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Impact of Node Deployment and Routing for Protection of Critical Infrastructures

FAZLI SUBHAN[1], **MADIHA NOREEN**[1], **MUHAMMAD IMRAN**[2], **MOEENUDDIN TARIQ**[1], **ASFANDYAR KHAN**[3], **AND MUHAMMAD SHOAIB**[2]
[1]Department of Computer Science, National University of Modern Languages, Islamabad 44000, Pakistan
[2]College of Computer and Information Sciences, King Saud University, Riyadh 11451, Saudi Arabia
[3]IBMS, The University of Agriculture Peshawar, Peshawar 25000, Pakistan

Corresponding authors: Fazli Subhan (fsubhan@numl.edu.pk) and Muhammad Imran (dr.m.imran@ieee.org)

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ABSTRACT Recently, linear wireless sensor networks (LWSNs) have been eliciting increasing attention because of their suitability for applications such as the protection of critical infrastructures. Most of these applications require LWSN to remain operational for a longer period. However, the non-replenishable limited battery power of sensor nodes does not allow them to meet these expectations. Therefore, a shorter network lifetime is one of the most prominent barriers in large-scale deployment of LWSN. Unlike most existing studies, in this paper, we analyze the impact of node placement and clustering on LWSN network lifetime. First, we categorize and classify existing node placement and clustering schemes for LWSN and introduce various topologies for disparate applications. Then, we highlight the peculiarities of LWSN applications and discuss their unique characteristics. Several application domains of LWSN are described. We present three node placement strategies (i.e., linear sequential, linear parallel, and grid) and various deployment methods such as random, uniform, decreasing distance, and triangular. Extensive simulation experiments are conducted to analyze the performance of the three state-of-the-art routing protocols in the context of node deployment strategies and methods. The experimental results demonstrate that the node deployment strategies and methods significantly affect LWSN lifetime.

INDEX TERMS Linear wireless sensor networks, node placement, clustering, network lifetime, energy efficiency, performance analysis.

I. INTRODUCTION

Monitoring and protection of critical infrastructure [1] have become vital issues in recent years. The internet of things (IoT) [2], [3] is an emerging paradigm that uses various technologies including wireless sensor networks (WSNs) for protection of critical infrastructures. Thus, researchers have identified and distinguished a disparate class of WSN applications based on the geometry of the deployment region. Such applications include real-time monitoring of pipelines [4] (e.g., oil, gas, water, and sewerage), international borders, railway tracks, tunnels, bridges, and high-power transmission and distribution cables [5]. Unlike traditional WSNs, real-time monitoring in these applications necessitates linear placement of sensor nodes to determine and report an event of interest to the base station (BS). Most of these applications require linear WSN (LWSN) to stay operational for a longer period. A trivial approach might be to employ rechargeable nodes or sensors with unlimited battery power. However, the approach may not be feasible or practical because of higher cost and limited battery capacity. The non-replenishable limited battery power of sensor nodes does not allow them to meet these expectations. Consequently, a short network lifetime is one of the most prominent barriers in deploying LWSN for large-scale deployment.

In LWSN, network lifetime relies primarily on node placement and clustering because both can cause non-uniform energy consumption and thus, shorter network lifetime. Efficient node placement may further enhance energy efficiency to maximize network lifetime. Similarly, selection of routing protocol, which is compatible with the node placement scheme will increase overall network performance. Node placement [6] is considered the most important component that can cause non-uniform energy consumption. Most existing WSN node placement schemes can be categorized into random, uniform, and non-uniform deployment. Unlike conventional WSN applications, random node distribution in

LWSN might not be feasible for large-scale deployment especially in case of static sensors [7]. Uniform placement schemes deploy nodes at equal distance. However, nodes near the BS deplete their energy rapidly because of additional data forwarding overhead from far sensors. Therefore, to prolong network lifetime, appropriate node placement and routing schemes must be designed to balance energy consumption in LWSN.

Similarly, clustering protocols proposed for conventional WSNs may not be suitable for linear WSNs because of various peculiarities such as direct data transmission from sensors to the BS may not be practical or feasible due to limited transmission range of sensors and energy constraints. Therefore, multi-hop communication is an inherent choice in which sensors transmit collected data to neighboring nodes towards the BS. However, unlike WSNs, alternative routing paths towards the BS [8] may not be available in LWSN especially in case of node failures, which may greatly affect overall network performance and lifetime. This situation occurs mainly because sensors near the BS deplete their energy quickly due to consistent data forwarding overhead of far nodes. Hence, the network becomes dysfunctional due to non-uniform energy consumption. Therefore, routing is another major concern in LWSNs in addition to node placement [9].

In this study, we analyze the effects of node placement and clustering on the performance of LWSN. First, we describe various characteristics of some prominent applications of LWSN for critical infrastructure monitoring and highlight their peculiarities. Then, we categorize and classify various node placement strategies that are suitable for various LWSN applications. Furthermore, a brief working description of recent prominent WSN clustering protocols is presented in the context of LWSN. Finally, we analyze the performance of various LWSN node placement techniques and comparative analysis of clustering protocols. To the best of our knowledge, none of the existing studies have analyzed the performance of clustering protocols for various topologies of LWSN.

The organization of this paper is as follows. Section 2 describes recent relevant literature on node placement and clustering in LWSN. Section 3 provides a brief description of some prominent applications of LWSN. Section 4 categorizes node placement strategies in LWSN. Section 5 presents descriptions of some existing clustering protocols. Section 6 analyzes our experimental result. Section 7 outlines the concluding remarks.

II. RELATED WORK

As stated earlier, the protection of critical infrastructures is a growing concern, and various technologies are used to monitor them. For example, Liu and Kleiner [10] investigated the technologies that can be used specifically for pipe and structural health monitoring. The scope of our work is broader in terms of LWSN applications, and we focused specifically on node placement and clustering issues. Although these approaches have been extensively investigated in [11]–[14] in the WSN context, they are still in their infancy in the LWSN context. A linear wireless sensor and actor network framework for autonomous monitoring and maintenance of lifeline infrastructures was proposed in [15]. However, the proposed framework did not address specific issues of node placement, routing, and clustering. Moreover, some of the existing schemes are generic and do not consider LWSN peculiarities; thus, they may not be feasible. Some efforts in LWSN have been conducted in various aspects; however, node placement and clustering require further investigation. Energy efficiency and network lifetime highly depend on node placement and clustering. Therefore, in this section, we focus on node placement schemes and clustering.

A. NODE PLACEMENT STRATEGIES IN LWSN

As stated earlier, node placement dominates the performance and network lifetime of LWSN in various terms, such as throughput, coverage, and connectivity. Various node placement strategies have been proposed in the LWSN context. For example, Skulic *et al.* [16] investigated an unbalanced data traffic distribution problem that results in network disconnection and proposed a solution by optimizing the positions of sensor nodes that reduce the overall energy consumption and extend the network lifetime. To balance energy consumption, a decreasing distance node deployment strategy was proposed for linear sequential WSN in [7]. The proposed strategy gradually reduces the distance between nodes towards the BS. By contrast, we analyze the performance of routing algorithms in various topology configurations such as linear parallel and grid. Hong and Xu [17] discussed uniform node placement scheme and found that the nodes near the BS die more quickly as compared with the nodes that are far from BS because the nodes near the BS have extra loads of data forwarding. To optimize energy use and improve network lifetime, a circular node deployment scheme was presented in [18] that reduce the load overhead a same node. A linear node placement scheme for oil pipeline monitoring was presented in [19] to improve network lifetime. The authors formulated equal-power placement as a mixed integer linear programming problem and showed that it can outperform equal-distance deployment schemes. To improve coverage, a node placement optimization for WSN was presented in [20] for a linear topology. Unlike [20], the focus of our work is on maximizing network lifetime by routing and node deployment. Mohamed *et al.* [21] investigated the issues of uniform node deployment in LWSN and proposed an analytical model that provides reliability analysis. Unlike most of the existing studies that only focus on node placement we also consider routing issues in the LWSN context.

B. CLUSTERING

In general, routing has been investigated extensively in various contexts of WSN. For example, an exhaustive survey of routing protocols for terrestrial WSN was recently presented in [22]. Similarly, various routing approaches [23] to balance energy consumption in underwater WSN have also been proposed recently. To boost routing performance, some approaches [24] used sink mobility. However, topological constraints in LWSN represent a challenging problem because alternative paths toward the BS may not be available. The focus of our work is specifically on LWSN clustering because it is an imperative design issue that has significant implications on network lifetime. An effective clustering protocol should strive to balance the energy consumption of sensor nodes. The reduction in the exhaustion of energy is performed by cluster heads. Therefore, most WSN clustering protocols may not be applicable in most LWSN applications. To increase network reliability and communication efficiency, a low energy adaptive clustering hierarchy (LEACH) was presented in [25]. To reduce energy consumption and increase network lifetime, LEACH used a few sensor nodes as cluster heads randomly on the base of probability. However, LEACH is not implemented in a linearly enhanced network. Javaid *et al.* [26] presented a clustering scheme for an energy-efficient clustering protocol. In this scheme, cluster head selection is based on a threshold value of nodes. Each node generates a random number if the number is less than or equal to the threshold value; when a node has not become a cluster head for last round, the node is marked to become a cluster head. A new linear clustering technique is presented in [27]. In this technique, each node has an equal chance to come a cluster head for the current round. However, CH election is based on the adjusted value of the threshold. Moreover, the increased network lifetime reduced the communication distance between cluster heads, and the sink nodes used multiple static sinks. For every iteration, CH collected data and sent it to the nearest sink. Another energy-efficient routing protocol, link aware clustering mechanism (LCM), has been proposed [28] to support the node and cluster formation and provide an idea of a predetermined count of transmissions (PTX). PTX is used to determine the priority of each CH. LCM selects the CH on the basis of derived priority. A survey on routing and clustering optimization techniques in WSN was presented in [29]. A routing performance and usage aware protocol was proposed for tunnel monitoring in [30]. Performance and usage-aware routing is suitable to monitor the sensor nodes that have long distance and linear structure. A recent study [31] presented chain-based routing schemes for single-, two-, and four-chain cylindrical underground sensor networks. However, node deployment was not considered in this study. These are few examples of existing LWSN clustering and routing protocols that work on the basis of energy efficiency and maximizing network lifetime. As we discussed previously, conventional clustering schemes may not be suitable for LWSN. In these scans, finding a full-fledged LWSN clustering base routing protocol that can be used for different conditions and applications is more difficult.

III. APPLICATIONS OF LINEAR WIRELESS SENSOR NETWORKS

This section briefly describes some prominent applications of LWSN and emphasizes their peculiarities compared with generic WSN applications, thereby facilitating improved understanding of LWSN topology. Moreover, the purpose is to demonstrate the feasibility and suitability of LWSN for real-time monitoring of critical infrastructures.

A. PIPELINE (OIL, GAS, AND WATER) MONITORING

The progress and economy of many countries at present depend considerably on their oil, water, and gas pipelines. In numerous countries, long pipelines are used for various purposes. For example, long pipelines are used to exchange water from desalination plants, which are usually close to the ocean, to metropolises that are not close to the ocean. Riyadh, the capital of Saudi Arabia, is totally dependent on water that is transferred through a network of pipes that are more than 3,800 km from the Shuoiba Desalination Plant [32], [33]. Saudi Arabia is reported to rely on more than 4000 km of pipeline to transport water from many desalination plants in the kingdom. Thus, Saudi Arabia is a worldwide leader in water desalination. Reference [34] formulated the Langeled pipeline with a length of 1,200 km that extended from the Ormen Lange field in Norway to the Easington Gas Terminal in England; England fulfills 20% of their gas needs through this pipeline. This study reported another long pipeline used by Qatar and the UAE. This pipeline is 367 km long and fulfills much of the UAE's gas needs. Mohamed and Jawhar [35] investigated the gas and oil pipelines extended around the United States, which are 800,000 km long. These oil and gas pipelines have a significant effect on the United States economy. However, these gas and oil pipelines need regular measurement and monitoring to ensure their proper operation and fault-free transmission. Manually finding the fault (assuming any) in these pipelines in exact locations is a difficult and time-consuming process. Some examples of these measurements are liquid leakages, bursts, pipeline corrosion detection, pipeline protection cameras, temperature, flow, and other anomaly measurements [36]. Thus, by using LWSNs, sensor nodes can easily and rapidly detect all faults that occur in pipeline infrastructure through real-time monitoring.

B. RAILROAD/SUBWAY AND BRIDGE MONITORING

Observing, supervision, and control of railways and metros are another task for LWSNs. Long distance travel via travel and luggage rail transportation is effective, affordable, and convenient in terms of expense, capacity, and use of space [37]. Population growth needs the quick deployment and services of long-distance railway tracks and bridges worldwide. As of 2010, all railroad monitoring railways. Here, staff members observe a particular distance of railroad for a specific period. Monitoring railroad tracks scattered over a huge number of miles is impossible, and continuous monitoring is not feasible with traditional methods. Therefore, improve the current monitoring systems is needed to make them relentless, reliable, and efficient; this situation can be achieved by using WSNs. Therefore, sensor nodes can be deployed for efficient monitoring of railroad tracks. WSNs can be used for monitoring railroad infrastructure, such as cracks in rail tracks, railway beds, and track equipment alongside obstruction discovery. The use of WSNs in railway monitoring provides a persistent perception for the railway track, regardless of its length. In this manner, the network cost will be diminished because of the use of wireless communication; the less power, the cheaper and smaller the sensor nodes. By contrast, the use of sensor nodes decreases the need for human investigation by automated monitoring and enhances safety and reliability. A railroad security framework is proposed in [38], in terms of WSNs that used electromagnetic and ultrasonic sensors, the collected data were sent to control centers and security is set up accordingly. Lee *et al.* [39] reported the distribution of fiber optic sensors on critical components in the railroad bridge superstructure of a railroad connection. Hodge *et al.* [40] employ WSN for railway track monitoring.

C. MONITORING OF VEHICULAR ACTIVITIES

At present, the quantity of vehicles has expanded quickly. However, the bedrock capability of streets and transportation frameworks have not developed equally to manage easily the number of vehicles that use them. Thus, road jamming, traffic accidents, and pollution have increased, thereby resulting in a non-negligible impact on the economy, the environment, and people. Roadway frameworks in any metropolis are essential in determining the physical structure of the metropolis. Furthermore, they highly affect how people move from one station to another. Thus, traffic congestion is an urgent challenge in many urban areas because of the rapid development of vehicles. Traffic congestion results in many problems in a life cycle. Traffic congestion can result in economic losses and increased air pollution. Therefore, traffic monitoring is important in avoiding traffic congestion. Compared with alternative networks, WSNs are inexpensive because of their faster exchange of data, simpler deployment, lower power consumption, and easier maintenance. In WSN use in traffic, congestion and accidents have been reduced. Sensors can continuously detect many factors such as speed, accidents, and flow of a vehicle. For traffic monitoring, a petrol control algorithm proposed in [41]. Reference [42] presented a comprehensive review of WSN-based intelligent transportation systems (ITS) for real-time traffic monitoring. Reference [43] reported vehicle real-time monitoring based on ITS used for detecting vehicle activities. Here, vehicle detection was based on WSN using an isometric magnetic resistive (AMR) sensor. The aim of AMR is to achieve an inexpensive, easy to coordinate, robust, flexible, and low maintenance wireless solution for vehicle detection.

D. BORDER MONITORING

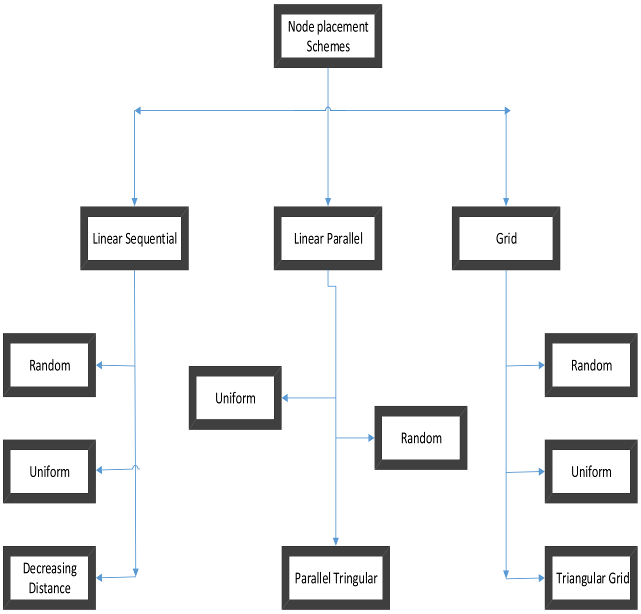


FIGURE 1. Overview of LWSN node placement schemes.

For activities such as terrorism, illegal drugs, illegal immigration, smuggling of goods, and unauthorized border crossing, international border monitoring is critical. LWSNs can also be used in border monitoring. Borders are extremely vulnerable and prone to terrorist attacks. The protection of long stretches borders has posed challenges. A traditional method for border inspection consists of security checkpoints. Different checkpoints are used on international roads to investigate the vehicles and persons that cross the border. This traditional method for border monitoring is not cost-effective and requires considerable time and effort, especially on long borders or severe environments. For example, the longest international border is the Canada–USA border, at 8,891 km long [37]. Adopting the traditional method increases the difficulty in constantly monitoring all border regions. Effective and continuous monitoring of a border requires the implementation of multi-surveillance technologies, such as WSNs, that operate as an integrated unit to meet the desired goals. Furthermore, LWSNs can be used to compensate for the limitations of the existing monitoring techniques. Sensors are used to monitor environmental conditions. The use of sensor nodes facilitates the easy continuous monitoring of the border and will reduce the border patrol's time, staff, and effort. Hammoudeh *et al.* [44] investigated some sensor deployment issues for border monitoring and designed a cross-layer routing protocol that is used to continuously monitor the border efficiently. A routing protocol for border surveillance was designed in [45].

IV. NODE PLACEMENT SCHEMES

As mentioned earlier, LWSN lifetime depend primarily on node placement. This section describes various node placement strategies that are suitable for disparate applications. Figure 1 presents taxonomy of node deployment in LWSNs. Depending on the geometry of the applications, node placement schemes can be categorized into linear sequential, linear parallel, and grid. Each of them is described below.

A. LINEAR SEQUENTIAL DEPLOYMENT

Some applications of LWSN, such as monitoring of borders, bridges, and pipelines, need linear sequential deployment of sensor nodes. Sensor nodes in these applications are placed along the infrastructure a single line. Linear sequential deployment can be highly challenging in terms of perspectives such as deployment, network lifetime, and routing. For example, addressing node failure is a real challenge because of the unavailability of alternative paths. Generally, three different strategies are used to deploy nodes in linear sequential applications. Figure 2 demonstrates the linear sequential deployment of sensors in various configurations.

1) RANDOM

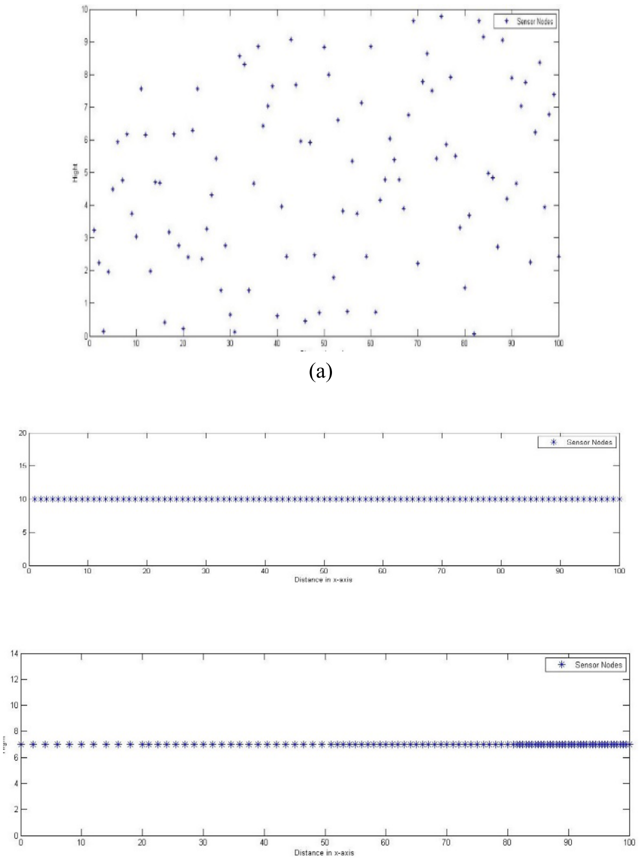
Most applications of LWSNs are hostile in nature, and the sensor nodes have to be deployed in inhospitable terrains. Such applications may include oil and gas pipelines, railway tracks, highways, and border monitoring. Most of these applications are the prime target of insurgents to sabotage critical economic infrastructure and disrupt lives of inhabitants. In these applications, planned deployment of sensors over thousands of miles is a real challenge because it may not only involve risk but also a cumbersome task. Random placement of sensors in such circumstances is a viable option. This process may involve moving vehicles, robots, and drones to place sensors randomly in the deployment region. Starting from one edge of the network segment, the position of the next sensor is determined randomly on the horizontal axis. To ensure connected coverage, the next node should be within the communication range of previous sensors. This procedure is executed recursively until all the nodes are placed. Figure 2(a) depicts a linear sequential random deployment scheme. Although random deployment is the only feasible choice in some circumstances, such placement may not satisfy essential design considerations such as coverage and connectivity, especially in the case of linear sequential configuration.

2) UNIFORM

The uniform node placement deploys sensor nodes at equal distance from each other. In other words, nodes are evenly distributed in a single line across the deployment region. Despite various merits of uniform deployment, it also suffers from uneven energy consumption; in particular, nodes near the BS quickly lose energy because of the extra load of data forwarding. This scheme is feasible for pre-planned and controlled deployment. Figure 2 (b) depicts a linear sequential uniform deployment scheme.

3) DECREASING DISTANCE

To address the problem of uneven energy consumption near the BS [7], the node placement scheme with linear sequential decreasing distance was proposed, in which the distance between sensor nodes is decreased gradually when nearing the BS. The design rationale is that increased node density near the BS will not only reduce the data forwarding overhead but also requires these sensors to transmit at shorter distances, thereby leading to energy conservation. Although this scheme is effective for LWSN, finding the optimum decreasing distance is a considerable challenge. Figure 2(c) depicts the scheme.



(a)

(c)

FIGURE 2. **(a) Linear sequential random deployment scheme. (b) Linear sequential uniform deployment scheme. (c) Node placement scheme with linear sequential decreasing distance.**

B. LINEAR PARALLEL DEPLOYMENT

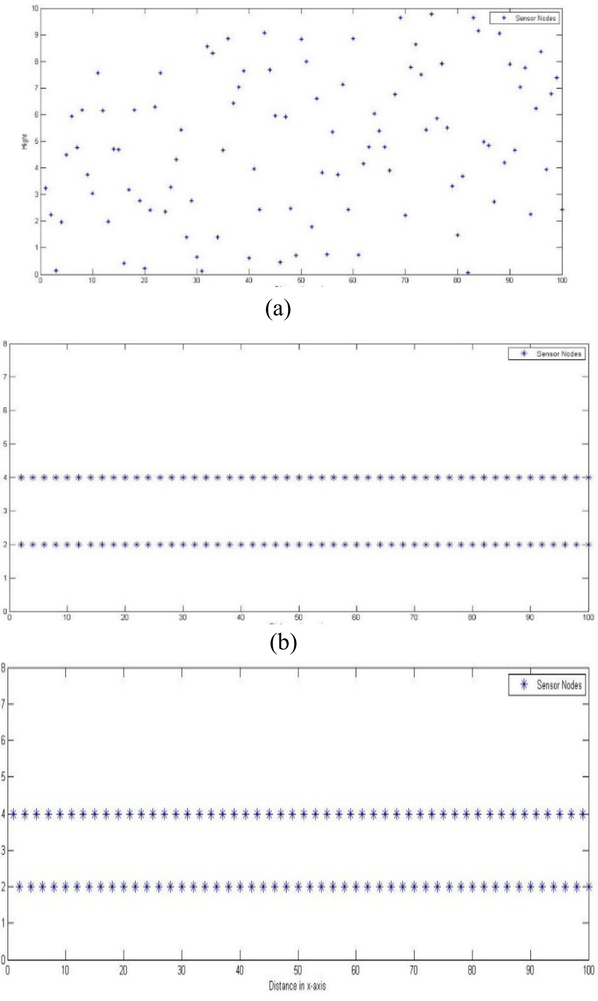
Some linear applications, such as railway track monitoring and highway road monitoring, require sensor node deployment in parallel. In this node deployment scheme, if any failure occurs, an alternative path is made for data forwarding. The main advantage of this scheme is the alternative route for data transfer. Figure 3 demonstrates the linear parallel deployment of sensors in various configurations.

1) RANDOM

In linear parallel random deployment, the sensor nodes are deployed randomly such that they lie in communication range with each other; if any fault occurs, an option exists for alternative routes for data forwarding. This scheme is suitable for vehicles activity monitoring on highways. Figure 3(a) depicts a linear parallel random deployment scheme.

2) UNIFORM

As stated earlier, the uniform node placement in an LWSN segment where all the nodes are placed at equal distance



(a)

(b)

(c)

FIGURE 3. **(a) Linear parallel random deployment scheme. (b) Linear parallel uniform node placement scheme. (c) Linear Parallel triangular node placement scheme.**

from each other. In the linear parallel uniform node placement scheme, two parallel lines are used, and nodes are placed at equal distances from each other. Thus, an alternative path is available; if any node fails, other nodes share its load. Parallel uniform node deployment is feasible for railway track monitoring. Figure 3(b) depicts a linear parallel uniform deployment scheme.

3) TRIANGULAR

Random and uniform schemes are unable to balance energy consumption, thereby prolonging LWSN lifetime. To overcome this problem, another scenario is used, in which nodes are placed in a triangular manner. In the parallel triangular node placement scheme, one node is placed in the middle of the next corresponding node. Thus, we achieve maximal coverage with the least number of sensors. If any fault occurs, many alternative paths are available for data transmission. This scheme maintains strong network connection. Figure 3(c) depicts the scheme.

C. GRID DEPLOYMENT

In this type, each node is connected to neighboring nodes along more than two dimensions. For data transfer, many alternative routes are available in case of failure. Paddy field monitoring systems are an example of this type of scheme. Figure 4 demonstrates the grid deployment of sensors in various configurations.

1) RANDOM

In grid random deployment, the sensor nodes are deployed randomly such that, they are in communication range with each other; if any fault occurs, many alternative paths are available for data forwarding. This scheme is suitable for battlefield monitoring. Figure 4 (a) depicts an example of the scheme.

2) UNIFORM

In this type, each node is connected to neighboring nodes along more than two dimensions with equal distance. This type of scheme is usually used in crop monitoring systems. Figure 4 (b) depicts an example of the scheme.

3) TRIANGULAR

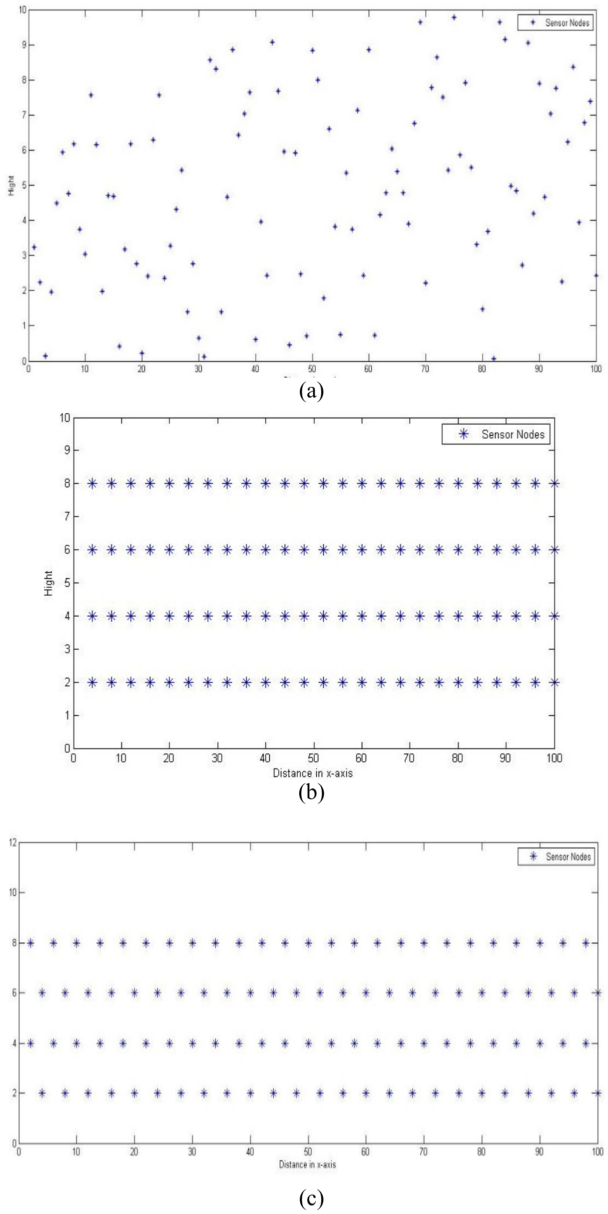
In this type, all nodes are placed in a triangular manner. This scheme is efficient for long LSNs because it has many alternative paths for data forwarding if any failure occurs. In this scheme, nodes have many minimum paths for data transmission to BS. In this scheme, all nodes share the traffic load because of network lifetime increase. When random and uniform schemes cannot balance energy consumption, we can apply this scheme to prolong network lifetime. Figure 4 (c) depicts a grid triangular node deployment scheme. It shows sensor node deployed in a grid with triangular shapes.

V. CLUSTERING PROTOCOLS FOR LWSNs

As mentioned earlier, the clustering protocol is pivotal in LWSN lifetime. In this section, we briefly describe three prominent clustering protocols and discuss their operation in case of LWSNs. These clustering protocols include distributed energy-efficient clustering (DEEC) [46], developed distributed energy-efficient clustering (DDEEC) [47], and energy efficient scheme for clustering protocol prolonging the lifetime of heterogeneous WSNs (TDEEC) [48].

A. DEEC

DEEC is a distributed energy-efficient clustering algorithm for heterogeneous WSNs. The main idea of this algorithm is to limit the energy consumption of sensors by adopting an optimal approach. The sensors must continuously report data to a remotely placed base station. DEEC roughly calculates the expected network lifetime based on the energy dissipated by each sensor during a round. It uses nodes with two different energy levels; that is, E0 refers to the initial energy of normal nodes, and $E0(1 + a)$ denotes the starting energy of advanced nodes. The probability of cluster-head selection is



(a)

(b)

(c)

FIGURE 4. **(a) Grid random node placement. (b) Grid uniform node placement scheme. (c) Triangular grid node placement scheme.**

based primarily on the ratio between the remaining energy of each sensor and the average network energy. To achieve an optimal count of cluster heads, the probability threshold that each sensor *si* uses to calculate for becoming a cluster-head in each round is as follows:

$$\mathrm{T(Si)} = \begin{cases} \dfrac{pi}{1 - pi(rmod\frac{1}{pi})} & \text{if si} \in \mathrm{G} \\ 0 & otherwise \end{cases} \tag{1}$$

Here, *G* is the group of sensors that are qualified to be cluster heads in round *r*. Each round *r* requires a sensor *si* to choose an arbitrary value amid 0 and 1 to determine its eligibility to be a cluster head. In case, the value is lower than the threshold T(*si*), the sensor *si* becomes a cluster-head during the present round. The cluster head dissipates more energy compared with other sensors. Thus, DEEC the role of cluster heads and prefers to delegate it to the sensors with high initial and residual energy, thereby resulting in increased network lifetime.

B. DDEEC

As stated earlier, DEEC continuously engages the advanced sensors to be cluster-heads until their remaining energy is almost equal with that of the normal sensors, thereby resulting in the early death of the advanced nodes. Thus, DDEEC strives to balance the cluster head selection process across the network based on the residual energy of nodes. Like its predecessor, DDEEC uses the same technique to estimate average network energy and choice of choosing the cluster head based on remaining energy. However, the main difference between them is the probability of using cluster heads for normal and advanced nodes, as stated earlier. The energy consumed by a sensor node to transmit a *L* bit packet over a distance *d* is given by the following equation:

$$E_{tx}(\mathrm{L, d}) = \begin{cases} LE_{elec} + LE\mathrm{fs}d^2 & if\ d < d0 \\ LE_{elec} + LE\mathrm{mp}d^4 & if\ d \geq d0 \end{cases} \tag{2}$$

where *Eelec* represents energy consumption per bit required by the transmitter (ETX). *Efs* and *Emp* denotes the energy required by the amplifier and distance between the sender and the receiver.

In DDEEC, the average energy of rth round for cluster head selection is given by the following:

$$\bar{E}(\mathrm{t}) = \frac{1}{N}\mathrm{Etotal}(1 - \frac{r}{R}) \tag{3}$$

where *R* denotes the total number of rounds used in network lifetime.

C. TDEEC

TDEEC operates on the same strategy for estimating the energy in the network as DEEC. TDEEC follows the concept of DEEC and adds another type of node, super nodes, to increase heterogeneity. The total initial energy of the networks is given by:

$$\begin{aligned} \mathrm{Etotal} &= \mathrm{N(1 - m).Eo + m.N.(1 + a)(1 - mo).Eo} \\ &\quad + \mathrm{N.m.mo.Eo} \\ \mathrm{(1 + b)} &= \mathrm{N.Eo(1 + m(a + mo.b))} \end{aligned} \tag{4}$$

In TDEEC, authors adjusted the value of the threshold, based on which a node decides to become a cluster head or not, following the ratio of the residual energy of node and the average energy of that round with respect to the optimum number of cluster heads. Thus, only the nodes with high energy become cluster heads.

$$\mathrm{T(s)} = \begin{cases} \dfrac{\mathrm{p}}{1-\mathrm{p}\left(\mathrm{r\ mod}\frac{1}{\mathrm{p}}\right)} \\ \quad * \dfrac{\text{Residdual Energy of a node} * \mathrm{k_{opt}}}{\text{Averageenergyofnetwork}}, & \text{if } \mathrm{s} \in \mathrm{G} \\ 0 \quad \text{Otherwise} \end{cases} \tag{5}$$

The probabilities of normal and advanced nodes in case of two level heterogeneity are:

$$\mathrm{Pi} = \begin{cases} \dfrac{\mathrm{PoptEi(r)}}{(1+\mathrm{am})\bar{\mathrm{E}}(\mathrm{r})} & \textit{if Si is the normal nodes} \\ \dfrac{(1+\mathrm{a})\mathrm{poptEi\ (r)}}{(1+\mathrm{am})\bar{\mathrm{E}}(\mathrm{r})} & \textit{if Si is the advance nodes} \end{cases} \tag{6}$$

The probabilities of normal, advanced and super nodes in case of two-level heterogeneity are:

$$\mathrm{pi} = \begin{cases} \dfrac{\mathrm{poptEi(r)}}{(1+\mathrm{m.\ (a+mo.b)})\bar{\mathrm{E}}(\mathrm{r})} & \text{if si is normal node} \\ \dfrac{(1+\mathrm{a})\mathrm{poptEi(r}}{(1+\mathrm{m.\ (a+mo.b)})\bar{\mathrm{E}}(\mathrm{r})} & \text{if si is advance node} \\ \dfrac{(1+\mathrm{b})\mathrm{poptEi(r)}}{(1+\mathrm{m.\ (a+mo.b)})\bar{\mathrm{E}}(\mathrm{r})} & \text{if si is the super node} \end{cases} \tag{7}$$

The probability of a node to be a cluster head in case of multilevel heterogeneity is given by:

$$\mathrm{Pi} = \frac{PoptN(1+ai)Ei(r)}{(N+\sum_{i=1}^{N} ai)\bar{E}(r)} \tag{8}$$

Threshold for cluster head selection is calculated for each type of heterogeneity by putting above values pi of Eq. (6), (7) and (8) in Eq. (5).

VI. EXPERIMENT SETUP AND RESULTS ANALYSIS

To analyze the comparative performance of the DEEC, DDEEC, and TDEEC in LWSN, this section describes the experimental setup, performance metrics, and analysis of experimental results. We develop a customized LWSN simulator to perform experiments. The deployment region is considered 100 m X 10 m. Simulation experiments involve 100 sensor nodes that use using different deployment schemes, as mentioned earlier. During deployment, we ensure connectivity of all sensor nodes. All simulation parameters remain the same throughout the experiments unless stated otherwise. All sensor nodes have an initial energy of 0.5 J. A sensor is considered dead if its energy level becomes 0 J. Table 1 shows various simulation parameters that are similar to [46].

We use two performance metrics, namely, the number of dead and alive nodes, to evaluate the performance of the deployment scheme. The earlier the nodes die, the lower the network lifetime. The number of rounds is used to gauge the network lifetime; that is, a higher number of alive nodes for an extended number of rounds indicates the increased network lifetime. The total number of rounds was kept at 5000 during all experiments.

TABLE 1. Simulation parameters.

Parameters	value
Network field	100 m×10 m
Number of nodes	100
Energy dissipated	5 nJ/bit
Multipath loss	0.0013 pJ/bit/
Initial energy	0.5
Data aggregation energy	5nJ/bit/message
Message size	4000 bits
Probability of cluster heads	0.1

A. LINEAR SEQUENTIAL DEPLOYMENT SCHEME

Figure 5 shows the network lifetime achieved by DEEC, DDEEC, and TDEEC when different deployment schemes (i.e., random, uniform, and decreasing distance) in linear sequential were used. Overall, the results of three routing protocols are almost the same for the three different topologies with few exceptions that will be explained later in this section mainly because only one path is found from each sensor to the BS in all three topologies.

1) RANDOM

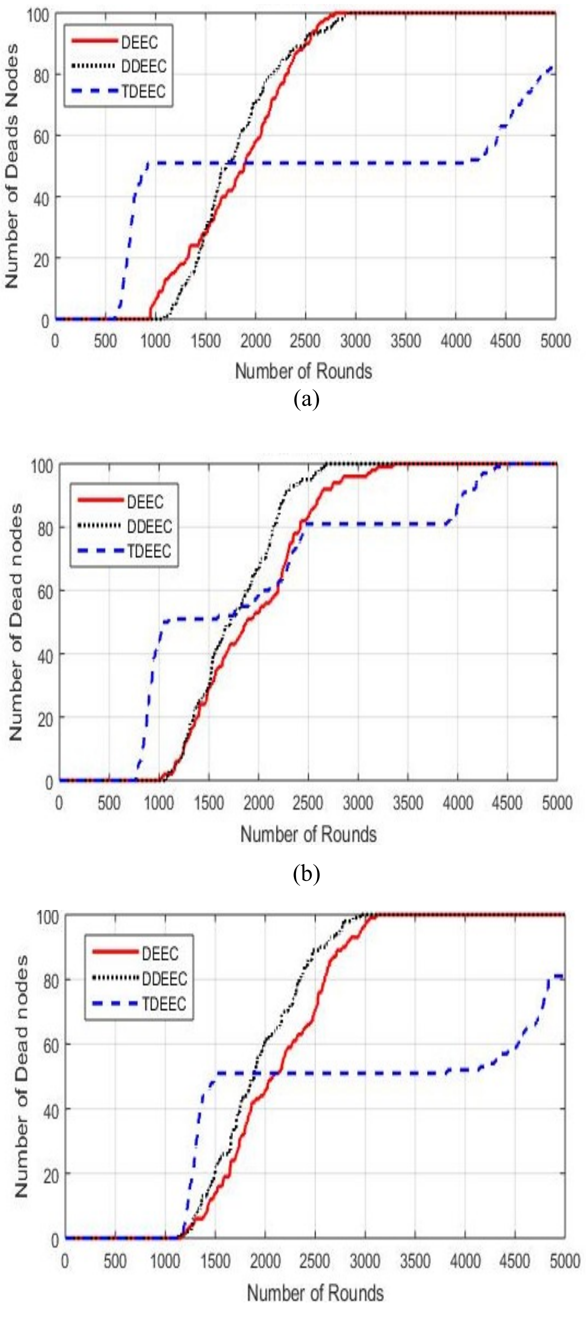
Figure 5(a) demonstrates the count of dead nodes as a function of number of rounds for the random linear sequential deployment. Overall, TDEEC prolongs network lifetime compared to DEEC and DDEEC. This is mainly because it adjusts the value of threshold based on which a node is selected as a cluster head. Due to linear sequential random deployment, nodes do not find alternative routing paths, deplete their energy quickly, and hence network lifetime is shorter.

2) UNIFORM

Figure 5(b) shows the result of linear sequential uniform node deployment. In DEEC, the first node dies in round 1114, and all nodes likely die in round 2469. In case of DDEEC, the first node dies in round 1075, and all nodes likely die in round 2671. In case of TDEEC, the first node died in round 870, and the all nodes died in 4769 rounds. As mentioned earlier, it also suffers from uneven energy consumption; in particular, nodes near the BS quickly lose energy because of the extra load of data forwarding. We can see the total number of dead nodes increased in linear sequential uniform nodes deployment scheme as linear sequential random.

3) DECREASING DISTANCE

We also observe the performance of these three algorithms in linear sequential gradually decreasing distance from the

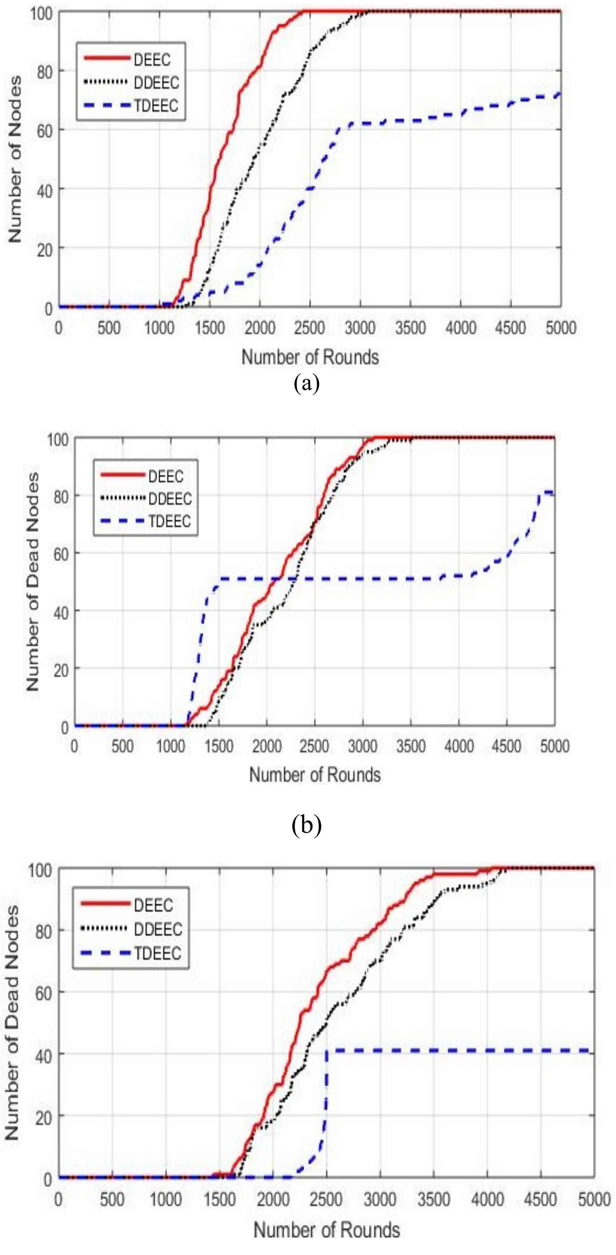


(a)

(b)

(c)

FIGURE 5. Number of dead nodes as a function of rounds with various linear sequential deployment schemes: a) random, b) uniform, and c) decreasing distance.



(a)

(b)

(c)

FIGURE 6. Number of dead nodes as a function of rounds with various deployment schemes a) Linear parallel random, b) Linear parallel uniform, and c) linear parallel triangular.

cluster head, as shown in Fig. 5 (c). In DEEC, node death starts at round 1160, whereas that for DDEEC, death starts at round 1140. The last node for DEEC and DDEEC dies at rounds 3110 and 2950, whereas for TDEEC, death starts at round 1180. In TDEEC, 77 nodes die at round 5000. Thus, by introducing a node placement period with linear sequential decreasing distance, lifetime increased as compared with the two other schemes discussed earlier because of increased node density near the BS and reduced the data forwarding overhead. This process also requires these sensors to transmit at a shorter distance, there by leading to energy conservation

B. LINEAR PARALLEL DEPLOYMENT

Figure 6 demonstrates the network lifetimes achieved by DEEC, DDEEC, and TDEEC when different deployment schemes (i.e., random, uniform, and triangular) in linear parallel were used. Linear parallel deployment increases network lifetime because alternative paths are available if any failure occurs.

1) RANDOM

Figure 6(a) presents the performance of these three algorithms under linear parallel random node deployment. In DEEC, nodes begin to die after 1050 rounds, whereas in DDEEC, death starts after round 650. The last node for DEEC and DDEEC died at rounds 3170 and 3390. By contrast, for TDEEC, node death started after round 700. In TDEEC, 75 nodes died at round 5000, clearly showing that by introducing linear parallel random node placement, lifetimes of DEEC, DDEEC, and TDEEC become longer as compared to its lifetime in linear sequential node deployments, which is due to alternative paths used.

2) UNIFORM

Figure 6(b) demonstrates the comparison in terms of the number of dead nodes in a linear parallel uniform distance environment. In DEEC, the first node died after round 1300, and all nodes die after round 3070. By contrast, in DDEEC, the first node died after round 1380 and all nodes died after round 3500. In TDEEC, the first node died at round 1100 and 46 nodes died at round 5000. This result clearly indicates the linear parallel uniform node deployment scheme performs better than the linear sequential uniform node deployment scheme because of the alternative cluster head path to the BS. And in this scheme no of dead nodes decreases because a node life time depends on distance between nodes, here data load decrease as compare to linear sequential uniform node deployment scheme.

3) TRIANGULAR

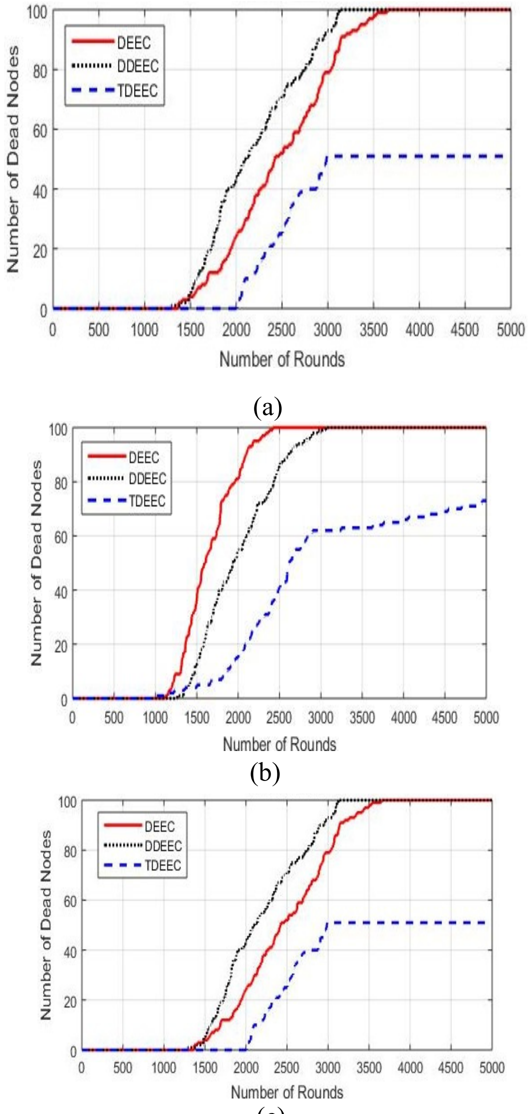
Figure 6(c) describes the dead nodes in the parallel triangular node deployment scheme. In DEEC, the first node died after round 1400, and all nodes died after round 4000. In DDEEC, the first node died after round 1490, and all nodes likely died after round 4190. In TDEEC, the first node likely died after round 2100 and 41 nodes died within 5000 rounds. The comparison results clearly indicate the linear parallel triangular scheme performs better than do the linear sequential and linear parallel uniform node deployment schemes because in the linear parallel triangular scheme, the data transfer alternative paths increase. Simulation results show the same conclusion. On the other hand in this scheme the distance between nodes reduced, that way this scheme perform better than other which discussed earlier.

C. GRID DEPLOYMENT

Figure 7 demonstrates the network lifetimes achieved by DEEC, DDEEC, and TDEEC when different deployment schemes (i.e., random, uniform, and triangular) in grid were used. Grid deployment increases network lifetime because of the presence of many alternative paths if any failure occurs. Data loss is less likely if any node fails; then, data can be sent to the base station through alternative paths.

1) RANDOM

Figure 7(a) shows the performance of these three algorithms under grid random node deployment. In DEEC, nodes start



(a)

(b)

(c)

FIGURE 7. **Number of dead nodes as a function of rounds with various deployment schemes a) grid random, b) grid uniform, and c) grid triangular.**

to die after round 1350, whereas in DDEEC, node death starts after round 1200. Total died nodes in DEEC, are 75 and in DDEEC, died nodes are 70, respectively within 5000 rounds. In enhance TDEEC, node died after round 2000. In enhance TDEEC, 41 nodes died within 5000 rounds. This result clearly shows that by introducing grid random node placement, the lifetimes of DEEC, DDEEC, and TDEEC become longer than the linear sequential and linear parallel node deployment schemes due to alternative paths.

2) UNIFORM

Figure 7(b) shows that in DEEC, number of dead node starts in 1001 rounds probably and total number of node drawn out from their energy are 73 in 5000 rounds. In DDEEC, first node drawn out from energy in 2250 rounds while total number of death nodes are 70 in 5000 rounds. Therefore in enhance TDEEC, the first node likely died within 2980 rounds, and 78 nodes died within 5000 rounds.

3) TRIANGULAR

Figure 7(c) shows the total number of nodes that depleted their energy and died in the grid triangular deployment scheme. Grid triangular node deployment approach reduces the number of dead nodes and maximizes network lifetime. In DEEC, nodes start to die after round 4140, whereas in DDEEC, node death starts after round 2400. The no of dead nodes in DEEC and DDEEC are 66 and 69, respectively. In TDEEC, node death started after round 3319. In TDEEC, 11 nodes died within 5000 rounds. Thus, the grid triangular node deployment scheme performs better than the other schemes because in this scheme, if any node fails, data can be transmitted to the BS using many alternative paths. Grid triangular have more alternative paths other all schemes which we discussed earlier.

VII. CONCLUSION

In this paper, we investigated the problem of sensor node placement and clustering in LWSNs and analyzed their performance. We also investigated the performance of linear sequential linear parallel and grid node deployment schemes. The simulation result clearly showed that the grid triangular node placement had better performance than the linear sequential and linear parallel schemes due to multiple paths for data transmission. Furthermore, we briefly described three prominent clustering protocols and discussed their operation in case of LWSNs. The comparison results clearly indicate the node placement and clustering scheme had a significant effect on LWSN lifetime and that conventional clustering routing schemes may not be suitable for LWSN. Moreover, it is important to mention that, this study is limited to node deployment and its effect on clustering on network lifetime. It is further recommended to explore more clustering schemes using linear sequential, linear parallel and grid based node deployment schemes and its effect on network lifetime.

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FAZLI SUBHAN received the M.Sc. degree in computer science from the University of Peshawar, Pakistan, in 2003, and the Ph.D. degree in information technology from the Universiti Teknologi PETRONAS, Malaysia, in 2012. He is currently an Assistant Professor with the Department of Computer Science, National University of Modern Languages, Islamabad, Pakistan. His research interests include indoor positioning systems, signal processing, and handover in wireless networks.

MADIHA NOREEN received the M.Sc. degree in computer science from the National University of Modern Languages (NUML), Islamabad, in 2014, where she is currently pursuing the M.Phil. degree with the Department of Computer Science. Since 2017, she has been teaching at NUML, as a Visiting Faculty. Her current research interest includes the field of linear wireless sensor network.

MUHAMMAD IMRAN is currently an Associate Professor with the College of Applied Computer Science, King Saud University. He is also a Visiting Scientist with Iowa State University, USA. He has published number of high-quality research papers in refereed international conferences and journals. His research is financially supported by several grants. His research interests include mobile *ad hoc* and sensor networks, WBANs, M2M, the Internet of Things, SDN, fault tolerant computing, and security and privacy. He has been involved in more than 50 conferences and workshops in various capacities, such as the Chair, the Co-Chair, and a Technical Program Committee Member, including the IEEE ICC, Globecom, AINA, LCN, IWCMC, IFIP WWIC, and BWCCA. He received number of awards, such as the Asia Pacific Advanced Network Fellowship. European Alliance for Innovation (EAI) has appointed him as the Co-Editor-in-Chief for the *EAI Endorsed Transactions on Pervasive Health and Technology*. He also serves as an Associate Editor for the IEEE ACCESS, the *IEEE Communications Magazine*, *Wireless Communications and Mobile Computing* journal (SCIE, Wiley), *Ad Hoc & Sensor Wireless Networks* journal (SCIE), *IET Wireless Sensor Systems*, *International Journal of Autonomous and Adaptive Communications Systems* (Inderscience), and *International Journal of Information Technology and Electrical Engineering*. He has served/serving as the Guest Editor for the *IEEE Communications Magazine* (SCIE), *Computer Networks* (SCIE, Elsevier), *Sensors* (SCIE, MDPI), *International Journal of Distributed Sensor Networks* (SCIE, Hindawi), *Journal of Internet Technology* (SCIE), and *International Journal of Autonomous and Adaptive Communications Systems*.

MOEENUDDIN TARIQ received the master's degree in computer science from the Comsats Institute of Information Technology, Wah Cantonment, Pakistan, in 2004, the M.S. degree in communication networks from Mohammad Ali Jinnah University Islamabad, Pakistan, in 2008, and the Ph.D. degree in computer sciences from Universiti Teknologi Malaysia, in 2016. He was an Access Engineer with Nayatel, Pvt., Ltd., an optical fiber-based ISP in Islamabad, Pakistan, from 2009 to 2010. From 2011 to 2013, he was a Lecturer with Federal Urdu University, Islamabad, Pakistan. He has few quality research publications in the field of underwater networks. His research interests include underwater sensor network routing protocols and mobile ad hoc networks.

ASFANDYAR KHAN received the M.Sc. degree from the University of Peshawar, Pakistan, in 2003, and the Ph.D. degree from the Department of Computer and Information Sciences, Universiti Teknologi Petronas, Malaysia, in 2011. From 2011 to 2017, he was an Assistant Professor with the Department of Computer science, University of Science and Technology at Bannu, Bannu, Pakistan. He is currently a Faculty Member with the Department of Computer Science and IT, IBMS, The University of Agriculture, Peshawar, Pakistan. His research interests include wireless sensor network, topology control algorithms, bioinformatics, and pattern recognition.

MUHAMMAD SHOAIB received the B.Eng. and M.Eng. degrees from the NED University of Engineering and Technology, Karachi, in 1995 and 2005, respectively, and the Ph.D. degree in communication and information system from the Beijing University of Posts and Telecommunications, China, in 2010. He was a Senior Manager (IP Operations, South) with Pakistan Telecommunication Company, Ltd., Pakistan. He was a Maintenance Engineer with R. M. International. He is currently an Assistant Professor with the Information Systems Department, College of Computer and Information Sciences, King Saud University. His research interests include the areas of video compression techniques, multilayer video coding, commercial data center facilities and IP packet-based network, and infrastructure and security.

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