Development of an Energy-Efficient Wireless Sensor Network Model for Perimeter Surveillance

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Abstract – *Wireless distributed microsensor systems have proven to be indispensable in facilitating reliable and efficient monitoring and surveillance in safety-critical infrastructure. The conventional routing protocols comprising direct transmission, minimum-transmission-energy, multihop routing, and static clustering are no longer optimal for wireless sensor networks (WSN) applications. There is a need for highly robust routing protocols to distribute the energy load among the sensors in a WSN. This paper aims at the development of an energy-efficient WSN model adapted for perimeter surveillance. An efficient routing algorithm that seeks to balance the energy among the nodes in a WSN is proposed. This is achieved by leveraging the low-energy adaptive clustering hierarchical protocol and amending its random cluster head selection features. The deployment of sensor nodes around the perimeter of an experimental region and the formation of clusters were initiated before selecting a cluster head. The node that requires the least transmission energy for a given transmission round was considered. The cluster head task is assigned so that the least transmission energy is expended, and the shortest distance between the transmitter and the receiver from the cluster heads is followed. Simulations were carried out for the non-hierarchical and the various levels of hierarchy-based clusters to test the validity of the proposed routing algorithm. Results indicate that the lifetime of the networks is 210, 380, 481, 543, 550, 557, and 559 for the non-hierarchical (1 cluster), level 1 hierarchy (5 clusters), level 2 hierarchy (10 clusters), level 3 hierarchy (20 clusters), level 4 hierarchy (30 clusters), level 5 hierarchy (60 clusters), and level 6 hierarchy (120 clusters), respectively. The standard deviation of the residual energy of the network decreases from approximately 1.2825 for the non-hierarchical to about 0.0138 for the level 6 hierarchy. The lowest standard deviation value of the level 6 hierarchy indicates that the perimeter network maximizes the initial energy of its nodes using the proposed algorithm. Additionally, the proposed routing technique significantly reduces the energy consumption of the sensor nodes in the perimeter of the investigated region, and tremendously elongates the lifespan of the network compared to the non-hierarchical routing technique. Finally, the optimal energy-efficient level of hierarchy in the studied perimeter sensor network is observed at the maximum possible cluster size.*

Keywords: *Wireless Sensor Network, Perimeter Surveillance, Cluster Head Selection, Energy-Efficient Model, Hierarchical and Non-hierarchical Clustering*

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I. Introduction

The pervasive scope of wireless communication applications has orchestrated the huge demand for wireless sensor networks (WSNs) in recent years [1]. Additionally, the proliferation of wireless sensor nodes has greatly enhanced human activities through monitoring, control, and automation. The primary purpose of WSNs' application is for: sensing – perceiving some signal in its environment; monitoring – sensing over time to track a signal, and surveillance – monitoring over a region of space. For operational safety and precision in industrial settings and other safety-critical systems, constant monitoring with the application of appropriate wireless sensor nodes is imperative [2]. In scenarios where the effort to increase operational safety is crucial, it is appropriate to have a continuously working surveillance system empowered by WSNs.

Wireless sensor networks are preferred candidate sensing technologies for several practical applications by millions of consumers globally [3]. This is perhaps attributed to their embeddable structure and distributed nature. Other distinguishing features of WSNs include, but are not limited to, nodes mobility, node heterogeneity, scalability, and energy conservation [4]. Additionally, WSNs deployment can be immediate, and they are highly adaptive to the environment in which they operate. This is because no elaborate network infrastructure is required for deployment [2], [5]. Apart from being relatively inexpensive to deploy, WSNs can employ mesh networking schemes that conserve a great deal of energy during data transmission from the transmitter to the receiver under certain circumstances [6]. Moreover, in applications that feature less energy-intensive distributed sampling, sensor networks can provide a realistic and in-depth evaluation of the state of the environment at any given time [7], [8].

The basic architecture of a wireless sensor node is made up of the power source, sensors to track a signal of interest, an analog-to-digital converter, the microcontroller sub-system, memory, and a radio sub-system, as shown in Fig. 1. Wireless sensor networks, due to their autonomous nature, find practical applications in underwater communications [9], military applications, smart buildings, smart agriculture, energy control systems, security and perimeter surveillance, industrial control and automation, health, and environmental monitoring, among others, as depicted in Fig. 2.

Wireless distributed microsensor systems are indispensable in facilitating reliable and efficient monitoring and surveillance in safety-critical infrastructure. The conventional routing protocols, direct transmission, minimum-transmission-energy, multihop routing, and static clustering are no longer optimal for several WSNs applications. The need for highly robust protocols to support even distribution of the energy load among the sensors in a typical WSN becomes imperative.

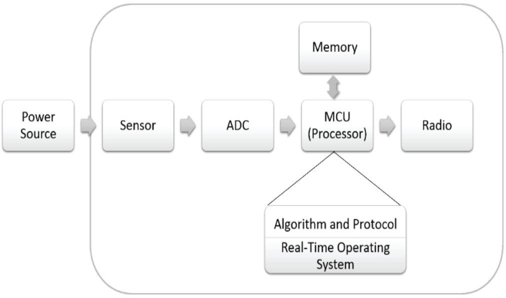


Fig. 1. A typical wireless sensor node showing the sensor, analog-to-digital converter, memory, microcontroller unit, and radio units

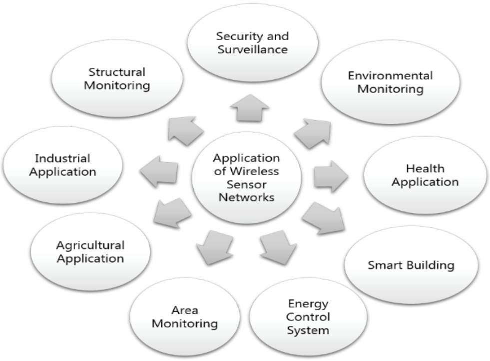


Fig. 2. Illustration of selected fields of applications of wireless sensor networks (WSNs)

Toward this end, this paper is focused on the development of an energy-efficient WSN model adapted for perimeter surveillance. An efficient routing algorithm that seeks to balance the energy among the nodes in a WSN is evolved in this case. This is achieved by leveraging the low-energy adaptive clustering hierarchical (LEACH) protocol and amending its random cluster head selection features. In the proposed model, the deployment of sensor nodes around the perimeter of an experimental region and cluster formation was conducted before selecting a cluster head. Additionally, the node that requires the least transmission energy for a specific transmission round was selected. The cluster head task is also assigned so that the least transmission energy is expended. The shortest distance between the transmitter and the receiver from the cluster heads is utilized. Additionally, computer simulations for the non-hierarchical and the various levels of hierarchy-based clusters were carried out to test the validity of the proposed routing algorithm.

The main contribution of this work is the development of an energy-efficient wireless sensor network model for perimeter surveillance. Specifically, the first-order radio energy model was derived using well-defined radio characteristics. Additionally, the routing protocol was developed based on an elaborate modification of some relevant parameters of the popular low-energy adaptive clustering hierarchical protocol [6], [10]. Further to this, the effectiveness of the proposed hierarchy-based routing protocol via computer simulations was demonstrated. Finally, we show that the proposed routing protocol has promising potentials to supporting further research related to energy efficiency in wireless networks-based surveillance systems.

The remainder of this paper is organized as follows; section II gives a comprehensive review of related literature, section III presents the energy model and the proposed hierarchy-based routing algorithm, section IV shows the simulation results and discussions, and finally, section V gives a conclusion to the study and recommendations for future work.

II. Related Work

Wireless sensor networks (WSNs) have garnered significant research interests in the last decade, and applications requiring the deployment of WSNs continue to evolve [11]–[14]. García-Hernández *et al.* [15] survey the applications of WSNs, focusing on WSN standards and protocols, coverage, energy and security trends [16], [17] middleware development for WSN management [18]-[19], application scenarios [20], and wireless sensor node manufacturing and authentication [21]. Additionally, Huang *et al.* [22] present a cognitive software-defined wireless sensor network (SDWSN) prototype. Adetona *et al.* [23] and Imoize *et al.* [24], Omenogor and Imoize [25] present related reports on WSNs involving a low-cost experimental testbed and their applications in power management systems. Hierarchy-based energy-efficient routing protocol similar to the proposed hierarchy-based routing technique is reported [26]. Additionally, a catalogue of evolving trends in energy-efficient WSNs is available in [27].

On routing algorithms, Heinzelman *et al.* [2] reported a protocol to solve the redundant sensing, redundant transmission, and resource blindness problems associated with classic flooding protocols in wireless sensor networks. In this routing algorithm, networks send the information available to neighbouring nodes, storing and moving to neighbouring nodes. The authors propose a family of protocols – Sensor Protocol for Information via Negotiation (SPIN) that uses metadata as data descriptors and allows the sensor to advertise their data and send them only on request. A SPIN variant implements system resource polling and adapts its operation to the available energy. The two SPIN protocols are simulated and contrasted with an idealized routing protocol and classic flooding protocols. The SPIN algorithms tend to employ some organization level to reduce transmission energy at the expense of communication speed. While this paper does not present a format for sensor metadata, it is agreed that the principle is only beneficial when it is smaller than the data itself. The metadata is unique for all distinguishable data. The algorithm reported efficiently disseminates information among sensors in an energy-constrained wireless sensor network. However, the proposed protocol cannot make resource-adaptive decisions key to making compute-intensive sensor applications a reality.

Furthermore, Heinzelman *et al.* [6] examine scenarios where direct communication protocols (direct transmission to base stations from each node) and minimum transmission energy protocol (neighbour – to – neighbour transmission with a minimal energy policy, before reaching the base station - MTE routing) are optimal. After that, the authors introduce clustering as an alternative routing technique to save power and further present the Low-Energy Adaptive Clustering Hierarchy (LEACH). The LEACH features localized coordination for cluster setup and randomized cluster-head rotation. The cluster-heads further create a schedule for sensors in its cluster and implements local data fusion before transmission to the base station to reduce energy usage. It is found to reduce energy by a factor of eight in comparison with MTE and direct transmission routing protocols. The work shows that LEACH can pave the way for future microsensor networks by doubling its useful system lifetime. However, the results require further simulation with a network simulator.

Aderohunmu *et al.* [28] extend the LEACH protocol, in line with the principle behind clustering – allowing the sensor nodes to elect themselves as cluster heads to their energy levels set at equilibrium, the energy among all nodes in the network. The authors acknowledge the problem of significant energy heterogeneity among sensor nodes – a substantial energy gap between a sensor node and its neighbors. The Low Energy Adaptive Clustering Hierarchy protocol assumes a homogenous energy setting (same energy across all nodes). Building on LEACH, they propose the stable election protocol (SEP) by robustly allowing for significant energy heterogeneity among sensor nodes. However, the authors did not provide any information on how to best control the number of associated cluster members in every cluster. In another related study [5], the stable election protocol (SEP) was used to improve the LEACH by allowing for two-energy levels in a two-layer hierarchical setting. The authors then proposed an enhanced SEP by considering different energy levels in a two-layer hierarchy setting. The designed scheme is shown to prolong network lifetime and to improve resource sharing. However, the security of the proposed system was not adequately discussed. Additionally, micro-scale thermoelectric generators (TEG) for monitoring are only sustainable for small buildings. Complex buildings would require massive infrastructure.

For an intelligent aggregation of node data at intermediary nodes, Li *et al.* [29] introduce an energy-efficient and high accuracy (EHHA) scheme for the security-enabled aggregation of data in WSNs. EHHA seeks to improve on a previous scheme–Slice-Mix-AggRegaTe (SMART), based on a tree network topology. The sensor - leaf nodes- forward its data to the base-station - root node- via intermediary sensor nodes. Slice-and-mix had been proposed and employed by SMART as a method of data privacy. EHHA improves the slice-and-mix such that node data cannot be easily snooped. The EEHA is more efficient and accurate than the existing scheme, but experimental results are required to verify the performance of the proposed system.

The authors [29] observed that, in SMART, each node decides on the number of its neighbouring nodes, including intermediary nodes, and slices its data such that it forwards a unique slice to each neighbour and still has a slice left. Each node then combines the sundry data slices from its neighbour with its residual data slice and forwards the aggregate to the base station. In EHHA, the intermediary nodes are restrained from slicing and forwarding, reducing computational and communication overhead, leading to fewer collisions, more accuracy, and less energy overhead. The intermediary nodes combine the sundry data slices from all neighbours, the aggregations of data slices from the leaf nodes, and its unsliced data, sending it to the base station. A waiting period is implemented after slicing and forwarding to ensure that the data gets to the recipients. The longer the wait time, the fewer the collisions. Encryption is also implemented at each node to strengthen the privacy policy. This makes eavesdropping successful only when each forwarded slice from the node to its neighbouring node is spied, and the encryption key is known. However, the practical application of the proposed scheme is not emphasized by the authors.

Sensor coverage and communication play a crucial role in the robustness of the WSN application. Zhu *et al.* [30] present cell deployment strategies, sleep schedule, and adjustable radius-based techniques for coverage optimization in WSNs. In the deployment of static nodes, the authors survey algorithms and tools that maximize the number of sensors over a given space, approaches that require more than one sensor coverage in any given area, and the path-coverage approach where sensors are randomly deployed to cover a path. Under dynamic coverage deployment techniques, the authors discuss virtual force-based techniques for redistribution after initial random deployment, robust algorithms to obstacles present in the terrain of interest, and coverage-hole repair strategies. They further discuss sleep scheduling and coverage preservation and how an adjustable coverage can reduce overlap while maintaining coverage. However, the work is a survey with no experimentation.

Energy-efficiency affects every part of the WSN design. To this end, the authors in [27] and [31] present a top-down taxonomy of energy-efficient techniques in wireless sensor networks and discuss their associated trade-offs for use as efficient schemes. The application requirements of a broad range of wireless sensor applications and the various low-power wireless communication standards are also delineated in [31]. However, the work did not cover the practical deployment of WSNs.

In applications related to efficient motion sensing, Bai *et al.* [32] assemble a membrane-based triboelectric sensor to measure air pressure. Triboelectric sensors employ the triboelectric effect, where certain materials become electrically charged after contact and separation from a different material to convert mechanical vibrations into electrical energy. The sensor exploits the triboelectric effect of circular fluorinated ethylene propylene (FEP) film with an air inlet, etched with FEP nanorod arrays on the surface, and a circular latex membrane edge-glued to the FEP film. The authors observed that the device is robust to frequent measurements over time. However, the air pressure must not exceed the latex membrane's yield for the device to work. With lower dimensions, the latex membrane is subject to a lower elastic limit. It suffers nonlinearities, perhaps due to the magnification of the elastic properties across the latex membrane or/and the etched nanorods on the FEP film. Higher dimensions also cause reduced sensitivity: the higher the dimension, the more air pressure is required for the latex membrane to be pushed out. As the authors note, the device must be adequately characterized to enhance smaller form factor designs. The device gives appreciable stability after a long time operation. However, achieving higher sensitivity and stability would require enhanced miniaturization of the device, which will come at a huge price.

Wu *et al.* [33] demonstrate how wireless sensor networks (WSNs) drive the progress of cyber-physical systems (CPS). While WSNs are context-specific networks deployed to gather data. CPS requires cross-domain data from multiple WSNs, for intelligent control in actuator networks, which may necessitate high processing and data communication requirements. A report on the issues around the enablement of CPS by WSNs from network formation, data gathering, data querying, coverage and connectivity, energy management, and node mobility is presented. When wireless sensor networks fail, the environmental, economic, and health-related impacts could be undesirable and severe at times. Fault diagnosis is hence crucial. A taxonomy for fault diagnosis approaches in WSNs, and a discussion on the shortcomings of available diagnostic techniques are reported [34]. However, the works [33] and [34] are reviews that do not discuss the practical deployment and experimentation of WSNs.

Several WSN-based monitoring systems have been designed in literature. Uchida *et al.* [35] propose an IEEE802.11p-based delay Tolerant Networks (DTN) routing for road surveillance. The system comprises mobile nodes (automobiles and mobile devices) and fixed nodes (traffic lights and electrical poles), which serve as the DTN gateways to other users through the internet. The automobiles are equipped with quasi electrostatic field (QEF) sensors on the wheels, which enable the determination of the road's critical nature. A sorting technique is also introduced to transmit data according to urgency rather than chronologically. If the road is deemed critical, the information is treated as a priority in the DTN and sent to other road users. The proposed system is reported to outperform IEEE802.11b/g-based DTNs. However, the simulations are based on the northern Japanese cities' GIS map and may not apply to other cities globally.

In another report, Hu *et al.* [36] develop a micro-climate monitoring solution in a city area using vehicular sensor networks (VSNs), which require fewer sensor nodes for environmental observation. It proposes using cars in motion, which could sense data at different locations, and based on the rate of sensing, gather much information. The scheme proposes a rate reporting adjustment based on the density of vehicular nodes per area and the sensing readings variance. An opportunistic collaborative communication by the vehicles is also proposed to reduce communication overhead. The authors demonstrated the prototype of a ZigBee-based intra-vehicle wireless network for micro-climate monitoring applications. The proposed scheme may not be feasible for application in macro-climate scenarios.

Similarly, Mehmood *et al.* [37] introduce cooperative sensing that uses a ranking strategy to select an efficient channel for the reliable transmission of the salient visual data. This framework significantly reduces transmission costs but introduces a loss in monitoring quality. The proposed scheme is feasible for limited-resource wireless surveillance networks in simulation environments. However, actual WSNs deployment scenarios would require further insights.

For sporting activities, Kos *et al.* [38] studied the applicability of sensors, wearable devices, and wireless networks in biofeedback applications. A description of the commonest sport-based sensor and actuators were made, and the most standard wireless technologies were enumerated. Biofeedback system operation constraints such as space, time, computational power, energy, and accuracy were presented, and its basic architecture (user, instructor, and cloud) was defined and classified. Low dynamic, high dynamic, and high dynamic multiple sensor biofeedback application scenarios in sports were also presented. However, a set of quality of service (QoS) parameters tailored to biofeedback applications must be well defined.

Zhao *et al.* [39] present a low-power sensor network for agriculture application in smart agriculture. The system includes a processor - ATMega128, an RF module, and a sensor control matrix, all powerable by DC sources or solar batteries through a voltage regulator. The system also includes a voltage-based analog switch for analog sensing and a current to voltage converter to make the sensing interface both current and voltage compatible. Scalar and image sensor nodes were used to accomplish two-way data transition and data acquisition. While scalar sensor nodes collected temperature and humidity data, image sensor nodes gathered crop growth images and transmitted them to the microcontroller unit. The result of the cropland monitoring system – the temperature changing curve and crop growth image – is observed to be intuitive and clear. However, the authors did not provide adequate information on improving the scheme's performance in low-power consumption.

Additionally, Georgieva *et al.* [40] implement a wireless sensor network to monitor and study soil components. The WSN employs Arduino microcontrollers for processing and the Zigbee technology for communication. Sensors are deployed in a mesh network topology to measure soil humidity, temperature, acidity, and conductivity, and a graphical user interface based on LabView software is developed for network management. However, different soil samples are required for rigorous analysis to ascertain the validity of the proposed scheme.

Abd El-Kader *et al.* [41] present surveys on precision farming implementation using wireless sensor networks (WSNs). The authors advocate the application of WSNs for precision agriculture in Egypt. A top-down WSN solution design for precision potato farming is further presented. The design, which employs the Periodic Threshold-sensitive Energy-Efficient sensor Network (APTEEN) protocol, is a cost-effective option for Egyptian farmers. However, the practical application of wireless sensor networks in the crop storage and land test phases is missing in the study.

On the development of a security surveillance system for application in prisons, Ismail *et al.* [42] present a three-tier surveillance model: a wireless underground sensor network (WUSN) based on magnetic induction-based vibration sensors, a wireless ground sensor network (WGSN) with dynamic clustering to track the location of an intruder in a protected area, and a wireless vision sensor network (WVSN) that is activated based on the observed data from the WUSN and WGSN. The WVSN includes multimedia sensors on surveillance towers to characterize the intruder, augmented with unmanned aerial vehicles (UAVs) to cover blind spots. However, the authors did not include other parameters necessary to determine the effect of intruder speed on such a system. Additionally, the possibility of a high rate of a false alarm, especially for tier 0 and 1, was not addressed. Furthermore, merging new surveillance techniques in such a hybrid system to achieve maximum security and the required coverage was not adequately treated.

Benzerbadj *et al.* [43] proposed an energy-efficient algorithm for surveillance around a site using the Greedy Perimeter Stateless Routing (GPSR) protocol. The approach identifies sentry (border) nodes during an initialization phase and puts all the non-sentry nodes to sleep. In case of an intrusion, a multi-hop data communication is implemented, which would require the awakening of sleeping nodes. Lower average power consumption due to node sleep is achieved at the expense of the number of alerts delivered to the sink. However, the authors did not consider the latency by the creation, every time there is an intrusion, of the reserved path between the sentry node and the sink.

Furthermore, Felemban [44] surveys the application of wireless sensor networks in border surveillance and intrusion detection. The works studied include stealth detection, detection of mobile targets, deduction of border evaders, and water vessel detection over the sea surface. The authors remarked that real-time deployment and experimentation are critical to the study of WSNs. On analyzing the quality of surveillance after deployment in wireless sensor networks surveillance, Onur *et al.* [45] present a detection probability using different sensing models. Several approaches to deployment quality measurements are reported. A simulation of a simple surveillance system using binary and probabilistic sensing models to evaluate the impact of node density on detection ratio and detection time was further presented. While this scheme showed exciting results, the network lifetime was not linked to deployment quality, which is crucial to the study.

However, the energy-balance among the sensing nodes, relevant to the design of safety-critical WSNs, was not treated adequately in the preceding literature. This paper proposes developing an energy-efficient WSN model adapted for perimeter surveillance to fill this knowledge gap. The energy model of the proposed routing technique is described in section III of this paper.

III. The Energy Model

The energy model comprising the radio characteristics is employed to evaluate the energy consumption during sensor node transmission or reception at each cycle, following the modeling approach [6], [28]. The wireless (radio) communication component of a sensor node consumes a great amount of energy. The low-energy radio has a power control to expend the least amount of energy to transmit messages to the receiving destination. The energy model is illustrated in Fig. 3.

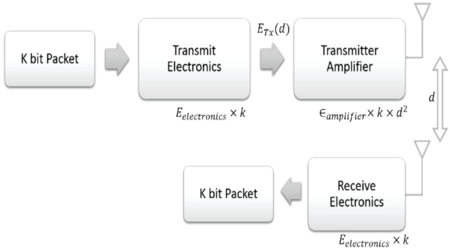


Fig. 3. A model depicting the first radio energy model for a wireless sensor network with *k*-bit packets transmitted

The radio operations characterize the energy model (transmit and receive electronics and the transmit amplifier) where the radio losses $\boldsymbol{E_{electronics}}$ = 50nJ/bit to maintain the circuit configuration of the transmitter and receiver, and $\boldsymbol{E_{amplifier}}$ = 100pJ/bit/m^2 for the amplifier responsible for signal transmission following the steps in [6], as given in Table I.

To transmit a *k*-bit message over a specified distance *d* using the radio model, the radio expends energy given in (1) and receives this message. The radio expends energy given in (2).

$$E_{Tx}(k,d) = E_{Tx-electronics}(k) + E_{Tx-amplifier}(k,d)$$
$$E_{Tx}(k,d) = E_{electronics} \times k + \epsilon_{amplifier} \times k \times d^2 \quad (1)$$

$$E_{Rx}(k) = E_{Rx-electronics}(k)$$
$$E_{Rx}(k) = E_{electronics} \times k \quad (2)$$

TABLE I
CHARACTERISTICS OF THE RADIO COMPONENTS AND ENERGY DISSIPATED

Radio Components	Energy Dissipated
$E_{Tx-electronics}$	50 nJ/bit
$E_{Rx-electronics}$	
$\begin{pmatrix} E_{Tx-electronics} = E_{Rx-electronics} \\ = E_{electronics} \end{pmatrix}$	50 nJ/bit
$E_{amplifier}$	100 pJ/bit/m^2

A. Proposed WSN Routing Protocol

We develop an efficient routing protocol for perimeter surveillance. In perimeter surveillance, the nodes are conventionally fixed in a geographic position throughout their lifetime and are powered by batteries more often than not. It is hence compelled that the nodes have an almost equal lifetime. This makes the necessary node-replacement task associated with battery-powered nodes more efficient. The entire system can be overhauled at once, and replacements are less randomized and less frequent.

In our proposition, the sensors are deployed along a perimeter and form a cluster based on geographical proximity. Cluster heads are elected, which would aggregate data from nodes in its cluster with its data and forward either to the base station or to the cluster head in the following network hierarchy. A block diagram of the process is shown in Fig. 4.

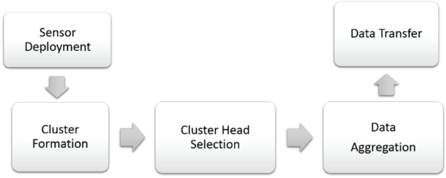


Fig. 4. Block diagram of the process from sensor deployment to data transfer

The routing protocol proposed in this study is formed based on the popular LEACH algorithm. In LEACH, the high-energy cluster-head position's election is randomized. Each node determines whether or not to be a cluster-head independently of the other nodes in the cluster. The LEACH algorithm thus distributes the energy-usage among the nodes in the network in a rather uneven fashion. This is especially non-desirable in perimeter surveillance applications. For clusters head selection in our algorithm, the LEACH protocol is carefully modified with interests on the hierarchical data transfer via any shortest path to the BS, which is here assumed to be positioned at the foci of the region under surveillance, and an energy prediction technique for energy levels after transmission.

In particular, the sensor nodes are assumed to be evenly allocated over the entire perimeter of the experimental region, and clusters are geographically formed based on an equal division of the perimeter to be monitored. Next, cluster head (CH) selection within each cluster formed at all levels is done by the election of the node that requires the least transmission energy for a particular transmission round, and re-election is carried out among the sensor nodes of each cluster at each transmission rounds. Energy estimation is carried out at the start of each transmission round to determine the node with the least transmission energy requirement. This ensures a significant fall in the energy consumed by the nodes, thereby lengthening the lifespan of the network.

A hierarchical routing protocol is developed after even distribution of the sensor nodes along the experimental region's perimeter as follows:

1. Phase one: Cluster is formed geographically around the region's perimeter.
2. Phase two: Cluster head (CH) selection is made in each cluster formed. This phase is based on an energy prediction technique using the first-order radio energy model [2].
   (a) The initial energy $\boldsymbol{E_{initial}(n)}$ of each node is determined, and the distance $\boldsymbol{d_n}$ between each regular node (RN) and the CH or base station, where, $\boldsymbol{n = 1, 2, 3, \ldots}$ is measured. It is calculated using equation (3). Note that $\boldsymbol{(x_1, y_1)}$ and $\boldsymbol{(x_2, y_2)}$ are the coordinates of RN and CH or base station, respectively.

   $$d_n = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \quad (3)$$

   (b) The energy requirements by each node for seamless transmission within the cluster are estimated using equation (4).

   $$E_{rn} = E_{amplifier} \times k \times d_n^{\,2} \quad (4)$$

   The greatest energy after the transmission round for each node (RN) is predicted using equation (5), and the selection of the cluster head (CH) is based on this value. The next CH selection will kick start after the current round is completed successfully.

   $$E_{rnode}(\max) = E_{initial}(n) - E_{rnode} \quad (5)$$

3. Phase three: In this phase, data collected by the CHs from the sensor nodes within their clusters are aggregated.
4. Phase four: In this phase, fused data obtained by the CHs are then forwarded to the receiver.

Flowchart of Cluster Head (CH) selection showing the predefined process from the first initialization phase to the second initialization phase is described as follows: Start the predefined process from previous initialization phases linked to the number of nodes, counting from $j=1$ to $n=240$. If the node j is not in the cluster m, set the predicted residual energy of node j to 0 (energy left if transmission to BS or next CH occurs). However, if node j is in cluster m, measure the node energy. Additionally, estimate the distance, *d(node(j))* to the BS or next CH. If $m \neq 1$, the smaller value is picked *Min (d(node(j)))*.

Further to this, estimate the predicted residual energy of node j (energy left if transmission to BS or next CH occurs). If $j \neq n$, increase j to $j+1$ and go back to check if node j is in cluster m. If, however, $j=n$, then estimate the maximum predicted residual energy across all nodes, and then assign the node with the highest residual energy, *jmax(j),* as the CH and continue the predefined process to the second initialization phase. This process is described as shown in the flow chart for the cluster head selection in Fig. 5.

The proposed Wireless Sensor Network (WSN) hierarchy–based routing protocol for perimeter surveillance is outlined in Fig. 6. To begin the process, deploy the required sensor nodes and form cluster size m. In this case, let i count from 1 to m clusters, i.e., set $i=1, \ldots, m$. Next, simulate x rounds. Let j count from 0 to x, and set $j=0$. Furthermore, select CH for each cluster based on the predicted energy level and shortest distance to the BS. Increase i, $i=i+1$. *If* $i<m$, select CH for each cluster based on the predicted energy-level and the shortest distance to the BS. However, if $i>m$, aggregate CH data collected from nodes CH transmits data to the BS and increases j, $j=j+1$. If $j<x$, select CH for each cluster based on the predicted energy-level and the shortest distance to the BS. However, if $j>x$, proceed to generate network lifetime and residual energy information of each node and end the process.

Following the procedure outlined above, numerical results are obtained for the non-hierarchical cluster (a single cluster) and other hierarchy levels. These include levels one, two, three, four, five, and six containing five, ten, twenty, thirty, sixty, and one hundred and twenty clusters, respectively, which are simulated accordingly. Specifically, Fig. 7(a) illustrates the deployment of the 240 sensor nodes in the experimental region. We envisioned the 240 nodes to be adequate for the dimensions of the observed region. Apart from the non-hierarchical formation with a cluster size of 1, as depicted in Fig. 7(a), the hierarchical cluster formation scenarios of 20 and 120 clusters with 12 and 2 sensors per cluster are shown in Fig. 7(b) - Cluster formation scenario 4; Level 3 hierarchy, and Fig. 7(c) - Cluster formation scenario 7; Level 6 hierarchy. Other simulated scenarios are clustered in the same manner but not shown here for brevity. Equal numbers of sensor nodes are contained in all clusters at each level of formation.

For the simulation, a total of 240 sensor nodes are evenly distributed along the perimeter of a square region, 600 by 600 with the center coordinate (300,300), the fixed BS location. The initial energy level of all nodes is set at 10J. The choice of 10J is premised on the estimated minimal power requirements of the nodes. The transmit electronic $\boldsymbol{E_{Tx}}$ and receive electronic $\boldsymbol{E_{Rx}}$ is set to 50nJ/bit, the transmit power amplifier electronic $\boldsymbol{E_{amp}}$ is set to 100pJ/bit/m^2, and the packet size sensor data is set to 2000 bits. These values are carefully chosen following the peculiarities of the sensor nodes. The first order radio model is used to predict the least transmission energy level for appropriate cluster head selection, data aggregation, and transmission phase for 700 rounds, for the one cluster network, and then for scenarios with 5, 10, 20, 30, 60 and 120 clusters. The parameters used for the simulation are briefly outlined in Table II.

The CH in each cluster created aggregates the data obtained from other sensor nodes alongside its data and transmits it to the receiver by observing the formation of clusters and the least propagation distance separating the CH from the BS. The results of the simulations are presented in section IV of this paper.

TABLE II
INITIAL PARAMETERS USED FOR SIMULATION

Parameters	Quantity
Total number of nodes	240
Initial sensor node energy (J)	10
Packet size (bits)	2000
Rounds	700
Data period (second)	1
Transmit electronic energy (nJ)	50
Receive electronic energy (nJ)	50
Transmit power amplifier energy (pJ)	100
Base station coordinate	(300, 300)

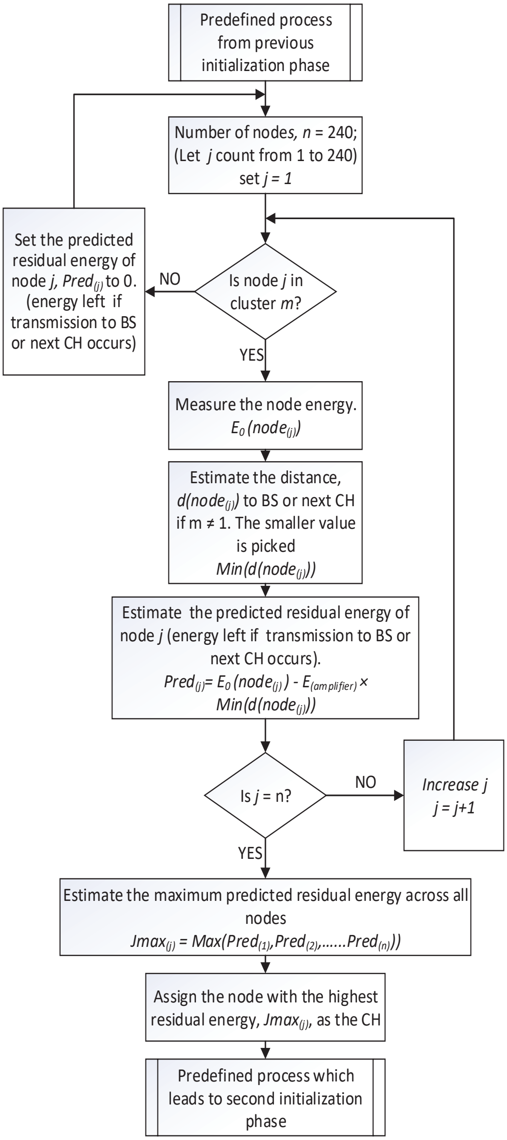


Fig. 5. Flowchart of Cluster Head (CH) selection showing the predefined process from the first initialization phase to the second initialization phase

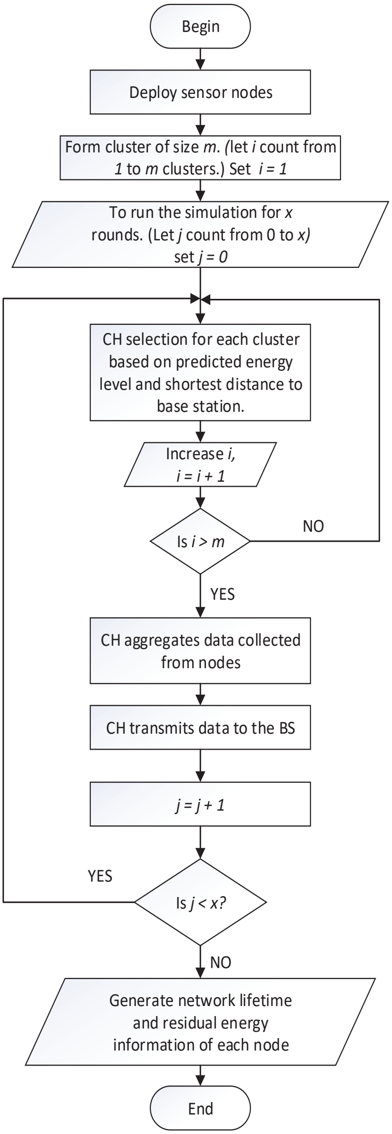


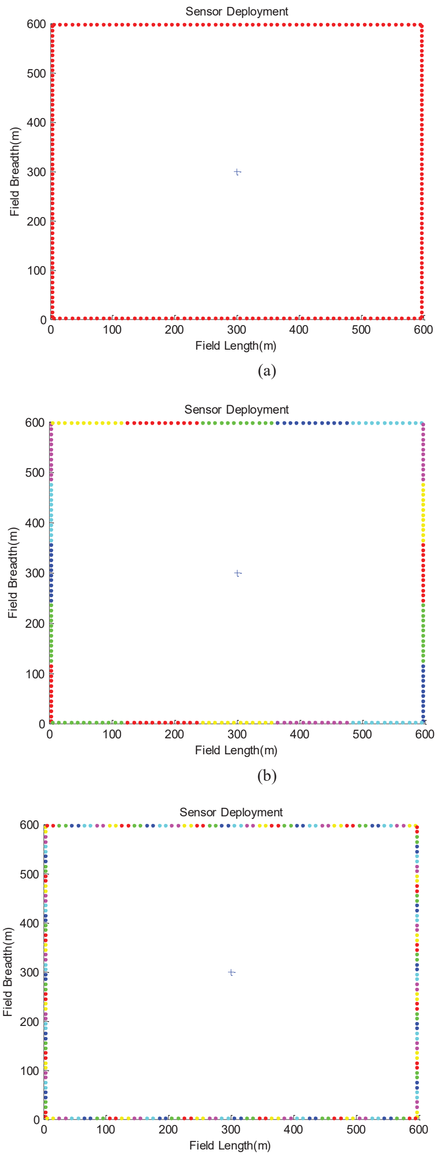
Fig. 6. Flowchart of the proposed Wireless Sensor Network (WSN) hierarchy–based routing protocol for perimeter surveillance

IV. Results and Discussions

A. Results

This section presents the cluster formation results for both the hierarchical and the non-hierarchical techniques, as given in Fig. 7. The results revealed that energy is significantly reduced for each node when data transmission or reception is carried out. This implies that the rotation of the cluster head appropriately elongates the lifecycle of the WSN. Further discussions on these results are given in section IV (*B*).

The network lifetime plots are presented in Fig. 8, and the node residual energy information is presented in Fig. 9. Finally, suitable histograms of the residual energy for both the hierarchical and the non-hierarchical techniques are shown in Fig. 10. The relationship between cluster size and rounds in the proposed protocol is given in Table III. The mean, range, and variance of the residual energy of all the routing techniques are presented in Table IV.

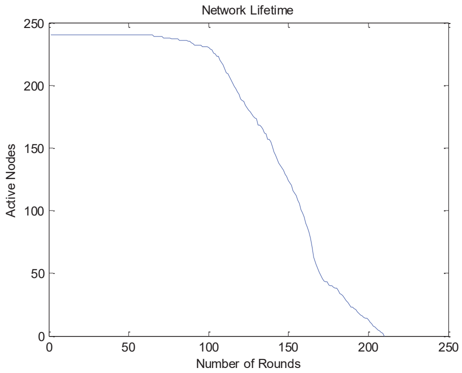


(a)

(b)

(c)

Fig. 7. Uniform distribution of 240 nodes around the perimeter of the investigated region. (a) Cluster formation scenario 1; Non-hierarchical formation. (b) Cluster formation scenario 4; Level 3 hierarchy. (c) Cluster formation scenario 7; Level 6 hierarchy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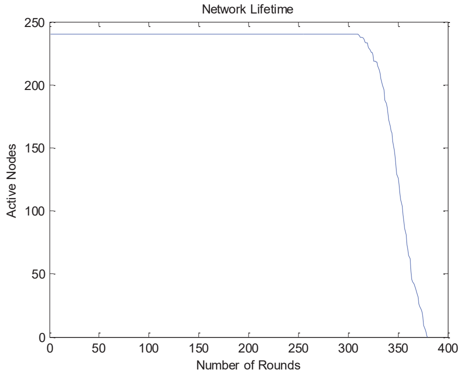
50
100
150
200
250
Number of Rounds
0
50
100
150
200
250

(a)


Network Lifetime
Active Nodes
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250
Number of Rounds
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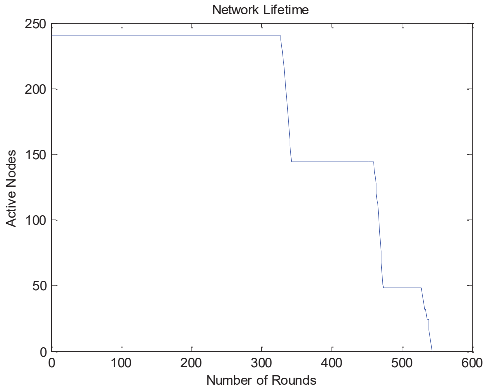
50
100
150
200
250
300
350
400

(b)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Number of Rounds
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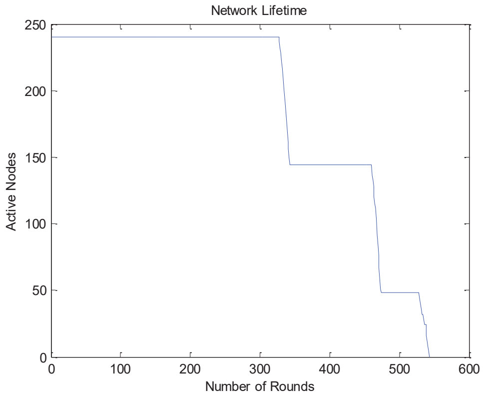
500
600

(c)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250
Number of Rounds
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100
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300
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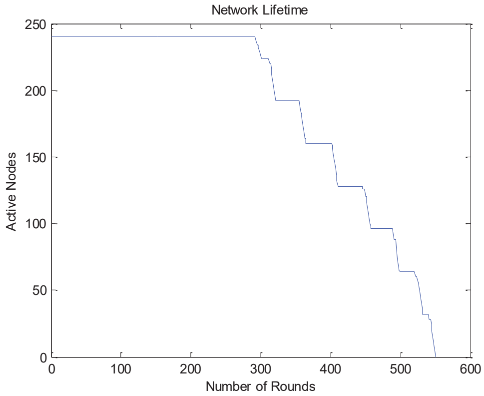
500
600

(d)


Network Lifetime
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200
250
Number of Rounds
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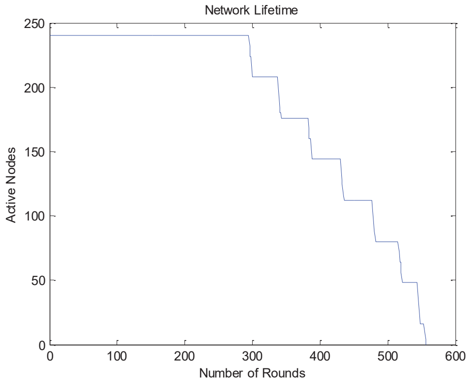
100
200
300
400
500
600

(e)


Network Lifetime
Active Nodes
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150
200
250
Number of Rounds
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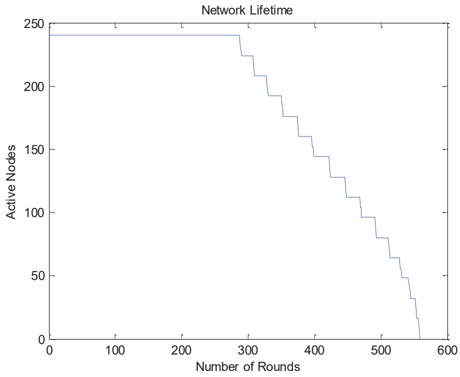
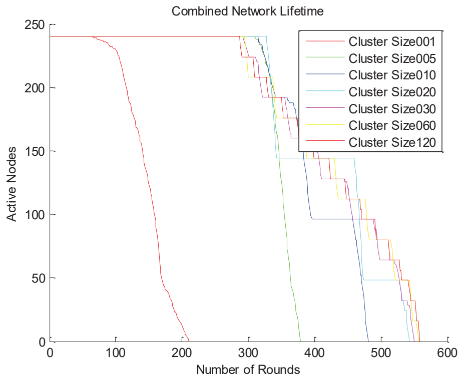
100
200
300
400
500
600

(f)

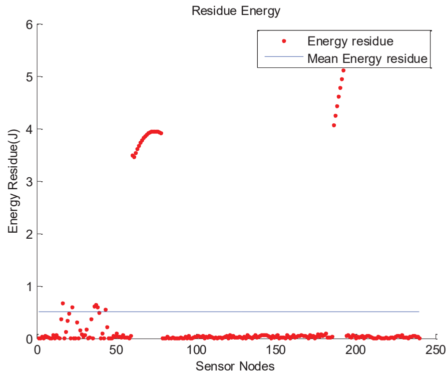


(g)

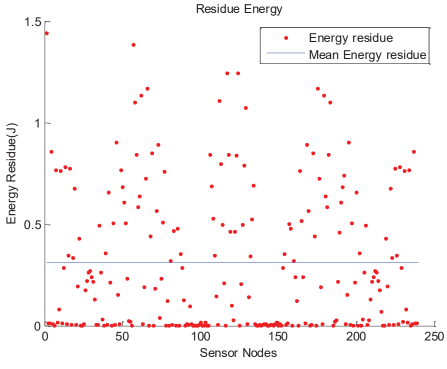


(h)

Fig. 8. (a) Network Lifetime for the non-hierarchical scenario. (b) Network Lifetime for level 1 hierarchy scenario. (c) Network Lifetime for level 2 scenario. (d) Network Lifetime for level 3 scenario. (e) Network Lifetime for level 4 scenario. (f) Network Lifetime for level 5 scenario. (g) Network Lifetime for level 6 scenario. (h) Combined Network Lifetime scenarios



(a)



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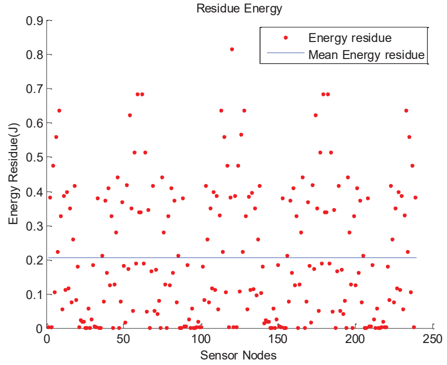

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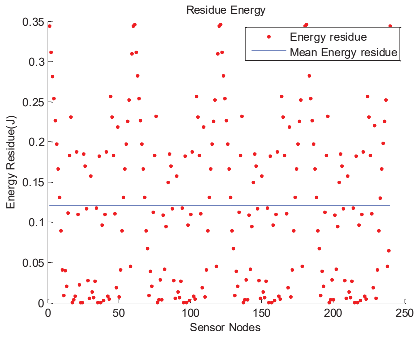

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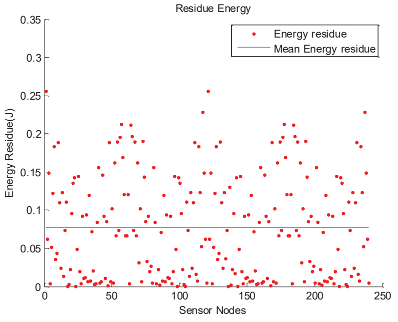

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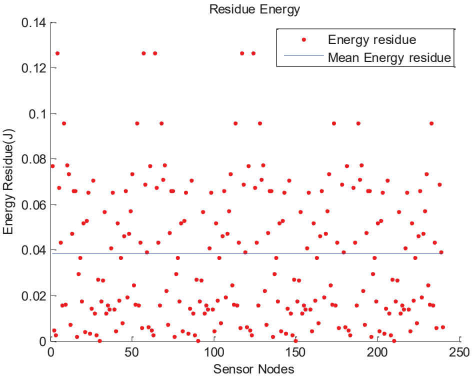
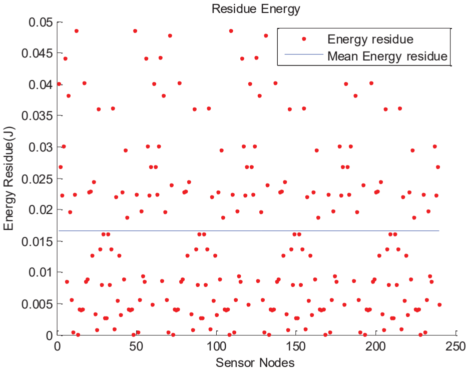
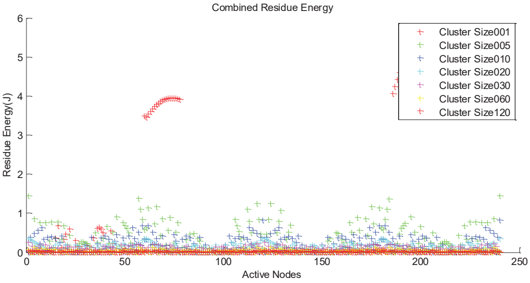


(f)

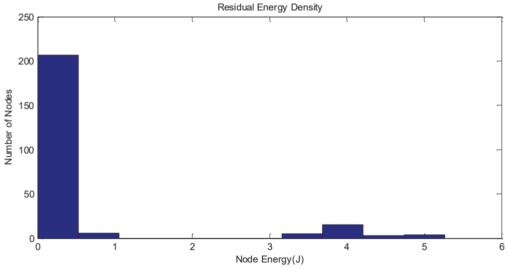


(g)

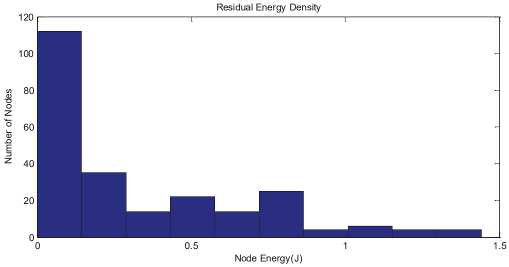


(h)

Fig. 9. (a) Nodes residue energy in non-hierarchical technique. (b) Nodes residue energy in level 1 hierarchy. (c) Nodes residue energy in level 2 hierarchy. (d) Nodes residue energy in level 3 hierarchy. (e) Nodes residue energy in level 4 hierarchy. (f) Nodes residue energy in level 5 hierarchy. (g) Nodes residue energy in level 6 hierarchy. (h) Combined nodes residue energy



(a)



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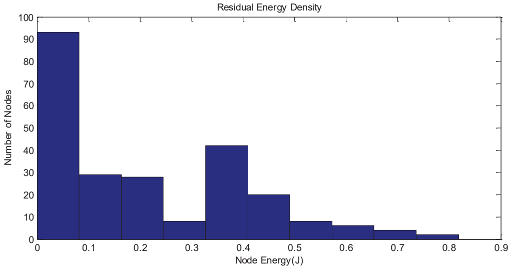

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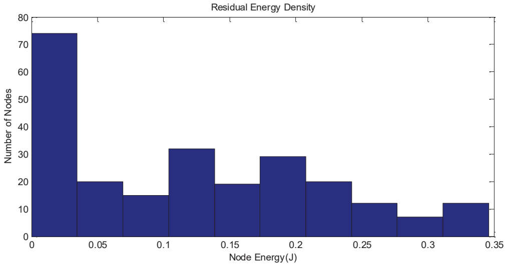

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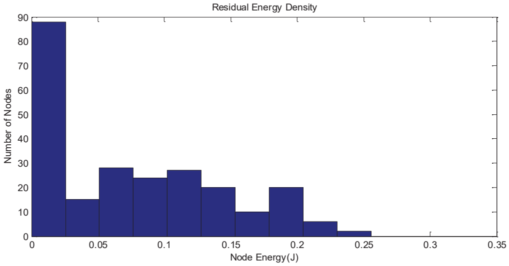

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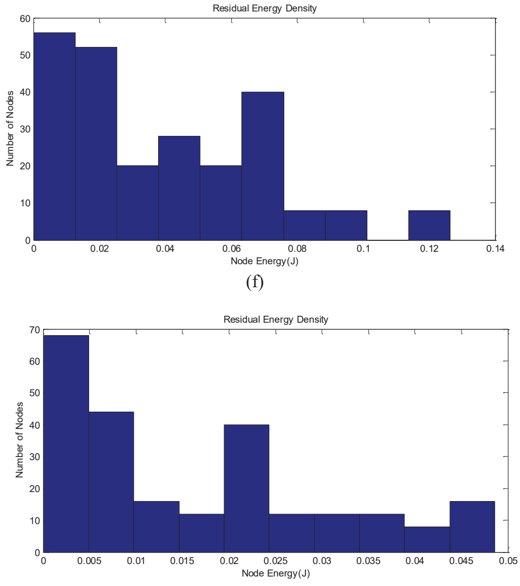

(f)

(g)

Fig. 10. Chart of (a) Residual energy for the non-hierarchical technique. (b) Residual energy for level 1 hierarchy. (c) Residual energy for level 2 hierarchy. (d) Residual energy for level 3 hierarchy. (e) Residual energy for level 4 hierarchy. (f) Residual energy for level 5 hierarchy. (g) Residual energy for level 6 hierarchy

TABLE III
RELATIONSHIP BETWEEN CLUSTER SIZE AND ROUNDS IN THE PROPOSED HIERARCHY-BASED ROUTING PROTOCOL

Level of Hierarchy	**Cluster size**	**Sensor per cluster**	**Number of Rounds**
Non-hierarchical	1	240	210
Level 1 hierarchy	5	48	380
Level 2 hierarchy	10	24	481
Level 3 hierarchy	20	12	543
Level 4 hierarchy	30	8	550
Level 5 hierarchy	60	4	557
Level 6 hierarchy	120	2	559

TABLE IV
MEAN, RANGE, AND VARIANCE OF THE RESIDUAL ENERGY OF THE ROUTING TECHNIQUES INVESTIGATED

Routing Technique	**Mean (J)**	**Variance (J)**	**Range (J)**
Non-hierarchical	0.5108	1.6449	5.2667
Level 1 hierarchy	0.3139	0.1322	1.4415
Level 2 hierarchy	0.2061	0.0385	0.8176
Level 3 hierarchy	0.1211	0.0101	0.3460
Level 4 hierarchy	0.0777	0.0045	0.2554
Level 5 hierarchy	0.0385	0.0009553	0.1263
Level 6 hierarchy	0.0166	0.0001891	0.0485

B. Discussion of Results

In this section, we discuss the results of the study. A comparison of the non-hierarchical and the hierarchical routing protocol was carried out for the developed perimeter surveillance network model, and an investigation into the best level of network hierarchy, concerning the network lifetime and sensor node residual energy, was determined by increasing the cluster size to 5, 10, 20, 30, 60 and 120. Fig. 7 gives the uniform distribution of 240 nodes around the perimeter of the investigated region. In particular, Fig. 7(a) shows cluster formation scenario 1 for the non-hierarchical formation. Here, the nodes are denoted by a uniform red color across the perimeter of the region. Fig. 7(b) depicts the cluster formation scenario 4 for the Level 3 hierarchy. Twelve identical nodes denoted by the same colors are arranged closely, and this is repeated for several nodes 20 times to accommodate the 240 nodes tested. In Fig. 7(c), the cluster formation scenario 7 for the Level 6 hierarchy is presented. The nodes of the same colors are paired and arranged in that order for the 240 nodes. The 240 nodes were uniformly distributed around the perimeter of the experimental region. Other formation scenarios are not shown for brevity. It is worthy of note that the observed region's dimensioning allows room for the simulated nodes.

Fig. 8(a) illustrates the network lifetime for the non-hierarchical scenario. The 240 active nodes were fairly stable up to the 50th round before falling steeply until the 210th round. Fig. 8(b) gives the network lifetime for the level 1 hierarchy scenario. Here, the nodes maintained a stable condition up to the 310th round before dying out drastically from this point onward. Fig. 8(c) presents the network lifetime for the level 2 scenario. The nodes appear to be stable throughout the first 320 rounds. Afterward, the nodes fall stepwise until the 340th round and remain temporarily stable until the 480th round. Short stability was seen before dying out at the 550th round. Fig. 8(d) shows the network lifetime for the level 3 scenario. Interestingly, Fig. 8(c) and Fig. 8(d) exhibit similar characteristics. Figure 8(e) represents the network lifetime for the level 4 scenario. Fig. 8(f) gives the network lifetime for the level 5 scenario. Fig. 8(g) presents the network lifetime for the level 6 scenario. Fig. 8(e) to Fig. 8(g) follow a similar trend. Each starts to die out at around the 290th round. Figures 8(e) and (f) show almost the same steps, whereas Fig. 8(g) has more steps before dying out at around 559th round. Finally, Fig. 8(h) shows the combined network lifetime scenarios.

As shown in Fig. 8(a) to (g), the lifetime of the non-hierarchical, 1, 2, 3, 4, 5, and 6 level hierarchy-based networks span 210, 380, 481, 543, 550, 557, and 559 transmission rounds, respectively. Hence, the proposed hierarchical network performs better than the non-hierarchical technique for perimeter surveillance. Besides, it was shown that the proposed technique gives an optimal network lifetime for the six-level hierarchy with 120 clusters and two sensors per cluster since it has the maximum 559 rounds of simulation and has the most prolonged period before the last node in the network runs out of energy, compared to the other scenarios. Hence, increasing the cluster size increases the network lifecycle.

Based on the results shown in Fig. 9(a) to (h), the nodes residue energy in the non-hierarchical technique appears to be quite different from the nodes residue energy in the levels 1-6 hierarchies. The levels 1-6 hierarchies show a somewhat similar spread of the nodes across the energy spectra. However, the sensor nodes appear to concentrate more at the least residue energy for the various levels of hierarchies investigated. Overall, the density of the sensor nodes at the region with the least residue energy is more evident with the non-hierarchical technique.

Additionally, as can be seen in Fig. 10 (a) to (g), the higher number of sensor nodes concentrate at the regions with the least node energy, as in Fig. 9 (a) to (g).

From the preceding results, it can be inferred that the maximum possible cluster size will yield the optimal and energy-efficient hierarchy in the perimeter sensor network. Although there is a close margin, a difference of two rounds of simulation between the lifetime of the fifth (557) and sixth (559) hierarchical levels are observed, as shown in Table III. Interestingly, this result compares favourably with earlier results reported by Heinzelman *et al.* [6].

Furthermore, the proposed hierarchical protocol was compared with the non-hierarchical technique using the residual energy metric in each sensor node for the round of simulations attained in each scenario. Figure 9(a) to (g) revealed that the mean values of the residual energy of the entire sensor nodes are lower for the hierarchical-based approach than the values recorded for the non-hierarchical network. Again, this indicates that implementing the proposed hierarchical technique results in an appreciable improvement in the lifetime of the network.

The mean, variance, and range of the residual energy after 700 rounds of simulations for the non-hierarchical and the hierarchical routing techniques are presented in Table IV. It is worthy of note that the level 6 hierarchical scenario produced the best outcome of all the other hierarchical scenarios in terms of the lowest mean residue energy value of sensor nodes. This indicates that a network with a greater energy balance level is obtained with an increasing hierarchy level as the sensors have been put to optimal use before dying out.

Moreover, the residual energy variance decreases with an increasing level of network hierarchy. The non-hierarchical case and the level 6 hierarchy take the highest and lowest residue energy variances, respectively. Again, it can be inferred from Table IV that the standard deviations - the square root of the variance- of the residual energy of the network decrease from approximately 1.2825 for the non-hierarchical to approximately 0.01375 for the level 6 hierarchy. The lowest standard deviation value of the level 6 hierarchy indicates that the perimeter network scenario maximizes its nodes' initial energy using this algorithm.

After the simulations, a high value indicates that the sensors' starting energies are not maximally utilized before the nodes died out for the residual energy range. It is observed that the non-hierarchical scenario has the most significant residue energy range value. It is, therefore, the least energy-efficient of all the scenarios.

Finally, Figure 10 (a) to (g) are histograms of the nodes residual energy for the non-hierarchical case and the hierarchical cases after 700 rounds of simulations. They are descriptive of the number of nodes and their amount of residual energy for each perimeter network scenario. Notice that the widths of the histogram bars are not the same. The highest number of nodes appear to be at the least node energy for all the tested scenarios. Only fewer nodes are observed at higher node energy.

V. Conclusion

The importance of wireless distributed microsensor systems in facilitating reliable and efficient monitoring of safety-critical infrastructure cannot be overemphasized. However, the conventional routing protocols consisting of direct transmission, minimum-transmission-energy, multihop routing, and static clustering are no longer optimal for wireless sensor network applications. To address this problem, this study is focused on the development of an energy-efficient, hierarchy–based wireless sensor network model for perimeter surveillance. This is aimed at improving performance–reduction in the energy consumed by sensor nodes and enhancing network durability–elongation of the lifetime of the node. The proposed model modifies the low–energy adaptive clustering hierarchy protocol in terms of hierarchical data transfer via any shortest path to the base station (BS) placed at the testing region center. This is achieved by using an efficient energy prediction tool for cluster head (CH) selection. CH selection within each cluster formed at all levels is done by the election of a node that requires the least transmission energy for a particular transmission round. A multi-hop communication protocol was employed for data transmission from the regular nodes (RNs) to the CH in each cluster and from the CHs to the BS in the entire network to reduce transmission costs. The simulation results reveal that an energy-efficient perimeter surveillance system could be achieved with the proposed hierarchical-based WSN protocol. Additionally, results show that the evolved technique offers a significantly better performance as per energy efficiency compared to the non-hierarchical protocol.

Furthermore, the proposed routing protocol prolongs the network lifetime to an appreciably level, as validated by experiments and simulations. Finally, the optimal level of hierarchy has been determined. Future work would focus on deriving the energy-level models when the base and mobile stations are located outside the experimental region.

Acknowledgments

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