taxonomy of WSN applications considering all the main design aspects and related network features. In Sect. 4, the main network design issues of WSN routing protocols are described in details to give a clear view of the system studied in this work. In Sect. 5, the most energy efficient routing protocols are analytically studied in terms of energy cost to derive an approximate estimation of stability period and network lifetime based on ideal assumptions. In Sect. 6, the protocols are simulated to give a sophisticated proof of the problems addressed in this work.

2 Related Work

In this section, we summarize the surveys performed on linking the need for lifetime extension with respect to application needs and the most important energy efficient routing protocols designed for WSN. To cover the energy hole problem, the surveys performed on linking the need for lifetime extension with respect to applications of WSN are presented to show how energy consumption is essential according to application type. In this section, we summarize the previous surveys, reviews and comparative studies performed through the last 6 years on WSN applications and lifetime maximization. Ehsan and Hamdaoui covered the energy-efficient routing protocols for Wireless Multimedia Sensor Networks WMSN in [12]. They outline the design challenges and limitations of non-multimedia data transmission techniques when used in WMSN. Further, they highlighted the performance issues of each energy-efficient routing strategy designed for WMSNs in a classification.

In [13], Naeimi et al. have conducted a comprehensive survey of cluster-based routing protocols for homogeneous sensor networks. They classified clustering protocols according to their objectives and clustering process method that includes cluster head CH selection, cluster formation, data aggregation and data communication. Thus, the authors provided detailed classifications of clustering protocols for homogeneous networks in each phase based on the existing research since 2012. The CH selection classification includes self-organized schemes, assisted schemes, and multi-factor evaluation schemes. In [14], Liu presented an extensive survey on clustering routing protocols in WSNs. He outlined the objectives of clustering for WSNs and developed a novel taxonomy of WSN clustering routing methods based on three main points: First, cluster characteristics that include variability of cluster count, uniformity of cluster sizes, the methods of inter-cluster routing, and the manners of inter-cluster routing. Second, cluster-head characteristics, which include the CH existence, CH difference of capabilities, CH mobility, and CH role. Third, clustering processes, which that include the control manners, execution nature, convergence time, parameters for CH election, and network proactivity.

Pantazis et al. [15] presented an influential expanded survey of the paper proposed by Al-Karaki in 2004 [16] on the energy efficiency of routing protocols for WSNs. The authors classified the routing protocols into flat, hierarchical, query-based, coherent and non- coherent- based, negotiation-based, location-based, mobile agent-based, multipath-based, QoS-based. They provide a detailed comparison among these protocols in terms of network scalability, nodes mobility, power usage, route selection metrics, periodic message type, and robustness. They also classified the protocols according to duty-cycling, data-driven and mobility to prove that the energy consumption of the radio is much higher than the energy consumption due to data sampling or data processing. Rault et al. [17] presented a holistic view of energy-saving solutions while taking into consideration the specific requirements of the applications. It provides WSN designers with an overview of the efficient solutions of their application-specific WSN architecture. They categorized WSN applications according to their specific requirements. These requirements include scalability, coverage, latency, QoS, security, mobility and robustness. Then they presented a new classification of energy-conservation schemes to be joined with applications specific requirements. These schemes are broadly divided into five main methods which are: radio optimization, data reduction, sleep/wakeup schemes, energy-efficient routing, charging. Finally, they classified energy efficiency and requirements trade-offs into three categories: Multi-metric protocols, Cross-layer approaches, and Multi-objective optimization.

Khan et al. [18] presented a high-level taxonomy of energy management in WSNs. They categorized energy provision approaches as battery driven, energy harvesting, and energy transference based schemes. They recommend considering both, the energy supply as well as the energy consumption in parallel while designing an energy efficient algorithm. Anisi et al. [19] covered the energy consumption issue of WSN specifically in Precision agriculture (PA). Such that, PA is the use of information and communication technology together in monitoring agriculture fields for farm management. The authors classified WSN approaches in PA according to their features, technical contribution, topology, heterogeneity, energy source, and data aggregation. Accordingly, they analyzed their energy consumption based on their power sources. Asharioun et al. [20] introduce a detailed survey that focuses on energy-balancing methods and analytical research in corona based WSN. The authors discussed the energy holes and hot spot areas in many-to-one WSNs where nodes located around the sink relay the data from other sensor nodes. Thus, energy depletion occurs quickly as shown in our introduction. Such energy holes cause the premature end of network lifetime. They discussed the relationship between the factors affecting network efficiency that include network lifetime, sensors coverage, the number of alive nodes, network connectivity, application quality of service requirement, and the energy hole problems. They classified the schemes proposed for solving the energy hole problem in corona-based WSNs into six categories: using dynamic clustering node, non-uniform node deployment, sink mobility, relay node, provisioning the node, and the use of multi-level transmission range. Then, they covered the basic mathematical modeling of network connectivity and coverage, energy consideration and optimum corona width.

Lui [21] performed an informative review covering atypical hierarchical WSN routing protocols using a comprehensive comparison based on their general performances and application scenarios showing their effect on prolonging network lifetime. He offered a classification of those protocols based on logical node topology to be divided into four types that are: Chain-Based Routing, Tree-Based Routing, Grid Based Routing, and Area-Based Routing. Accordingly, we provide a detailed analysis of selective energy efficient routing protocols that covers energy consumption during packet transmissions. Our comparative study is based on energy fairness during data transmission phase and network overhead during network setup phase. The previous efforts exerted in this direction are summarized in Table 1 showing their area of study and main classification building blocks.

3 WSN Applications

In this section, we introduce a detailed taxonomy of WSN applications considering all the main design aspects and related network features. Since WSN cover nearly all aspects of life nowadays, especially after the extension of IoT technology, such a taxonomy will provide readers with all the required information to start any real life application considering all the application physical and logical requirements.

In fact, WSN solutions already cover a very broad range of applications, and research and technology advance continuously expand their application field. This trend also increases their use in IoT applications for versatile low-cost data acquisition and actuation. The last years have shown us a wide range of Wireless Sensor Networks (WSNs)

Table 1 Comparisons among recent surveys about energy-efficiency and network lifetime of WSN

Publication year	Author(s)	References	Area of study	Classification criteria
2010	Maimour et al.	[22]	Proactive, multi-hop routing protocols	Energy overhead and load balancing
2011	Ehsan et al.	[23]	Energy efficient routing combining QoS assurance for WMSNs	QOS requirement, type of multimedia data, data delivery model, class of algorithm, and hole bypassing
2012	Naeimi et al.	[13]	Homogeneous cluster-based routing protocols	Objectives, characteristic, and issues of every individual scheme and approach of each phase
2012 30	Liu	[24]	All cluster-based routing protocols	Cluster characteristics, cluster-head characteristics, and clustering processes
2013	Pantazis et al.	[25]	Energy efficient routing protocols	Network structure, communication model, topology-based and reliable routing
2014	Rault et al.	[17]	WSN application and lifetime extension mechanisms	*WSN applications* according to scalability, coverage, latency, QoS, security, mobility and robustness *Energy-conservation* schemes based on radio optimization, data reduction, sleep/wakeup schemes, energy-efficient routing, charging
2014	Khan et al.	[18]	Energy management schemes	Duty cycling, data-driven schemes, and mobility
2015	Anisi et al.	[19]	WSN approaches that are used in PA	Power sources and the type of the nodes used
2015	Asharioun et al.	[20]	The schemes of solving the energy hole problem in corona-based WSNs	Using dynamic clustering node, non-uniform node deployment, sink mobility, relay node, provisioning the node, and the use of multi-level transmission range
2015	Lui	[21]	A typical hierarchical WSN routing protocols	Logical node topology
2016	R. M. Curry et al.	[26]	Optimization algorithms for lifetime maximization	Online routing, clustering approaches, and lifetime maximization on specially structured networks

applications [27]. Internet of Things IoT technology encourages the expansion of WSN in every aspect of life, as discussed in [28]. We classify the applications according to five main points, as in Fig. 2, which are; their targets, their data transmission requirements, their node deployment, their area of service and their required measurements. Sensor nodes cover ROIs to inspect certain phenomena by monitoring or track a target event or object. WSN monitoring is typically for maintaining system efficiency or detecting failures. It saves money and time by preventing further damage and maintaining high-quality systems. Target tracking [29] is also essential for saving money and effort of searching for lost targets. Generally, all WSN applications may be indoor or outdoor.

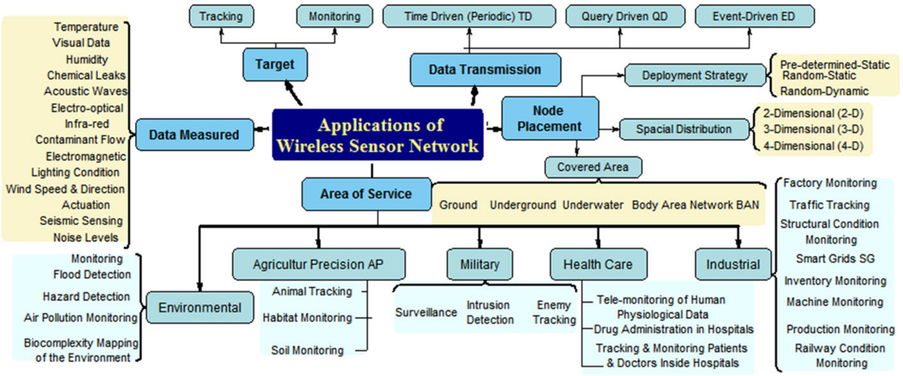

Fig. 2 Taxonomy of WSN design issues

Multiple types of sensors or sensor nodes with several sensing capabilities may be used in one application to give a complete view of the monitored data. These sensors can sense different measurements, like temperature, pressure, humidity, wind speed and direction, seismic changes that measure geographical change and others take photos and videos to give a clearer view of the monitored area or the tracked target. According to the authors in [30], WSN applications are categorized based on data transmission need. They can be event-driven that are triggered by a certain event, time-driven where data are transmitted in a timely manner like in periodic data gathering applications and query- driven where data are requested by the system administrator and sent to sensor nodes through the BS at random times for specific reasons. Researchers have developed routing protocols to cover the different data transmission requirements, as discussed in the previous section.

Different application environments of WSN have made deployment process of sensor nodes vary from the predetermined method to random methods. The predetermined deployment method is preferable where ROI is easily accessible and has limited area while the random deployment is sometimes the only choice in many applications as shown in [31]. Thus, several studies have been performed to study the optimal deployment strategies to avoid WSN connectivity and energy depletion issues, as in [32]. Other research directions provide several solutions to random deployment strategies by introducing initial dynamic stage using a virtual force algorithm (VFA) or adding dynamic nodes to maintain connectivity using parallel particle swarm optimization (PPSO); as shown in [33, 34], respectively. On the other hand, nodes may all locate in two-dimensional fields or in 3-dimensional and 4-dimensional fields. Some applications like the Body Area Networks *BAN*s [35], Wireless Underground Sensor Networks WUSN [36] or underwater sensor networks [37, 38] require three dimensional node deployment.

According to [39], QoS requirements are summarized in the main three points that are: firstly, *an adjustable sensitivity* which means accommodating different environments and security requirements. Thus, a false alarm can be tolerated in some applications and should be avoided in others. Second, *stealthiness* by avoiding detection or interception; thus, communication is canceled in the absence of significant events. Finally, *effectiveness* which is the accuracy and data latency of the system that varies according to the application requirement and sensitivity. Nowadays, the WSN are widely used in various application areas. These areas need WSN sometimes to save human lives or prevent problem occurrence. WSN application areas can be broadly classified into five main types according to their environmental specifications and specific requirements as follows: Environmental Applications, Habitat Applications, Military Applications, Healthcare Applications, and Industrial Applications. Each application area has its own environment restrictions, QoS requirements, and tolerances to be considered in the WSN system in the form of node physical structure and data transmission protocols. The services applied by these applications can be discussed in more details by showing the recent research progress in each dimension.

3.1 Environmental Applications

Firstly, environmental applications that include measuring certain environmental changes to detect or track certain events, as in [40, 41]. For example, detecting fire, flooding or volcano blow up helps the government to take the right precautions in saving human lives. Monitoring air pollution [42] also helps to improve human life and prevent diseases. Monitoring soil helps farmers to prevent loss of crops and thus saves money and effort. It also provides sophisticated solutions for the more sustainable environment by providing light control system for more environment-friendly buildings [43]. Underwater Acoustic Sensor Networks (UW-ASNs) consists of sensors and vehicles deployed underwater and networked via acoustic links to perform monitoring tasks. The monitoring tasks include pollution monitoring (chemical, biological, and nuclear), monitoring currents and winds of ocean, improved weather forecast, detecting climate change, understanding and predicting the effect of human activities on marine ecosystems, and biological monitoring such as tracking of fishes or micro-organisms. Additionally, UW-ASN can be used for disaster detection by measuring seismic activity from remote locations to provide tsunami and earthquakes warnings to coastal areas, as in [44], preventions to water-based sports facilitation.

In [44], the authors proposed a system that combines ground and an underwater sensor network to tackle natural disasters such as Tsunamis, earthquakes, landslides and floods by providing a timely early warning. Underwater wireless sensor network (UWSN) seems to be one promising solution. The project detects and analyzes seismic events in Ocean to warn at-risk countries by means of a network of detectors made up of broadband seismometers, land, and ocean-surface based GPS instruments, tide gauges, and ocean bottom pressure control devices by transmitting the data obtained by these instruments to a central station using satellites. The system requires low power consuming, good BER system with low complexity.

To conveniently access information of forestry, wireless sensor network is introduced in precision forestry applications. Many research papers have been proposed in this direction that target two main purposes; the first is fire detection like the work proposed in [44, 45]. The second target is monitoring forest growth that is similar to Agriculture Precision AP applications. Thus, the authors in [46] integrate the monitoring and environmental hazard detection targets to provide precision forestry. However, precision forestry lags behind the development of precision agriculture due to the high interference and complex conditions, in forestry production. In [46] hardware architecture and software flow of forestry information monitoring system using WSN technology that is based on ZigBee chip 2430 is introduced. The sensors measure environmental factors periodically like temperature, soil moisture, light intensity, nitrogen concentration and visual information. Thus, the collected information is analyzed to indicate the forestry growth to achieve maximum benefits and minimum environmental hazards.

WSN is used in [47] to monitor volcanic eruptions with infrasonic microphone nodes, seismic elements, and spatial and temporal measurements. The research group monitored the active in central Ecuador volcano Volc'an Tungurahua. The nodes measured infrasonic signals to transmit the collected data over a 9 km wireless link to a remote base station in a real time manner; such that, the nodes were time-synchronized using a separate GPS receiver, and the data was correlated with a nearby wired sensor array. They developed a distributed event detector that automatically triggers data transmission when a well-correlated signal is received by multiple nodes. Similarly, Earthquake detection has gained great attention. The detection and alarm systems studied in [48] to provide a specific routing protocol for ensuring fast data delivery.

An innovative air pollution monitoring system named Wireless Sensor Network Air Pollution Monitoring System (WAPMS) is introduced in [49]. The research group monitored air pollution problem in terms of smoke emission and other industrial pollutants in Mauritius using an Air Quality Index (AQI) that categorizes the various levels of air pollution and associated meaningful and intuitive colors to the different categories. The pollutants are ozone, fine particulate matter, nitrogen dioxide, carbon monoxide, sulphur dioxide and total reduced sulphur compounds. Thus, the state of air pollution can be communicated to the user very easily. WAPMS provides real-time information about the level of air pollution and alerts in cases of drastic change in the quality of air defined by the "seriousness" variable. Thus, authorities can take prompt actions such as evacuating people or sending emergency response team. Similarly, in [84], the authors introduced a completely decentralized ad-hoc wireless sensor network to detect oil spill in the ocean. Their proposal aimed at maximizing network lifetime while improving its Quality of Service (QoS).

3.2 Precision Agriculture (PA)

Farming and forestry have gained great attention as well as precision Agriculture (PA) applications. Precision Agriculture (PA) applications include habitat monitoring and animal tracking application projects and have shown great improvement due to their impact on increasing profits, as in [19, 50]. Some projects allow remote monitoring of animals in vast areas and build a virtual fence for saving animals from getting lost, as in [51]. As discussed in [6], habitat monitoring where a mobile robot is used to collect information from the sensor nodes are delay-tolerant. Since the mobile robot will trace predetermined paths and stop by a set of pre-arranged locations regularly for data collection, in the case of large habitat areas to minimize disturbance to the targeted animal species.

One of the efficient technologies that are used to monitor and collect data in PA is a wireless sensor network (WSN). WSNs collect data of essential spatial and temporal variables that are necessary for decision making in agricultural farm management [52–54]. In [54], Yu et al. proposed a hybrid architecture involving terrestrial WSN that is adopted 40 cm above the ground, and a Wireless Underground Sensor Network WUSN is adopted below depths of 40 cm, while the sink node is static or mobile on the ground. Their work represents an advancement in water-saving agricultural applications. The WUSN nodes can be located at the same depth or at different depths according to the specific application. There are three communication channels, based on the locations of the transmitter and the receiver, in a WUSN: underground- to- underground, underground-to-aboveground, and above ground to- underground. Thus, three-dimensional network information is obtained. Experiments were conducted using a soil that was 50% sand, 35% silt, and 15% clay; it had a bulk density of 1.5 g/cm^3 and a specific density of 2.6 cm^{-3}. The experiment was conducted for several soil moistures (5, 10, 15, 20 and 25%) and three signal frequencies (433, 868 and 915 MHz). To monitor the temperature and water content of the soil in real time, signal acquisition nodes are buried in and below the cultivated layer; thus, the best node deployment depth for effective transmission in a wireless underground sensor network was determined.

WSN is involved in many applications as well as creating novel systems in PA and several other applications, such as global-scale environmental monitoring, pest and disease control and animal tracing [55]. Similar to the work introduced in [56], the authors of [51] used wireless sensor and actuator networks (WSANs) in controlling large herds of 40 cattle through virtual fencing to protect environmentally sensitive regions from damage, in 2009. However, the system in [51] aimed at changing animal behavior besides measuring the state of the climate, soil, and pasture using sensors and small camera nodes. They work on both, the individual animal's behavior and the animal's relation to a virtual fence line that borders an environmentally sensitive area. When the animals cross this virtual fence identified by acoustic sound; thus, the animals receive mild electrical stimuli. Consequently, animals learn to associate the stimuli with the sound, which influences their future actions. This idea has previously discussed in [57]. However, in [51], the problem of managing commercial herd sizes in a wide range of natural environments for a long time is solved. Their system spatially controls the animal herds' location and return real-time information about their state every 10 s to a static sink. The authors in [51] provide a radical shift in the future management of farm enterprises by integrating their system with earth observation information will add higher managing capabilities to the natural environment.

In [58], a research group designed a simple integrated WSN-RFID system to monitor seabirds on Skomer Island in March 2007 in a real world scenario and discussed their experiences, conclusions and resulting modifications 1 year later. The target of their experiment was to inform researchers about the birds' arrivals and departures by almost instantly detecting birds' activity around entrances to the burrows. They monitored the temperature and humidity inside and outside of the burrows over the period of the study every 2 min. They also used two passive infrared (PIR) sensors and a Radio Frequency Identification (RFID) reader in the burrows for identification. They addressed the challenges arising from the the real world that include the design of flexible interfaces to the WSNs and the integration of deployment, management, and Comprehensible reconfigurability.

In [59], Vellidis et al. proposed a system in which multiple homogeneous sensor nodes were used for monitoring soil moisture and temperature to schedule irrigation in a cotton farm. There was single-hop data transmission of data via RFID to a fixed central receiving unit. A laptop connected to the receiver was placed at one end of the field. The sensor nodes were composed of sensors, a sensor circuit board, and a RFID tag. At periodic intervals, the smart sensor board acquired sensor values and transmitted those values wirelessly to the receiver. The presence of plant biomass, terrain and objects imposed transmission difficulties during field testing of the prototype. This difficulty was solved when tags were removed from the electronic boards and mounted on hollow flexible fiberglass rods at approximately 1.2 m above ground level. A large number of sensor nodes were deployed to cover a large area. However, such a large number of nodes can cause interference problems which may result in more packet loss. A sensor circuit board which was called ''smart sensor board'' was supported by battery power. The micro-controller switched to sleep mode between sensor readings and data transmission. Sub-circuits also went ON and OFF as required. The microcontroller transmitted an alarm code when the voltage dropped below an acceptable threshold. This was meant to send an alarm and thereby avoid regular inspections. This method of power management increased the battery life through the growing season.

3.3 Military Applications

Thirdly, Military applications of WSN which have special requirements due to their sensitive nature in terms of accuracy and security; in addition to their effect on fortifying the country's army by monitoring sensitive military areas. Thus, sophisticated network architecture and more specialized protocols are developed to cover its needs, as discussed in [60]. Military applications described as special surveillance applications for confined or open areas as classified in [61]. According to [6], in battlefield surveillance, the sensor nodes are deployed to monitor the movement of enemy vehicles or troops. A mobile sink attached to an unmanned aerial vehicle (UAV) flying over the monitored region regularly to harvest the collected data. To avoid being intercepted or detected by enemy forces, a mobile sink is used and operates in only a few safe locations within a limited operation time. Thus, system protection against inspection is above the real-time transmission.

Military surveillance includes intrusion detection which involves security issues, as described in [62, 63]. In ground surveillance application introduced in [64] the sensor nodes alert the military command and control unit by monitoring the intrusion of hostile regions. It targets monitoring the region and tracking the intruders with acceptable latency. The system is time-driven for monitoring and event drove for awakening the nodes in the sleep state to start the collaborative tracking in case of intrusion. Magnetic sensors [65], motion and acoustic sensors were used to classify the moving object by detecting the magnetic field generated by vehicles and detecting its motion. Similarly, [39] introduced similar approach considering cost effectiveness. WSN in remote large-scale areas is a system that consists of thousands of self-organized sensor nodes deployed in enemy forces areas is introduced in [66]. The nodes use RFID or key-exchange to identify forces. Especially in the remote large-scale network, tactical military sensor network has high priority challenges. The authors proposed a cluster-tree based multi-hop network architecture that optimized cluster head election and a model that is designed to meet the tactical requirements of the remote large-scale environments. Thus, the proposed network guarantees the following; self-organization, energy-efficiency, connectivity, low probability of intercept (LPI) and low probability of detection (LPD) for security [67].

Surveillance applications include underwater sensor networks as well. In [68], the communication performance of the UAN (Underwater Acoustic Network) network project is reported in terms of the round-trip time, packet loss, and average delivery ratio. UAN is project funded by EU and aimed at integrating underwater and above-water sensors in a global protection system that protects offshore and coastline critical infrastructures. It covers security features and integration details about autonomous underwater vehicles (AUVs) and surveillance assets that are acoustically controlled by control center to respond to intrusions. Moreover, in [69], the node deployment of antisubmarine detection application is performed using a limited number of sensor nodes in UWSN that use acoustic communication medium. However, the work is simulation based experiments using particle swarm optimization coverage scheme in the 3-D environment.

3.4 Healthcare Applications

HealthCare applications of WSN are introduced because of the need for inefficient and labor-intensive procedures, such as recording the patients' vital signs periodically. The use of WSN automates these manual tasks to improve the efficiency and quality of patient care. Such WSN clinical tasks include continuous monitoring of unattended patients during routine or extreme event surges, and monitoring of intra- hospital transports and pediatric patients. WSN healthcare applications need special types of sensors to measure body signal and require very high accuracy in measurements. They involve special types of sensors like skin/chest electrode, phonocardiograph and pulse oximeter to measure electrocardiogram ECG; hear sounds, oxygen saturation and heart rate and more special types of sensors mentioned in [70].

Using WSN in medical applications is now one of the most important advancements in the medical life. However, it introduced physical requirements on measurement accuracy and logical networking requirements on security and robustness that are studied in [71]. Doctors monitor patient's blood pressure, temperature, heart beat rates and other health indicators remotely as proposed in [72] to take actions in case of any health problem, as proposed in [73]. Most of the healthcare applications include BAN [35] that involves three-dimensional node deployment in many cases and wearable technology [70]. Although the need for clinical applications is widely accepted, there has been little practical experience with deploying them in clinical environments, as proposed in [74]. In this work the authors used MEDiSN, a WSN designed to monitor the vital signs of ambulatory patients continuously. Thus, they introduce the challenges that such systems must overcome and provide insights on the techniques and features that system designers should consider for successful deployments in clinical settings. In [75], an energy efficient indoor patient localization system is introduced. The system includes TelosB nodes, deployed as one per room, mobile medical prototype nodes to measure body temperature, and a gateway which is a fixed TelosB destination placed in the living room. The results represented in their work are the average of measurements taken every two-second interval.

3.5 Industrial Applications

The range of industrial applications of WSN is growing through time, as discussed in [72, 76]. WSN applications have great contributions in improving the product's quality and monitoring machine's efficiency. The WSN systems used in industrial applications are called Industrial Wireless Sensor Networks IWSN and have major technical challenges extensively described in [76]. It saves money for both owners and customers, as well.

WSN applications in the industry include monitoring railway infrastructure including bridges, rail tracks, track beds, and track equipment. It is also used in vehicle health monitoring such as chassis, bogies, wheels, and wagons, as in [77]. Railway monitoring is vital for developing, upgrading, and expanding the railway networks. Industrial applications of WSN reduce human inspection requirements and maintenance and improve safety and reliability. Great involvement of WSN in Smart grid systems, as described in [78]. WSN applications in this area of industry ensure higher performance and faster problem solutions method to increase the productivity of smart grid systems, as discussed in [79]. It also includes monitoring structural buildings as in [80].

Underground sensor networks are challenging but the efficient technique to save maintenance costs of hardy accessible systems [36]. In [81], PipeNet project is studied where sensor nodes monitor underground water pipeline to measure different parameters. It is based on wireless sensor networks to detect, localize and quantify bursts and leaks and other anomalies in water transmission pipelines. It is also used for monitoring water quality in transmission and distribution water systems and monitoring the water level in sewer collectors. The sensor nodes are used for measuring hydraulic and acoustic/vibration on bulk-water transmission pipelines, collect data at high sampling rates, use aggressive duty cycling to ensure months of longevity and tight time synchronization for accurate data analyses, and transmit the data to the lab using long-range communication.

Wireless sensor network topology used for road traffic has been studied in several research works. In [82], the authors designed and implemented a low-cost pervasive traffic information acquisition system based on wireless sensor networks called EasiTi that has a collaborative traffic information processing mechanism. EasiTi was analyzed based on real road environment experimental analysis. EasiTia tackled the low signal-to-noise ratios (SNRs) and stochastic disturbances in traffic information acquisition and implemented a cross-correlation-based vehicle-detection algorithm. It resolved the problems of data association, vehicle velocity calculation, and vehicle identification. On the other hand, civil infrastructure monitoring introduces new challenges to sensor data transmission due to obstacles. However, the need for structure monitoring encourages researchers to find solutions and implement the essential application in this direction, as described in [82].

Periodic data gathering applications include periodic monitoring, target tracking, and some event-driven and query-based applications that require energy conservation due to the difficulty of human access. Monitoring applications include the following three types. First, ubiquitous monitoring applications [45, 83]. Second, healthcare applications [49, 71, 72, 79], that include monitoring patient's blood pressure, temperature, heart beat rates and other health indicators remotely to take actions in case of any health problem, environmental surveillance, e.g. monitoring the quality of air [49, 79] and detecting oil spill in water [84]. Third, industrial applications, e.g. pipeline monitoring [85], monitoring the data that are necessary for decision making in Precision Agriculture (PA) for agricultural farm management [11, 52–54], and smart grid system monitoring [79]. Other applications combine more than one class, like the one introduced by the authors in [46] who integrated the monitoring forest growth and environmental hazard detection to provide precision forestry. Based on the taxonomy of WN applications, the most effective WSN applications performed in the last two decades are summarized in Table 2, such that the categories of application are highlighted with gray colour.

4 WSN Routing Protocol

WSNs have a great potential for process, manufacturing and industrial applications, although it has several challenges. For example, during excessive data transmission especially in data gathering applications, some nodes deplete their energy before other nodes leading to the creation of routing holes that disconnect some nodes from the others; and thus, lose the coverage of significant part of ROI. Manual fixing is impossible in many applications; thus, various researches are made for detecting holes and their causes and their impact on network performance while providing solutions [15, 46]. The main factors affecting network efficiency of WSNs can be summarized in the following:

- The limited sensor node energy.
- The long duration of sensor operation.

Table 2 Applications of WSN

Application Area	Application	Project	Covered area			Ta-rget		Data measured	Deploy-ment			Data Transmission					QoS Requirement
			Ground	Under ground	Underwater	Monitoring	Tracking		Pre-determined	Random static	Random dynamic	2-Dimensional	3-Dimensional	Periodic -TD	Query- driven-QD	Event- driven-ED	
Environmental	Volcanic events	[47]	■			■		Acoustic signals and Seismic data	■				■			■	• Long transmission range • Energy efficiency • Bandwidth • Data accuracy
	Flood, Tsunamis earthquake, and andslides detection	[44]	■		■	■		Seismic data tide gauges, and pressure	■				■			■	• Energy-efficiency, • good BER • real-time processing
	Air pollution monitoring	WAPMS [49]	■			■		Ozone, fine particulate matter, Nitrogen dioxide, Carbon monoxide, Sulphur dioxide, and total reduced Sulphur compounds	■ CHs	■ sensors		■		■		■	• Data accuracy • Data aggregation
	ocean pollution prevention	[84]			■	■		Temperature, Chemical, and density		■			■		■		Energy efficiency
	Forest precision	Fire detection [45]	■			■		Temperature, humidity, and wind speed	■				■		■		• Energy-efficiency • Fault tolerance • Limited delay
		Precision forestry [46]	■			■		Temperature, Soil moisture, Humidity, Light intensity, Nitrogen concentration, and Visual		■			■	■		■	• Energy-efficiency • Real-time transmission
ecision Agriculture	Herd monitoring	Virtual ence [52]	■			■	■	Temperature, Camera, Water content, Acoustic sound	■			■		■			• Real-time • Fast response to electrical stimuli
	Habitat Monitoring	[58]	■			■		Temperature, Humidity	■			■		■			• Energy-efficiency
	Soil monitoring	[54]	■	■		■		Water content, Temperature	■				■	■			• Energy-efficiency • Real-time reliability • Low cost
Military & Surveillance	Intrusion detection and tracking	[39] [64]	■			■	■	magnetic, acoustic, motion sensors		■		■		■		■	• Longevity, • Adjustable Sensitivity • Effectiveness • self-organization, • LPI and LPD
	UAN11	project [67]	■		■	■		Temperature, and salinity	■				■	■			• Round-Trip Time • Packet Loss • Average Delivery Ratio
	Underwater antisubmarine	[68]			■	■		Not mentioned	■				■	■			• Robustness in routing • Real-time • Coverage
Healthcare	Patient Monitoring	MEDiSN [72]	■			■		Pulse rate and blood oxygen level, and Indoor location	■			■		■			• Low latency • High reliability • Security
	Drug administration in hospitals	WSN4QoL [75]	■			■	■	Temperature, Indoor location	■			■		■			• Energy-efficiency • Low-latency • Data reliability, • Context-awareness security.
Industrial	underground pipelines	PipeNet [79]		■		■		Acoustic/vibration, Hydraulic, Pressure, pH	■				■	■			• energy efficiency • End-to-end delay • Long-range communication
	traffic information acquisition system	EasiTia [80]	■			■		Image (camera) sensor, inductive loop detector, acoustic sensor, seismic sensor, and magnetic sensor	■			■		■			• Low-cost • Easy installment

- The many-to-one traffic flow due to centric data collection process to the sink or BS.
- The environmental factors or the nature of the monitored environment such as forest or battlefield.
- The random deployment of sensor nodes in many applications

Sensor networks can be deployed in a variety of ways according to the application environment. For example in environmental applications, especially forest fire detection, and volcanic events, the inspected area is vast and perilous for human involvement. Thus, sensor nodes are dropped down from aeroplane in a random deployment way. Other similar examples, such applications include tracking the enemy movements in a battlefield or in detecting the impact of various dynamics of glaciers on global warming. However, in other applications where the inspected area is safe, like habitat, healthcare and most of the industrial applications, the nodes are deployed manually in predetermined locations. Moreover, typically human interference in wireless sensor network field is difficult after the deployment stage. Therefore, sensor networks are expected to operate for an extended period of time without being attended by individuals. However, there is always a chance of node failure due to its limited energy source. According to [86], sensing tasks, safety devices, and power down energy required by the node components in their lowest power consumption mode depend mostly on component selection, while the energy for radio system communication and processing depend mostly on the communication protocol and the application, respectively.

According to [87], the radio system is responsible for five basic functions that affect the lifetime time of each sensor node. These functions are: (1) radio transmission power, (2) bit rate, (3) turn-on time, (4) modulation type and (5) the wireless technology used. The radio system is the most power consuming part in WSN and any wireless communication system. Thus, the lifetime of WSN increases by working on one of these factors. The transmission power can be limited by controlling the transceiver of each node in the ROI (Region of Interest), and the turn-on time can be decreased using the suitable scheduling technique to suit the duty cycle of the network; so that, the transmission time and power are being used efficiently to conserve the whole network connectivity and lifetime. Modulation type and bit rate are related to the operating frequency chosen, typical IEEE 802.15.4 modulation standards are BPSK, ASK, and O-QPSK with bit rates vary from (10–250) Kb/s [87] which are sufficient for sensor network applications. The IEEE 802.15.4 standards represent the tradeoff between high speed and low power consumption and low cost [88].

The transmission power of a wireless radio is proportional to distance squared or higher order in the presence of obstacles. Meanwhile, covering a large Region of Interest ROI strongly affect the energy consideration required for most wireless sensor network applications. Consequently, multi-hop routing process for setting up routes is essential instead of direct communication which encourages researchers to design and improve routing protocols for coping with the need for connectivity while considering transmission power consumption [12, 13, 53, 54, 79]. Therefore optimizing power consumption using suitable communication protocols has a significant impact on prolonging WSN lifetime.

The challenges of WSN can be broadly categorized into two main categories: Firstly, Hardware challenges that are concerned with the node design and fabrication [89]. Secondly, protocol design challenges that are concerned with the system implementation and application. In the development of WSN systems, system objective, as well as, the system environment represents the factors to be considered in protocol design. For example, in control systems, taking the right decision at the right moment despite any traffic condition, even in the presence of unexpected congestion, network failures or external manipulations of the environment is a must, as discussed in [90]. The challenges of underwater sensor networks consider restrictions on the system design that are more challenging than the ground WSN, as discussed in [91].

The same network protocol may perform differently under different frequency allocations—moving to a higher frequency region will cause more attenuation to the desired signal while minimizing interference, possibly boosting the overall performance. On the other hand, propagation delay and packet duration are effective, since a channel that is sensed to be free may nonetheless contain interfering packets. And packet length probably affects collision rate and the efficiency of re-transmission (throughput). Finally, power control and intelligent routing can greatly help in limiting interference and maximizing network lifetime, as discussed in [91].

4.1 WSN Protocol Design

The existing routing protocols for WSNs employ different strategies in the design process. This section presents a schematic taxonomy of the key design issues for any WSN system. Normally, the nodes in the WSN run routing protocols in a self-organized manner due to the difficulty of manual accessibility. Thus, basic design factors should exist to ensure network efficiency. However, some design aspects are more prioritized than others according to the application needs, as discussed in the previous section.

According to [92], the main design issues are categorized according to application dependency into three main categories, basic, essential, and optional. In designing WSN system, the basic design factors have to be decided at the initial stage of protocol design to ensure network reliability. Then, the essential factors should be applied to achieve energy efficiency, adaptation to the varying network environment, and consideration of a tradeoff between reliability and energy consumption. Finally, optional factors are considered according to the application need while providing the ability of the system to extend to achieve network adaptability and QoS.

First, the basic design factors where routing protocols are highly influenced by two basic factors which are: (1) node deployment that indicates the style of node placement in the sensor network environment, and (2) data reporting model that indicates the time criticality of the data routing. Second, the essential design factors that are tightly constrained in providing the security aspect in the network while providing durability. Thus, these factors include (1) energy consumption that preserves the network efficiency during the network life- time, (2) fault tolerance that represents the ability of sensor nodes to retain their functionalities without interruption from single or multiple failures by performing quick recovery after node changes, and (3) security which is imperative against network attacks in many applications, for instance, smoke detection system needs some level of security, especially in terms of robustness against false alarm. Third, the optional factors are mainly application dependent. They include (1) scalability that reflects the ability of network to work well as it grows large and can be fine-tuned according to the application demands, (2) data aggregation that reduces the number of transmission at one time by using functions such as suppression, max, min and average and represents an extra challenge that can be adapted to the design requirement of certain protocols, and (3) QoS that represents the metrics required for the network to be fulfilled for ensuring the level of network performance for certain application, since some applications are delay-sensitive such as in battlefield, fire-detection, or disaster-forecast applications. Hence, QoS factor depends on the application requirement and may include fairness, delay, jitter, available bandwidth, and packet loss.

Due to these issues, new algorithms have been developed considering the basic characteristics of sensor nodes along with the application and network architecture requirements. In designing a WSN routing, carrying out data communication is the main concern while prolonging the network lifetime The Base Station (BS) may be static or dynamic, single or multiple with different topologies. In the following section, we mainly cover the WSN system with single static BS, where energy efficiency is a critical issue that gained the attention of researchers through the last 20 years.

4.2 Energy-Efficient Routing Protocols

WSN design can be more challenging if the network topology is purely static with a single path. Thus, all the proposed protocols designed for this type of networks are dynamic with certain levels to preserve the network lifetime while using multi-hop routing instead of direct transmission.

The most famous cluster-based routing protocols that lead the improvement in WSN lifetime are LEACH [93, 94] and PEGASIS [95]. LEACH was the most appropriate for maintaining connectivity, especially for periodic data gathering applications. However, cluster heads (CHs) are not well distributed and waste very high percentage on protocol overhead, as proven in [96]. Accordingly, PEGASIS [95] was introduced to limit both the setup and data transmission energy consumption using single chain-based topology. It limits the topology change to only the case of node loss. However, continuous selection of the node that is responsible for ROI to BS transmission “the chain leader” is performed to ensure the loss of nodes at random positions. Thus, simulation results performed on PEGASIS in [97] have proven the extremely high data latency at different network densities and data compression factors, especially as the number of nodes increases; thus, it is not suitable for large networks or time critical applications.

The most suitable routing protocols for monitoring applications are the proactive ones. Accordingly, many cluster-based energy-efficient routing protocols outspread from LEACH to provide higher network stability and lifetime. These protocols include HEED [98], T-LEACH [99], IBLEACH [100], and NEECP [101]. In HEED [98], each sensor’s primal probability of becoming a cluster-head depends on its remaining energy. It outperforms LEACH in terms of network lifetime due to its uniform distribution of cluster heads across the network through localized communications with little overhead. However, in large-scale networks, synchronization during data transmission for far cluster heads is a must. The intra-balanced LEACH, IBLEACH [100], studied the energy gap problem, that is between CHS and cluster members (CMs) by bearing in mind energy fairness constraint through distributing the data aggregation task. To minimize protocol overhead, IBLEACH elongates the round to contain a set of frames, so that the setup procedure is performed every set of frames; unlike LEACH. However, it couldn’t introduce a suitable way to find the number of frames per round or a process to calculate this value. If the frame length is not well chosen, it may cause data loss if CHs deplete their energy within the frame. The network lifetime using IBLEACH is increased compared to LEACH, ELEACH, TLEACH, VRLEACH and LEACHB. Due to the given reasons: (1) IBLEACH evenly distribute the work among the CHs and CMs which increases the lifetime of the network. (2) IBLEACH distributes the workload every round, unlike others, (3) IBLEACH considers data gathering process on frame level by a certain node; thus, the death of this node will only affect the gathering process of current frame.

Recently, LEACH [93, 94] and PEGASIS [95] are combined in the Novel energy-efficient clustering protocol NEECP [101] to offer a noticeable increase in network lifetime where CHs are chosen using a more energy efficient algorithm than LEACH. Moreover, the operation of data aggregation within a cluster is performed based on the chaining approach in PEGASIS. CHs make a chain to send data to BS which is their chain leader. Although NEECP achieves energy efficiency in data transmission, it introduces higher overhead than PEGASIS due to the periodic cluster formation operation. This energy overhead upturns energy dissipation of the tiny nodes in the ROI. Thus, the SEcure sharing of Tasks (SETA), presented in [102] was designed to fulfill confidentiality, adaptive aggregation, integrity, and privacy issues while minimizing communication overhead. In UCCGRA [103], voting replaced CH selection. The authors combine unequal clustering using vote-based measure and connected graph theories to prolong the network lifetime by balancing the load among CHs. Additionally, the energy consumed in inter-cluster routing was reduced to avoid energy hole problem. However, the periodic voting and connected graph formation add very high complexity and energy overhead to the setup phase.

5 Analysis on Network Lifetime

In this section, a detailed analytical study is performed on the most energy efficient proactive routing protocols showing their strengths and weaknesses. It covers the network setup and data transmission process. To the best of our knowledge, this is the only analytical study performed on network lifetime and stability period as defined in [11]. Additionally, a comparison of the covered energy efficient protocols is provided on a periodic monitoring application to show the network lifetime and stability period using simulation results. This may help network designers to select suitable routing protocols for their applications according to their system parameters.

5.1 Radio Transmission Model

For the purpose of our study, the energy model and analysis in [104] is used; such that, the transmitter dissipates energy to run the radio electronics and the power amplifier, and the receiver dissipates energy to run the radio electronics. For the experiments described here, both the free space (d^2 power loss) and the multipath fading (d^4 power loss) channel models were used, depending on the distance between the transmitter and receiver. Power control can be used to invert this loss by appropriately setting the power amplifier—if the distance is less than a threshold d_o, the free space (*fs*) model is used; otherwise, the multipath (*mp*) model is used. Thus, the energy consumed in transmitting and receiving *l*-bit message through distance *d* are shown in Eqs. (1) and (2), respectively

$$E_{Tx}(l,d) = E_{Tx-elec}(l) + E_{Tx-amp}(l,d) \tag{1}$$

To receive this packet, the radio consumes

$$E_{Rx}(l,d) = E_{Rx-elec}(l) = l\,E_{elec} \tag{2}$$

This work is based on randomly distributed nodes in 100 × 100 unit length where the BS is at (x = 50, y = 200). Using the data gathering process in [105], each node receives and transmits one packet in each round. The electronics energy, E_{elec} depends on factors such as the digital coding, modulation, filtering, and spreading of the signal, whereas the amplifier energy, $\varepsilon_{fs}d^2$ or $\varepsilon_{mp}d^4$, depends on the distance to the receiver and the acceptable bit-error rate.

Thus,

$$E_{Tx}(l,d) = \begin{cases} lE_{elec} + l\varepsilon_{fs}d^2 & d < d_o \\ lE_{elec} + l\varepsilon_{mp}d^4 & else \end{cases} \tag{3}$$

5.2 Energy Efficient Routing Protocols in Homogeneous WSNs

At early times, Maimour et al. [22] studied the energy efficiency and load balancing of routing protocols to ensure that energy consumption and load balancing management is a global task that maximizes WSN lifetime. Additionally, it clarifies that minimal clustering overhead and optimal traffic distribution among CHs have a great role in keeping the network connectivity and coverage. Accordingly, we are going to analyze the two main issues of any energy efficient routing protocols that are Protocol overhead and Lack of energy fairness or the problem of energy consumption balancing as defined in [106] Energy hole problem solutions. However, in this section, we will cover those issues analytically to clarify their effect and help new researchers consider these issues in their design of new energy efficient routing protocols.

In this section, we are going to analytically discuss two main important WSN issues. Firstly, the network overhead introduced to network protocols to ensure connectivity. Secondly, the energy gap problem between nodes in the ROI. Since relay nodes are responsible for data transmission to the BS, they consume more energy in data transmission compared to other nodes leading to the energy gap problem. The energy consumption model for both the topology formation and data transmission phases are introduced, respectively. The transmission power consumed in the network during the setup phase and the data collection phase are shown in details for all types of nodes in the network topology according to the routing protocol procedure. Thus, the total energy consumed by each node give an estimation of the total energy consumption by the network through its lifetime.

According to [107, 108], we assume that the total energy is consumed in radio system only. Consequently, the internal operational energy consumption of each node $E_{setup-op}$ is not addressed in this work. Therefore, the energy consumed in communication $E\mathcal{N}(r)$ during setup phase is used to address the protocol overhead in terms of energy consumption; where energy efficiency is inversely proportional to the percentage of overhead. Overhead affects also the network lifetime r_N and the stability period r_s. Thus, we drive an approximate estimation of stability period and the network lifetime based on the worst case analysis and best case analysis, respectively. However, this estimation doesn't work well due to random deployment of sensor nodes and random nature of the addressed protocols and typical random deployment strategies of WSN; it provides a useful estimation of energy fairness and overhead of each protocol. To eliminate the ambiguity, the symbols of common parameters in different equations are unified and presented in the Table 3 based on their occurrence in equations.

Based on the authors' simulation model in [10, 11], most cluster-based protocols can be divided into two distinct phases; (1) set-up phase, which is formed by cluster head selection and cluster formation, (2) steady-state phase, when all the nodes in the RIO send at least one packet to the CH which is responsible for data collection, aggregation, and delivery to the base station. Accordingly, we studied both phases for the routing protocols covered in this paper to give a clear view of the reason for their energy efficiency and connectivity tradeoff. For energy efficient roaring protocol, the energy consumed in the setup phase must be relatively less than that is consumed in the steady-state phase to minimize the protocol overhead. Thus, the energy consumption problem is addressed in the network two stages, the setup phase $E\mathcal{N}$ and the data gathering phase $E\mathcal{G}$, the total energy consumed is $E = E\mathcal{N} + E\mathcal{G}$.

Table 3 List of mathematical notations

Symbol	Definition
N	The current number of alive sensors
d_{CH}	Maximum distance between the CH and its cluster members
r	The round number, it is the unit time used to complete one data collection process from all sensors in the ROI
r_N	The network lifetime, in rounds, it is the maximum lifetime of all of the sensors in the network
r_s	The stability period, in rounds, it is the number of rounds taken till the first node is dead, as defined in [109]
k	The number of CHs, the optimal number of CHs in terms of energy consumption is k_{opt}
p	The probability of CH selection, the optimal probability of CH selection in terms of energy consumption is p_{opt}
$E\mathcal{G}$	The energy consumed in data gathering phase
$E\mathcal{N}$	The network setup energy, it is the total network overhead, it is the total network energy consumed in topology making, for low network overhead $E\mathcal{N}(r) \ll E\mathcal{G}(r)$
E	The total energy consumed in the network $E = E\mathcal{G} + E\mathcal{N}$
OE	The network overhead in terms of energy consumption $OE(r) = \sum_{r=1}^{r_N} \frac{E\mathcal{N}(r)}{E\mathcal{G}(r)}$ that needs to be minimized
$E\mathcal{N}_{CH}$	The network overhead of CH in LEACH
$E\mathcal{N}_{non}$	The network overhead of non-CH in LEACH
E_{CH}	The total energy consumed by CH in LEACH
E_{non}	The total energy consumed by non-CH in LEACH
E_{nLEACH}	The total energy consumed by any node using LEACH routing protocol
$E\mathcal{N}_l$	The network overhead of a leader node in PEGASIS
$E\mathcal{N}_{nl}$	The network overhead of a non-leader node in PEGASIS
d_{nn}	The nearest neighbor distance in a chain or a tree-based network topology
E_{BD}	The breakdown energy of any node that uses PEGASIS or OHA Algorithm
E_n	The total energy consumed by any node in the ROI during the network lifetime
$dead$	The number of dead nodes
$E\mathcal{G}_l$	The energy consumed in data gathering phase by leader node in PEGASIS
$E\mathcal{G}_{nl}$	The energy consumed in data gathering phase by non-leader node in PEGASIS
E_l	The total energy consumed by leader in PEGASIS
E_{nl}	The total energy consumed by non-leader in PEGASIS
E_{nPEG}	The total energy consumed by any node using PEGASIS routing protocol

5.2.1 *Periodic Clustering Protocol (LEACH)*

In LEACH, the clustering operation is performed periodically to maintain network connectivity. The clustering process involves selection of CHs and cluster formation by non-CHs that join the advertised CHs. After cluster formation, the data flow from each cluster member to its CH and then to the BS in a two-hop fashion. An analysis of the energy consumed in this process is shown in the given subsections. Thus, we derive an equation to roughly estimate the stability period and the network lifetime based on the transmission energy consumption of each node.

A. The setup phase $E\mathcal{N}$

The given equations show that each CH consumes energy in transmission in three procedures (1) a broadcast of its advertisement as a cluster head to the whole network ($d = M$), (2) receiving number of cluster join requests equals to the number of its cluster members and the advertisements from other CHs, and (3) a broadcast of the TDMA schedule. On the other hand, each non-CH consumes energy in transmission in three complementary procedures of the setup phase (1) receive CH advertisements, (2) send joint request to the CH $d = d_{CH}$, and (3) receive the cluster joining advertisement.

$$E\mathcal{N}_{CH}(r) = \begin{cases} l_c\left[\left(1 + \dfrac{N}{k} + k\right)E_{elec} + \varepsilon_{mp}\, M^4\right] & M \geq d_o \\ l_c\left[\left(1 + \dfrac{N}{k} + k\right)E_{elec} + \varepsilon_{fs}\, M^2\right] & else \end{cases} \tag{4}$$

$$E\mathcal{N}_{non}(r) = \begin{cases} l_c\left[(1 + k)E_{elec} + \varepsilon_{mp}\, d_{CH}^4\right] & d_{CH} \geq d_o \\ l_c\left[(1 + k)E_{elec} + \varepsilon_{fs}\, d_{CH}^2\right] & else \end{cases} \tag{5}$$

B. The data gathering phase $E\mathcal{G}$

In this subsection, we rely on the data transmission model of LEACH shown in [93] and its clear derivation of the optimal number of cluster heads, k_{opt} that ensures minimum total energy consumption calculated as shown

$$k_{opt} = \begin{cases} \sqrt{\dfrac{N\varepsilon_{fs}}{2\pi\ \varepsilon_{mp}}} \dfrac{M}{d_{to\ BS}^2} & d_{to\ BS} \geq d_o \\ \sqrt{\dfrac{N}{2\pi}} \dfrac{M}{d_{to\ BS}} & else \end{cases} \tag{6}$$

However, the optimal probability of a node to become a cluster head, p_{opt}, is calculated as follows

$$p_{opt} = \frac{k_{opt}}{N} \tag{7}$$

C. Stability period and network lifetime estimation

The total energy consumed by CHs and non-CHs affect the network lifetime. Thus, the stability period can be estimated according to the worst case scenario from the energy dissipation equations of CH nodes and non-CH nodes, respectively, shown in the given equations

$$E_{CH}(r) = \begin{cases} l_c\left[\left(\dfrac{N}{k} + k\right)E_{elec} + \varepsilon_{mp}\, M^4\right] + l_s\left[\left(\dfrac{N}{k} + 1\right)E_{elec} + \varepsilon_{mp}\, d_{to\ BS}^4 + \dfrac{N}{k}E_{DA}\right] & M \& d_{toBS} \geq d_o \\ l_c\left[\left(\dfrac{N}{k} + k\right)E_{elec} + \varepsilon_{mp}\, M^4\right] + l_s\left[\left(\dfrac{N}{k} + 1\right)E_{elec} + \varepsilon_{fs}\, d_{to\ BS}^2 + \dfrac{N}{k}E_{DA}\right] & M \geq d_o\ \&\ d_{toBS} < d_o \\ l_c\left[\left(\dfrac{N}{k} + k\right)E_{elec} + \varepsilon_{fs}\, M^2\right] + l_s\left[\left(\dfrac{N}{k} + 1\right)E_{elec} + \varepsilon_{mp}\, d_{to\ BS}^4 + \dfrac{N}{k}E_{DA}\right] & M < d_o\ \&\ d_{toBS} \geq d_o \\ l_c\left[\left(\dfrac{N}{k} + k\right)E_{elec} + \varepsilon_{fs}\, M^2\right] + l_s\left[\left(\dfrac{N}{k} + 1\right)E_{elec} + \varepsilon_{fs}\, d_{to\ BS}^2 + \dfrac{N}{k}E_{DA}\right] & M \& d_{toBS} < d_o \end{cases} \tag{8}$$

$$E_{non}(r) = \begin{cases} l_c\left[(k+2)E_{elec} + \varepsilon_{mp}\, d_{CH}^4\right] + l_s\left[(E_{elec} + \varepsilon_{mp}\, d_{CH}^4\right] & d_{CH} \ge d_o \\ l_c\left[(k+2)E_{elec} + \varepsilon_{fs}\, d_{CH}^2\right] + l_s\left[(E_{elec} + \varepsilon_{fs}\, d_{CH}^2\right] & else \end{cases} \tag{9}$$

During the network lifetime, each node becomes a CH every N/k rounds, in the worst case the node is selected as a CH at least once, thus the overall node energy during its lifetime can be estimated for any node in the ROI from Eq. (10), such that $\frac{rk}{N} \in \mathbb{Z}^+$

$$E_{nLEACH} = \begin{cases} \left(r_N - \dfrac{N}{k}\right) E_{non}(r) + \dfrac{r_N k}{N} E_{CH}(r) & r_N \ge \dfrac{N}{k} \\ (r-1)\; E_{non}(r) + E_{CH}(r) & r_N < N/k,\; Worst\ case \\ r\; E_{non}(r) & r_N < N/k,\; Best\ case \end{cases} \tag{10}$$

Thus, the stability period is when the first node depletes all its initial energy in data transmission and the number of nodes is the same as its initial value as shown

$$E_o = \begin{cases} \left(r_s - \dfrac{N}{k}\right) E_{non}(r) + \dfrac{r_s k}{N} E_{CH}(r) & r_s \ge \dfrac{N}{k} \quad \dfrac{r_s k}{N} \in \mathbb{Z}^+ \\ (r_s - 1)E_{non}(r) + E_{CH}(r) & else \end{cases} \tag{11}$$

5.2.2 *IBLEACH*

In IBLEACH, the setup energy of the network is similar to that in LEACH. However, dealing with frames, defined in [100] instead of rounds minimizes this overhead. On the other side, every round a broadcast advertisement of aggregator nodes is added in the pre-steady state operation. Finally, the steady state phase energy consumption of each frame is exactly like the steady state energy consumption of each round.

A. The setup phase $E\mathcal{N}$

According to the authors in [100] and their definition of *Nframes*, each CH consumes energy in transmission every in *Nframes* of rounds in three procedures within the setup and pre-steady state phase (1) a broadcast of its advertisement as a CH to the whole network ($d = M$), (2) receiving number of cluster join requests equals to the number of its cluster members, and (3) broadcasts the TDMA schedule and the aggregator list. On the other hand, each non-CH consumes energy in transmission in three complementary procedures in the setup phase and pre-steady state phases: (1) receives CH advertisement, (2) sends joint request to the CH within $d = d_{CH}$, and (3) receive the TDMA schedule and aggregator list.

$$E\mathcal{N}_{CH}(r) = \begin{cases} \dfrac{l_c\left[\left(1 + \dfrac{N}{k} + k\right)E_{elec} + \varepsilon_{mp}\, M^4\right]}{Nframes} & M \ge d_o \\ \dfrac{l_c\left[\left(1 + \dfrac{N}{k} + k\right)E_{elec} + \varepsilon_{fs}\, M^2\right]}{Nframes} & else \end{cases} \tag{12}$$

$$E\mathcal{N}_{non}(r)=\begin{cases}\dfrac{l_c\left[(1+k)E_{elec}+\varepsilon_{mp}\ d_{CH}^4\right]}{Nframes} & d_{CH}\geq d_o\\ \dfrac{l_c\left[(1+k)E_{elec}+\varepsilon_{fs}\ d_{CH}^2\right]}{Nframes} & else\end{cases}\tag{13}$$

B. Stability period and network lifetime estimation

The total energy consumed by CHs and non-CHs affect the network lifetime. Thus, the stability period can be estimated according to the worst case scenario from the energy dissipation equations of CH nodes and non-CH nodes in every frame are in Eqs. (14) and (15), respectively. We deal with the frame as a round considering that the topology setup is performed once every *Nframes*; unlike LEACH. If the CH couldn't find suitable data aggregator node for the whole round, it performs the aggregation task, this can be considered the worst case scenario in Eq. (20)

$$E_{CH}(r)=\begin{cases}\dfrac{l_c\left[\left(1+\dfrac{N}{k}+k\right)E_{elec}+\varepsilon_{mp}\ M^4\right]}{Nframes}+l_s\left[\left(\dfrac{N}{k}+1\right)E_{elec}+\varepsilon_{mp}\ d_{BS}^4+\dfrac{N}{k}E_{DA}\right] & M\ \&\ d_{BS}\geq d_o\\ \dfrac{l_c\left[\left(1+\dfrac{N}{k}+k\right)E_{elec}+\varepsilon_{mp}\ M^4\right]}{Nframes}+l_s\left[\left(\dfrac{N}{k}+1\right)E_{elec}+\varepsilon_{fs}\ d_{BS}^2+\dfrac{N}{k}E_{DA}\right] & M\geq d_o\ \&\ d_{BS}<d_o\\ \dfrac{l_c\left[\left(1+\dfrac{N}{k}+k\right)E_{elec}+\varepsilon_{fs}\ M^2\right]}{Nframes}+l_s\left[\left(\dfrac{N}{k}+1\right)E_{elec}+\varepsilon_{mp}\ d_{BS}^4+\dfrac{N}{k}E_{DA}\right] & M<d_o\ \&\ d_{BS}\geq d_o\\ \dfrac{l_c\left[\left(1+\dfrac{N}{k}+k\right)E_{elec}+\varepsilon_{fs}\ M^2\right]}{Nframes}+l_s\left[\left(\dfrac{N}{k}+1\right)E_{elec}+\varepsilon_{fs}\ d_{BS}^2+\dfrac{N}{k}E_{DA}\right] & M\&d_{BS}<d_o\end{cases}\tag{14}$$

$$E_{non}(r)=\begin{cases}\dfrac{l_c\left[(1+k)E_{elec}+\varepsilon_{mp}\ d_{CH}^4\right]}{Nframes}+l_s\left[(E_{elec}+\varepsilon_{mp}\ d_{CH}^4\right] & d_{CH}\geq d_o\\ \dfrac{l_c\left[(1+k)E_{elec}+\varepsilon_{fs}\ d_{CH}^2\right]}{Nframes}+l_s\left[(E_{elec}+\varepsilon_{fs}\ d_{CH}^2\right] & else\end{cases}\tag{15}$$

However, if the CH finds suitable aggregator nodes within the round the non-CH nodes are then divided into two types: the normal non-CHs and aggregators that consume the energy as in Eq. (15). Thus, the data aggregation task is no longer required from the CHs as it consumes the energy as in Eq. (16)

$$E_{agg}(r)=\begin{cases}\dfrac{l_c\left[(1+k)E_{elec}+\varepsilon_{mp}\ d_{CH}^4\right]}{Nframes}+l_s\left[\left(\dfrac{N}{k}+1\right)E_{elec}+\varepsilon_{mp}\ d_{CH}^4+\dfrac{N}{k}E_{DA}\right] & d_{CH}\geq d_o\\ \dfrac{l_c\left[(1+k)E_{elec}+\varepsilon_{fs}\ d_{CH}^2\right]}{Nframes}+l_s\left[\left(\dfrac{N}{k}+1\right)E_{elec}+\varepsilon_{fs}\ d_{CH}^2+\dfrac{N}{k}E_{DA}\right] & else\end{cases}\tag{16}$$

$$E_{CH-bc}(r)=\begin{cases}\dfrac{l_c\left[\left(1+\dfrac{N}{k}+k\right)E_{elec}+\varepsilon_{mp}\,M^4\right]}{Nframes}+l_s\left[2E_{elec}+\varepsilon_{mp}\,d_{BS}^4\right] & M\ \&\ d_{BS}\geq d_o\\ \dfrac{l_c\left[\left(1+\dfrac{N}{k}+k\right)E_{elec}+\varepsilon_{mp}\,M^4\right]}{Nframes}+l_s\left[2E_{elec}+\varepsilon_{fs}\,d_{BS}^2\right] & M\ \geq\ d_o\ \&\ d_{BS}<d_o\\ \dfrac{l_c\left[\left(1+\dfrac{N}{k}+k\right)E_{elec}+\varepsilon_{fs}\,M^2\right]}{Nframes}+l_s\left[2E_{elec}+\varepsilon_{mp}\,d_{BS}^4\right] & M\ <\ d_o\ \&\ d_{BS}\geq d_o\\ \dfrac{l_c\left[\left(1+\dfrac{N}{k}+k\right)E_{elec}+\varepsilon_{fs}\,M^2\right]}{Nframes}+l_s\left[E_{elec}+\varepsilon_{fs}\,d_{BS}^2\right] & M\ \&\ d_{BS}<d_o\end{cases}\tag{17}$$

During the network lifetime, each node becomes a CH every *N*/*k* rounds, in the worst case the node is selected as a CH at least once and never find a suitable data aggregator. On the other hand, every time it becomes a cluster member, it is selected as an aggregator. Thus, the overall node energy during its lifetime can be estimated for any node in the ROI from Eq. (18), such that $\frac{rk}{N}\in\mathbb{Z}^{+}$

$$E_{nIBLEACH}=\begin{cases}\left(r_N-\dfrac{N}{k}\right)E_{non}(r)+\dfrac{r_Nk}{N}E_{CH-bc}\ (r) & r_N\geq\dfrac{N}{k},\mathit{Best\ case}\\ \left(r_N-\dfrac{N}{k}\right)E_{agg}(r)+\dfrac{r_Nk}{N}E_{CH}\ (r) & r_N\geq\dfrac{N}{k},\mathit{Worst\ case}\\ (r-1)E_{agg}(r)+E_{CH}(r) & r_N<N/k,\mathit{Worst\ case}\\ r\ E_{non}(r) & r_N<N/k,\mathit{Best\ case}\end{cases}\tag{18}$$

Thus, the stability period is when the first node depletes all its initial energy in data transmission and the number of nodes is the same as its initial value. It depends on the worst condition which represents the case of highest possible energy depletion of the node as in Eq. (19)

$$E_o=\begin{cases}\left(r_s-\dfrac{N}{k}\right)E_{agg}(r)+\dfrac{r_sk}{N}E_{CH}(r) & r_s\geq\dfrac{N}{k}\quad\dfrac{r_sk}{N}\in\mathbb{Z}^{+}\\ (r_s-1)E_{agg}(r)+E_{CH}(r) & \mathit{else}\end{cases}\tag{19}$$

5.2.3 Chain Based Protocol (PEGASIS)

PEGASIS Power-Efficient GAthering in Sensor Information Systems, the greedy chain protocol introduced in [110], was designed specifically for data gathering applications of WSN. The network setup is performed in the beginning of network lifetime and in the case of node loss only, unlike LEACH; however, the chain leader changes every round.

The overhead of periodic cluster formation is eliminated and the need for broadcasts is limited to the node loss or routing hole occurrence. Each node in the network is selected as a leader once every *N* rounds and is connected to its nearest neighbor in the chain only at the beginning of network lifetime and in the case of node loss; where *N* is the number of the current alive nodes in the ROI. We assume a breakdown advertisement broadcast that is performed by the node on depleting its energy to inform other nodes, named as E_{BD}, a control packet of 10% of the size of the control packet is used in this advertisement.

However, the number of dead nodes during round r is *dead*. Periodic Leader node advertisement equation is shown below.

A. The setup phase $E\mathcal{N}$

The overhead of periodic cluster formation is eliminated and the need for broadcasts is limited to node loss case or leader advertisement. Each node in the network is selected as a leader once every N rounds and is connected to its nearest neighbor in the chain only at the beginning of network lifetime and in the case of node loss; where N is the number of the current alive nodes in the ROI. We assume a breakdown advertisement broadcast that is performed by the node on depleting its energy to inform other nodes, named as E_{BD}, a control packet of 10% of the size of the control packet is used in this advertisement. However, the number of dead nodes during round r is *dead*. Periodic Leader node advertisement equation is shown below

$$E\mathcal{N}_l(r) = \begin{cases} l_c\left(E_{elec} + \epsilon_{mp}M^4\right) & M \geq d_o else \\ l_c\left(E_{elec} + \epsilon_{fs}M^2\right) & \end{cases} \tag{20}$$

The Conditional chain reformation consumes one transmission of nearest neighbor join request and one reception from at most one neighbor if the node is not at the end of the chain as shown

$$E\mathcal{N}_{nl}(r) = \begin{cases} l_c\left(2E_{elec} + \epsilon_{mp}d_{nn}^4\right) & d_{nn} \geq d_o else \\ l_c\left(2E_{elec} + \epsilon_{fs}d_{nn}^2\right) & \end{cases} \tag{21}$$

Node loss notification is considered the breakdown energy of every node in the network, thus the end of node lifetime is when its energy reaches E_{BD}, however, 10% of the control packet size used in such notification.

$$E_{BD} = \begin{cases} 0.1l_c\left(E_{elec} + \epsilon_{mp}M^4\right) & M \geq d_o \\ 0.1l_c\left(E_{elec} + \epsilon_{fs}M^2\right) & else \end{cases} \tag{22}$$

However, each node receives the periodic leader advertisement and the dead node advertisement

$$E\mathcal{N}_{nl}(r) = (l_c + 0.1\ dead\ l_c)E_{elec} \tag{23}$$

B. The data gathering phase $E\mathcal{G}$

In PEGASIS, each node communicates with its nearest neighbor and the gathered data get fused till the randomly chosen chain leader transmits the aggregated packet to the BS. We provide the nearest neighbor transmission equation through one round that shows the reception ad transmission of one packet from and to another node in the ROI, respectively. Thus, each node aggregates at most two packets. On the other side, when the node becomes a leader it receives from two nodes, aggregates at most three packets to transmit them to BS which may be outside the ROI, thus, the energy consumed in the data transmission process is shown below for non-leader and leader nodes, respectively

$$E\mathcal{G}_l(r) = \begin{cases} l_s\left(3E_{elec} + \varepsilon_{mp}d_{toBS}^4 + 3E_{DA}\right) & d_{toBS} \geq d_o \\ l_s\left(3E_{elec} + \varepsilon_{fs}d_{toBS}^2 + 3E_{DA}\right) & else \end{cases} \tag{24}$$

$$E\mathcal{G}_{nl}(r) = \begin{cases} l_s\left(2E_{elec} + \varepsilon_{mp} d_{nn}^4 + 2E_{DA}\right) & d_{nn} \geq d_o \\ l_s\left(2E_{elec} + \varepsilon_{fs} d_{nn}^2 + 2E_{DA}\right) & else \end{cases} \tag{25}$$

C. Stability period and network lifetime estimation

Since each node is selected as a leader every N rounds, the chain formation is performed once at the beginning of network lifetime and breakdown broadcast is only used when a node is dead, the total energy consumed by sensor node during its r_N, by leader node in the middle of the chain and non-leader, respectively, are shown in the given equations

$$E_l(r) = \begin{cases} l_c\left(3E_{elec} + \varepsilon_{mp} M^4\right) + l_s\left(3E_{elec} + \varepsilon_{mp} d_{BS}^4 + 3E_{DA}\right) & M \ \& \ d_{BS} \geq do \\ l_c\left(3E_{elec} + \varepsilon_{mp} M^4\right) + l_s\left(3E_{elec} + \varepsilon_{fs} d_{BS}^2 + 3E_{DA}\right) & M \geq d_o \ \& \ d_{BS} < d_o \\ l_c\left(3E_{elec} + \varepsilon_{fs} M^2\right) + l_s\left(3E_{elec} + \varepsilon_{mp} d_{BS}^4 + 3E_{DA}\right) & M < d_o \ \& \ d_{BS} \geq d_o \\ l_c\left(3E_{elec} + \varepsilon_{fs} M^2\right) + l_s\left(3E_{elec} + \varepsilon_{fs} d_{BS}^2 + 3E_{DA}\right) & M \ \& \ d_{BS} < d_o \end{cases} \tag{26}$$

$$E_{nl}(r) = \begin{cases} l_c\left(1 + 2E_{elec} + \varepsilon_{mp} d_{nn}^4 + 0.1\ dead\right) + l_s\left(2E_{elec} + \varepsilon_{mp} d_{nn}^4 + 2E_{DA}\right) & d_{nn} \geq d_o \\ l_c\left(1 + 2E_{elec} + \varepsilon_{fs} d_{nn}^2 + 0.1\ dead\right) + l_s\left(2E_{elec} + \varepsilon_{fs} d_{nn}^2 + 2E_{DA}\right) & Else \end{cases} \tag{27}$$

During the network lifetime, each node becomes a leader every N round, in the worst case, the node is selected as a leader at least once, thus, the node energy during its lifetime can be estimated from Eq. (20), such that $\frac{rk}{N} \in \mathbb{Z}^+$

$$E_{nPEG}(r) = \begin{cases} \left(r_N - \frac{r_N}{N}\right) E_{nl}(r) + \frac{r_N}{N} E_l(r) + E_{BD}(r) & r_N/N \geq N \\ (r_N - 1) E_{nl}(r) + E_l(r) + E_{BD}(r) & \frac{r_N}{N} < N, worst\ case \\ r_N E_{nl}(r) + E_{BD}(r) & \frac{r_N}{N} < N, best\ case \end{cases} \tag{28}$$

Thus, the stability period is when the first node depletes all its initial energy in data transmission and the number of nodes is the same as its initial value as shown

$$E_o - E_{BD} = \begin{cases} \left(r_s - \frac{r_s}{N}\right) E_{nl}(r) + \frac{r_s}{N} E_l(r) & \frac{r_N}{N} \geq N \ \frac{rk}{N} \in \mathbb{Z}^+ \\ (r_s - 1) E_{nl}(r) + E_l(r) & Else \end{cases} \tag{29}$$

5.2.4 NEECP Protocol

This technique selects the cluster heads in a way similar to LEACH but using different CH selection function and performs the data aggregation using chaining approach within the cluster and among CHs similar to PEGASIS. It is implemented by considering the data with aggregation and without aggregation using NEECPWA and NEECPWOA, respectively. However, we deal with applying data aggregation to limit the increase of schedule length and thus data latency. Thus, we cover the energy consumption analysis in the case of NEECPWA.

A. The setup phase $E\mathcal{N}$

The implementation of NEECP is divided into rounds and each round is divided into two phases: setup and steady-state phases. At the beginning of each round, the CHs are selected and advertised, similar to LEACH; however, they don't receive cluster joining requests. Although the intra-cluster and inter-cluster transmission depend mainly on chain formation as in PEGASIS, no node breakdown notification is added due to the periodic chain reconstruction. Thus, this protocol has CHs and leader of CHs that is responsible for BS transmission.

In this protocol, the CHs have one leader, so we have CHs and leader CH. The energy consumed by CH for cluster formation is only advertising itself as a CH using a broadcast as in Eq. (34) and the energy consumed by leader CH is the same as that is consumed by CH but with leader advertisement as in Eq. (29). While the non-CH receives the advertising and starts the chain formation process with other cluster members by connecting to its nearest neighbor in the direction of the closest advertised CH. According to the chain formation process shown in Eq. (18), the energy consumed by non-CH is in Eq. (30)

$$E\mathcal{N}_{CH}(r) = \begin{cases} l_c\left[E_{elec} + \varepsilon_{mp}\, M^4\right] & M \geq d_o \\ l_c\left[E_{elec} + \varepsilon_{fs}\, M^2\right] & Else \end{cases} \tag{30}$$

$$E\mathcal{N}_{lCH}(r) = \begin{cases} 2\, l_c\left[E_{elec} + \varepsilon_{mp}\, M^4\right] & M \geq d_o \\ 2\, l_c\left[E_{elec} + \varepsilon_{fs}\, M^2\right] & Else \end{cases} \tag{31}$$

$$E\mathcal{N}_{non}(r) = \begin{cases} l_c\left(3E_{elec} + \epsilon_{mp} d_{nn}^4\right) & d_{nn} \geq d_o \\ l_c\left(3E_{elec} + \epsilon_{fs} d_{nn}^2\right) & else \end{cases} \tag{32}$$

where d_{nn} is the distance between the non-CH and the nearest neighbor in the direction of its CH. However, when a CH becomes a leader it consumes energy as in Eq. (26).

However, each node receives the periodic leader advertisement as in Eq. (33)

$$E\mathcal{N}_{nl}(r) = l_c E_{elec} \tag{33}$$

B. The data gathering phase $E\mathcal{G}$

In NEECP, each node communicates with its nearest neighbor and the gathered data get fused till the CH which transmits the aggregated packet to its nearest neighbor CH in the CH chain till the selected leader transmits the aggregated packet to the BS. Similar to PEGASIS, the data are transmitted through the network. Where the nodes are treated as leader or non-leaders, since the non-leader CH task becomes similar to any non-CH. Thus, $E\mathcal{G}$ is shown in Eqs. (16–17) for leader CHs and non-leader CHs

C. Stability period and network lifetime estimation

Since the chain formation is done every round, the total energy consumed by sensor node during it's r_N, by leader CH in the middle of the CH chain, non-leader CH and non-CH are given in Eqs. (31, 33, 34), respectively

$$E_{lCH}(r) = \begin{cases} 2l_c\left(E_{elec} + \varepsilon_{mp} M^4\right) + l_s\left(3E_{elec} + \varepsilon_{mp} d_{BS}^4 + 3E_{DA}\right) & M \;\&\; d_{BS} \geq d_o \\ 2l_c\left(E_{elec} + \varepsilon_{mp} M^4\right) + l_s\left(3E_{elec} + \varepsilon_{fs} d_{BS}^2 + 3E_{DA}\right) & M \geq d_o \;\&\; d_{BS} < d_o \\ 2l_c\left(E_{elec} + \varepsilon_{fs} M^2\right) + l_s\left(3E_{elec} + \varepsilon_{mp} d_{BS}^4 + 3E_{DA}\right) & M < d_o \;\&\; d_{BS} \geq d_o \\ 2l_c\left(E_{elec} + \varepsilon_{fs} M^2\right) + l_s\left(3E_{elec} + \varepsilon_{fs} d_{BS}^2 + 3E_{DA}\right) & M \;\&\; d_{BS} < d_o \end{cases} \tag{34}$$

$$E_{CH}(r) = \begin{cases} l_c\left(E_{elec} + \varepsilon_{mp}M^4\right) + l_s\left(2E_{elec} + \varepsilon_{mp}d_{nn}^4 + 2E_{DA}\right) & M \geq d_o \\ l_c\left(E_{elec} + \varepsilon_{fs}M^2\right) + l_s\left(2E_{elec} + \varepsilon_{fs}d_{nn}^2 + 2E_{DA}\right) & else \end{cases} \tag{35}$$

$$E_{non}(r) = \begin{cases} l_c\left(3E_{elec} + \varepsilon_{mp}d_{nn}^4\right) + l_s\left(2E_{elec} + \varepsilon_{mp}d_{nn}^4 + 2E_{DA}\right) & d_{nn} \geq d_o \\ l_c\left(3E_{elec} + \varepsilon_{fs}d_{nn}^2\right) + l_s\left(2E_{elec} + \varepsilon_{fs}d_{nn}^2 + 2E_{DA}\right) & Else \end{cases} \tag{36}$$

In the worst case, the node is selected as a leader every time it becomes a CH, thus, the node energy during its lifetime can be estimated from Eq. (34), such that $\frac{rk}{N} \in \mathbb{Z}^+$

$$E_{nNEECP}(r) = \begin{cases} \left(r_{\mathcal{N}} - \dfrac{N}{k}\right)E_{non}(r) + \dfrac{r_{\mathcal{N}}k}{N}E_{lCH}(r) & r_{\mathcal{N}} \geq \dfrac{N}{k}, worst\,case \\ \left(r_{\mathcal{N}} - \dfrac{N}{k}\right)E_{non}(r) + \dfrac{r_{\mathcal{N}}k}{N}E_{CH}(r) & r_{\mathcal{N}} \geq \dfrac{N}{k}, best\,case \\ E_{lCH}(r) + (r_{\mathcal{N}} - 1)E_{non}(r) & r_{\mathcal{N}} < \dfrac{N}{k}, worst\,case \\ r_{\mathcal{N}}E_{non}(r) & r_{\mathcal{N}} < \dfrac{N}{k}, best\,case \end{cases} \tag{37}$$

Thus, the stability period is when the first node depletes all its initial energy in data transmission and the number of nodes is the same as its initial value as shown

$$E_o - E_{BD} = \begin{cases} \left(r_s - \dfrac{r_s}{N}\right)E_{nl}(r) + \dfrac{r_s}{N}E_l(r) & \dfrac{r_N}{N} \geq N \;\; \dfrac{rk}{N} \in \mathbb{Z}^+ \\ (r_s - 1)E_{nl}(r) + E_l(r) & else \end{cases} \tag{38}$$

6 Results

To show the impact of the routing protocol design on network on increasing network lifetime r_N, we performed simulation experiments on N randomly deployed sensor nodes in 100 × 100 ROI with one BS located at (200, 50). The system is homogeneous; such that, all sensor nodes have the same initial energy. Based on the radio transmission model in Sect. 5.1 and the system parameters in Table 4, the simulation experiments were carried out using Matlab Ra 2015 to prove of the derived relation between number of levels and node degree. Additionally, based on the analysis in the previous section, we study the energy consumption in LEACH [93, 94], PEGASIS [95], IBLEACH [100], and NEECP [101] and show the percentage of dead node throughout the network lifetime. Thus, the stability period and the rate of node loss can be studied in details on applying each of the studied energy efficient protocols, the change in average network energy is measured to reflect the ability of each protocol to save network energy.

The recent energy efficient routing protocols IBLEACH and NEECP are compared against the parent of energy efficient clustering protocols, LEACH, and PEGASIS. PEGASIS doesn't require any network initialization parameters. However, the other three protocols require network initialization parameters. For NEECP, NEECPWA that provides the data aggregation capability to avoid data latency was chosen for the comparison. For IBLEACH, a frame length that is equal to three rounds was chosen. For LEACH, the probability of CH selection used in our simulation environment is the optimal probability for energy efficiency $\mathrm{p_{opt}}$, and $\mathrm{k_{opt}}$, the optimal number of CHs that minimizes the average

Table 4 System parameters

Type	Parameter	Symbol	Value
Homogeneous network	The number of nodes in the ROI	N	100
	Initial energy of sensor node	E_o	0.5
	Node distribution	–	Random
	BS location	–	(50, 200)
Application	Minimum distance from ROI to BS	$d_{to\ BS}$	100
	Diameter of maximum dimension of the *ROI*	M	100
	Data packet size in bits	l_s	800 Bytes
	Control packet size in bits	l_c	50 Bytes
	Transmitter/receiver electronics	E_{elec}	$50\,\mathrm{nJ/bit}$
	Energy consumed in data aggregation	E_{DA}	$\frac{5\,\mathrm{nJ}}{\mathrm{bit}}/\mathrm{signal}$
Radio model	Multi-path propagation loss	ε_{mp}	$0.0013\ \frac{\mathrm{pj}}{\mathrm{bit}}/\mathrm{m}^4$
	Free space propagation loss	ε_{fs}	$10\ \frac{\mathrm{pj}}{\mathrm{bit}}/\mathrm{m}^2$
	The threshold distance of wireless propagation energy model	d_o	$\sqrt{\frac{\varepsilon_{fs}}{\epsilon_{mp}}}$

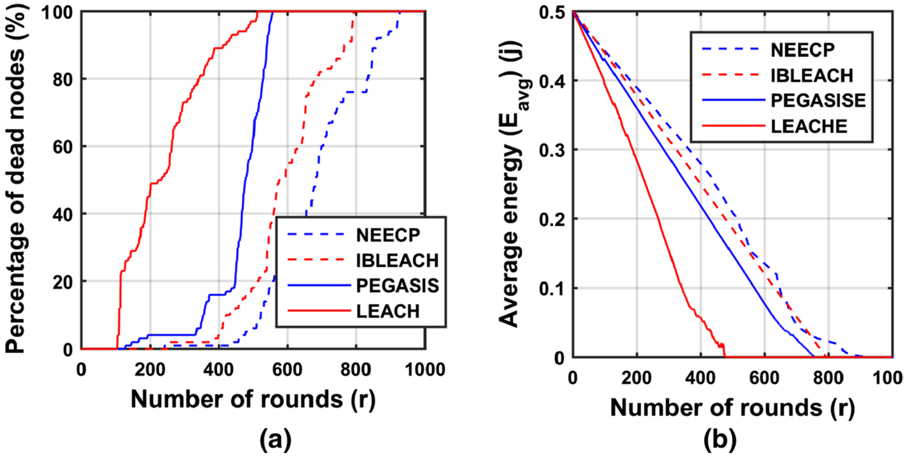

Fig. 3 **a** Percentage of dead node and **b** average network energy with respect to the number of rounds

energy consumption of the network, as proven in [94], can be calculated according to system parameters from Eqs. (39, 40)

$$k_{opt} = \sqrt{\frac{N}{2\pi}\frac{M}{d_{toBS}^2}}\sqrt{\frac{\epsilon_{fs}}{\epsilon_{mp}}} \tag{39}$$

$$p_{opt} = \frac{k_{opt}}{N} \tag{40}$$

The given routing protocols are based on losing nodes at random positions to avoid the coverage hole problem. As shown in Fig. 3a, b, optimal LEACH provides about double the lifetime introduced by single-phase networks with the highest rate of node loss, while PEGASIS provides about 3.5 times increase in $r_{\mathcal{N}}$ with very high rate of node loss after 450 rounds as the nodes become exhausted. The useless network reformation that occurs in PEGASIS after losing any node regardless of its role in data transmission adds network overhead which increases the number of dead nodes tremendously after sufficient amount of rounds after the stability period; as the nodes become exhausted.

On the other hand, the long network setup process of IBLEACH that is divided into three phases, Setup, Pre-Steady and the Steady State lead to high network overhead. However, performing this process is every set of rounds (frame) synchronized clock, the long frame length may lead to the energy-hole problem and the short frame length didn’t solve the high network overhead. Thus, based on our network setup parameters of frame length = 3 rounds, IBLEACH has proven better network performance than LEACH and PEGASIS in terms of rate of node loss and average network energy. It provides more than two times higher stability period that LEACH and PEGASIS. However, the decrease in average network energy is close to that is provided by PEGASIS, since IBLEACH adds much network overhead than PEGASIS.

NEECP avoids this problem that occurs in ROI to BS transmission by using the chain of CHs where the BS is their leader. Thus, at most two CHs transmit to BS if the single chain is formed. Additionally, each CH doesn’t consume too much energy in data aggregation due to the chain topology within the clusters. NEECP has a mixed nature between clustering and chain-based protocols which help in maintaining connectivity with limited overhead. NEECP offers about half the network overhead offered by LEACH due to the use of chain formation within clusters. Thus, non-CHs needn’t transmit any join request or wait for an acknowledgement from the CHs. However, they join their nearest neighbor in the direction of the CH which limits transmission distance of control packets. NEECP provides higher stability period than its competitive due to the better CH distribution and the more energy efficient CH selection algorithm used.

7 Conclusion

The structure of WSN system may take any form according to the application need. WSN has covered a variety of applications including on ground, underground and underwater applications. One of the most important aspects of WSN design is energy harvesting which mainly affects network lifetime. Generally, single setup networks add no network setup overhead which is positively reflected on the stability period but negatively reflected on network lifetime. Thus, we have covered the lifetime analysis of the most energy efficient proactive routing protocols for a homogeneous system. Thus, the energy efficiency of WSN is a result of three basic requirements; first, network adaptability or fault tolerance, second, network overhead during network setup and reset-up, third, route selection for data transmission. Thus, to ensure higher network lifetime the network should be adaptable to change, overhead should be limited to a minimum and multi-hop routing should be applied. Accordingly, energy efficient routing protocols should be carefully chosen according to system requirements and application needs. We are looking forward to covering the network lifetime analysis for the reactive routing protocols for both homogeneous and heterogeneous systems.

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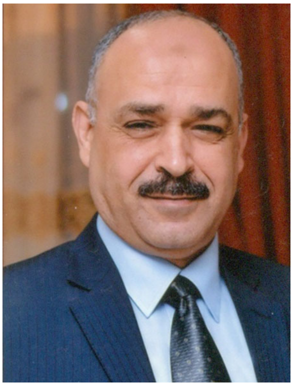

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