Wireless Communications and Mobile Computing

Multiobjective Optimization Algorithms for Wireless Sensor Networks

Lead Guest Editor: Dionisis Kandris
Guest Editors: Alex Alexandridis, Tasos Dagiuklas, Emmanouil Panaousis, and Dimitrios D. Vergados

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Contents

Hindawi
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Editorial

Multiobjective Optimization Algorithms for Wireless Sensor Networks

Dionisis Kandris,[1] **Alex Alexandridis**,[1] **Tasos Dagiuklas**,[2] **Emmanouil Panaousis**,[3] **and Dimitrios D. Vergados**[4]

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A Wireless Sensor Network (WSN), distributed within an area of interest, is a network that contains many wirelessly interconnected devices, with sensing, communication, and processing abilities called sensor nodes. A WSN also comprises of at least one sink node, called base station, which has enhanced energy, computational, and communication resources [1]. Based on the combined use of its constituting elements, a WSN is capable of monitoring the conditions existing at extensive regions of interest [2, 3]. For this reason, the domain of WSNs is considered the basis for Internet of Things (IoT) and Internet of Everything (IoE) and supports a continuously growing range of human activities [4–11].

On the other hand, the development of WSNs is obstructed due to both the restricted resources of sensor nodes in energy supply, memory and processing, and the inherent limitations of wireless communications, in terms of power, speed, and capacity of communication channels as well as resistance to interferences and intrusion detection and prevention to preserve data security.

Particularly, the most important weakness of WSNs is the extremely restricted energy sufficiency of sensor nodes that reduces their operational time and thus shortens the overall network lifetime [12]. Consequently, the achievement of energy conservation is vital for WSNs to remain operational. This is why all possible causes of energy waste in sensor nodes must be eliminated. Given that, the procedure of wireless communication is by far the most energy consuming task of a sensor node, and numerous research works have been proposed in order to accomplish power control and energy efficient routing of data among the sensor nodes themselves and the BS [13–18].

Also, several data aggregation methodologies that aim at eliminating redundant data in order to reduce the volume of the data transmitted have been developed [19, 20]. Their usage saves energy, under the condition that the energy expended for aggregation purposes is lower than the energy consumed for raw data transmission.

Additionally, the preservation of network connectivity in WSNs is an issue of crucial importance for both the execution of the routing process and the prolongation of network lifetime. This is because, as soon as a sensor node is disconnected from its neighboring nodes due to either a malfunction or the depletion of its energy reserves, the data routing is obstructed for them, and the corresponding communication cost is considerably increased, thus accelerating their depletion. For these reasons, various methods pursuing connectivity conservation are used [21, 22].

Another very important performance metric is that is that of coverage. Three types of coverage in WSNs are identified, namely, area coverage, point coverage, and barrier coverage. Specifically, area coverage expresses the ability of the network to monitor an area of interest, meaning that all points within this area are within the sensing range of at least one sensor node. Similarly, k-coverage refers to the ability of the network to assure that all points within an area of interest are always within the sensing range of at least k sensor nodes (where k is a positive integer number). Also, point coverage refers to the ability of the network to guarantee that a predetermined group of points are observed by at least one sensor node. Additionally, barrier coverage refers to the ability to detect the movement across a barrier of sensor nodes. The maximization of area coverage is the most widely referred case in WSNs. There are various factors that affect coverage. For example, the deployment of sensor nodes can be either random or deterministic. Likewise, the sensitivity of sensor nodes may be either Boolean or probabilistic. Also, the sensing area may be deterministic or probabilistic. Similarly, the communication range of sensor nodes may be invariable or variable. Additionally, sensor nodes may be either static or mobile. Moreover, the coverage scheme adopted may be either centralized or distributed [23]. Therefore, the maximization of coverage using the resource constrained sensor nodes in a WSN is a nontrivial problem. This is why sophisticated methodologies for coverage maximization are used [24–26].

Congestion is an additional problem for WSNs. Actually, two types of congestion may occur in WSNs. The first of them is the so-called node-level congestion that is caused by the overflow of sensor node buffers. The link-level congestion is the second type. It occurs when many sensor nodes try to use simultaneously the same communication channel [27]. Both types of congestion cause packet losses and consequently necessitate packet retransmissions thus depleting the energy reserves of sensor nodes and reducing communication throughput [28]. For these reasons, numerous methodologies for congestion avoidance [29–32] that aim at preventing the occurrence of congestion and congestion control [33–35] that try to alleviate existent congestion are used.

Likewise, in WSNs where multimedia data are transmitted, there is need to transfer huge volume of information in high rates, thus increasing the energy cost of communication and overloading the communication channels [36, 37]. The usage of appropriate schemes that have been proposed in order to accomplish compression and restoration of images [38–41] or video [42, 43], in such cases, provides considerable decrease of communication load.

The attainment of high QoS is very important not only for wireless multimedia sensor networks (WMSNs) but also for all kinds of WSNs. QoS in WSNs may consider collective parameters such as latency, packet losses, bandwidth, and throughput, which are also taken into account in conventional networks. Yet, there other QoS metrics too that are related with the distinctive features of WSNs such as the limitations of the sensor nodes, the unbalance of traffic, the heterogeneity of senor nodes, the scalability requirements, the dynamic nature of networks, the differences in message priorities, the variety of traffic types, and the coexistence of various sinks [44]. For these reasons, various methods for QoS preservation in WSNs have been proposed [45, 46].

Security is also an issue of critical importance, because cyberattacks have become one of the most challenging problems that organizations must face, and WSNs are not the exemption to this. General methods have been proposed for the optimization of cybersecurity controls [47, 48]. Yet, such methods are not directly applicable to WSNs. This is because, in WSNs, sensor nodes may operate unattended and connected in a ubiquitous manner with a number of devices within the context of zero-trust security. This makes WSNs a challenging infrastructure to secure against numerous threats. The application of cyber controls to WSNs at operational level is not a straightforward process not only due to the above reasons but also due to the limited resources that sensor nodes have available. Numerous works have investigated secure data transmission in WSNs or device-to-device communications in general [49–53].

Scientific literature is rich in approaches that aim at achieving performance optimization in terms of individual metrics, like the aforementioned ones. However, meeting desired requirements in terms of more than one of these metrics is much more difficult, due to the fact that in many cases, the conditions required to optimize each one of these metrics may conflict with each other.

Thus, the combinational use of conventional single-objective optimization algorithms may be unsuitable for real applications, since they act to the detriment of the rest of the performance parameters. For instance, the coverage maximization objective in a WSN requires the sparse placing of nodes, which increases the energy cost of communication and thus obstructs the pursuit of maximizing the network lifetime. Similarly, the sparse deployment of sensor nodes worsens connectivity. Also, in order to save energy, it is preferable to transmit sensed data over reduced distance at each hop. Yet this increases the accumulative time for data transmission from source to final destination. So the minimization of energy cost of communications in a WSN contradicts the objective of minimizing the end-to-end latency. Similarly, the objective of attaining high QoS obstructs the conservation of energy. Likewise, the increase of the number of sensor nodes is beneficial for the connectivity, the coverage, and the overall network operability at the expense of increasing energy consumption. In the same way, the accomplishment of high security standards acts to the detriment of numerous nonsecurity requirements, like the abovementioned ones, that may occasionally or always be more critical than protecting a WSN infrastructure against cyberattacks [54]. For these reasons, the development of multiobjective optimization algorithms which aim at simultaneously achieving various goals, subject to a set of constraints in order to enhance the performance of WSNs, is a critical challenge [54–60].

Metaheuristic search methods have been very promising in this area, as most of them can approximate multiple elements of the Pareto front in a single evaluation, due to their population-based nature. Another important advantage of these methods is their ability to avoid getting trapped in local minima, which makes them suitable for global optimization [60]. Some of the most popular metaheuristic search methods are based on evolutionary computation [61–63], where the objective is to imitate biological evolution, and on swarm intelligence methods [64–66], which mimic the collective behavior exhibited by swarms of birds. Hybrid methods, combining the advantages of both worlds, have also been proposed [67].

Within this line of research, Kong and Yu, in their work entitled *Modeling and Optimization of RFID Networks Planning Problem*, presented a mathematical model that considers the tag coverage and the reader interference, in order to solve the planning problem at Radio Frequency Identification (RFID) Networks. For this reason, they introduced the DEEPSO algorithm, which adds Differential Evolution (DE) and Evolutionary Strategies (ES) to the standard Particle Swarm Optimization (PSO) algorithm. It was shown that DEEPSO improves global convergence ability and particle diversity, while also avoiding local convergence.

A different approach involves decentralized schemes which make use of cooperative agents, where data are partitioned and processed in individual clusters, thus avoiding the need of solving the optimization problem in a centralized way [68]. Within this context, Aznaoui et al., in their work entitled *A Heuristic Algorithm of Cooperative Agents Communication for Enhanced GAF Routing Protocol in WSNs* proposed a novel routing protocol. This protocol, named the Cooperative Agents GAF (CAGAF) protocol, uses a heuristic method based on cooperative agent communication, in order to find an optimal path in terms of energy to transmit data collected until reaching the base station. The proposed protocol was found to outperform GAF protocol in terms of considering important data, energy consumed, and dead nodes.

Jadoon et al., in their work entitled *Performance Evaluation of Zone-Based Routing with Hierarchical Routing in Wireless Sensor Networks*, also focus on data routing protocols in WSNs. Precisely, they made a comparative study among zone-based and static cluster hierarchical routing protocols in terms of three performance criteria, namely, energy efficiency, network throughput, and overall network lifetime. It was shown that in zone-based protocols, contrary to what happens in static cluster hierarchical protocols, no extra control information is needed while selecting the next hop nodes, thus achieving better performance in terms of the three abovementioned criteria.

Last but not least, Mo et al. in the research work entitled *Transmit Power Allocation with Connectivity Probability for Multi-QoS in Cluster Flight Spacecraft Network* proposed a transmit power allocation strategy to minimize the average packet error rate at the access point in cluster flight spacecraft networks (CFSNs). By using Monte Carlo method for the validation of the analytical model developed, the influence of node transmit power on the QoS performance of cluster flight spacecraft network was simulated and analyzed under the assumption of finite overall network transmit power and low traffic load. It was verified that the proposed transmit power allocation strategy allows to minimize the packet error rate for a given total network transmit power at any time slot for CFSNs.

Based on the ceaseless evolution of WSNs, and the ever growing range of their applications, it is logical to suppose that more and more challenges will arise for the development of sophisticated algorithms that will be able to achieve the performance optimization of WSNs in terms of multiple objectives.

Conflicts of Interest

The editors declare that they have no conflicts of interest regarding the publication of this special issue.

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Research Article

Transmit Power Allocation with Connectivity Probability for Multi-QoS in Cluster Flight Spacecraft Network

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In this paper, we investigate the transmit power allocation problem to minimize the average packet error rate at the access point in the cluster flight spacecraft network, which adopts the CSMA/CA channel access mechanism. First, the node mobility, nodal distance distribution, and probabilistic adjacency matrix were formulated for cluster flight spacecraft network based on twin-satellite mode. Then, the optimization-theoretic model described the optimized transmit power allocation strategy and its implementation algorithm was proposed. And the problem of minimizing the packet error rate of the cluster flight spacecraft network system can be converted into maximizing the expectation of the binary probabilistic adjacency matrix, i.e., maximizing the sum of the nondiagonal elements in the probabilistic adjacency matrix. Due to discreteness of nodal distance distribution, Monte Carlo method was applied to solve the transmit power allocation problem. Yet importantly, the influence of node transmit power on the QoS performance of cluster flight spacecraft network was simulated and analyzed under the assumption of finite overall network transmit power and low traffic load. Finally, the results show that the pocket error rate increases with the provided traffic load, but the pocket error rate hardly changes with the same traffic load in different sequential time slots of any orbital hyperperiod or in the same time slot of different orbital hyperperiods, and by maximizing the sum of the nondiagonal elements in the probabilistic adjacency matrix, the pocket error rate minimum is achieved for a given total network transmit power at any time slot for cluster flight spacecraft network.

1. Introduction

In recent years, fractionated spacecraft with cluster flight model has become a hot topic in the field of distributed space network, due to its advantages of flexibility, rapid response, low cost, strong scalability, and long lifetime. The previous work has made a contribution to earth observation and space exploration [1–3]. Fractionated spacecraft distributes the functionality of a traditional large monolithic spacecraft into a number of heterogeneous modules. Each module can be regarded as a node through wireless communication, and the nodes construct the cluster flight spacecraft network (CFSN). Cluster flight spacecraft require mutual cooperation between nodes to realize information exchange, navigation communication, and power sharing. These spacecraft constitute a virtual satellite platform with information exchange structure. In addition, like other distributed space systems, the cluster flight spacecraft is a resource-sharing and energy-limited system. Therefore, how to allocate nodal transmit power efficiently and optimize the performance of the cluster flight spacecraft is an important issue needs to be solved [4–6].

For wireless communication systems, including wireless sensor networks and radar networks, research on optimizing systematic performance by allocating nodal power efficiently has always been a hotspot [7, 8]. For example, in an end-to-end MIMO multihops wireless network with outage probability limited, the power allocation method was studied and the analytic solution of optimal power allocation with the minimum total transmit power of the system was obtained in [9]. Aiming at the problem that it is difficult to obtain an analytic solution for the optimal power allocation in amplification and forwarding (AF) relay selection of cooperative communication system, artificial neural network was adopted to obtain an efficient solution from the target of minimum bit error rate in [10]. For the cooperative network of spectrum sharing, by solving the convex optimization problem, the optimal power allocation strategy with minimum energy consumption under the requirements of QoS was obtained in [11]. For the symbol programming problem of target detection in distributed radar sensor network, the closed-form expression of optimal power allocation by establishing the optimal linear unbiased estimation model was obtained in [12]. In [13], based on the received signal interference plus noise ratio, Markov chain was adopted to obtain the dynamic power control method with the minimum packet error rate (PER).

To the best of our knowledge, there are few research reports on the optimal power allocation in CFSN. Only the solution of the minimum spanning tree by constructing the spatial-temporal network topology to improve energy efficiency was obtained for the CFSN in [14]. In fact, due to the fact that heterogeneous modules have to meet miscellaneous requirements given different tasks, the CFSN faces the requirements of multi-QoS, including the requirements of different delay and bit error [3]. In general, the resource allocation with multi-QoS, including power, bandwidth, and CPU, is an NP-hard problem in the static network [15, 16]. However, because of the high-speed flight of modules, the topology of the CFSN is highly dynamic and nodes are randomly connected. Therefore, it is foreseeable that the resource allocation with QoS is more complicated in CFSN.

Many researchers have studied the problem of power distribution with multi-QoS in static networks. Among them, based on the resource allocation mode with QoS under the constraint of resource [17], the resource allocation problem with multiresources multi-QoS and single-resource multi-QoS by adopting polynomial concave optimal control method was solved in [15]. By introducing a truncated based on slope, an approximated method of concave optimal control was obtained and the resource allocation problem with multiresources multi-QoS was solved efficiently [16]. In addition, as for radar tracking under the constraints of radar bandwidth, processing time, and transmit power, the method of [16] was adopted to solve the optimization problem of radar tracking and speed accuracy efficiently in [18, 19]. In recent years, with the development of large-scale MIMO technology, the optimization of transmit power allocation has also received widespread attention. For example, the issue of the minimum total transmit power of the system from the perspective of satisfying QoS constraints was studied in [20]. An efficient energy allocation algorithm was studied based on binary search for 5G carrier aggregation scenario in [21]. Under the conditions of given QoS requirements, the optimization of transmit power allocation of full-duplex access core network was studied in [22].

The connection between nodes is the fundamental problem of wireless communication networks. It not only reflects link quality, but also determines network performance. In general, for a static and deterministic network composed of n nodes, the nodes can be denoted as a graph $G(V, E)$, where $V = \{v_1, v_2, \ldots, v_n\}$ denotes the vertex set and E denotes the edge set. The probabilistic adjacency matrix, denoted by A_G, describes the state of the nodal connection and is a symmetric matrix. If there exists an edge between nodes v_i and v_j, $a_{ij} = 1\,(i \neq j)$, otherwise 0, that is, nodes v_i and v_j are not connected [23]. From the perspective of wireless communication, the power of transmitter determines the connection between nodes. Therefore, intuitively, the adjacency matrix A_G directly reflects the transmit power of the system. In this way, based on the probabilistic adjacency matrix, the research on transmit power allocation of wireless communication system is plausible. However, as mentioned above, as the topology of the CFSN is highly dynamic and nodes are randomly connected, we proposed a method of transmit power allocation with multi-QoS by establishing the nodal distance distribution model, defining the binary probabilistic adjacency matrix, and adopting the CSMA/CA channel access mechanism. Our transmit power allocation method is proposed on the following premises: (1) low traffic load, (2) finite overall transmit power, and (3) the star topology of the network, that is, one node is responsible for the earth communication, and others are connected to the node by frequency division multiple access (FDMA) with subcarrier binary phase-shift keying (BPSK) modulation [24]. The purpose of optimal transmit power allocation is to minimize the average PER at the access point (AP) based on the probabilistic adjacency matrix.

The structure of this paper is organized as follows: Section 2 introduces and analyzes the basic model of CFSN and describes the definition of the probabilistic adjacency matrix of this model. In Section 3, the optimization-theoretic model is present. And based on the model, the optimized transmit power allocation strategy is proposed. In Section 4, the simulation results of the PER and delay in the network are presented, focusing on the impact of the probabilistic adjacency matrix, the traffic load, and the adopted power allocation strategy. Finally, Section 5 concludes the paper.

2. System Model

2.1. Definition of a Simplified Model in CFSN. The link connection characteristics between nodes in CFSN depend on the relative orbits, transmit power, and receiving sensitivity of the nodes. Therefore, the following definition is given:

Definition 1. In ECI coordinates [24, 25], for each time slot in an orbital hyperperiod of CFSN, a node can be defined as a couple $s = (x, P)$, where $x \in R^3$ is the location of node and $P \in R$ is its transmit power.

Given a spacecraft network consisting of L nodes with interference limited, if node $s_j = (x_j, P_{tj})$ can receive the signal transmitted by the node $s_i = (x_i, P_{ti})$, the bit-signal-to-noise ratio at the receiving node s_j should satisfy the following equation:

$$\frac{E_b}{N_0} = \frac{P_{ti} G_t G_r \lambda^2}{(4\pi)^2 \left\| x_i - x_j \right\|^2 kTR_b} \geq \Gamma, \tag{1}$$

where N_0 is the additive white noise power spectral density of receiver, k is Boltzmann's constant, T is the noise temperature, P_{ti} is the transmit power of node s_i, $\|x_i - x_j\|$ is the Euclidean distance between s_i and s_j, R_b is the rate of data transmission, G_{ti} and G_{rj} are the gains of the transmit and receive antennas, λ is the working wavelength, and Γ is the receiving sensitivity and depends on the modulation mode, etc. For QPSK modulation, when the bit error rate is less than 10^{-5}, $\Gamma = 9.6$ dB. In order to facilitate the calculation, it can be assumed that $G_{ti} = G_{rj} = 1$.

In CFSN, $m \leq \|x_i - x_j\| \leq M$, M and m are the upper bound and the lower bound of nodal distance, respectively [24].

Therefore, equation (1) can be simplified as follows:

$$\left\| x_i - x_j \right\|^2 \leq \frac{P_{ti}\lambda^2}{(4\pi)^2 kTR_b\Gamma}. \tag{2}$$

According to the following equation, the distance threshold of any successful connection between s_i and s_j can be obtained:

$$d_\Gamma = \sqrt{\frac{P_{ti}\lambda^2}{(4\pi)^2 kTR_b\Gamma}}, \quad m \leq d_\Gamma \leq M. \tag{3}$$

That is, if $\|x_i - x_j\| \leq d_\Gamma$, then s_i and s_j are connected to each other. And we can derive from equation (3):

$$m^2 \frac{(4\pi)^2 kTR_b\Gamma}{\lambda^2} \leq P_{ti} \leq M^2 \frac{(4\pi)^2 kTR_b\Gamma}{\lambda^2}. \tag{4}$$

Therefore, the network can be defined as follows:

Definition 2. A CFSN of L nodes, in each time slot of its orbital hyperperiod, can be defined as an order set: $S = (s_{\mathrm{AP}}, d_\Gamma, s_1, s_2, \ldots, s_L)$, where $s_{\mathrm{AP}} \in R^3$ is the location of the AP.

Based on Definition 2, the definition of binary adjacency matrix in CFSN can be obtained.

Definition 3. For a given CFSN $S = (s_{\mathrm{AP}}, d_\Gamma, s_1, s_2, \ldots, s_L)$, in each time slot of its orbital hyperperiod, the binary adjacency matrix is given by $A(S) \in R^{L\times L}$, where

$$A_{ij} = A(S)_{ij} = \begin{cases} 1, & \left\| x_i - x_j \right\| \leq d_\Gamma, \\ 0, & \text{otherwise.} \end{cases} \tag{5}$$

And the complement of $A(S)$ corresponds to

$$\overline{A}(S) = \begin{cases} 1, & A_{ij} = 0, \\ 0, & \text{otherwise.} \end{cases} \tag{6}$$

To simplify the calculation, the number of ones in the adjacency matrix is denoted by $|A(S)|$, and the complementary adjacency is given by the number of zeros in adjacency matrix, denoted by $|\overline{A}(S)|$.

Moreover, for the sake of analysis, for $i = 1, 2, \ldots, L$, two index sets of nodes are defined: $R_i = \{j = 1, \ldots, L \mid A_{ji} = 1\}$ and $T_i = \{j = 1, \ldots, L \mid A_{ij} = 1\}$. They represent the node index that node s_i can receive from and transmit to, respectively.

2.2. Nodal Mobility Model and Distance Distributions in CFSN. To accomplish the cluster flight model within bounded distance, twin-satellite mode was adopted to study the nodal mobility model. The node position is uniformly distributed on sphere within $(M - m)/4$ radius as shown in Figure 1.

So the mobility model $M(t)$ within bounded distance for CFSN can be defined as follows.

Definition 4. In ECI coordinates, if the position sets of n nodes in CFSN are $\mathbf{R}(0) = \{\mathbf{r}_1(0), \mathbf{r}_2(0), \ldots, \mathbf{r}_n(0)\}$ at initial time T_0, the position set is $\mathbf{R}(k) = \{\mathbf{r}_1(k), \mathbf{r}_2(k), \ldots, \mathbf{r}_n(k)\}$, and the positions are uniformly distributed within sphere $B(\mathbf{r}_i(0), a)$ $(i = 1, 2, \ldots, n)$ at time T_k, where $\mathbf{r}_i(0)$ and $a = ((M - m)/4)$ are center and radius of the sphere, respectively. Moreover, positions among all nodes are mutually independent and independent of all previous locations.

Based on the nodal mobility model, the nodal distance distribution can be described in Figure 2. Nodes are assumed to be uniformly located in a circle of the two-dimensional plane.

In Figure 2, the coordinates of the transmitter A and the receiver B are $(r_A \cos\varphi_A \varphi, r_A \sin\varphi_A)$ and $(D + r_B\cos\varphi_B, r_B\sin\varphi_B)$, respectively, where, $r_A, r_B \in [0, a]$ and $\varphi_A, \varphi_B \in [0, 2\pi]$, and D with the value $(M + m)/2$ is the distance between the centers of the two circle. The random variables with probability density functions are given by

$$f_{r_{A,B}}\left(r_{A,B}\right) = \begin{cases} \dfrac{2r_{A,B}}{a^2}, & 0 \leq r_{A,B} \leq a, \\ 0, & \text{otherwise,} \end{cases}$$
$$f_{\varphi_{A,B}}\left(\varphi_{A,B}\right) = U(0, 2\pi), \tag{7}$$

where $U(0, 2\pi)$ is the uniform distribution over range $[0, 2\pi)$, and the subscripts denote r_A, r_B and φ_A, φ_B, respectively.

Therefore, the distance between the transmitter A and the receiver B is given by

$$\|AB\| = \sqrt{\left(r_A\cos\varphi_A - \left(D + r_B\cos\varphi_B\right)\right)^2 + \left(r_A\sin\varphi_A - r_B\sin\varphi_B\right)^2}. \tag{8}$$

Despite the simplicity of equation (8), the derivation of the distance density cannot be given in closed form. According to Glivenko–Cantelli Lemma, adopting empirical statistical method and eighth-order polynomial approximation, the probability density function of the distance between nodes with eighth-order polynomial can be denoted by

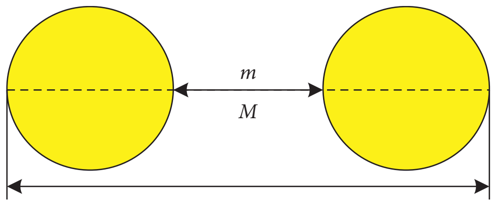


Figure 1: Nodal mobility model.

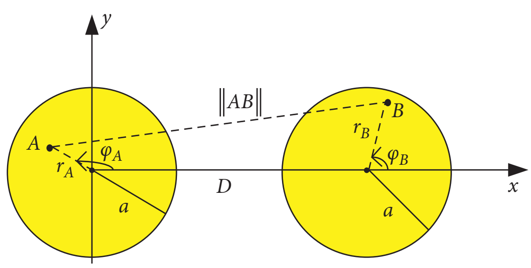


Figure 2: Nodal distance distribution.

$$\hat{f}_8(h) \approx \begin{cases} \sum_{i=0}^{8} p_i h^i, & \frac{m}{D} \le h \le \frac{M}{D}, \\ 0, & \text{otherwise}. \end{cases} \quad (9)$$

When $m = 2.5$ km and $M = 90.1$ km, the polynomial coefficients of the empirical probability density function are provided in Table 1.

2.3. Determination of Probabilistic Adjacency Matrix in CFSN. According to the foregoing, the definition of the probabilistic adjacency matrix for CFSN is described as follows.

Definition 5. Given the CFSN $S = (s_{AP}, d_\Gamma, s_1, s_2, \ldots, s_L)$, in each time slot of an orbital hyperperiod, the probabilistic adjacency matrix is a $L \times L$ matrix. p_{ij} is the (i, j) element, and $p_{ij} = p_{ji}$. p_{ij} is the probability that s_i and s_j successfully connect. The diagonal entries are all equal to 1.

Because the satellite has the capability of storage and forwarding, the diagonal entries are all equal to 1.

If $d = \|x_i - x_j\|$, the connectivity probability between s_i and s_j is given by

$$p_{ij} = \Pr\left\{d = d_{ij} \,\middle|\, d < d_\Gamma\right\}. \quad (10)$$

3. Packet Error Rate, Transmission Delay, and Power Optimization of the System

In order to analyze the relationship between the system's PER, transmission delay, and the probabilistic adjacent matrix, the following two counting processes [26] are assumed: in the time interval $(0, t)$, the number of times that packet transmission of other nodes has been checked by node i is a homogeneous Poisson process G_i with intensity g (dimension: pck/s), and the number of times that a node i has transmitted packet is also a homogeneous Poisson process $T_i(t)$ with intensity g. Besides, the processes associated with different nodes are independent of each other, all data can be transmitted successfully within $(0, t)$, and the data transmission length is $T_{\text{trans}} = B_L/R$, where B_L is the packet length (dimension: b/pck) and R is the transmission data rate (dimension: b/s).

Table 1: Coefficients of the fitting polynomials.

p_i	
p_0	0.0872
p_1	−0.7380
p_2	2.5135
p_3	−4.3913
p_4	4.1737
p_5	−2.1499
p_6	0.5919
p_7	−0.0764
p_8	0.0034

3.1. Packet Error Rate and Delay of the System

3.1.1. Packet Error Rate. For a certain time slot in the orbital hyperperiod of CFSN, if only the adjacency matrix is taken into account, the bidirectional packet error intensity accumulated by node i will be

$$F[E_i] = \gamma_i F[G_i] + \lambda_i F[T_i], \quad (11)$$

where $\gamma_i F[G_i]$ represents the intensity of transmission errors that s_i cannot receive the packet because the nodes are not connected. $\lambda_i F[T_i]$ represents the intensity of transmission errors due to interference from other nodes that cannot receive s_i.

When the system has low traffic load, i.e., $gT_{\text{trans}} < < 1$, the coefficients γ_i and λ_i in equation (11) can be expressed, respectively, as follows:

$$\begin{aligned} \gamma_i &= \lim_{t \longrightarrow \infty} P\left\{\max_{j \in \overline{R}_i}\left\{T_j[t + T_{\text{trans}}] - T_j[t]\right\} > 0\right\} \\ &= 1 - \prod_{j \in \overline{R}_i}\left(1 - e^{-F[T_j]T_{\text{trans}}}\right) \approx \sum_{j \in \overline{R}} F[T_j]T_{\text{trans}} = |\overline{R}_i| T_{\text{trans}} g, \end{aligned} \quad (12)$$

$$\begin{aligned} \lambda_i &= \lim_{t \longrightarrow \infty} P\left\{\max_{j \in \overline{G}_i}\left\{G_j[t + T_{\text{trans}}] - G_j[t]\right\} > 0\right\} \\ &= 1 - \prod_{j \in \overline{T}_i}\left(1 - e^{-F[G_j]T_{\text{trans}}}\right) \approx \sum_{j \in \overline{T}_j} F[G_j]T_{\text{trans}} = |\overline{T}_i| T_{\text{trans}} g. \end{aligned} \quad (13)$$

Using the expressions above for coefficients γ_i and λ_i in (12) and (13), the transmission error intensity of node i is given by

$$F[E_i] = \mathbb{E}\left[\left(\left|\overline{T}_j\right| + \left|\overline{R}_i\right|\right)\right] T_{\text{trans}} g^2, \quad (14)$$

where $\mathbb{E}[\cdot]$ denotes the expected value. Therefore, the overall network error intensity is given by

$$\sum_{i=1}^{L} F[E_i] = 2\mathbb{E}[|\overline{A}(S)|]T_{\text{trans}}g^2. \quad (15)$$

According to the previous assumption, the overall network intensity is$g$, so the probability of packet error, i.e., the ratio between the overall network error intensity and the generation intensity (given by Lg), is as follows:

$$P_{\text{er}} = \frac{\sum_{i=1}^{L} F[E_i]}{Lg} = \frac{2\mathbb{E}[|\overline{A}(S)|]T_{\text{trans}}g}{L}. \quad (16)$$

3.1.2. Transmission Delay. In order to analyze the relation between transmission delay and probabilistic adjacency matrix, the CSMA/CA mechanism is assumed to be adopted for the node access in CFSN. If the channel idle assessment time is T_{CCA}, and the access back-off time of the busy channel is T_B, the transmission delay connecting node i that can receive the data packet is as follows:

$$\begin{aligned} D_i &= (T_{\text{CCA}} + T_B) \sum_{j\in\mathcal{R}_i} F\left[T_j\right]T_{\text{trans}} \\ &\approx (T_{\text{CCA}} + T_B)\mathbb{E}[\mathcal{R}_i]gT_{\text{trans}}. \end{aligned} \quad (17)$$

Therefore, the average transmission delay of CFSN can be estimated as follows:

$$\overline{D} = \frac{\sum_{i=1}^{L} D_i}{L} \approx (T_{CCA} + T_B)\frac{\mathbb{E}[|A(S)|]}{L}T_{\text{trans}}g. \quad (18)$$

3.2. Optimal Transmit Power Allocation. The purpose of the transmit power allocation is to optimize the QoS of the CFSN system. It can be seen from equation (14) that the problem of optimizing the transmit power allocation for minimizing the PER of the CFSN system is equivalent to maximizing $\mathbb{E}[|A(S)|]$, i.e., maximizing the sum of the nondiagonal elements in the probabilistic adjacency matrix.

If $\mathcal{P} = [0.0002, 0.25]$, and total power of CFSN system is P_{tot}, the discrete optimization problems can be formulated as follows.

Problem. For a given CFSN $S = (s_{\text{AP}}, d_\Gamma, s_1, s_2, \ldots, s_L)$, in each time slot of its orbital hyperperiod, each node chooses a transmit power $P_{ti} \in \mathcal{P}\,(i = 1, \ldots, L)$, and the transmit power allocation with the smallest PER needs be optimized as follows:

$$\begin{aligned} &\max \quad \mathbb{E}[|A(S)|] \\ &\text{s.t.} \quad \sum_{i=1}^{L} P_{ti} \le P_{\text{tot}}. \end{aligned} \quad (19)$$

Using the conditional probability method, (10) can be rewritten as

$$p_{ij} = \frac{\Pr\left\{d = d_{ij}\right\}}{\Pr\left\{d < d_\Gamma\right\}}. \quad (20)$$

Substituting (20) to (19), because maximizing $\mathbb{E}[|A(S)|]$ is equivalent to maximizing the sum of the nondiagonal elements in the probabilistic adjacency matrix, the optimization problem can be converted into

$$\begin{aligned} &\max \quad \sum_{i=1}^{L} \sum_{j=1, j\ne i}^{L} \frac{\Pr\left\{d = d_{ij}\right\}}{\Pr\left\{d < d_\Gamma\right\}} \\ &\text{s.t.} \quad C1: \sum_{i=1}^{L} P_{ti} \le P_{\text{tot}} \\ &\qquad\quad C2: d_{ij} < d_\Gamma. \end{aligned} \quad (21)$$

The constraint $C1$ and $C2$ denote that the total network transmit power is finite and the distance between connected nodes is within the threshold of node s_i and s_j. Since $d_{ij} = \sqrt{(P_{ti}\lambda^2)/((4\pi)^2 kTR_b\Gamma)}$, the nonconvexity of constraint $C2$ can be proved by the second-order partial derivative with respect to the variable.

It is noted that equation (21) is a nonlinear multichoice knapsack problem, which can be solved by Monte Carlo method [27, 28]. Moreover, it is also noted from equations (16) and (18) that the PER and the average delay of the system are linear with $\mathbb{E}[|A(S)|]$.

The outline of the power allocation algorithm is given as follows.

Step 1: initialization: set $B_L = 632$, $R = 1\times 10^5$, $T_{\text{CCA}} = 128\times 10^{-6}$, $T_B = 320\times 10^{-6}$, $L = 5$, $P_{\text{tot}} = 0.65$, $0 \le \sum_{i=1}^{L} P_{\text{ti}} \le P_{\text{tot}}$.

Step 2: set $k = 1$, and choose a large value for N, where: $k = 1$, $N =$ total number of trials.

Step 3: generate a uniformly distributed random transmit power for each node, $RN = 0.0002 + 0.2498 \times \text{rand}(1, L)$ (using MATLAB, $\text{rand}(X, Y)$ denotes a $X \times Y$ matrix where its elements range from 0 to 1. In this paper, the transmit power for each node is $P_{ti} \in \mathcal{P}$, so RN can be computed by mapping $\text{rand}(1, L)$).

Step 4: calculate the probability of the AP received from node $j\,(i = \text{AP}, j \ne i)$: compute the transmit distance threshold from node i to AP using equation (3), and compute the connectivity probability of this link using equation (21).

Step 5: calculate the probability of the AP transmitted to node $j\,(i = \text{AP}, j \ne i)$: compute the transmit distance threshold from AP to node i using equation (3), and compute the connectivity probability of this link by using equation (21).

Step 6: sum the connectivity probability of Step 4 and Step 5.

Step 7: add 1 to k, if $k > N$, calculate the max sum of Step 6 and end; otherwise, go to Step 3.

NOTE: Monte Carlo algorithm means that the more the samples, the more approximate the optimal value

[29]. As $N \longrightarrow \infty$, the objective value tends to the optimal solution.

4. Simulation Analysis

In order to simulate and analyze the influence of node transmit power on the QoS performance of CFSN, packet error rate, average delay, and two allocation strategies are considered: (1) each node has the same transmit power and (2) the optimal transmit power varies from node to node and is allocated using strategy presented in Section 3.2.

The simulations have been carried out referring to star topology, i.e., all nodes transmit (receive) directly to (from) the AP, and using different values of the overall network transmit power and, consequently, different values of the transmit powers allocated to the spacecraft. Simulation parameter settings are as follows: (1) transmit power. It is assumed that the module used to collect solar panels is powered by microwave wireless power transfer to other modules, and each module provides an effective total power of 0.13 W [24]. (2) The number of nodes of the cluster flight spacecraft $L1 = 5$ and $L2 = 7$, and the orbital elements are derived from [24]. (3) The noise temperature is 300 K. The QPSK modulation is adopted between nodes. The transmission data rate is 100 kbps, the operating frequency is S-band, and $f = 2.2$ GHz [30]. The gains of the transmit and receive antennas are 1 [31]. Other parameters are listed in Table 2 and one considered topology with $L1 = 5$ is shown in Figure 3.

Table 2: Parameter setting.

Parameter	Value
Γ	9.6 dB
P_{tot}	0.65 W
m	2.5 km
M	90.1 km

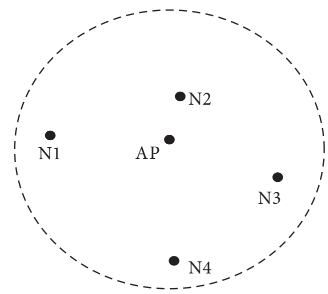


Figure 3: One considered CFSN topology with $L = 5$.

4.1. Each Node with the Same Transmit Power

4.1.1. Impact of the Traffic Load on PER. According to STK and MATLAB simulation, the nodal distance between AP and other nodes can be listed in Tables 3 and 4. Tables 3 and 4 show that the distance between AP and other nodes changes slowly in different time slots of an orbital hyperperiod, and the distance also has a slight change in corresponding time slots of different orbital hyperperiods.

Since the transmit power of each node is the same, it can be assigned to $P_{t1} = P_{t2} = \cdots = P_{t5} = P_{t6} = P_{t7} = 0.13 \quad W$ by equation (4), and the value satisfies all the constraints. The PER is shown as a function of the offered traffic load g in CFSN. Comparing the first, the second, and the third time slots in an orbital hyperperiod, the PER hardly changes. The simulation curves are almost overlapping, as shown in Figure 4. Because the change of the distance is not obvious, the probability of connection between nodes has small change in different sequential time slots of any orbital hyperperiod. Comparing the first and the second orbital hyperperiod in a time slot, the phenomenon in Figure 5 is the same as Figure 4. The reason is that the probability of connection between nodes has a slight change in corresponding time slots of different hyperperiods, and the PER is likely to change periodically.

In order to verify the impacts of different transmit power on PER, the same transmit power is allocated to each node with different values in the first time slot. The result is shown in Figure 6. Comparing the curves referring to each node with 0.13 W, each node with 0.08 W with referring to each node with 0.03 W, it can be concluded that if the transmit power is higher, the PER will be lower under the satisfied constraints. As shown in Figures 4–6, the PER increases with the offered traffic load. In other words, when the traffic load is low, the number of collisions at the AP is likely to be low. Instead, when the traffic load is lager, the probability that two nodes transmit at the same time increases and, subsequently, the PER increases as well.

Keeping other parameters unchanged, the PER under two cases of different numbers of nodes was analyzed. As shown in (b) of Figures 4–6, the PER also increases with the offered traffic load. Comparing (a) and (b) of Figures 4–6, it can be further obtained that the number of nodes increases in the network and the PER increases.

4.1.2. Impact of Each Time Slot $\mathbb{E}[|A(S)|]$ on PER and Delay. According to the analytical results in Section 3.2, the performance, in terms of PER, depends only on the adjacency matrix. For this scenario, the packet generation rate is set to $g = 1$ pck/s. We consider the first time slot of the first orbital hyperperiod in CSFN. Figure 7 shows the impact of $\mathbb{E}[|A(S)|]$ on PER and delay. When the number of nodes increases, the dimension of the adjacency matrix increases, which in turn affects $\mathbb{E}[|A(S)|]$. The dotted line and solid line indicate 7 nodes and 5 nodes, respectively. The results show that the larger the $\mathbb{E}[|A(S)|]$ becomes, the lower the PER will be, and the lager the delay will be. However, the PER and the delay increase with the number of nodes.

4.2. Optimal Transmit Power Allocation Strategy. In this section, we present the impact of the adopted transmit power allocation strategy on the PER of CFSN. In particular,

Table 3: The nodal distance between AP and other nodes ($L1 = 5$) (km).

	Nodal distance	AP to node 1	AP to node 2	AP to node 3	AP to node 4
The first orbital hyperperiod	Time slot 1	5.233	13.748	45.049	53.210
	Time slot 2	4.897	14.446	46.426	55.118
	Time slot 3	4.568	15.177	47.798	57.036
The second orbital hyperperiod	Time slot 1	4.812	14.629	46.762	55.607
	Time slot 2	4.485	15.367	48.131	57.526
	Time slot 3	4.171	16.129	49.486	59.442

Table 4: The nodal distance between AP and other nodes ($L2 = 7$) (km).

	Nodal distance	AP to node 1	AP to node 2	AP to node 3	AP to node 4	AP to node 5	AP to node 6
The first orbital hyperperiod	Time slot 1	7.724	19.582	28.159	53.190	29.171	49.567
	Time slot 2	8.052	20.406	29.380	55.091	30.010	51.422
	Time slot 3	8.385	21.243	30.621	57.002	30.851	53.267
The second orbital hyperperiod	Time slot 1	8.137	20.614	29.694	55.584	30.219	51.900
	Time slot 2	8.471	21.452	30.940	57.496	31.060	53.740
	Time slot 3	8.807	22.296	32.196	59.405	31.900	55.561

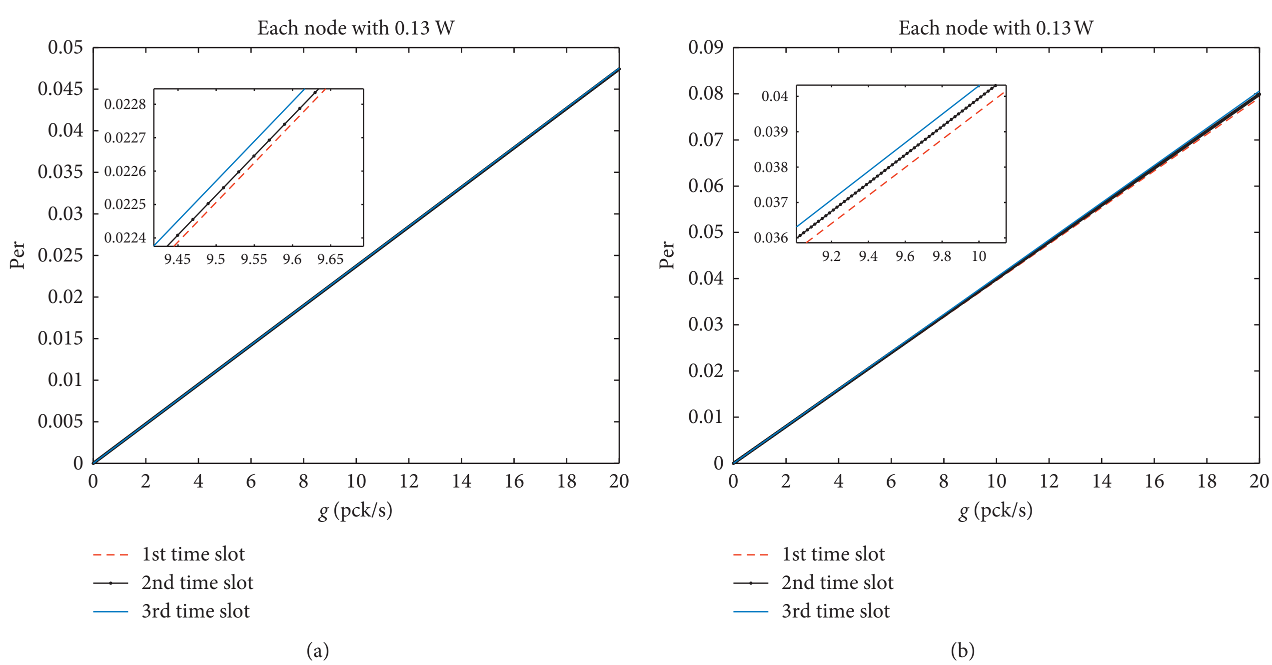


Figure 4: PER as a function of the offered traffic load g in different time slots with the same transmit power. (a) $L1 = 5$. (b) $L2 = 7$.

we consider strategies such that optimized and uniformly distributed transmit power is allocated to each node. The optimized transmit power is different at each node and is set according to the power allocation algorithm presented in Section 3.2, where the total transmit power is assigned to each node in order to minimize the PER in the CFSN. This method leads to allocating transmit power reasonably.

Figure 8 shows the impacts of optimized and uniformly distributed transmit power on PER in the first time slot of the first orbital hyperperiod in CSFN. Different values of total network transmit power are considered. Under the transmit power allocation strategy presented in Section 3.2, in Figure 8, a performance comparison between scenarios with and without the use of the proposed transmit power allocation strategy is presented. Comparing the curves referring to $P_{tot} = 0.65$ W with referring to $P_{tot} = 0.5$ W, it can be concluded that if the total transmit power is higher, the sum of the nondiagonal elements in the probabilistic adjacency matrix will be larger and the PER will be lower under the satisfied constraints. Comparing (a) and (b) of Figure 8, it can be concluded that the increment in the number of

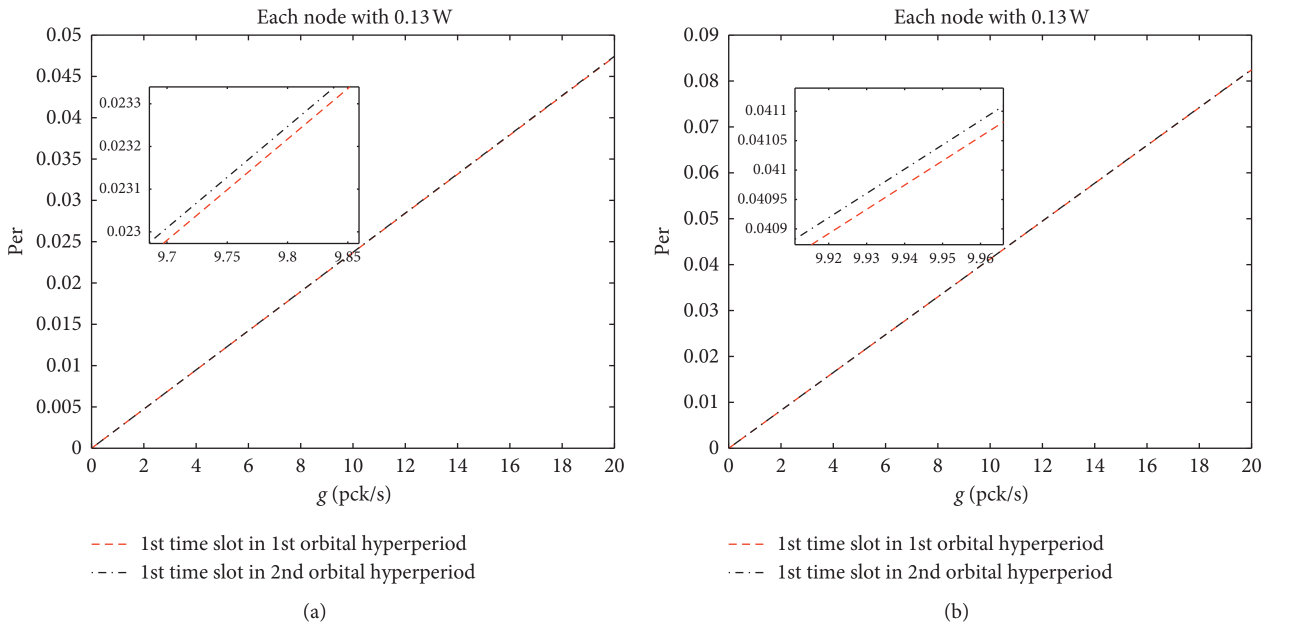


FIGURE 5: PER as a function of the offered traffic load g in the 1st time slots of different orbital hyperperiods with the same transmit power. (a) $L1 = 5$. (b) $L2 = 7$.

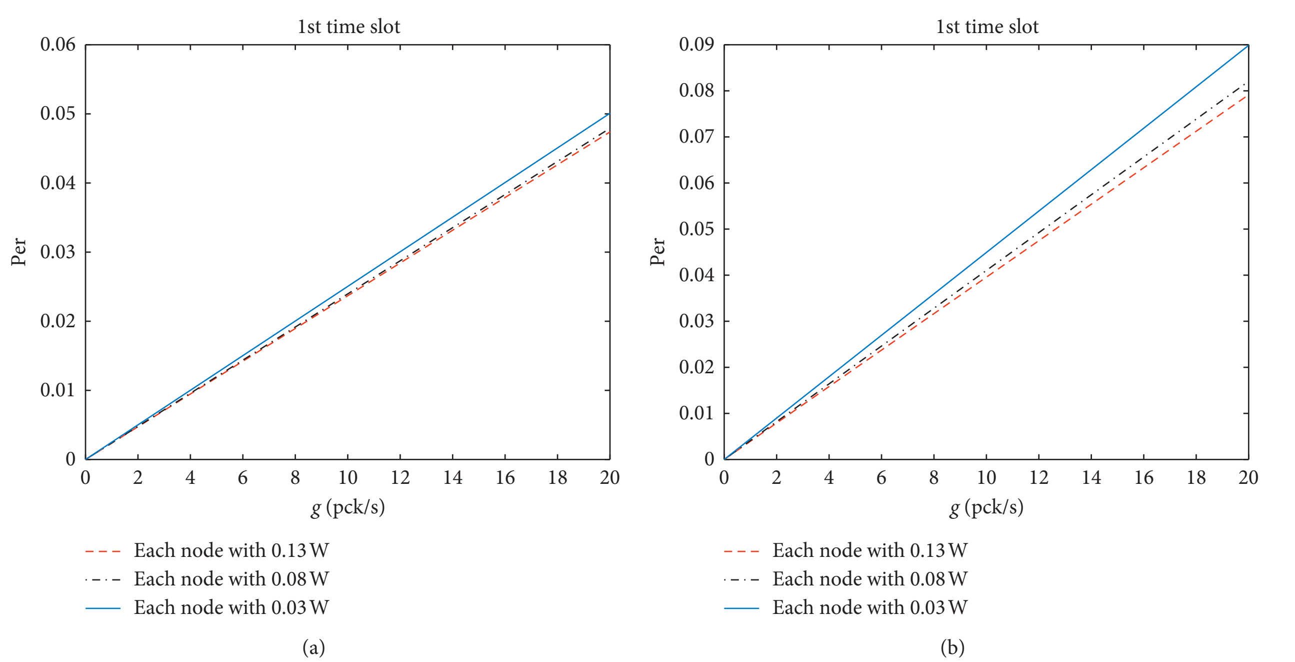
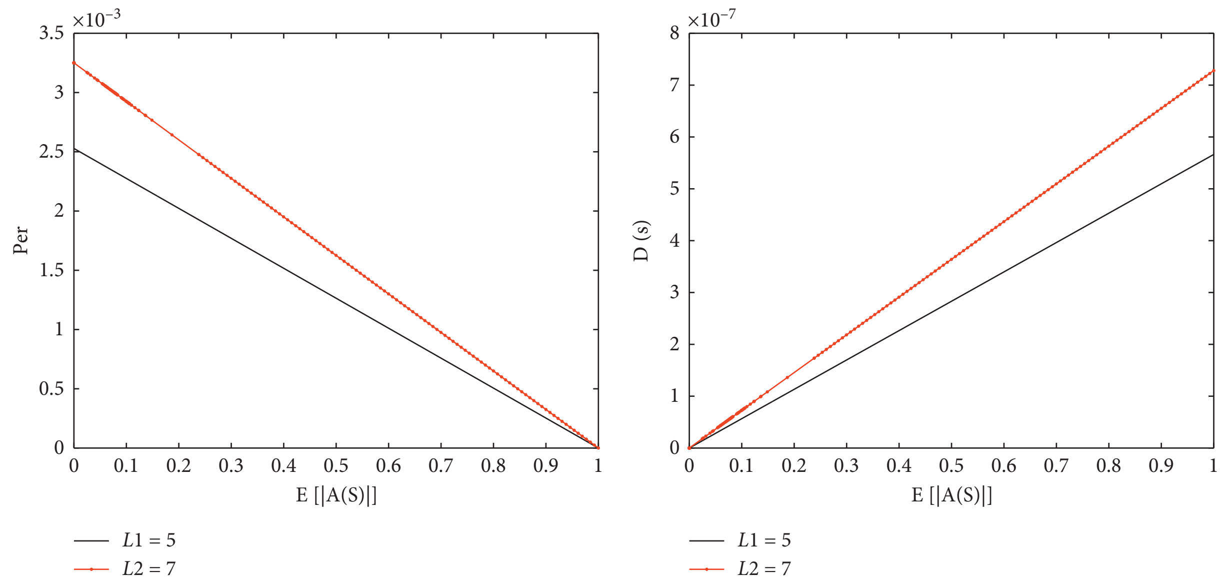


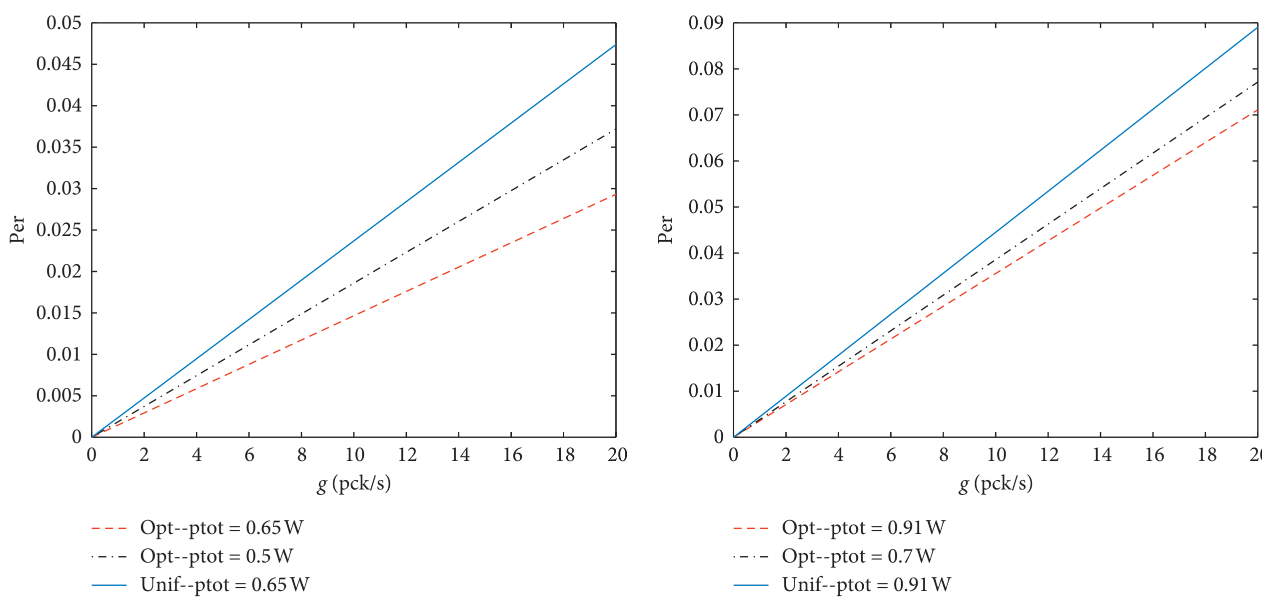
FIGURE 6: PER as a function of the offered traffic load g in a time slot with different transmit power. (a) $L1 = 5$. (b) $L2 = 7$.

nodes will increase the PER of the system. For the sake of comparison, in Figure 8, the PER in scenarios where no transmit power allocation strategy is used (solid line) is also shown. In this case, the performance is worse than the case with the optimized transmit power allocation strategy. In fact, given a value of total network transmit power, the proposed transmit power allocation strategy allows to maximize the sum of the nondiagonal elements in the probabilistic adjacency matrix and, therefore, reduce the PER.



(a) (b)

Figure 7: PER and delay as a function of the $\mathbb{E}[|A(S)|]$. (a) PER. (b) Delay.



(a) (b)

Figure 8: PER as a function of the offered traffic load g in the 1st time slot. (a) $L1 = 5$. (b) $L2 = 7$.

5. Conclusion

In this paper, we have presented an optimized transmit power allocation strategy which allows to minimize the PER of CFSN. First, according to the probabilistic adjacency matrix, we have derived a simplified analytical model which describes the performance of CFSN in different time slots, under the assumption of offered traffic load. Then, we have presented optimization-theoretic transmit power allocation algorithm and implemented it under the assumption of finite total network transmit power under two cases of different numbers of nodes. In particular, we have shown the performance depends on the probabilistic adjacency matrix: the sum of the nondiagonal elements and traffic load. Our analytical model has been validated through the Monte Carlo method. This paper has presented the impact of the probabilistic adjacency matrix, the offered traffic load, and transmit power allocation strategy on relevant network performance indicators (PER and delay). Finally, we have verified that the proposed transmit power allocation strategy, by maximizing the sum of the nondiagonal elements in the probabilistic adjacency matrix, allows to minimize the PER for a given total network transmit power at any time slot for CFSN.

Data Availability

The orbital data of CFSN composed of 5 satellites and 7 satellites that used to support the findings of this study are included within the article and from literature [24].

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Acknowledgments

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Research Article

Modeling and Optimization of RFID Networks Planning Problem

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Aimed at solving the RFID networks planning problem, a mathematical model considering tag coverage and reader interference is presented. The DEEPSO algorithm that adds differential evolution and evolutionary strategies to the standard PSO is introduced to the optimization of RFID Networks Planning, which can improve the global convergence ability and particle diversity and can avoid falling into local convergence. According to the simulation results, compared with RFID networks planning by standard PSO, RFID networks planning by DEEPSO is superior.

1. Introduction

Radio frequency identification (RFID) technology has been widely applied to asset tracking, smart grid, car manufacturing, and supply chain management. The basic components of RFID system are tags and readers. Readers gain access to the information stored on the tags within a distance of several meters [1]. Then, readers and tags need to be deployed in the working area, which must consider several practical problems, such as the tag coverage, the cost efficiency, and the quality of service (QoS) [2]. The RFID network planning (RNP) problem aims to optimize a set of objectives by adjusting the control variables of the system and RNP is a difficult NP problem [3]. Because RNP is a large-scale, high-dimensional nonlinear optimization problem with large number of uncertain parameters, it cannot be tackled by the traditional techniques [4].

Metaheuristic is an efficient approach for hard optimization problems. For solving the RNP problem, evolutionary computation and swarm intelligence techniques have been applied, such as genetic algorithms [5], evolutionary strategy [6], particle swarm optimization (PSO) algorithms [7, 8], firefly algorithms [9], artificial bee colony algorithms [2], and bacterial foraging algorithms [10]. However, with the increasing number of the deployed readers and tags in the large-scale RFID deployment environment, the degree of complexity for solving the RNP optimization increases exponentially. The previous methods to solve the RNP optimization are incompetent for being prone to premature convergence.

For avoiding premature convergence, the idea of heuristic algorithm has been developed into an important and effective way to improve the optimization performance, which can combine the advantages of various algorithms. In [11], a hybrid algorithm combining genetic algorithm and particle swarm optimization is proposed and applied RNP optimization. In [12], a hybrid algorithm combining genetic algorithm and artificial bee colony algorithm is proposed and applied RNP optimization. DEEPSO [13] is a hybrid algorithm based on PSO combining differential evolution and evolutionary computation, which was the winner in 2014 of the competition on the application of modern heuristic optimization algorithms for solving optimal power flow problems [14]. For increasing the optimization performance of RFID Networks Planning, the DEEPSO algorithm is introduced and applied.

The rest of the paper is organized as follows. In Section 2, RFID network planning problem and Mathematical model are presented. Section 3 first gives a review of the DEEPSO algorithm and then proposes the realization method of RFID network planning problem using DEEPSO. In Section 4, the simulation experiments and results analysis of RFID network planning problem using DEEPSO are presented. Finally, Section 5 outlines the conclusions.

2. RFID Network Planning Problem and Modeling

2.1. Problem Description. The key components of an RFID system are the tags and readers. The RFID tag, which is attached to the item to be tracked, stores the unique identification number of the item using a small integrated circuit. The RFID readers communicate with the tags by reading the information stored on them. The reader has a limit on its interrogation range, within which the tags can be read. Thus, the RFID network planning problem is a difficult problem that needs to be solved in order to deploy and operate the large-scale network of RFID readers in an optimal fashion. Consider the following:

(1) The monitoring area is a two-dimensional plane

(2) An appropriate amount of tags are randomly placed in the area

(3) The coverage of the reader is a circular area centered

(4) The readers are isomorphic with the same perceived radius

(5) The reader can be moved and the energy is sufficient to ensure that the final positional movement is completed

2.2. Mathematical Model. The symbols and declarations of the mathematical model are shown in Table 1.

The first objective function f_c represents the tag coverage, which is the most important in an RFID system. If the distance between the i^{th} tag and the k^{th} reader is smaller than the sensing radius of reader, the communication between the i^{th} tag and the k^{th} reader can be established. Then the function is formulated as

$$\max f_c = \frac{1}{N_t} \cdot \sum_{i=1}^{N_t} \sum_{k=1}^{N_r} p_1(t_i, r_k), \tag{1}$$

where

$$p_1(t_i, r_k) = \begin{cases} 1, & \text{if } d(t_i, r_k) \le R, \\ 0, & \text{else.} \end{cases} \tag{2}$$

The second objective function f_i represents the reader interference. Reader collision mainly occurs in a dense reader environment, where several readers try to interrogate tags at the same time, which results in an unacceptable level of misreads. The objective function is formulated as

$$\min f_i = \frac{1}{N_t} \cdot \sum_{i=1}^{N_t} p_2(t_i), \tag{3}$$

where

$$p_2(t_i) = \begin{cases} 1, & \text{if } \sum_{k=1}^{N_t} p_1(t_i, r_k) \ge 2, \\ 0, & \text{else.} \end{cases} \tag{4}$$

In order to align with the first objective optimization direction, modify (3) into the following formula:

Table 1: The symbols and declarations.

Symbol	Declaration
N_t	The number of tags
t_i	The coordinates of i^{th} tag, $t_i = (xt_i, yt_i)$
N_r	The number of readers
r_k	The coordinates of k^{th} reader, $r_k = (xr_k, yr_k)$
R	The sensing radius of reader
$d(t_i, r_k)$	The distance between the i^{th} tag and the k^{th} reader

$$\max f_i' = \frac{1}{\sum_{i=1}^{N_t} p_2(t_i) + 1}. \tag{5}$$

Then, the RNP problem concerns the tag coverage and the reader interference that are formulated as follows:

$$\begin{cases} \max f = w_c f_c + w_i f_i', \\ w_c + w_i = 1. \end{cases} \tag{6}$$

3. RFID Network Planning Optimization Based on DEEPSO

3.1. DEEPSO. Assumed in the space D, randomly initialize a population of particles $P = \{p_1, p_2, \ldots, p_N\}$ with number of particles N. The position and velocity of the i particle are $x_i = (x_{i1}, x_{i2}, \ldots, x_{iD})^T$ and $v_i = (v_{i1}, v_{i2}, \ldots, v_{iD})^T$. The individual extremum of the population is expressed as $\text{best}_i = (\text{best}_{i1}, \text{best}_{i2}, \ldots, \text{best}_{iD})^T$, the global extremum is expressed as $g\text{best} = (g\text{best}_1, g\text{best}_2, \ldots, g\text{best}_D)^T$, particles update speed, and position according to the following formula:

$$\begin{aligned} v^{(k+1)} &= w v_i^{(k)} + c_1 \cdot \text{rand}() \cdot \left(\text{best}_i^{(k)} - x_i^{(k)}\right) \\ &\quad + c_2 \cdot \text{rand}() \cdot \left(g\text{best} - x_i^{(k)}\right), \end{aligned} \tag{7}$$

$$x_i^{(k+1)} = x_i^{(k)} + v_i^{(k)}, \tag{8}$$

in which k denotes the current generation, rand( ) is a random number between (0, 1), c_1 and c_2 are acceleration constants, which represent the weight of particles moving toward individual extremum and global extremum, and w is the inertia coefficient, when w is larger, representations have stronger global search capabilities, when w is smaller, representations have stronger local search capabilities.

The improvement of DEEPSO over PSO consists of using a recombination mechanism with Differential Evolution (DE) and using a self-adaptive recombination operator with Evolutionary Strategies (ES). On one hand, DEEPSO relies on the past information of optimization process to create new promising solutions and proposes the replacement of the individual memory by a collective memory to enable an improved sensitivity of the optimization landscape. On the other hand, DEEPSO has self-adaptive properties by a self-adaptive recombination operator. The DEEPSO movement rule based on classical PSO by replacing the memory term by the perception term as

$$v^{(k+1)} = w_1 \cdot v^{(k)} + w_2 \cdot \left(\text{best}_r^{(k)} - x^{(k)}\right) + w_3 \cdot \left[C \cdot \left(g\text{best}^* - x^{(k)}\right)\right], \quad (9)$$

in which w_1, w_2, and w_3 represent inertia, memory, and cooperation weights, respectively, C is an $N \times N$ diagonal matrix of random variables that follow a Bernoulli distribution with success probability P, $\text{best}_r^{(k)}$ represents an individual from memory B that is computed every iteration according to one strategy of sampling in the same generation and sampling from the past bests, the superscript $g\text{best}^*$ indicates that the parameter undergoes evolution under a mutation process:

$$g\text{best}^* = g\text{best} + \tau \cdot N(0,1), \quad (10)$$

where τ is the mutation rate and $N(0,1)$ is a number sampled from the standard Gaussian distribution.

3.2. RFID Network Planning Optimization Based on DEEPSO. When applying the DEEPSO algorithm to RFID network planning optimization, two problems must be solved: parameter coding and fitness function. Randomly deploying m nodes to the monitoring area can be seen as a continuous optimization problem. Each deployment scenario includes $2m$ elements, which represent the x coordinates and the y coordinates of m nodes. Define the fitness function of particles in the RFID network planning optimization algorithm as equation (6). Suppose the number of particles is N, each deployment scenario can be thought of as a particle. The goal of RFID network planning optimization is to find the particle that maximizes the fitness function value.

To using DEEPSO to solve the RNP problem, the following steps should be taken and repeated.

Step 1. Initialization: There are RFID deployment parameters and simulation parameters. The deployment parameters consist of the shape, size, and dimension of the working area, the number of tags N_t, the coordinates of tags t_i, the number of readers N_r, and the sensing radius of reader R. Simulation parameters consist of the positions $\{x_k^{(i)}\}_{i=1}^{N}$ and the velocities $\{v_k^{(i)}\}_{i=1}^{N}$ of particles, the inertia weight w_1, the memory weight w_2, and the cooperation weight w_3, the success probability P, the mutation rate τ, and the simulation generation Gen.

Step 2. Evaluate: Calculate the fitness function values of all particles using equation (6), get the best individual $g$best and memory B.

Step 3. Loop: Determine whether the generation number is smaller than the simulation generation Gen. If so, firstly, compute the perception term $\text{best}_r^{(k)}$ for the current individual according to the perception strategy; secondly, copy the current individual; thirdly, mutate the strategic parameters $g\text{best}^*$ of the copied individual according to (10); fourthly, move the current individual and its copy according to 8) and (9); lastly, evaluate the current individual and its copy, and update the best individual $g$best and memory B. If not, stop the procedure.

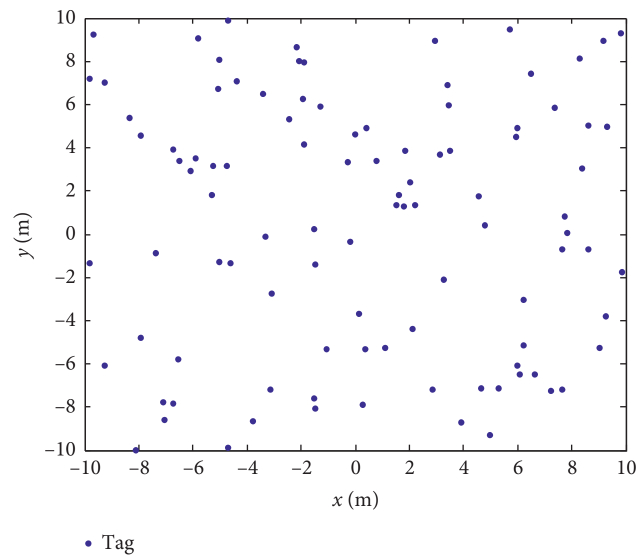

Figure 1: The initial placement of square working area.

Table 2: Simulation parameter setting.

Parameters	Setting values	Algorithms
N	50	PSO and DEEPSO
Gen	150	PSO and DEEPSO
c_1	1.467	PSO
c_2	1.467	PSO
w	0.729844	PSO
w_1	rand( )	DEEPSO
w_2	rand( )	DEEPSO
w_3	rand( )	DEEPSO
P	0.8	DEEPSO
τ	0.4	DEEPSO
ω_c	0.8	DEEPSO
ω_i	0.2	DEEPSO

Step 4. Termination: The results containing the coordinates of readers and the fitness values are given.

4. Simulation Experiment and Analysis

In order to measure the optimization performance of the proposed method, the MATLAB software was used to implement numerical simulation.

4.1. Simulation Experiment Environment and Parameter Settings. All the algorithms are evaluated against an ideal square working area (a 30 m ∗ 30 m working space with 100 tags that distributed randomly), which is shown in Figure 1.

The RFID reader has a working radius of 3 m and uses 10 RFID readers to collect data from the tags in the work area. The experiment uses PSO and DEEPSO to optimize the planning of the RFID reader network. The parameters are shown in Table 2.

In the work area, 50 deployment locations are randomly generated for 10 readers, respectively, and are the initial position values of the particles in the particle swarm

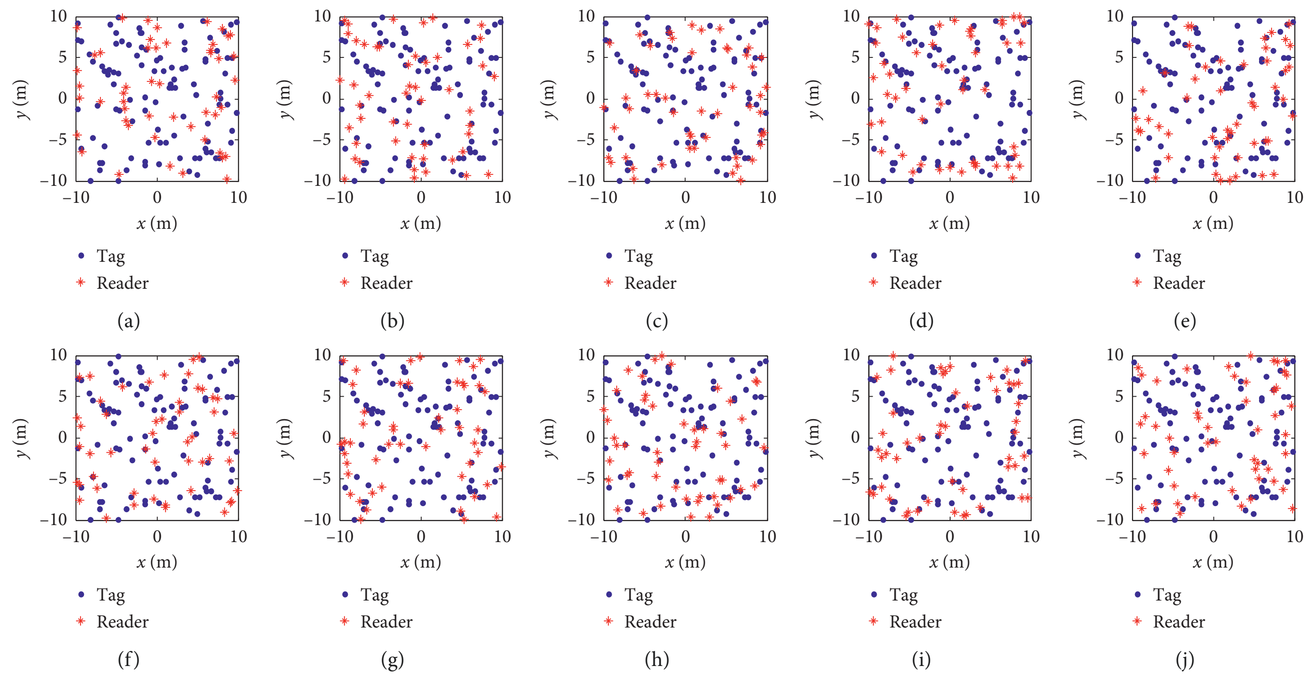

Figure 2: The initial position values of the 50 particles. (a) Reader 1. (b) Reader 2. (c) Reader 3. (d) Reader 4. (e) Reader 5. (f) Reader 6. (g) Reader 7. (h) Reader 8. (i) Reader 9. (j) Reader 10.

algorithm, which corresponds to 50 deployment scenarios. The initial position values of the 50 particles are shown in Figure 2.

In the 50 deployment scenarios, the best scenario is the 1st through calculating the fitness value, which is shown in Figure 3. The coordinates of the 10 readers are, respectively, (−4.28, 9.73), (−1.36, 1.48), (0.54, −6.05), (−6.69, −0.02), (9.80, −2.12), (4.28, −6.48), (−8.59, −6.85), (−6.77, −4.33), (0.73, 5.46), and (7.61, 2.75), and the function value is 51.6%.

A random number between two [−7, 7] is randomly generated as the X-axis velocity and the Y-axis velocity of each deployment position, the initial velocity value of the particles in the particle swarm algorithm, and the initial velocity of the readers 1 to 6 is shown in Figure 4.

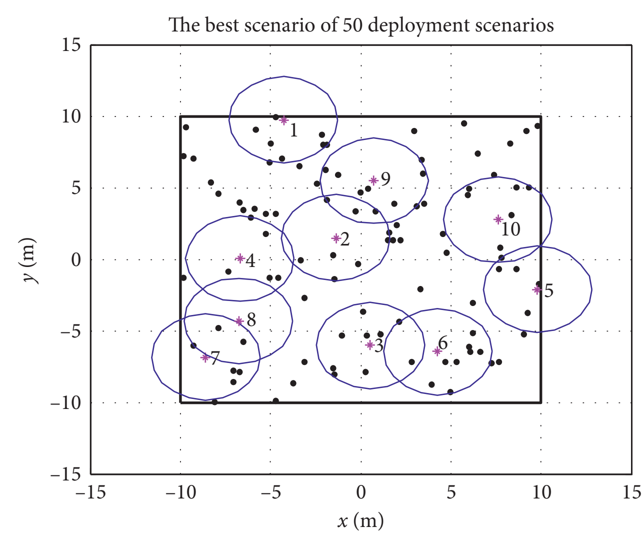

Figure 3: The best scenario of 50 deployment scenarios.

4.2. Simulation Results and Analysis. The result of the RFID network planning simulation run once using standard PSO and DEEPSO is shown in Figures 5 and 6.

It can be seen from Figures 5 and 6 that the distribution of readers after optimization is more reasonable. The coordinates of the 10 readers by the standard PSO are, respectively, (−4.96, 9.52), (0.09, 0.16), (−1.55, −5.49), (−5.21, −1.99), (9.93, −1.77), (5.02, −5.96), (−7.00, −9.30), (−5.13, −3.87), (−1.55, 5.16), and (8.27, 5.71), the optimization function value is 79.2% when the generation value is 35. The coordinates of the 10 readers by the DEEPSO are, respectively, (2.40, 4.45), (1.97, −1.2), (8.86, −3.15), (5.28, −0.48), (0.32, 8.20), (−0.59, −4.04), (−4.95, -7.87), (5.17, −7.47), (−5.26, 5.24), and (7.30, 4.73), the optimization function value is 81.6% when the generation value is 119. Compared with RFID networks planning using PSO, RFID networks planning using DEEPSO shows the better optimization performance, which makes the function value increase by 2.4%.

In order to further verify the optimization performance of the proposed method, the simulation experiment environment and parameters remain unchanged, 50 independent optimization experiments are performed respectively. The performance comparison of the two methods is shown in Figure 7.

It can be seen from Figure 7 that the min fitness value is 58.4%, the max fitness value is 84%, the mean fitness value is

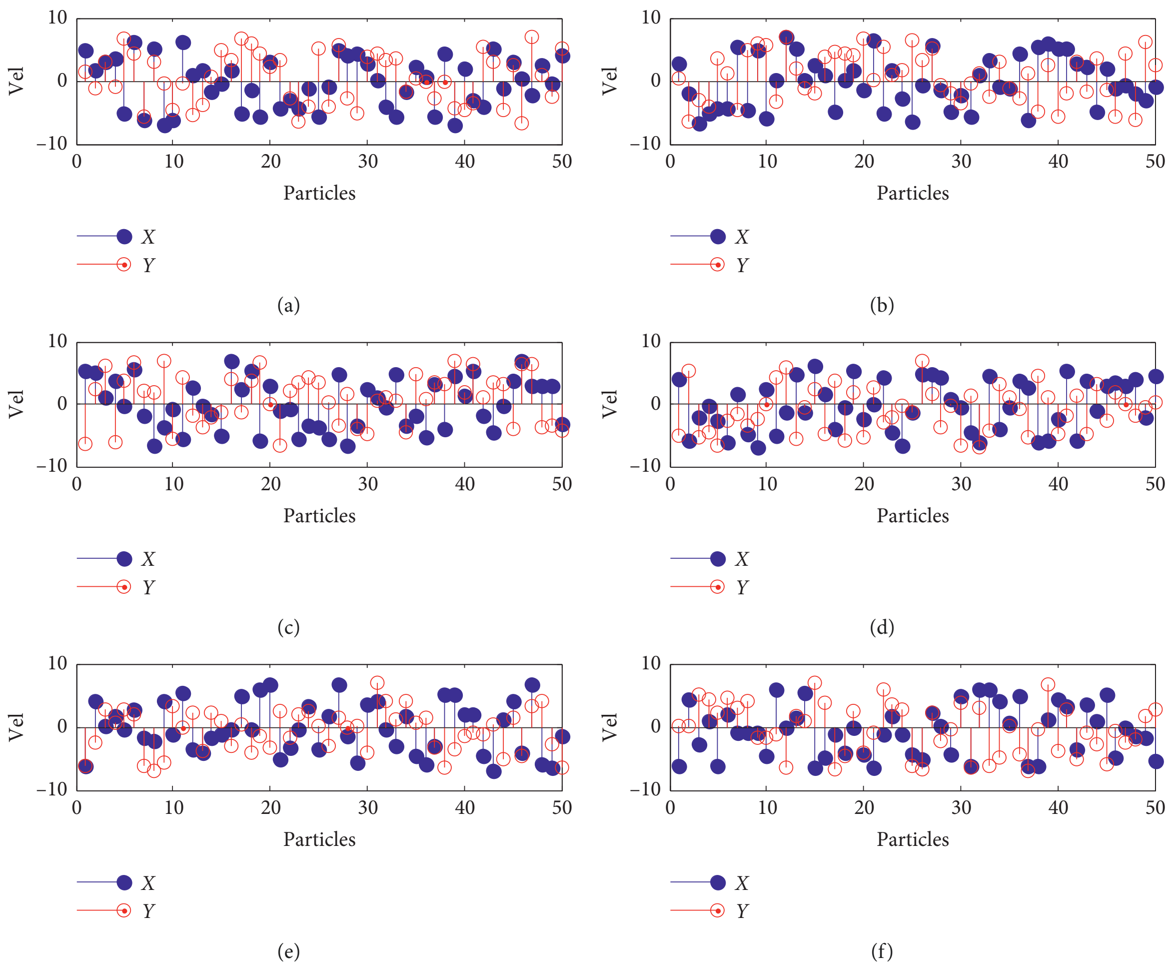

Figure 4: The initial velocity of the 50 particles in the readers 1 to 6. (a) Reader 1. (b) Reader 2. (c) Reader 3. (d) Reader 4. (e) Reader 5. (f) Reader 6.

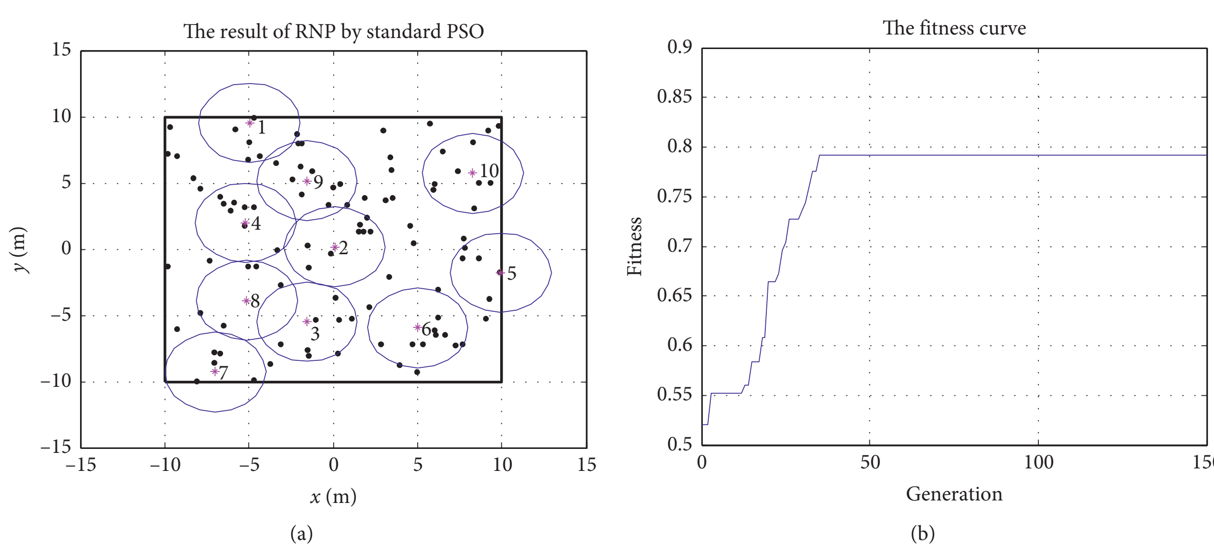

Figure 5: The simulation result of RFID network planning by the standard PSO.

77.36% in RNP by PSO, and the min fitness value is 72%, the max fitness value is 88%, the mean fitness value is 80.75% in RNP by DEEPSO. Comparing with RNP by PSO, the mean fitness value of RNP by DEEPSO can be improved by 3.39%. The simulation results show that the method of RNP by DEEPSO has the better optimization performance. This is

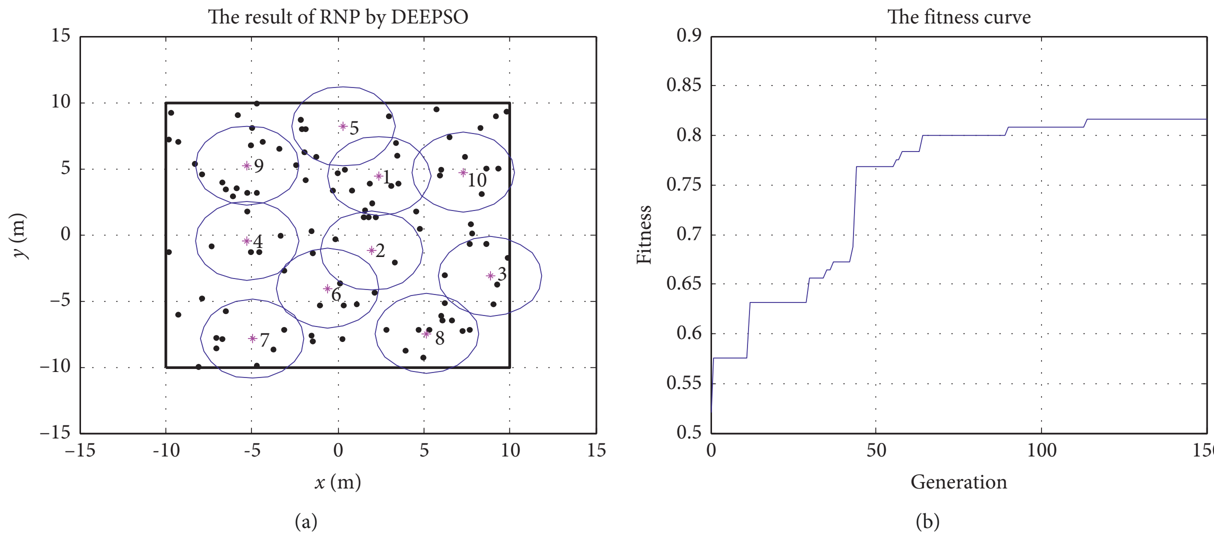

Figure 6: The simulation result of RFID network planning by DEEPSO.

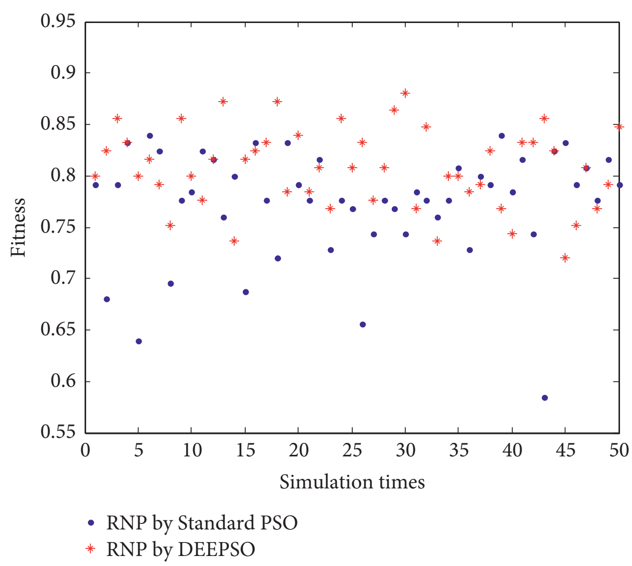

Figure 7: Comparison of two methods running 50 times.

because DEEPSO, which adds Differential Evolution (DE) and Evolutionary Strategies (ES) to the standard PSO, has continuous optimization ability, especially the later of the optimization process.

5. Conclusions

In this paper, aimed at solving the RFID networks planning problem, we present a mathematical model considering the tag coverage and the reader interference. In order to align with the same objective optimization direction, we present a transformed formula of the mathematical model as the fitness function. The DEEPSO algorithm that adds Differential Evolution (DE) and Evolutionary Strategies (ES) to the standard PSO is introduced to the optimization of RFID Networks Planning, which can improve the global convergence ability and particle diversity and can avoid falling into local convergence. According to the simulation results, compared with RFID networks planning by standard PSO, RFID networks planning by DEEPSO shows better optimization performance superior. Further research efforts should focus on the modeling and optimization of RFID network planning problem considering the adjustable radiated power of RFID reader.

Data Availability

The experiment data used to support the findings of this study were supplied by Hongshan Kong under license and so cannot be made freely available. Requests for access to these data should be made to m13643861930@163.com.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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Research Article

Performance Evaluation of Zone-Based Routing with Hierarchical Routing in Wireless Sensor Networks

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Routing remains a most challenging task in sensor networks because of constrained resources like battery power, processing, and memory. Many energy efficiency techniques for the sensor networks have been proposed, among which hierarchical routing is considered the most energy-efficient and extended network lifetime technique. This technique has a lesser number of transmissions in the network. On the contrary, zone-based routing claims lesser control and routing overhead on the overall network lifetime. In this research, a simulation-based comparison of zone-based routing with static clustering hierarchical routing is conducted. The simulation results show that the zone-based routing outperforms hierarchical routing with static clustering in terms of energy efficiency, network lifetime, and throughput.

1. Introduction

Wireless sensor networks (WSNs) have spatially distributed nodes used to sense the physical phenomenon of interest. The nodes in the networks are wirelessly connected with each other [1–4]. Each network has one or more base stations (BSs) used to gather the data from the sensors. Nodes in the network have the capability to sense, process, and route the data efficiently to the desired destination. The main issue associated with these networks is that they are constrained by energy, processing power, bandwidth, and internal memory [5, 6]. It is highly environment and application specific that once the nodes are deployed, it is almost impossible to reach the nodes in the deployed region to replace or recharge their battery [7]. The idea of these networks was first coined for military applications. Recently, it is applied in many different application areas spanning from environment sensing to health, engineering, agricultural, industrial, and biohabitat monitoring where sensor networks are playing a vital role [8].

Every protocol developed in the sensor networks stresses on energy efficiency to prolong the network lifetime [9]. The protocol developed at the medium access control (MAC) layer, network layer, transport layer, or the layers above these layers must be energy efficient along with possessing other QoS parameters. Routing is considered to be the most energy-intensive task in the sensor networks [2, 8]. Various energy-efficient protocols have been developed for routing the data from the source to the destination (i.e., BS). As far as network lifetime is concerned, the sensor should consume lesser energy to route the data in the network.

For the routing purpose, the main categories are direct communication protocols, flat (multihop) routing protocols, and hierarchical routing protocols [2, 10]. Hierarchical routing protocols are also called cluster-based protocols. Researchers have extended the developments in cluster-based routing because of the claims that it performs best because of lower transmissions to the BS as compared to other categories of the protocols.

The main drawback of direct communication protocols is that the nodes are located far away from the BS. This results in quick depletion of their energy as they need high energy to transmit the data to reach the ultimate destination. Direct communication is also not suitable for scalable environments because a lot of collisions happen in the system which drastically affects the network throughput.

In contrast, multihop routing seems to be realistic in the sense that whenever a node has data to send, it may reach the BS by utilizing several hops along the path. The routing strategy ensures the nodes with most energy in the path to route the data to the BS [2]. Multihop routing is best suited for the environment where node density is high and nodes are not directly reachable to the BS.

In cluster-based routing/hierarchical routing protocols, the whole sensing region is divided into different equal or unequal regions with one designed cluster head (CH) in each region [11]. All the associated cluster nodes will send their data to the CH in their allotted time slot communicated beforehand, and then the CH performs data aggregation to send the accumulated information to the BS either directly or from the CH to the CH to the BS. The clusters are either static or dynamic. In static clustering, once the clusters are formed, they will never be changed till the end of the network. On the contrary, after each or certain round of communications, the clusters and CHs are rotated for balancing energy dissipation across the network [12]. In cluster-based routing, a smaller number of transmissions are carried out as only the aggregated information is transmitted to the BS. Either the clusters are formed by the BS or they organize themselves in a distributed way into a different cluster. Once we limit the transmissions in the network, ultimately, energy is saved and the overall network lifetime is extended [2, 9].

In zone-based routing, the sensing region is divided into different zones as done in clustering. The difference is that it utilizes only those nodes in the network that are energy efficient. It removes the concept of the CH selection and its rotation after each round of communication [2]. Then, the BS is responsible for cluster formation at the start of the network. Control traffic is exchanged as well as the CH while setting up clusters after each round of communication in hierarchical routing. This unnecessary traffic greatly affects the overall network lifetime. If this control overhead could be eliminated, then there is a chance of network lifetime improvement.

The main motivation behind this work is to investigate and to compare the performance of zone-based routing with that of hierarchical routing, i.e., cluster-based routing. In this paper, we compare the routing algorithm using the ring-zone (RARZ) [2] protocol and energy-efficient technique for handling redundant traffic (EEHRT) [9] which is purely a zone-based protocol with two well-renowned hierarchical routing protocols like the energy-efficient protocol using static clustering (EEPSC) [7] and low-energy adaptive clustering hierarchy (LEACH) [11, 13]. The EEPSC, EEHRT, RARZ, and LEACH protocols all have the same designed philosophy of splitting the network into different zones through the BS. But the routing strategy used in them is different.

In this paper, we consider the same network model as used in the RARZ [2], EEHRT [9], EEPSC [7], and LEACH [11], with the following assumptions:

(i) All the nodes in the network are immobile

(ii) The BS is responsible for dividing the region into different clusters/zones

(iii) The nodes are homogeneous with limited battery power

(iv) BS location can be set up either inside or outside the sensing region

(v) The data sampling rate is fixed

The brief overview of the description of all the protocols presented in this paper is under Section 3. Following are some points that distinguish the RARZ routing from EEPSC routing:

(i) The RARZ and EEHRT did not utilize the concept of CH selection and CH to CH or CH to BS routing as done in the EEPSC and in LEACH.

(ii) The RARZ and EEHRT utilize multihop communication instead of direct communication as in the EEPSC and in the LEACH.

(iii) The RARZ and EEHRT eliminated the concept of control traffic during the routing phase while selecting the next hop node.

(iv) In the RARZ and EEHRT, the next hop node is selected on the fly without having any topological information.

(v) The RARZ and EEHRT are totally nonreactive and nonposition based.

(vi) The RARZ and EEHRT algorithms are not energy aware, but EEPSC and LEACH algorithms are energy-aware protocols. The BS knows the energy level of each node before the start of each round, and each node in the network shares its energy level to the BS.

(vii) In RARZ and EEHRT routing, the next hop node is selected based on a timer, which is a function of node residual energy and its zone where it is located.

(viii) In the EEPSC and LEACH, all the nodes in the network are assumed to be directly reachable to each other and the BS; if they are reachable to each other, then there is no need for routing. This is not a valid assumption made in the EEPSC.

After each round of communication, the CHs are reselected and the direct communication paradigm is adapted to route the aggregated data to the BS by CHs in both the protocols (EEPSC and LEACH).

The rest of this paper is organized as follows: Section 2 describes the related work. Section 3 presents the short description of the protocols used in this paper for comparison. Section 4 describes the simulation results. Finally, Section 5 concludes this paper.

2. Related Works

A lot of work regarding energy-efficient routing has been investigated in sensor networks since 2002. A plethora of work presented on routing stuff is available in the digital library. Among all the routing protocols developed till now, people have contributed a lot to cluster-based routing. The first idea of clustering was given by Wendy Heinzelman at MIT in her PhD dissertation [14], in which she developed a protocol called low-energy adaptive clustering hierarchy (LEACH) [11] which is based on distributed as well as centralized CH selection and cluster formation, where sensor nodes elect themselves as CH nodes with some probability based on remaining energy and location information. A centralized approach is also developed to form the clusters through the BS. LEACH-C [10] is based on LEACH and uses a centralized approach for cluster formation and CH selection. Direct communication is formulated between CHs and the BS. LEACH works in different phases or rounds. Each round starts with a configuration phase also called the network setup phase followed by a data communication phase. Once all the nodes associate themselves with their designated cluster, they will send their data in their allotted time slot to the CH, and then the CH will send the whole cluster data after making some necessary aggregation to the BS.

Another similar solution based on hierarchical routing is presented in [5], in which each node can send its data to its immediate closest neighbour. After that, among neighbours, one leader node is selected to route the aggregated data to the BS directly. This solution was named "power-efficient gathering in sensor information systems" (PEGASIS). The main purpose of this algorithm is to evenly distribute the energy dissipation across the network.

Researchers also considered optimization of the routing process to some extent by combining different features in one algorithm. According to this design philosophy, a similar effort is done in [15], where the authors combine the data aggregation, energy-aware routing, and clustering into one protocol. This greatly enhances the overall network lifetime. The authors utilize dynamic clustering for energy balancing across the network. To conserve energy, multihop hierarchical routing is used to cover the large distances efficiently.

Another concept of energy-efficient and context-aware cluster-based routing is presented in [16] that also claims the energy-efficient communication in the system by utilizing only those nodes that are energy efficient and best suited as per the context. In ordinary clustering, the node deployment or arrangement is fixed [13, 14], but people also gave a solution to implement the hierarchical routing in ad hoc way [17].

A connected cluster architecture idea is presented and tested in [16]. As per that idea, the CHs and gateways assume the same nodes in the network. The CH is assumed to be the central node, while the gateway node is the backbone node to transmit data to different users placed at different locations. A distributed clustering solution is presented in [3]. According to this algorithm, nodes in the sensing region are organized into equal-sized clusters first, and then CH to CH routing is performed to extend the overall network lifetime. The energy consumption among all the CHs is evenly distributed for enhancing the network lifetime.

As sensor nodes are equipped with a built-in battery power, their lifespan is short. The researcher gave keen attention to this issue in almost every protocol developed at every layer of the protocol stack. To further enhance the network lifetime and conserve energy, a data query dissemination and gathering scheme is presented in [18]. In this work, authors conceived a concept of the parameterized query based on the user's profile to get the required data from the sensor nodes. The scheme is proven to be the most energy efficient as compared to the rest of the techniques of a similar domain.

A lot of work has also been investigated on energy-aware routing. A similar work is presented in [19], in which authors utilize an energy-aware technique with static clustering called centralized control clustering (EACCC) in order to achieve energy efficiency and greater lifespan of the network, especially in a scalable environment. The performance of the EACCC is accessed through extensive analytical proofs and simulation, and it has been shown that the EACCC is highly efficient in terms of balancing the energy consumption and prolonging the network lifetime.

The work in [17] is based on hybrid clustering. According to this scheme, clusters are static and never changed up to 10 rounds. The BS is responsible for the selection of next-phase CHs. If the round number is less than 10, the current CH selects the new utmost energy level node as a CH and intimates its status to the BS. After round number 10, all the nodes send their energy status and location information to the BS and the BS will set up new clusters for the next time.

The researchers also presented the solutions to reduce the control overhead of the cluster-based routing protocols and to increase the network lifetime. These categories of protocols are called zone-based routing protocols [2, 9]. A similar sort of solution is presented in [3] called the zone-based routing protocol (ZBRP), which is an energy-efficient and edge-based network partitioning technique. It divides the whole sensing region into equal-sized clusters. The BS is responsible for dividing the whole sensing region into different zones around the BS, and then it further divides each zone into equal-sized clusters. Multihop cluster-based routing is performed at the start of each round of communication. New CHs are selected for evenly distributing the energy consumption among all the clusters and CHs in the network. This greatly increases the overall network lifetime as compared to the previous solutions presented in static as well as dynamic clustering. People have contributed to the area where the protocols are energy efficient along with the security measures. A similar sort of work is done in [20, 21]. Even in the current time, the environment sensing through IoTs and other application-specific sensors are used for integration with many online forensic and real-time surveillance applications where innovative techniques are highly desirable to overcome the cybercrime issues [22]. To make the network fully connected to handle the converge

[23] issues due to many obstacles is also highly desirable in the protocol along with other core issues like network lifetime by ensuring energy efficiency in the network.

From the literature review above, it can be concluded that researchers are striving to make protocols energy efficient as well as adding other lifetime-increasing capabilities with less control overhead. This research work also has dug another new way of designing energy-efficient routing protocols.

3. Zone-Based Routing (ZBR) vs Hierarchical Routing (HR)

Both zone-based routing and cluster-based routing are used interchangeably, but their routing philosophy is different. Zone-based routing claims that, along with other methods that greatly ensure energy efficiency, it has less control overhead in the network.

In this section, we present the normal working of the ring zone-based routing protocol and energy-efficient protocol using static clustering.

3.1. RARZ Routing. The ring zone-based routing protocol [2] works in the following two phases:

(a) Network configuration phase

(b) Data communication phase

3.1.1. Network Configuration Phase. This phase is also called the network setup phase in which the whole sensing region is divided into equal-sized zones. The BS is responsible for dividing the whole sensing region into equal-sized zones by sending different transmission power messages having *zoneID* to the sensing region. The nodes that sense that packet will set their ID as per ID received in the message. The BS broadcasts different communication range messages progressively till covering the whole field. Nodes that receive a zone i message will set themselves to zone i, unless they have already joined the lower *zoneID*. All the nodes in a zone share the same *zoneID*. Once they set their *zoneID*, the *zoneID* will never be changed till the end of the network.

Upon successful completion of the network configuration phase, the data communication phase begins. The working phases of the RARZ are presented in Figure 1. Only the lower zone nodes will route the data of higher zones to the BS. The nodes located in the same and the higher zone will delete the packet after checking *zoneID* at the MAC layer. For medium access, distributed coordination function of 802.11 is used with two assumptions: (1) there is no pre-MAC addressing used and (2) it does not use strict addressing per node for communication. In RARZ routing, the BS is located among the sensor nodes, but it can be set up everywhere in the sensing region either inside or outside. BS location does not affect the data communication or routing process.

3.1.2. Data Communication and Next Hop Node Selection Phase. In the RARZ, whenever a node has data to send, it just broadcasts its data with its *zoneID*. The nodes that hear that packet in the same, lower, and high zones will process the packet. As per the routing strategy defined in the RARZ, only the lower zone will schedule the packet further, and the same and the higher zone node will delete the packet. The nodes in the lower zone will schedule the packet for further relaying it. All the nodes in the lower zone will schedule the packet according to a timer. A timer is a function of node *residual energy* and its *zoneID*:

$$\text{timer}(t) = \alpha * zoneID + \beta\left[\frac{\text{IE}}{\text{CE}}\right], \tag{1}$$

where *zoneID* is the network address of the node which is the same as that of all the nodes in a specific zone, IE is the initial energy, and CE is the current energy. The lower the *ZoneID* and the higher the CE, the smaller the timer, and vice versa. For the node having higher energy and lower *zoneID*, its timer will be expired first. α and β are the weighted tuning parameters for node network address and residual energy. The values of α and β are set in Table 1. The node whose timer expires first will become the next potential hop node for the received packet. Once this node further relays the packet, the nodes in the vicinity of sensing the same packet sequence number will kill their timer and delete the packet. This protocol works efficiently without considering any location and topological information to route the packet to its ultimate destination. At each hop falling in the routing path, the most energy level nodes are selected for data transmission. The location-based routing is performed without the need for the nodes to know the position of the neighbouring node. No prior control information is needed for the next hop selection or path construction before the start of transmission. This protocol is totally blind and does routing decisions on the fly. The detailed description of the protocol is presented in [2]. In ZBR, redundant traffic is normally observed which reduces the overall network lifetime. Redundant traffic is handled in [9], to make the routing more effective w.r.t. energy efficiency and overall network lifetime.

3.2. Energy-Efficient Technique for Handling Redundant Traffic (EEHRT). This protocol is an extended version of the RARZ routing which handles the redundant traffic generated in zone-based routing. Moreover, the source node is acknowledged by the next hop node using a wireless broadcast advantage (WBA) technique [24] without having any special ACK packet to the sender, which ensures the reliability without incurring any extra control overhead at each hop along the routing path. The EEHRT improves the routing against the RARZ by ensuring only one copy of the packet is propagated to each hop along the routing path till reaching the BS by introducing a short beacon message in RARZ routing. The detailed working of the EEHRT is presented in [9].

3.3. Energy-Efficient Protocol Using Static Clustering (EEPSC). This EEPSC [7] also works in two phases: the network configuration phase and the data communication phase.

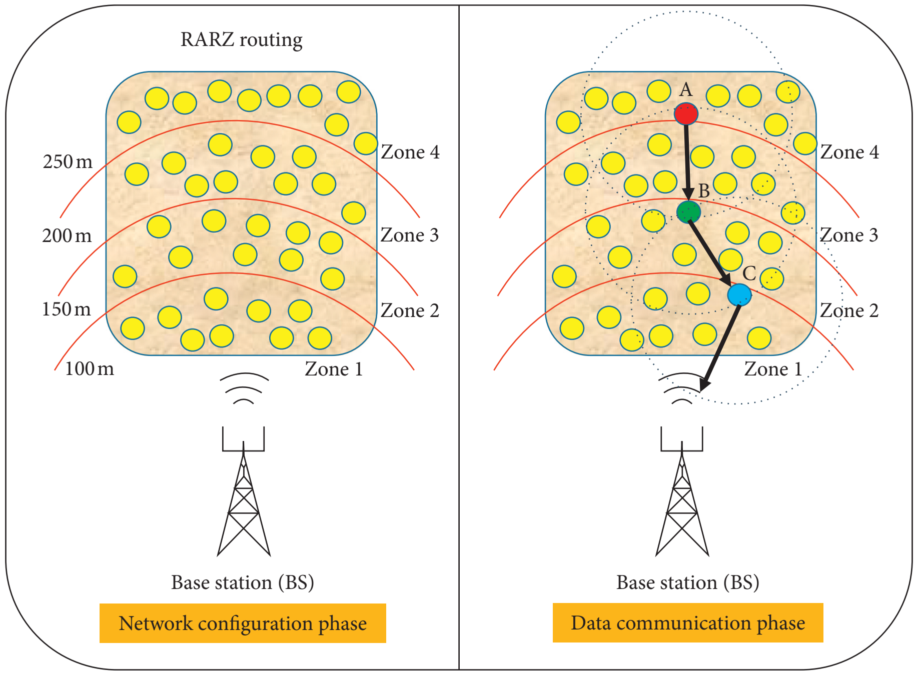


FIGURE 1: RARZ protocol phases.

TABLE 1: Simulation setup.

Type	Parameter	Value
Network	Size	600×600
	Energy of each node	3000 mJ
	Network deployment	Random
	Number of zones	10
	Total number of nodes	100
Application	Data packet size	100 bytes
	Broadcast packet size	25 bytes
	Packet header size	25 bytes
Energy consumption model	E_{elec}	50 nJ/bit
	$E_{amp}(\alpha, \beta)$	0.0013 pJ/bit/m^4 (0.003, 0.001)

3.3.1. Network Configuration Phase. The network configuration or setup phase is almost the same as in that in RARZ routing. The BS is responsible for dividing the whole sensing region into different cluster or zones by broadcasting different transmission power messages to the sensing region.

The main difference as compared to RARZ routing is that once the nodes receive the zone i message from the BS, they will set their ID accordingly and inform the BS that they belong to zone i by sending a join request message (*join-req*) back to the BS directly. This is an extra control message sent by all the nodes in the network which is an overhead. This process will be repeated at the start of each new round of communication. The complete working of the EEPSC is shown in Figure 2.

3.3.2. Data Communication Phase. Once the whole sensing region is divided into different clusters or zones, the data communication phase also called the steady phase begins. As the BS receives join request messages from all the sensor nodes in the sensing region, it randomly selects one temporary cluster head (TCH) in each zone and broadcast this information to all the clusters along with the time-division multiple-access (TDMA) schedule for each node. After that, the TCH will select one utmost energy level node as a CH and lowest energy level node as a TCH for the next round and inform all the nodes in the cluster. Afterward, all the nodes will send their sensed information to the designated CH, and then the CH will send the accumulated information directly to the BS.

In this protocol, some major issues are identified. Firstly, all the nodes are directly reachable to each other. If all the nodes are directly reachable to each other, then there is no need for routing. Secondly, a lot of control information is needed for the selection of the CH and TCH before the start of each round of communication which is an overhead. The authors also claim that direct communication is energy efficient as compared to multihop routing which is not a valid point because we cannot

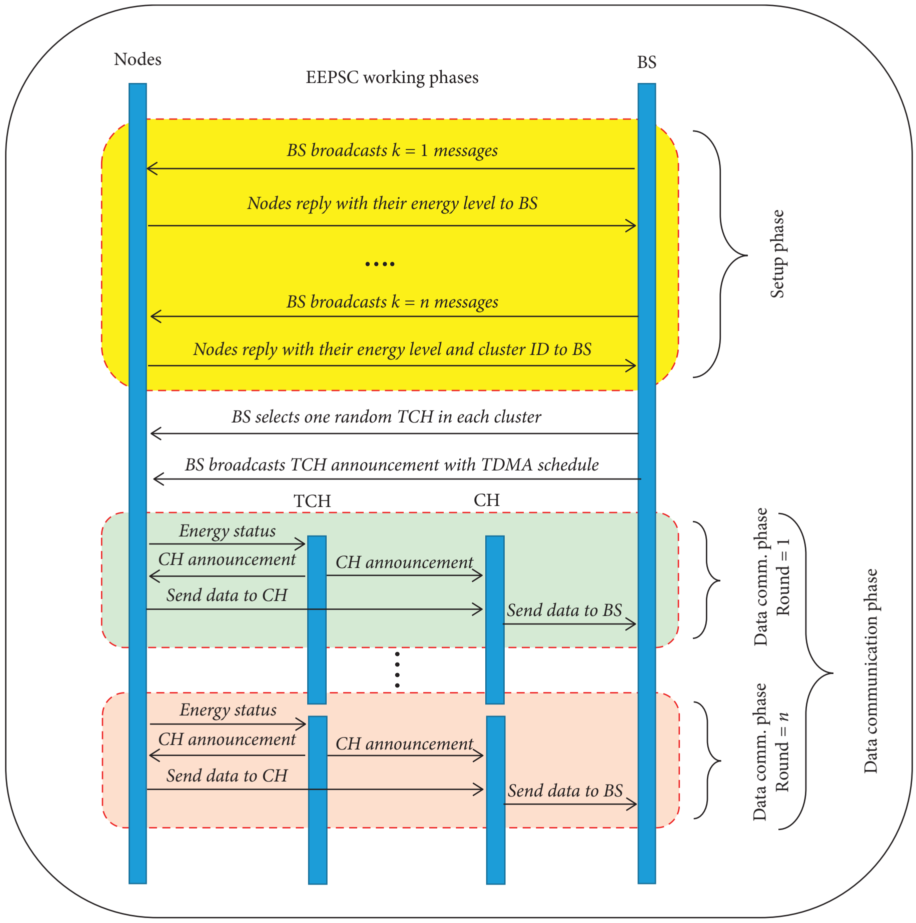


FIGURE 2: Working phases of the EEPSC.

compare the sensor node specification with the BS as the BS is more powerful and can cover the whole sensing region. And thirdly, if the network diameter is very large, then the nodes located at the edge of the network will require more transmission power to reach the BS and will deplete their energy very quickly. This greatly affects the overall network life. The assumptions made in the EEPSC are not valid as per the general prospects of the sensor networks. If all the nodes in the network are directly reachable to the BS, then because of the scalable environment, more collisions can occur in the network, which ultimately ends up in greater packet loss.

3.3.3. Energy Dissipation Model. The same energy model is used in simulation as used in the RARZ [2], EEHRT [9], EEPSC [7], and LEACH [11]. This is also called the first-order radio model as developed and tested in [8]. According to this model, whenever a node sends or receives an n bit message over distance x, energy will be consumed. For sending a message, the following model is utilized:

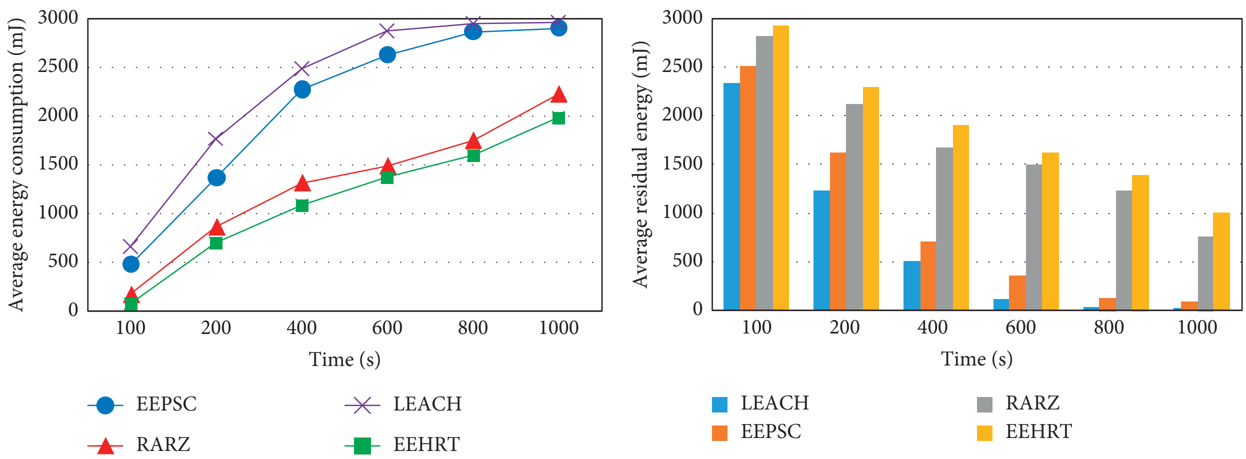
$$E_{\mathrm{Tx}}(n,x) = E_{\mathrm{Tx-elec}}(n) + E_{\mathrm{Tx-amp}}(n,x),$$
$$E_{\mathrm{Tx}}(n,x) = E_{\mathrm{elec}} \times n + E_{\mathrm{amp}} \times n \times x^2. \quad (2)$$

For receiving a message, the following model is utilized:

$$E_{\mathrm{Rx}}(n) = E_{\mathrm{Rx-elec}}(x),$$
$$E_{\mathrm{Rx}}(n) = E_{\mathrm{elec}} \times x. \quad (3)$$

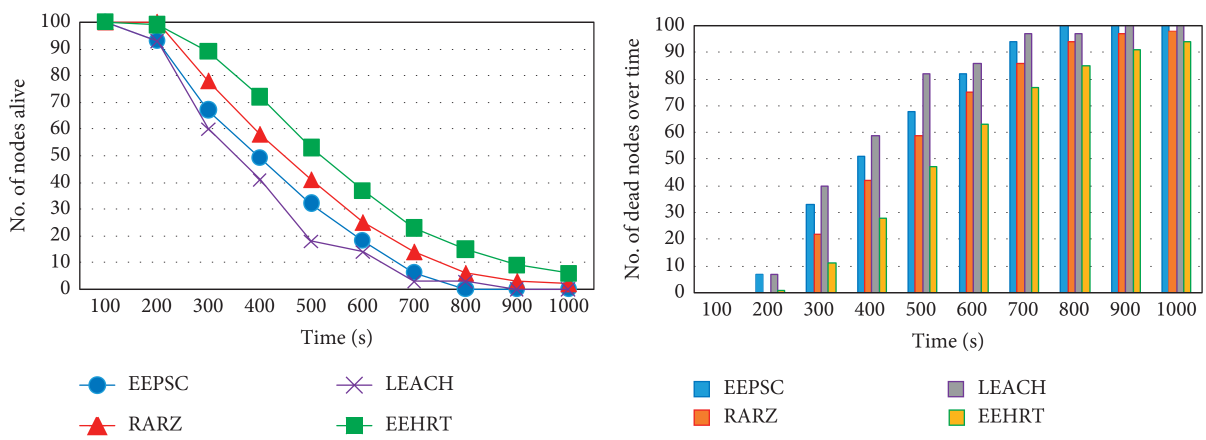
In (2), $E_{\mathrm{Tx}}(n,x)$ is the energy required to transmit an n bit message over a distance of x meters and E_{amp} is the energy used for the amplifier to realize an acceptable signal-to-noise ratio (SNR). In (3), $E_{\mathrm{Rx}}(n)$ is the energy required to receive an n bit message and E_{elec} is the energy for transceiver circuitry.

3.4. Low-Energy Adaptive Clustering Hierarchy (LEACH). A plethora of work presented on routing stuff is available in the digital library. Among all the routing protocols developed till now, people have contributed a lot to cluster-based routing. LEACH [11] is based on distributed CH selection and cluster formation, where sensor nodes elect themselves as CH nodes with some probability based on remaining energy and location information. A centralized approach is also developed to form the clusters through the BS. LEACH-C is based on LEACH and uses a centralized approach for cluster formation and CH selection. Direct communication is formulated between CHs and the BS. LEACH works in different phases or rounds. Each round starts with a configuration phase also called the network



(a) (b)

Figure 3: (a) Average energy consumption (b) and average residual energy in the system over time.



(a) (b)

Figure 4: (a) Number of nodes alive (network lifetime) and (b) number of dead nodes over time.

setup phase followed by a data communication phase. Once all the nodes associate themselves with their designated cluster, they will send their data in their allotted time slot to the CH, and then the CH will send the whole cluster data after making some necessary aggregation to the BS.

4. Simulation and Result Discussion

We compare the zone-based routing (ZBR) with hierarchical routing (HR) based on following metrics used in the simulation. Simulation is done in OMNeT++, using an INET framework [25].

(i) Average energy consumption and remaining energy in the system over time

(ii) The number of nodes alive and dead over time (network lifetime)

(iii) Messages successfully received at the BS over time, i.e., network throughput

We have used the same parameters as those used in the RARZ, EEHRT, LEACH, and EEPSC to assess the performance of all the protocols. The parameters of the simulation setup are listed in Table 1.

In Figures 3(a) and 3(b), the average energy consumption and remaining energy in the system over time are shown for all the protocols. The EEHRT and RARZ perform better as compared to the EEPSC and LEACH because in the RARZ and EEHRT, no extra control information is needed to set up the routing path and CH selection in the network. On the contrary, a lot of control packets are exchanged abundantly at the start of each round of communication in the EEPSC and LEACH which consumes most of the energy in the network. Various control packets are exchanged among the nodes to find the appropriate CH, but the RARZ and EEHRT eliminated this overhead by selecting the next hop node without considering any control information that greatly affects the overall network lifetime.

Figures 4(a) and 4(b) show the number of nodes alive and dead over time, respectively. The EEHRT and RARZ outperform the EEPSC and LEACH in terms of a network lifetime because in the EEHRT and RARZ, the energy consumption is evenly distributed and the most energy level

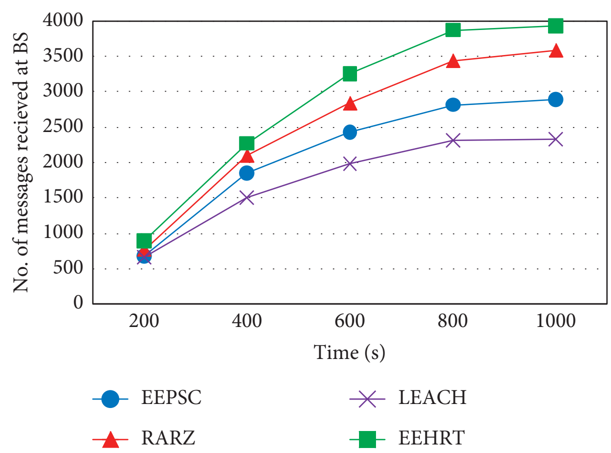


Figure 5: Number of data messages received at the BS over time.

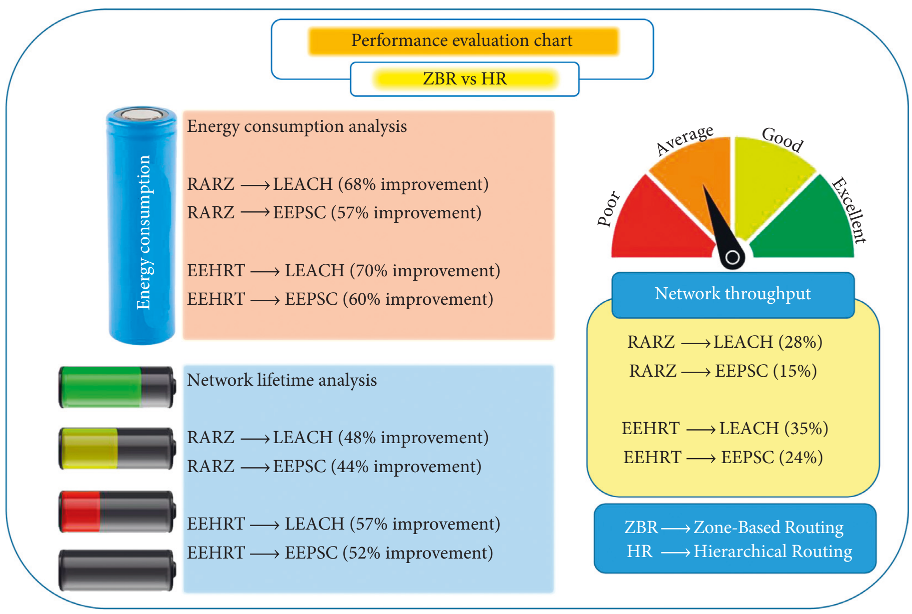


Figure 6: Performance analysis chart.

nodes are always engaged for the routing purpose. As shown in Figure 4, in the EEPSC and LEACH, all the nodes are alive for 100 seconds before the first node completely drains its energy, while in EEHRT and RARZ routing, even within 200 s, none of the nodes in the network dies, which is better than the EEPSC.

The total number of messages successfully received at the BS is shown in Figure 5. It is clearly shown that the number of messages received at the BS is more in the EEHRT and RARZ as compared to that in the EEPSC and LEACH because whenever a node has data to send directly, it broadcasts its data in zone-based routing without exchanging any information before the start of each round of communication. If we thoroughly examine the routing procedure of the EEPSC and LEACH protocol, it is clearly seen that, before the actual data transmission, a lot of control information is exchanged for cluster setup and routing, but in EEHRT and RARZ routing, there is no such information needed for routing the data to the BS. The routing is totally blind, and routing is done on the fly without having any topological information stored in the network.

The performance improvement chart shows the comparative analysis of ZBR with HR in terms of energy efficiency, network throughput, and network lifetime. The general findings are presented in % improvements. The detailed comparative analysis findings of ZBR against HR are presented in Figure 6.

5. Conclusion

In this paper, we have compared the performance of two different categories of routing protocols, i.e., zone-based routing (ZBR) and hierarchical routing (HR), in wireless sensor networks. The simulation shows that ZBR outperforms HR in terms of overall network lifetime, throughput, and energy efficiency. The main finding is that extra control information greatly affects the overall network lifetime and routing process. In ZBR (EEHRT and RARZ), it is shown that no extra control information is needed and exchanged among the nodes or with the BS while selecting the next hop node. ZBR does location-based routing without making any assumption of location services like GPS. It also improves the routing by giving more priority to those nodes which are located immediately to the next zone which greatly reduces the number of hops to the BS. Hence, it is concluded that ZBR outperforms HR in the sensor networks in terms of energy efficiency, network throughput, and overall network lifetime.

Data Availability

No data were used to support this study. We have conducted the simulations to evaluate the performance of zone-based routing with hierarchical routing. However, any query about the research conducted in this paper is highly appreciated and can be asked directly to the corresponding author through email (rabnawaz@mail.ustc.edu.cn).

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

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Research Article

Quality of Service-Based Node Relocation Technique for Mobile Sensor Networks

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Wireless sensor networks (WSNs) deployed in harsh and unfavorable environments become inoperable because of the failure of multiple sensor nodes. This results into the division of WSNs into small disjoint networks and causes stoppage of the transmission to the sink node. Furthermore, the internodal collaboration among sensor nodes also gets disturbed. Internodal connectivity is essential for the usefulness of WSNs. The arrangement of this connectivity could be setup at the time of network startup. If multiple sensor nodes fail, the tasks assigned to those nodes cannot be performed; hence, the objective of such WSNs will be compromised. Recently, different techniques for repositioning of sensor nodes to recover the connectivity have been proposed. Although capable to restore connectivity, these techniques do not focus on the coverage loss. The objective of this research is to provide a solution for both coverage and connectivity via an integrated approach. A novel technique to reposition neighbouring nodes for multinode failure is introduced. In this technique, neighbouring nodes of the failed nodes relocate themselves one by one and come back to their original location after some allocated time. Hence, it restores both prefailure connectivity and coverage. The simulations show our proposed technique outperforms other baseline techniques.

1. Introduction

WSNs gained global attention in the present times. The building block of WSNs is a sensor node. These sensors nodes can measure, gather, and sense the information from the external environment. This information can be used for decision making by the end users. There are various areas of interests for WSNs applications; for example, military surveillance and target tracking, providing relief in a natural disaster, monitoring biomedical health, and exploration of the hazardous environment and seismic sensing [1, 2].

The sensing nodes in WSNs have low power, memory, and computational and radio capabilities. On the contrary, these sensors must perform variety of thermal, mechanical, chemical, biological, magnetic, and optical tasks to measure the environmental properties. Furthermore, these sensors must also communicate from hostile/harsh environment via attached radio to the base station. The major power source of the sensor is the battery. The secondary power supply may be equipped such as the solar panel to gather the power from the external environment. An actuator can be attached to sensors, depending on the type of sensor and application [3, 4].

Typically, WSNs have little infrastructure. They may be composed of few sensors to thousands of sensor nodes for the prescribed activities. The researchers classified WSNs into two categories: the structured and the unstructured WSNs. In the unstructured WSNs, sensor nodes are densely deployed. These sensors can be deployed in the field in an ad hoc manner. Once the network is deployed, it remains unattended to perform reporting and monitoring functions. In unstructured WSNs, maintenance of networks such as failure detection and connectivity management is done in a reactive manner because of random deployment of sensor nodes. Whereas in structured WSNs, the preplanned approach may be used for some or all sensors nodes. The main advantage of structured WSNs is the deployment of a limited number of sensor nodes with lower management cost and network maintenance. The drawback is that the deployment of limited sensors in larger areas may result into an uncovered region [5].

WSNs have their own resource and design constraints. A design constraint depends on the monitoring environment and the type of application. For example, short-range of communication, limited power, lower bandwidth, and limited storage and processing memory could result into different designs. The environment in which a WSN will be deployed also plays a vital role in the formation of the network size and network topology and the scheme of deployment. Monitoring environment directly affects the network size. The indoor environment required a smaller number of nodes for the formation of the network in a limited area while more nodes are required to form a network in the outdoor environment to cover larger area. The ad hoc deployment is better in a hostile/out-of-range environment where communication among sensors becomes limited due to the obstacles in the environment [6].

Multiple sensors may fail simultaneously due to the hostile/harsh environment. In addition, large-scale node failure involving multiple nodes may occur causing many disjoint segments in a WSN. Connectivity restoration is a greater challenge in this case as compared to the failure of a single node problem. In many cases, simultaneous node failure is not contiguous, yet it is expressively a much difficult problem. To the best of the authors' knowledge, three types of approaches have been proposed in the recent research literature to reclaim multiple node failures.

The first approach suggests that to restore connectivity, the topology of the network may be rearranged by repositioning sensor nodes from the original positions of the WSN. Such techniques support self-healing of WSNs and are used in a distributive manner. The second approach recommends that multiple-relay sensor nodes should be deployed to reinstate the multiple dismember segments. In the third approach, data is collected by the help of mobile mules, which make trips to the critical areas and transfer that data from one partition to another in a WSN [7].

In context of the above sections, the key contributions of this paper are elaborated as follows:

(i) As the first contribution, a technique to dynamically reposition the neighbouring nodes on multinode failure is proposed to enhance network performance.

(ii) The second contribution is energy efficiency of the proposed algorithm. Here, common neighbouring nodes of the failure node must select one failure node within their neighbourhood. Therefore, these nodes do not have to travel more than one node, and this saves energy.

(iii) The third contribution is the better performance in QoS parameters like total distance travelled by nodes, numbers of messages exchanged within all nodes, average node relocation, and reduction in the percentage of field coverage as compared to other baseline techniques.

The remaining paper is organised as follows: Section 2 highlights the relevant related work in a summarized manner. Section 3 discusses the details of the proposed algorithm for WSNs. The energy model used is discussed in Section 4, whereas the proposed algorithm validation and the simulation procedure are presented in Section 5. Section 6 concludes the paper and proposes some possible future work.

2. Related Work

The failure of the multinode problem has been addressed many times in the literature in the recent past. To handle the multinode failure problem, the centralized approaches provided better solutions. These approaches handle problem by developing a recovery schedule for multinode failure by relocating nodes in WSNs. Among these approaches, in [7], the integer linear problem (ILP) is formulated for the recovery problem. In this work, a node's individual travelling distance and coverage loss caused by multinode failure were minimized by the optimization-based ILP that formed the connected topology. In this technique, the position of the node is assumed prior to the failure in WSNs. In [8], a technique grounded on the network flow transportation model is used where normally every single node should have the capability to go to each destination of WSNs. Here, the problem was solved by the polygon approximation model and the formulation of mixed-integer approach. This approach is better from the approach provided in [9] in terms of total distance travelled. However, for more than 30 nodes, this technique does not measure accurately and results in errors. In [10], an alternative employment technique is suggested to reduce the number of node locations for improving scalability. It is a practice to find the number of positions that promise connectivity if the relay sensors are deployed at these locations. As alternative relay sensors, the calculated locations are failed by the survival nodes in the WSN.

In PADRA (partition detection and recovery algorithm), repositioned sensors are recognized by the CDS (connected dominating set) of each partition and select the optimal nodes for recovery [11]. A greedy heuristic method is used to minimize the total travelled distance of the sensors. In this technique, the nearest dominating pair of nodes are picked, and the dominate sensor is relocated to the target position. The CDS of partitioned WSNs are updated until the connectivity is to be restored. The result of this technique shows that the heuristic method outperforms the solution and scales well as compared to [7, 8]. The distributed techniques are proposed for the recovery of a single node, and these techniques avoid the conflict which occurs during the recovery. The study by Imran et al. [12] was an extended version of DCR (design of partitioning detection and connectivity restoration) which handles multinode failures [9]. This extended technique was known as RAM (recovery algorithm to handle multiple failures) and selected critical sensors and designated backup for these nodes. The key parameter which enabled the RAM was the backup of the selection processes that handled the multiple simultaneous node failures. The idea was to improve the backup node, criticality backup, and primary deterioration at the same time. As the criticality improved, it warrantied the designating backups in the recursive fashion. To avoid the race condition, mutex is used during the relocation of nodes to prevent the new failure. This technique shows the tolerance of non-collocated multiple nodes and adjacent node failure.

Similar approach as described above is used to tolerate the multiple sensor failures that occur at different locations simultaneously [13]. This technique uses the PADRA algorithm in multiple positions. Two failure handlers are used: primary and secondary. In the primary handler, there is no prespecified time for the recovery, although the relocation of the nodes in a cascaded manner was done. The two processes of recovery are required for the relocation of the same nodes to create the race condition at two different positions. It is different than a single node failure, in which the neighbouring node of the failed node has a deterministic and reliable interpretation of the problem. It is important to make some assumptions like centre region knowledge, route knowledge, and camera availability. The major theme of the technique AUR (autonomous repair) is based on the relocation/repositioning towards the preknown area centre and as per assumptions. Vigorous nodes regrouped by AUR and moved them towards the deployment centre area and towards one another [14]. The AUR design principle is based on the connectivity modelling between neighbouring sensor nodes. AUR considers the localized repossession with sensors that interact with immediate neighbours. The failed nodes stretched the intrasegment topology. If the restoration of connectivity is not done, the block segment is moved towards the centre deployment area. The node density in the centre point was increased by moving the segments towards the centre. This ensures the reestablishment of the connectivity. A distributed technique is used in the minimum Steiner tree (DORMS) for optimized placement of the relay node, which assumes that the network centre must be known beforehand [15]. The difficulty is tolerated as the relay appointment problem, but relay nodes are selected among the survival nodes in the WSN partitions. Hence, to diminish the number of obligatory relays, DORMS enhanced as Steiner minimum tree (SMT). K-LCA is employed by DROMS, which reduced the number of the node for finding the topology [16].

Yet another technique is proposed to handle multiple node failures by getting the knowledge of full paths of nodes to sink in [17]. For determining the location of the damaged node, prefailure route information is utilized. The position of the nodes and their path towards sink are then collected after the establishment of the path. The DARA (distributed actor recovery algorithm) calculates the probability to identify cut vertices and select the neighbour node for the failed node. It relocates the neighbour node based on the communication link number [18]. This technique is further enhanced by the proximity factor to the node failure and then using PADRA for the optimization of the cascaded relocation in intrapartition [19, 20].

The technique in [21] is based on incomplete sensor failure information. The assumption of this work is to equip nodes with cameras to collect topology facts (normally the numeral of end nodes). In this technique, the function of remuneration is established on a node degree, where options to increase the node degree level are available. In [22], the authors proposed geometric skeleton-based reconnection (GSR). The approach split the network into various logical segments. A group of nodes that have the maximum connectivity with other nodes is known as geometrical skeleton backbone (GS backbone). The record of all the skeletal backbone nodes is maintained by each segment. In the case of network segregation, each segment attempts to join the GS backbone. In this way, connectivity can be restored. In [23], HRSRT (hybrid recovery strategy established on random terrain) for restoration of connectivity is recommended for impaired WSNs. The realistic terrain influence of area of interest (AOI) is considered in this algorithm. The terrain is planned by plotting the AOI and dividing it into a grid of cells of equal size. Each cell is characterized by the weight (cell). The weight of each path ω (Path) is also considered by adding the weight of each cell (cell) along path ω. By (cell) and (Path), the thorough graph "Kni" is built by taking the least weight of paths between the segments. RTPP (random terrain-based path planning algorithm) is established by "Kni" for creating a tour T for connectivity restoration of mobile data collectors (MDCs). Hence, MDCs were responsible for the restoration of connectivity. The SACR (survivability-aware connectivity restoration) for segregated WSNs by using mobile nodes is presented in [24]. The levels of load data of segregated segments for connection of the separated segments of the segmented network were considered by the SACR technique. These isolated segments could be found between different disconnected segments. The location of inaccessible segments is found by a group of moveable nodes to reinstate connectivity. A relay partition is created for every isolated segment. In [25], a robot control strategy for the provision of a connected path from the AOI to the base station is proposed by the authors. The core objective of this algorithm is to find out smallest distance having a smaller number of hop counts for mobile robots with unbroken network connectivity. The proposed strategy encompasses two algorithms. The first algorithm is to recognize the nearest robot to the event area and assigns that robot to such location. Then, this algorithm quests for the nearest nonallocated robot to ask it to forward itself to the communication range of any of the connected section having allotted robot. The algorithm proceeds on till the network is completely connected. The second algorithm discovers out those locations, which have minimum hop count between the event area and the base station. A method for cut-vertex or critical-node determination is done in [26]. This technique comprises two localized distributed algorithms to determine the states of nodes that they are either critical or noncritical. Two-hop local subgraph and connected dominating set (CDS) information for the detection of most of the critical and noncritical dominator nodes is used by the first algorithm. The second proposed algorithm uses a limited distributed depth-first search algorithm in unrecognized parts of the network without going over the whole network. This algorithm determines the states of all nodes by comprehensive test bed experiments. Simulation results show that, in the presence of a CDS, this algorithm discovers all critical nodes using low energy consumption. Table 1 provides the summary of protocols discussed in the related literature above.

3. Details of the Proposed Algorithm

3.1. Problem Specification and Proposed Solution. The loss of multiple sensor nodes because of the destruction, battery drainage, or another malfunctioning not only disturbs the overall coverage of the network but also limits the connectivity of WSNs. The method of the proposed procedure for the reinstatement of network connectivity and coverage is initiated in the same manner as C^3R [27]. Our proposed solution takes the assumption that all sensor nodes are independent from each other, i.e., each sensor node takes data from surroundings and uses other sensor nodes to send these data to the sink node. The said algorithm in [27] suggests that the sensor nodes involved in recovery shall take turns by moving to and fro from their original position to failed node position. This would result in prefailure coverage. The problem arises in the said algorithm when the neighbouring nodes take part in the recovery process fail. If a neighbouring node of a recovery node fails, then a recovery node must take care of both failed nodes, i.e., the previous one and the latest one. So, the concerned node has to travel to and fro towards both failed nodes. This may drain its battery very rapidly and make such recovery node as a failed node. If a recovery node itself failed, then there may be some other recovery neighbour nodes. They also must take care of previous and latest failed nodes, and soon they will also become failed nodes due to battery drainage. Due to this problem, coverage will be decreased. To solve this problem, an energy-efficient relocation of a neighbouring node for a multinode failure method has been proposed in this paper. This method restores the prefailure connectivity as well as coverage in the network. As specified earlier, the failure of multisensor nodes causing the network to be disjointed is the most challenging issue and of utmost importance. Our solution suggests that if the neighbouring node of recovery node fails, then the recovery node has to decide to take care of only one node, previous or latest on the basis of its distance towards the failed nodes. The concerned node will take care of the failed node with a shorter distance. There might be a situation when there are two recovery nodes having the same distance to the latest failed nodes, then the node with higher ID will take care of the latest node and the lesser ID will stick to the previous node failure. There might be a case when the recovery node itself fails due to some reason and it has neighbouring nodes which are part of the previous node failed recovery process. In such situation, such nodes must decide whether they take care of the previous node failure or latest failed recovery node based on their distance and coverage from both nodes. So, they will take care of the node having a smaller distance with them. This technique will save a lot of energy as the recovery nodes do not need to travel to two nodes for taking care of them.

3.2. Prefailure Operations. A prefailure 1-hop neighbours' list is maintained by a node in our proposed technique. This list is generated as soon as nodes start off after deployment. For an introduction to its all neighbours, a "HELLO" message is broadcasted by each node in the network. Besides this, each node must know the location and neighbouring nodes' IDs. The proposed algorithm uses normal GPS coordinates for locations of neighbouring nodes. This information of neighbouring nodes' locations is needed for use in case of failure of some sensor nodes. HEARTBEAT messages are sent to all neighbours in a timely manner to confirm their liveliness. Therefore, if a sensor node, let us say A, does not receive its predetermined number of HEARTBEAT messages from the neighbouring sensor node, let us say F, then, consider F as the failed node. After node failure detection, a sensor node will send a message about its movement towards the failed node to each of its neighbour nodes. Each heartbeat contains node's ID and its location information. Each node sends HEARTBEAT messages after τ seconds. On missing HEARTBEAT message, each node waits for some allowed number of heartbeats. As there is a chance, a HEARTBEAT message can be missed due to packet loss due to some unavoidable reasons. After the completion of countdown time, still if a neighbour's heartbeat is not received, then that neighbour is declared as failed node. These thresholds of τ and countdown must be chosen wisely that it must not be short enough to declare an alive node failed, which would trigger unnecessary recovery process, and these thresholds must not be long enough that the recovery process gets delayed. We have not focused on optimization of these thresholds in this research article, as it is itself a research problem. Our focus is on the recovery process.

The recovery process is initiated by node A as soon as it comes to know that the neighbouring node, i.e., F has failed. It is notable that, in the literature, there are two approaches discussed when some node fails in the network. The first approach determines if the failure of node F will divide the network into disjoint partitions, and the response will be established only if the failed node is a cut-vertex node. This technique avoids the overhead of communicating all the nodes in the network. The drawback of this technique is that it requires 2-hop information to find cut vertices in the network; hence, messaging overhead is increased. The second approach proposes the restoration process when connectivity and coverage are vanished irrespective of the failed node is a cut vertex or not. The proposed technique uses the simplest technique used in PCR (partitioning detection and connectivity restoration) [9]. In which, each sensor node

Table 1: Protocol summary.

Reference	Main objective	Secondary goal	Approach type	State of network	Type of movement
[7]	Connectivity restoration	Minimize the distance and coverage aware	Centralized	Global	Controlled
[8]	Connectivity restoration	Minimize the maximum and total distance travelled	Centralized	Global	Controlled
[10]	Connectivity	Minimize the maximum and total distance travelled	Centralized	Global	Controlled
[12]	Connectivity	Minimize the recovery scope and total distance	Distributed	1-hop	Cascaded
[13]	Connectivity	Minimize the message cost and distance travelled	Distributed	2-hop	Cascaded
[14]	Connectivity	Minimize the total distance travelled	Distributed	1-hop	Block
[15]	Connectivity	Minimize the relays populated number and create an efficient topology	Distributed	None	Cascaded
[17]	Connectivity	Minimize the maximum and total distance travelled	Distributed	2-hop	Cascaded
[20]	Connectivity	Minimize the total distance	Distributed	2-hop	Cascaded
[21]	Connectivity	Minimize the total distance	Distributed	2-hop	Cascaded
[22]	Connectivity	Minimize the coverage loss and total distance travelled	Distributed	1-hop	Cascaded
[23]	Connectivity	Minimize the total distance travelled	Centralized	Global	Cascaded
[24]	Connectivity	Minimize the coverage loss	Distributed	1-hop	Controlled
[25]	Connectivity	Minimize the coverage loss	Distributed	1-hop	Controlled
[26]	Connectivity	Minimize the coverage loss	Distributed	1-hop	Controlled

determines itself as a critical or noncritical node by calculating the distance between their neighbours by GPS coordinates by the famous haversine formula (details of the formula are given in Section 3.5 of this research article). If the distance is less than the communication range (R_c), then it declares itself as the noncritical node as its neighbours will stay connected on its failure. Otherwise, it declared it as the critical node. This technique will avoid all the recovery processes triggered for leaf nodes, and critical nodes will be determined in advance.

3.3. Neighbours' Node Management. As mentioned earlier that as momentarily as a node perceives that its neighbouring sensor node has failed, it quickly starts the process of restoration of prefailure connectivity and coverage. The first thing that the sensor node must need to know is whether there are any other neighbouring sensor nodes of the failed node which can take part in the recovery process. It is possible if this node and each of the other neighbouring nodes ought to travel to the location of the failed node till they come in the communication range of each other. These neighbouring nodes of the failed node must travel the distance of $R_c/2$ towards the failed node. If their communication range is R_c, then they can connect with each other. As there is no solution provided in C^3R for neighbouring nodes to detect the node failure and react to such situation, when a recovery process is already going on. Therefore, some synchronisation of neighbouring nodes is needed for this situation. Besides this concern, neighbouring nodes could travel to the position of the latest failed node to synchronise. The travelling distance will be increased as there will be some common neighbouring nodes participating in the previous node fail recovery process for which the recovery process is going on. Such common nodes must travel to a previous node failure location for its recovery process and to travel to the latest node failure location. This will result in an increase in overhead, and their battery will be drained off very soon. Our technique gives the solution that such common nodes must decide to restrict them either with a previous failed recovery node process or with the latest failure node process based on the minimum distance and the maximum coverage area from the failed nodes. The calculations of distance and coverage area and their relationship with each other are described in detail in the next section.

3.4. Distance between Nodes and Coverage Area. The sensor node which reaches to the location of the failed node becomes the coordinator of the recovery process. If two nodes reach the failed location at the same time, then the node with lesser ID will become a coordinator. The role of the coordinator is to develop a recovery plan and distribute the turns of each node participating in the recovery process. The criteria for selecting the nodes taking part in the recovery procedure are constructed on the coverage overlap area of the nodes, the distance between the failed node, and the remaining energy they have. The sensor nodes must reckon all these parametric values as they are criteria for selection in the recovery process. Then, these values are shared with the coordinator of the recovery process. The coverage overlap of two sensor nodes is the intersectional area of their communication range (Figure 1). The calculation of coverage overlap becomes very simple when the disk coverage model is taken in to account. There is an inverse proportional relationship between the distance between sensor nodes and the coverage overlap. When the distance between nodes is smaller, then there will be a larger intersection between two circles around the sensor nodes, thereby increasing the coverage overlap. Two neighbour nodes will have coverage overlapped if the distance (d) between them fulfils the condition $d \leq 2 \times R_c$. For the distance "d" between two

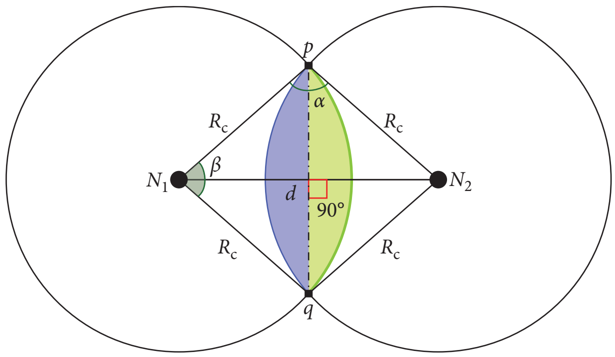


Figure 1: Calculation of overlapped coverage area of nodes N1 and N2.

nodes, the following equations can be derived by using GPS coordinates of a sensor node 1 and its neighbour sensor node 2 by the famous haversine formula:

$$\begin{aligned} \text{dlong} &= \text{long\_2} - \text{long\_1}, \\ \text{dlati} &= \text{lati\_2} - \text{lati\_1}, \\ a &= (\sin(\text{dlati}/2))^2 + \cos(\text{lati1}) * \cos(\text{lati2}) \\ &\quad * (\sin(\text{dlong}/2))^2, \\ c &= 2 * a\tan 2(\sqrt{a}, \sqrt{1-a}), \\ d &= R * c, \end{aligned} \tag{1}$$

where lati_1 is the latitude of node 1, lati_2 is the latitude of node 2, long_1 is the longitude of node 1, long_2 is the longitude of node 2, dlati is the difference of lati_1 and lati_2, dlong is the difference of long_1 and long_2, and R is the earth's radius (mean radius = 6,371 km); note that angles need to be in radians.

From Figure 1, the overlap of two nodes N1 and N2 can be calculated, if the area of the chord (pq) have angle β also called as area (β). The distance between nodes N1 and N2 is found at the start of nodes after deployment by GPS coordinates. By using the law of cosines angle, α can be found as

$$\angle\alpha = 2\sin^{-1}\frac{d}{2R_c}. \tag{2}$$

The area (β), the area of the sector "pq," depicted by blue shade in Figure 2 can be found by using the right-angled triangle and using $\beta/2$:

$$\text{area}(\beta) = \frac{\beta}{\pi}R_c^2 - \frac{d}{2}R_c \times \sin\left(\frac{\beta}{2}\right). \tag{3}$$

The overall coverage area can be found by multiplying twice the area of sector depicted by blue shade as the sector area in the blue shade is equal to the sector area in a light green shade.

$$\text{Overlap} = \left(2 \times \frac{\text{area}(\beta)}{\pi R_c^2}\right). \tag{4}$$

3.5. Proposed Algorithm Implementation. The implementation of the proposed algorithm can be best understood by the scenario given in Figure 2, by considering the scenario depicted in Figure 2(a) where node n7 has failed. The steps for restoration of connectivity and coverage of the proposed algorithm are explained below.

(i) Initially, the neighbouring nodes of failed node n7, which are n2, n3, n4, n6, n8, and n10, will detect that n7 has failed due to missing HEARTBEAT message from node n7 and become recovery nodes.

(ii) Then, these recovery nodes will calculate the distance with n7, its coverage overlap, and remaining energy before they begin to move towards the position of n7.

(iii) Each recovery node sends a message of temporary relocation to their immediate neighbouring nodes and asks their neighbours to find alternating route or buffer their data until such nodes return to their original position.

(iv) All the recovery nodes move towards n7 to get connected with each other. The recovery node which reaches the location first will become a recovery coordinator. If two recovery nodes reach at the same time, then the node with the lowest ID will become the recovery coordinator.

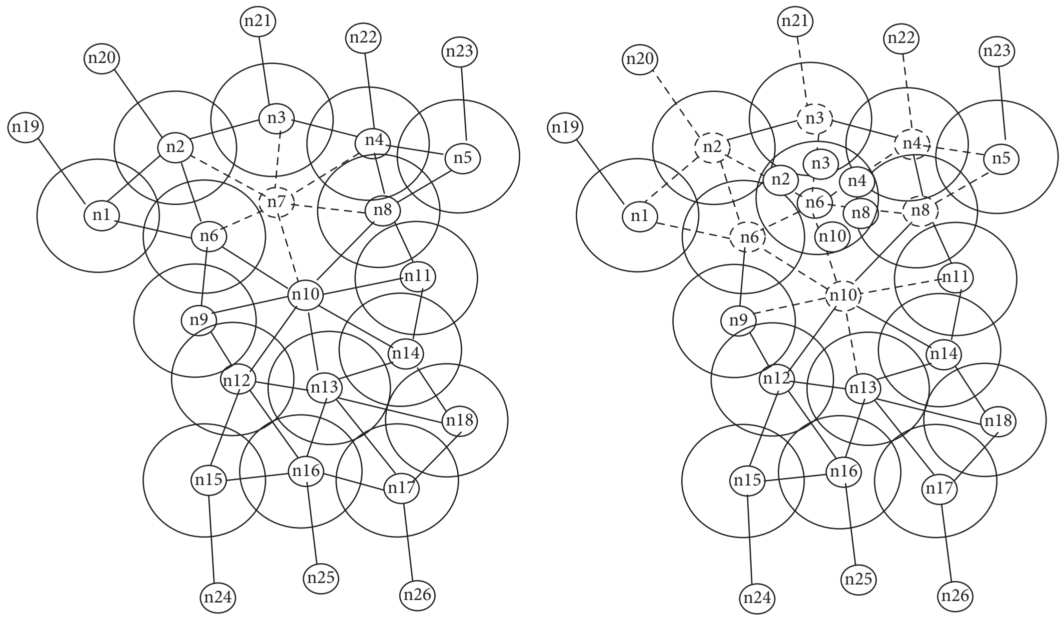
(v) The list of recovery nodes according to their priority with regard to the parameters like the overlap of coverage, distance travelled during relocation, and amount of energy in remaining is maintained by the coordinator node.

(vi) After this recovery, the node on the top of the list, suppose n2, will stay at the location of n7 and rest of the neighbours will return to their respective positions and stay there until their turn.

(vii) After some time, the recovery node on the top of the list returns to its position and the second on the list will resume the position of n7. On the returning to the original position, a recovery node informs its neighbour by broadcasting message to them and begins to establish the transmission of the buffered data again. The same node will repeat a like preset process after that.

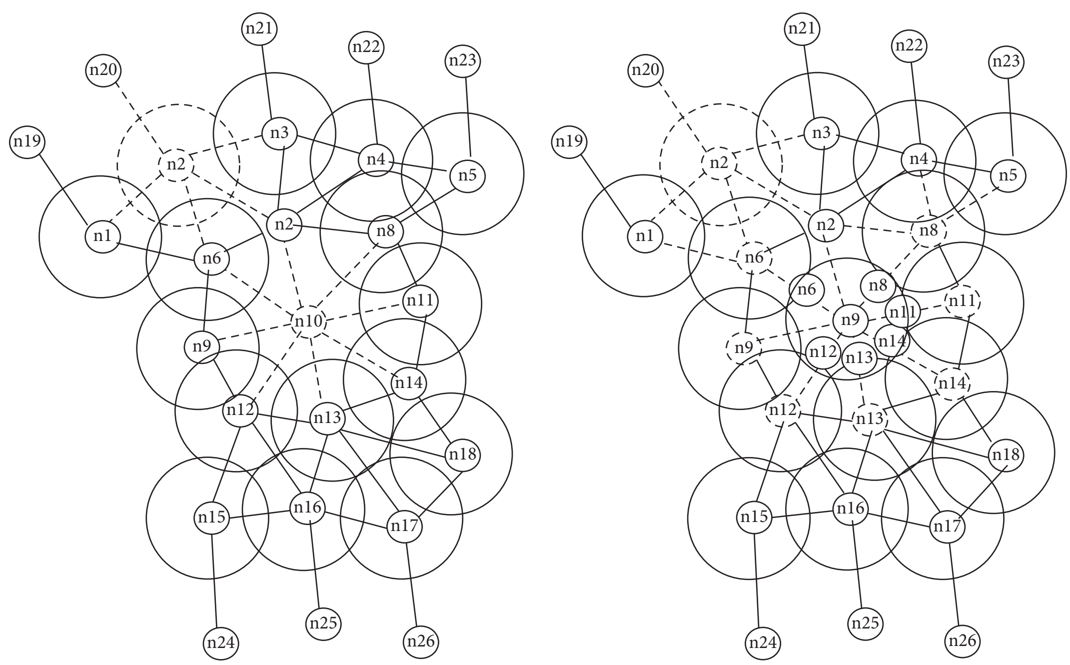
(viii) Once the energy of a recovery coordinator node reaches below the specified threshold level, the coordinator will transmit a request to other recovery nodes. The recovery node presently situated in the locality of n7 will accept the request. The request-receiving node will become a new recovery coordinator, travel to previous coordinator position, and generate the new schedule.

(ix) There might be another situation such that if a neighbouring node of some recovery node fails during the recovering process of some other nodes, e.g., in Figure 3(a), recovery process of n7 is going on and n10 fails. Then, the neighbours of n10



(a) (b)

Figure 2: (a) First node failure. (b) Recovery process after the first node failed.



(a) (b)

Figure 3: (a) During the recovery process, another node failure happened. (b) Recovery process after the failure of the latest node.

which are n2, n6, n8, n9, n10, n11, n12, n13, and n14 will have to take part in the recovery process. However, n2, n6, and n8 must decide whether they remain to restrict with the n7 recovery process or take part in the n10 recovery process.

(x) For the decision purpose, the one having lesser distance amongst n6, n8, and n9 from n10 will take part in the recovery process of n10. Besides this, the node which is already at the place of the previous failure node, i.e., n2 in the example cannot take part in the latest node failure recovery process. The selected node will take part in the latest node failure and will detach itself from the recovery process of the previous node failure.

(xi) The recovery coordinator of the previous node failure will update the recovery list by excluding the entry of a selected node, which has detached itself from such a recovery process.

(xii) If the recovery coordinator of the previous node failure is self-selected as the recovery node for latest node failure, then it will inform other recovery nodes taking part in the previous node failure recovery, so they can nominate any node as their new coordinator.

(xiii) Figure 3(b) shows that n2 will remain at the failed location of n7, whereas n6 and n8 will compete for the recovery node of n10 and the node with lesser distance will win the competition.

(xiv) If both n6 and n8 have same distance with failed node n10, then higher ID will become the recovery node for latest node failure and lesser ID node remains as the recovery node for the previous node failure (Algorithm 1).

4. Energy Model

An energy model which we have used in this paper is presented in [28]. The energy consumption of a node to transmit and receive a "B-bit data packet" over distance "*d*" is shown in equation (5). The energy expended per bit by the receiver circuit is given by (6). Whereas the residual energy can be calculated by equation (7).

$$E_{Tx}(B,d) = \begin{cases} \left(E_{elec} + \varepsilon_{fs} d^2\right)B, & d < d_0, \\ \left(E_{elec} + \varepsilon_{mp} d^4\right)B, & d \geq d_0, \end{cases} \quad (5)$$

$$E_{Rx}(B) = E_{Rx-elec}\, B, \quad (6)$$

$$E_{reng}(n) = E_{max} - E_{Tx}(B,d) - E_{Rx}(B). \quad (7)$$

Different terms used in this model are explained in Table 2.

5. Simulations and Results

All the simulations were carried out using the platform of OMNet++ for the performance appraisal of the proposed algorithm. A comparison is made between the proposed algorithm with and increased robustness against recurrent failure (RIR) of damaged WSN topologies in the event of multiple node failures [25] and autonomous repair (AuR) [26] protocols. This section presents niceties of the simulation setup and the discussion of the results.

5.1. Simulation Parameters. The accomplishment of the proposed algorithm is authenticated through simultaneous simulations. This section discusses the simulation setup, performance metrics, and results. For the validation of the results, the OMNeT++ platform is used. All the simulation parameters are given in Table 3.

All the results are subjected to 90% confidence analysis interval and stay within 10% of a simple mean.

5.2. Results and Discussion. For the analysis and performance comparison of the parameters such as the number of messages exchanged, distance travelled by nodes, number of nodes relocated, and reduction in the percentage of field coverage and recovery time consumption of the proposed algorithm, RIR and AuR were employed.

5.2.1. Distance Travelled. The total distance that the nodes travelled while performing the recovery process is presented in Figure 4. The sensing and communication ranges are taken as equal in all these series of experiments. How far the node should travel depended on nearness of one node to another node. This vicinity was at most the R_c communication range. Therefore, an increase in R_c, there was an increase in how far a sensor node travelled. This was easy in cases of AuR and RIR as the distance travelled increases rapidly. Unlike AuR and RIR, with the proposed technique, the sensor node participation was limited in the recovery process to the neighbours of the sensor node that failed. It does not use cascaded relocation that is initiated in AuR and RIR. It is very significant to designate that when communication range (R_c) is too high, the proposed procedure shows the growth in connectivity of the WSN very well.

5.2.2. Number of Packets Exchanged. The number of packets that were exchanged, i.e., received and delivered during the restoration of connectivity using each of the three methods is presented in Figure 5. Every broadcast message was a single message. Using the proposed technique, messaging overhead was negligible. However, using AuR provided the maximum number of the packets exchanged. The reason behind this is that, in the proposed technique, only neighbour nodes of the failed node were involved in the restoration process. On the contrary, with AuR and RIR, the message exchange had to coordinate their achievement with a total number of nodes that were relocated. However, there was an increase in network connectivity for large R_c. This is because of the interaction which rarely takes place between other involved sensor nodes and recovery coordinators. The proposed technique can be scaled up for the several rounds. Also, it would offer coverage and connectivity reestablishment at the sensible price. Comparative performance has shown improvement in the proposed solution. Hence, by Figure 5, it is confirmed that a minute messaging overhead is added by the proposed procedure.

5.2.3. Number of Relocated Nodes. Figure 6 shows the recovery process of the total number of nodes relocated in the algorithms used for the comparison purpose with the proposed algorithm. For this purpose, the total distance travelled will increase with a greater number of travelling nodes. From Figure 6, the result shows that the node movement of RIR is greater than AuR. In any circumstances in the proposed technique, there are a smaller amount of node movements because the proposed algorithm restricts the time of the recovery process to the neighbour nodes of the failed node.

```
Input: distances of neighbouring nodes
IF (node, A, detects the neighbour node, F, had been failed)
Routing table updated (information about failed node will be deleted)
IF F = leaf node
Do not move
Else
On-board energy level check
IF (energy is sufficient)
Calculate the area of the overlapped coverage
Broadcast "Temporary Relocation" MSG to neighbours
move to (F)
END IF
ELSE IF (the node, A, receives "Temporary Relocation")
Search (new route)
IF new route available
Transmit data to a new path
IF (new route undiscovered)
Buffer the Data
END IF
ELSE IF node A receives ("Back to original position")
IF (data is buffered)
Send data using "reallocated back node"
END IF
END IF
Temporarily Relocation to (F)
Step towards F
IF (reached F)
Broadcast "Will manage recovery" message
Coordinator = 1
END IF
IF (received "Will manage recovery" from node j)
IF (ID ≥ j) Coordinator = 0
Stop moving
Transmit relevant data to the coordinator
Receive recovery schedule
IF (first node not on schedule)
Relocate back to orign ()
END IF
IF Coordinator = 1
From all concerned nodes collect significant information
Form ranked list and recovery schedule
Broadcast recovery schedule
IF (not the first node on schedule)
Relocate back to self ()
END IF
ELSE IF
Relocate to (F)
END IF
Another neighbour node failed during the recovery process
IF (node, A, detects the neighbour node, J, had been failed)
Routing table updated
On-board energy level check
IF (energy is sufficient)
Compare (distance F with distance J)//distance F = distance b/w A and F, distance J = distance b/w A and J
IF distance F < distance J
Do not move to J
IF distance F > distance J
Broadcast "Going to save J" MSG to recovery nodes
move to (J)
Go to (step 5)//replace F with J
IF receive (Going to save J)
Update list
END IF
```

Algorithm 1: Proposed algorithm's pseudocode.

Table 2: Meaning of different terms in the energy model.

Term	Meaning
E_{Tx}	Energy consumption of node for transmission
E_{Rx}	Energy consumption to receive data by a node
E_{reng}	Residual energy
E_{elec}	Energy consumed per bit by the transmitter circuitry
E_{max}	The initial energy of sensor nodes
$E_{Rx-elec}$	Energy consumed per bit of a receiver
ε_{fs}	Energy required for a radio frequency (RF) amplifier in free space
ε_{mp}	Energy required for a radio frequency (RF) amplifier in multipath
d_0	Threshold distance

Table 3: Simulation parameters.

Simulation parameters	Values
Simulation area	$900 \times 900\, m^2$
Number of nodes	25–150
Data packet size	800 bits
E_{elec}	50 nano-Joule/bit
E_{max}	20 J
ε_{fs}	10 pico-Joule/bit/m^2
ε_{mp}	0.0013 pico-Joule/bit/m^2
d_0	75 m
Rc	25–150 m
Simulation tool	OMNeT++

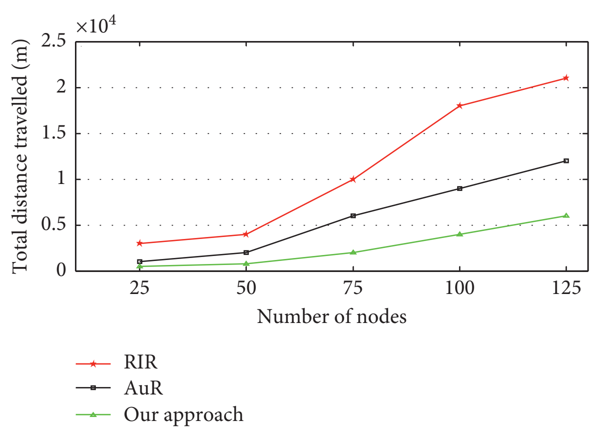


Figure 4: Total distance travelled vs. number of nodes.

5.2.4. Percentage Field Coverage Reduction. The impact of the restoration process on coverage is illustrated in Figures 7 and 8. It can be observed from the figures that the percentage reduction of the field coverage is considered by using the level of coverage before the failure and the level after the failure. The overall loss in coverage is limited reasonably by our proposed algorithm. Furthermore, for networks where nodes are not dense and evenly distributed, the overlapping coverage is at the minimal level under the proposed algorithm and the field coverage is reduced equitably as compared to RIR. A greater field coverage reduction was observed in RIR, when the overlapping of the coverage of the nodes began to rise, which are in cases where the nodes were deployed in a dense manner. The prefailure field coverage level was restored by applying the proposed algorithm. This

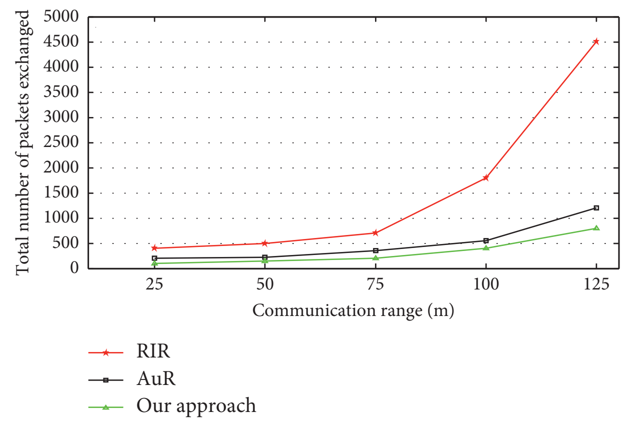


Figure 5: No. of packets exchanged vs. R_c in meters.

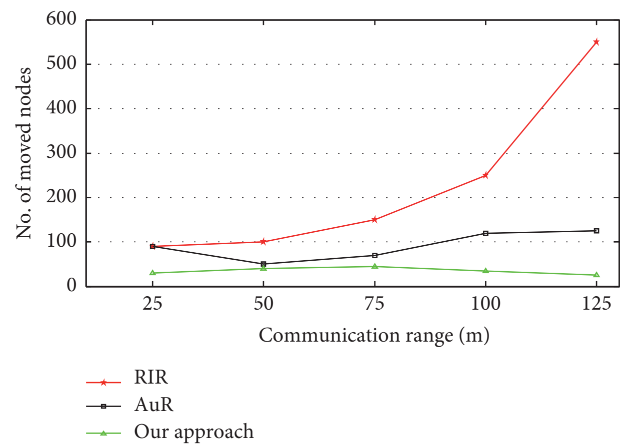


Figure 6: The total number of relocated nodes vs. R_c in meters.

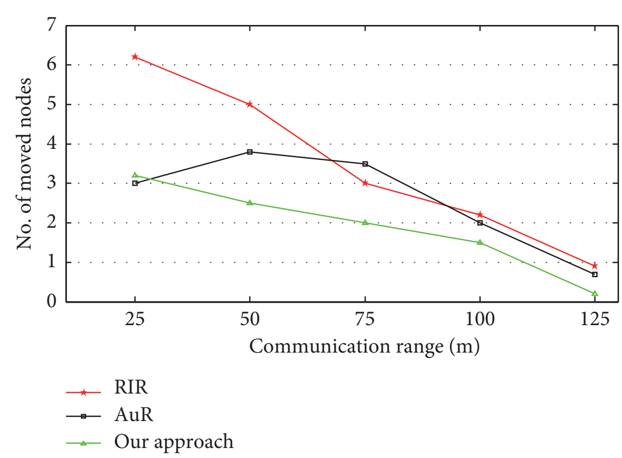


Figure 7: Percentage field reduction vs. R_c in meters.

restoration was done by the fact that the auxiliary nodes only move a little distance or do not move because of the growth in the coverage overlap. Besides this, there were numerous nodes available for the relocation process. However, networks with sparse node positioning did not have adequate nodes that could be substituted by the failure node. Furthermore, a greater area was left unattended with the

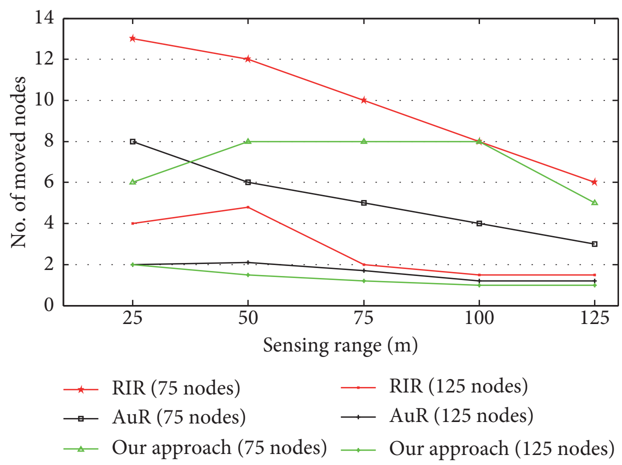


FIGURE 8: Percentage field reduction for the proposed technique vs. R_s in meters.

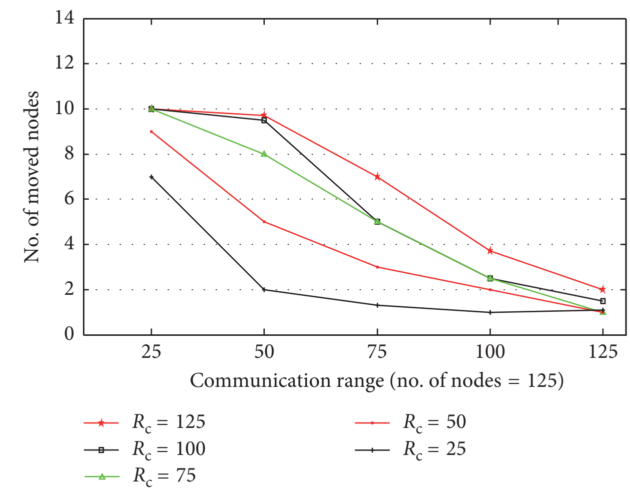


FIGURE 9: Percentage reduction in field coverage for the proposed technique vs. R_c for different communication ranges in meters.

relocation of nodes, resulting in creation of a gap in the coverage of the network. The percentage reduction of the field coverage for several communication and sensing ranges is revealed in Figure 9. Fair coverage reduction was perceived when R_c (communication range) dominated R_s (Sensing range). This was because longer distances needed to be travelled by the nodes between their home area and the position of the node they were replacing. Even so, the reduction was limited to 10% with the proposed algorithm even if R_s is taken as six times the R_c, i.e, $R_c = 6R_s$.

5.2.5. Recovery Time Consumption. Figure 10. shows the time consumption of recovery process by the sensor nodes when the number of recovery nodes increases due to the failure of other sensor nodes in WSNs. Therefore, for calculating recovery time of our approach and other baseline approaches, τ is taken as 5 secs. Whereas there are three allowed number of missed heartbeats. So, overall, a node waits for 25 seconds for its neighbour to respond. It is obvious that with the increase in recovery nodes, time consumption will be increased as recovery nodes must cover more distance. But, it is also a fact and it is clear from Figure 10 that our proposed approach takes less recovery time as compared to RIR and AuR. The main reason is that as it is discussed earlier that our approach does not have cascade movements and the recovery process is only restricted to the neighbouring nodes. Then, it is obvious that the proposed approach will take less time to recover because now recovery nodes do not cover large distances as in the case of cascade movements. Besides this, distance is the prime criteria for the recovery nodes in case of multiple node failure, i.e., recovery nodes restrict themselves to the recovery process of the failure nodes having lesser distance to them. That is why the recovery time of our approach is lesser than the other baseline approaches.

5.2.6. Results' Summary. The OMNeT++ platform is used to evaluate the performance of the proposed protocol to compare alongside the existing baseline algorithm. It is revealed from the results of simulations that the proposed algorithm accomplished substantial energy-saving and improved the network lifetime. It can easily be concluded from results that the proposed approach is operative in refining parameters of quality of service like the number of exchanged messages, average number of nodes relocated, and reduction of the percentage of field coverage reduction, when compared with RTR and AuR techniques. Table 3 reviews the conclusions from these results (Table 4).

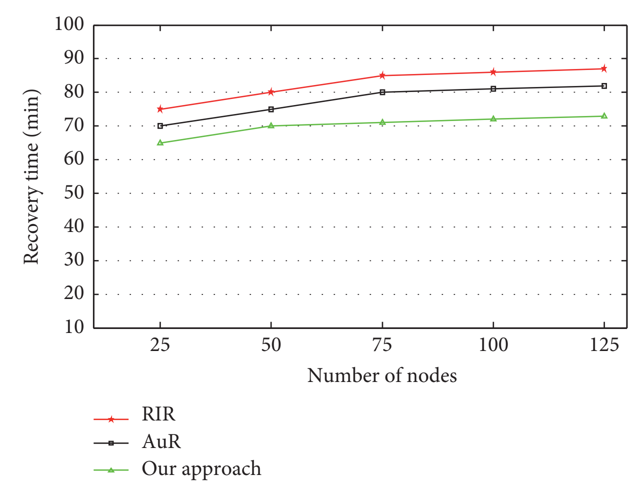


FIGURE 10: Number of nodes vs. their recovery time consumption.

6. Conclusion

The maintenance of connectivity and coverage is very important in mobile sensor networks. Node failure may partition the network which causes the operations of application to be malfunctioned. The proposed procedure deals with the connectivity-loss issue as well as the issue of coverage by not relocating the nodes in a permanent manner. The neighbouring nodes are responsible for the node failure recovery. The neighbouring nodes of the failed

Table 4: Results' summary.

Comparison of protocols for 125 nodes	Average distance travelled (m)	No. of messages exchanged (average)	No. of nodes relocated (average)	% age reduction in field coverage (average)
Proposed technique	2600	400	50	4
RIR	14000	2000	200	13
AuR	19000	4500	700	19

node organize between themselves to fix roles of each node in the process of the recovery. For the restoration of connectivity, all the neighbouring nodes contribute in the recovery process to transfer the nodes to the location of the failed node, to bring prefailure coverage in the location of the failed node. After expenditure, an allocated expanse of time at the place of the failed node, each recovery node returns to its original location. Stability in connectivity and coverage provided by the proposed algorithm enhanced the lifetime of the network. The proposed method is a hybrid form of localized and distributed algorithms. Overall messaging overhead is minor, and for trivial networks, the proposed algorithm can be evaluated. The endorsement, effectiveness, and validity of the proposed scheme are accomplished by extensive simulations.

Data Availability

No data were used to support this study. We have conducted the simulations to evaluate the performance of the proposed protocol. However, any query about the research conducted in this paper is highly appreciated and can be asked from the principal author (Adnan Anwar Awan) upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Authors' Contributions

Adnan Anwar Awan, Muhammad Amir Khan, and Aqdas Naveed Malik conceived and designed the experiments; Adnan Anwar Awan, Muhammad Amir Khan, and Syed Ayaz Ali Shah performed the experiments; Muhammad Amir Khan, Aamir Shahzad, and Naveed Shahzad analyzed the data; Adnan Anwar Awan, Muhammad Amir Khan, and Aqdas Naveed Malik wrote the paper; and Babar Nazir, Iftikhar Ahmed Khan, and Waqas Jadoon technically reviewed the paper. Rab Nawaz Jadoon contributed in technical revisions and final technical proofreading.

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Research Article

A Heuristic Algorithm of Cooperative Agents Communication for Enhanced GAF Routing Protocol in WSNs

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Rapid progress in technologies has led to the development of small sensor nodes. A wireless sensor network (WSN) is an interconnected collection of a large number of these small sensor nodes that is used to monitor and record the physical environment. WSNs have applications in diverse scenarios. They play an important role in tracking and monitoring in different domains, such as environmental research, military, and health care. In most of these applications, the WSN is composed of a large number of nodes deployed in an area of interest, and not all nodes are directly connected to the base station (BS). In some cases, batteries of nodes cannot be recharged or changed. For that, the most solution required to overcome these problems is to optimize energy consumed during communication. Data transmission in networks is maintained by routing protocols, which are responsible for discovering the required paths. This paper presents an improvement of the Geographic Adaptive Fidelity (GAF) routing protocol created on a smart actives node selection. The routing process works on cooperative agents communication where another node is activated in the same grid if the data collected are considered as important data, and a heuristic method is used to find an optimal path in terms of energy to transmit data collected until reaching the BS. Simulation results prove that the cooperative agents GAF (CAGAF) routing protocol proposed is more efficient compared to the basic version in terms of considering important data, energy consumed, and dead nodes.

1. Introduction

Due to the rapid development in technology, wireless sensor networks (WSNs) [1] have been invented to make our daily lives easier. They have been applied in diverse domains [2], such as health care, military applications, and environmental studies, for extracting data, monitoring, tracking, and disaster prevention. In WSN, a large number of sensor nodes are deployed in an area of interest to sense physical parameters of the environment and send them to a central point called the base station (BS) or sink, which extracts them for analysis or storage. Despite their various advantages, WSNs [3] are still subject to some constraints. The most challenging issue is their limited energy [4]. For example, in some cases, it is not possible to change or recharge the large number of batteries needed to run such a network, especially one spanning a large area of interest. Sensors execute various tasks, such as sensing data, processing the data, and deciding where and when to send them; these processes of receiving and transmitting data are inherently energy consuming [5]. The energy consumed during WSN operation directly affects the performance of the network and degrades the network lifetime. Various techniques are used to decrease the energy consumption, reduce the total amount of data through methods of aggregation or compression [6], design efficient routing protocols, and activate sleep mode for unneeded nodes in the network. Diverse routing protocols [7] have been developed to ensure the communication in WSNs, and these protocols can be categorized into three families [8]: data-centric, hierarchical [9–11], and location-based [12, 13] protocols. In the last type, location information is already known by the use of geographic positions system (GPS) or other methods [14]; each node must know the location of its neighboring nodes that is one hop away from it. Moreover, the source must know the location of the destination node. For many wireless sensor network applications, location information is essential; it expects that each wireless sensor node in the network will be equipped with certain location devices. In this paper, we focus our goal to improve the existing studies by presenting a new Cooperative Agents Geographic Adaptive Fidelity (CAGAF) routing protocol created on a smart actives node selection by using some criteria of selection as maximum residual energy, data importance, and minimum distance to the base station. Also, the routing process in our approach is based on cooperative agents communication, where the agents are selected on the basis of the following parameters: the residual energy, the density, the defined position type of each sensor, and the importance of the information. Moreover, a heuristic approach is used to find optimal path in terms of energy. Many methods [15, 16] are used to reduce the total amount of data by the use of aggregation approach, compression methods, or operational research (OR) that has been used widely in a few areas to resolve optimization problems as augmenting network lifetime and improving sensors performance. Operational research comprises different techniques such as graph theory and linear programs for making better decisions. We have joined localization-based routing, active node selection method, and graph theory approach to find the optimal path to the base station. That helps in reducing energy consumed, therefore prolonging the network lifetime. A new GAF routing protocol is created on graph theory approach. The improved protocol can produce the optimal path and select the active node responsible for transmitting data collected, not as in the traditional GAF process which diffused their data to the neighboring grids, without considering remaining energy of active nodes, the importance of information transmitted, or if the next hop is near to the base station or not. This paper is organized as follows. In Section 2, related works are presented. Section 3 refers to the proposed approach that explains the process of active node selection and optimal path used. Section 4 presents simulation results and discussions. Finally, Section 5 concludes the paper.

2. Related Work

In this section, we introduce the GAF routing protocol and previous studies [17] on data aggregation problems and cooperative schemes in WSNs. In a routing protocol based on location type [18], also known as geographic routing [19], sensor nodes are identified by their positions. The distance between a pair of neighbouring nodes can be calculated based on the received signal strength. The relative coordinates of neighbouring nodes can be obtained by exchanging information between neighbours. Alternatively, the locations of sensor nodes may be directly obtained by communicating with a satellite using the Global Positioning System (GPS) if each node is equipped with a small, low-power GPS receiver.

GAF for adaptive geographic fidelity [20] is a location-based method founded on an energy-aware routing protocol that is designed principally for mobile ad hoc networks and used for WSNs. In the GAF protocol, the network area is divided into virtual fixed grids, as shown in Figure 1. In each grid cell, nodes communicate with each other to play different roles, transitioning through three different states in Figure 2: the active state, where the node is responsible for routing data; the discovery state, in which the node tries to determine its neighbours in the grid; and the sleep state, in which the radio is turned off. Each node uses its GPS-indicated location to associate itself with a point on the virtual grid.

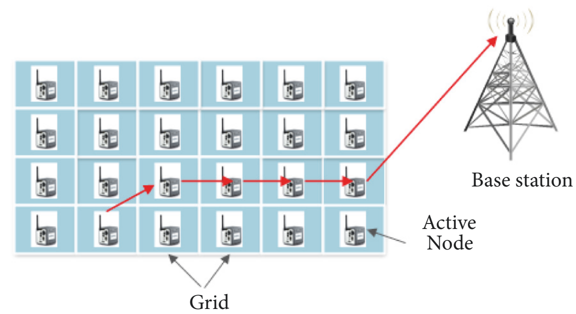

Figure 1: Network grid in GAF.

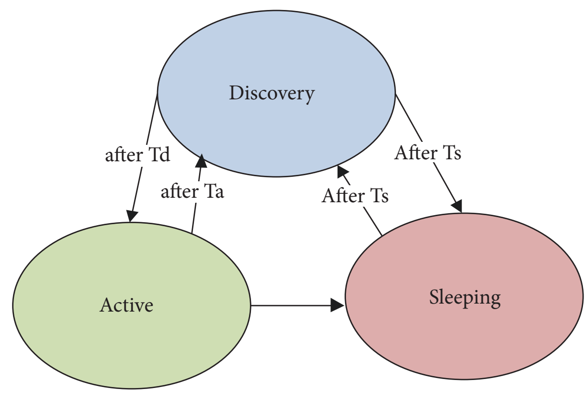

Figure 2: Transition states in GAF.

The advantage of the GAF routing protocol over other protocols is represented by the use of transition states that prolong the network lifetime. GAF can significantly decrease energy consumption since only one node is activated in each grid to be responsible for routing, while the other nodes in the same grid are into the sleep state for a certain time. Even though the GAF protocol was anticipated to solve the critical problem of energy, it remains limited in terms of some disadvantages such as that it allows communication between only adjacent grids, it does not consider energy of nodes or data importance to select active nodes, and it does not take into account the distance to the base station. For that, some improved versions appeared to overcome these limits, such as DGAF protocol, two-level GAF, optimized GAF, and GAFDG.

Diagonal GAF (DGAF) [21] routing protocol is an enhanced form of original GAF that permits a direct communication between two diagonal grids. In addition, it allows avoiding the problem of basic GAF, where forwarding packets arise only in two directions: vertical and horizontal way.

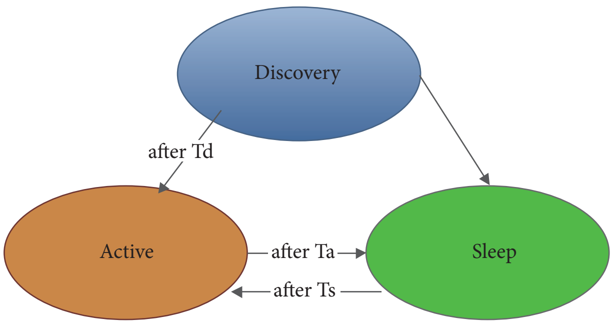

Figure 3: Transitions between states in optimized GAF.

Two-level GAF (TGAF) routing protocol [22] is proposed in order to overcome the problem of communication between only neighboring grids. It helps in reducing the number of hop counts, to facilitate to the sensors in the same grid forwarding the data packets to the neighbor in its adjacent grids. This permits reducing the number of nodes responsible for routing data. The main goal of TGAF is based on using two levels for transmitting data using highest residual energy for selecting active nodes. Authors prove that this concept helps in minimizing the energy consumed and automatically extending the network lifetime.

Optimized GAF routing protocol is an improved version of the basic GAF [23]. The improvement achieved by this approach is related to the transitions states. The enhanced protocol also involves three states, as does the original GAF protocol. However, its process is performed differently as shown in Figure 3, with the main aim of the discovery phase being to define a sequence of nodes that will be selected as active nodes. This phase is executed only once. Hence, the energy consumed is minimized. The transitions between phases are implemented as follows:

(i) Discovery phase: The purpose of this phase is to define a sequence of nodes that will be chosen to play the role of active nodes. The nodes are selected by considering the highest remaining energy. This phase is executed only once to reduce the energy consumed.

(ii) Active phase: After Ta (time of activity for a node), the next active node is selected from the previously defined sequence without executing the discovery phase again.

(iii) Sleep phase: After Ts (sleep time), the next node is activated as active node.

A new dislocated Grid GAF (GAFDG) [24] algorithm is proposed, based on the basic traditional GAF with aligned grid (GAFAG) to overcome the problem of limited energy in wireless sensor networks. The operating principle of this protocol permits dividing area of monitoring into dislocated grids and then, each node is affected in each grid according to its localization information and the side length of it. All nodes in the same grid constitute a cluster where a cluster head is selected based on two criteria, the node having the maximum residual energy compared to the average residual energy in each cluster and the closest to the center of the intracluster nodes. Each cluster head routes its data. The emulation results show that the energy consumption and the lifetime of the GAFDG network are better than those of GAFAG.

The main idea of network data aggregation [25] is that rather than transmitting individual data from the source sensor nodes to the destination nodes, multiple data elements can be aggregated for being transmitted on WSN.

Several works have focused on cooperative communication in various network applications. For example, in [26], the authors studied cooperative communication in wireless systems with multiple source nodes, multiple relay sensor nodes, and a single destination node.

The authors of [25] proposed a framework that combines data aggregation in the application layer and the Medium Access Control (MAC) layer based on sleeping mechanisms to reduce energy consumption in WSNs. In [27], a new approach was suggested for studying the energy efficiency problem by using cooperative communication with a structured topology based on aware trees in WSNs. This idea is centred on an algorithm that starts with a random aggregation tree to define the best transmission policy and to select a suitable corresponding time slot for each node to transfer the aggregated data to its father node.

A multiagent framework was proposed by the authors of [28] to help improve the performance of existing routing protocols in terms of energy consumption and packet relay. This framework permits each sensor node to construct a cooperative neighbour set on the basis of past routing experience. This allows the sensor nodes to successfully transmit packets in the future using the global view provided by the created set, which improves the quality of data reception during communication and helps to extend the network lifetime.

In [29], authors proposed an effective data aggregation method for finding the most informative route in a WSN. This technique considered energy efficiency based on a cost function and the information gain. A mobile agent migrates to its nearest first-hop node. Then, it moves to the next hop with the minimum cost as computed by a cost function that includes the information gain. This approach focuses on checking the information gain for the second hop and then allowing migration only if the difference in the information gain exceeds a predefined threshold. In such case, the current agent aggregates the available data, and this process is repeated to select the most informative agents with the minimal costs until the required node is reached. This work considered the following cost function for the migration of an agent from V_j to V_k:

$$C_{ij} = a\left(1 - \frac{I_j(x,y)}{I_{max}}\right) + b\left(N_{visit}+1\right)\left(\frac{e_j}{e_{max}}\right)c\frac{E_{ij}}{E_{max}}, \quad 0 \le a,b,c \le 1,\ N_{visit} \ge 0 \tag{1}$$

where I_j is the information gain of node V_j for agent migration, I_{max} is the maximum value of information gain related to nodes, E_{jk} is the energy consumed to achieve agent migration from V_j to V_k, E_{max} is the maximum energy value that necessitates agent migration, and N_v is the number of times an agent visits node V_j. α, β, and γ represent weight values associated with the information gain, the residual energy, and the energy required to achieve agent migration, respectively.

Due to the user Quality of Service (QOS) requirement, WSNs have been applied on different fields such as Flying Ad Hoc Sensor Networks (FASNETs). In [30], authors have designed a new clustering FASNET architecture based on Software Defined Networking (SDN) technique. This work aims to guarantee several QOS services as delay-sensitive and reliability where an efficient transmission prediction model is exploited.

Another work has been proposed in [31]. This work reviews the recent architectures suitable for 5G networks and presented a qualitative comparison of direct wireless connection (D-WCP) and indirect wireless connection (ID-WCP) schemes. In order to improve heterogeneous devices management in recent 5G networks, authors designed an effective framework based on direct and indirect WCP.

In [32], authors have proposed another scheme based on SDN paradigm. The main objective of this work is maximizing the network lifetime by reducing the number of active anchors. Anchor state is determined by SDN controller.

In [33], authors have designed an effective routing mechanism based on SDN paradigm. This novel approach aims to prolong network lifetime using a novel discovery routing mechanism and fuzzy decision routing algorithm. Moreover, authors improve the transmission phase where the routing path can be changed. For proving the routing scheme realistic application, the approach evaluation is conducted using Riverbed Modeler Software.

In order to provide a high-level authentication as well as simplifying the connectivity control of Wi-Fi devices authors in [34] proposed an SDN based connectivity control system that allows the administrator or the network owner to manage Wi-Fi devices through a remote service. No configuration information is required for the devices. Authors proved the feasibility of proposed approach through the real testbed and expect the suggested connectivity control system to be widely used to enhance the user and manufacture experience.

3. Positioning of the Contribution

Previous reviewed works permit communication between diagonal grids, enhance the number of hop counts, make sorting nodes in terms of remaining energy to enhance transition states, replace the aligned grids with dislocated grids, use cooperation strategy to aggregate data, and so on. Even though several energy-efficient protocols have been proposed, no one takes into account the optimal path research for reducing the consumed energy. We propose an improved version of GAF that considers a smart active node selection and routing process based on cooperative agents communication. Agents are selected on the basis of the following parameters: the residual energy, the density, the defined position type of each sensor, and the importance of the information. To guarantee an extended lifetime of the whole network, proposed work helps in ensuring an optimal path to transmit data collected until reaching the base station. More details of the proposed work are given in the next sections.

4. Proposed Mathematical Model

This paper studies the energy consumption problem on the basis of aggregated data communication based on cooperative agents in a WSN. Specifically, a sensor source node can use a cooperative agent as a relay to transmit its collected data without consuming more energy, such that the data reach the BS via cooperative communication, which will help to reduce the number of messages in the network, decrease the energy consumption, and extend the network lifetime.

We describe a general mathematical problem modeling the data communication. For that, we consider the graph defined with nonnegative edge weights $N(V, E, W)$, where V is the set consisting of sensor nodes and a base station of the considered network, E is the set of edges, and W is the set of edge weights. We describe in the following the definitions and the constraints on the sets V, E, and W. The base station is immobile and located at last virtual grid at (x_{max}, y_{max}) position in the sensing area. The sensor nodes are immobile, homogeneous, and identical in terms of functionality, initial energy, and capability. Then, the coordinates (x_k, y_k) of all nodes k in the set V are assumed available. The location information is known for each sensor by the use of localization devices and that of the base station is known for each source sensor node. So, we can evaluate the distance between two sensor nodes i and j or between a sensor node i and the base station s using the Euclidian distance and the location information, that is,

$$\begin{aligned} d(i, j) &= \sqrt{\left(i_x - j_x\right)^2 + \left(i_y - j_y\right)^2} \\ \text{and } d(i, s) &= \sqrt{\left(i_x - x_{max}\right)^2 + \left(i_y - y_{max}\right)^2}. \end{aligned} \tag{2}$$

The communication relation is bidirectional over the set E of edges. For transmitting/receiving a K-bits message over a distance d, the energy model is calculated by the following equations:

$$\begin{aligned} E_x^T &= E_{elec}K + E_{amp}Kd^2 \\ \text{and } E_x^R &= E_{elec}K \end{aligned} \tag{3}$$

where E_x^T means the energy of transmission, E_{elec} is the electronic energy, E_{amp} is the transmitter amplifier, and E_x^R

is the energy of reception of data of K-bits above a distance d. Hence, the total energy consumed is calculated by

$$E = \left(2E_{elec} + E_{amp}d^2\right)K. \tag{4}$$

For each edge ij, we design with w_{ij} the weight of the edge ij defined by the energy consumed for transmitting/receiving a message from i to j by

$$E = \left(2E_{elec} + E_{amp}d\left(i,j\right)^2\right)K. \tag{5}$$

So, the routing cost of a spanning tree T is defined as

$$C\left(T\right) = \sum_{r\in R} c\left(r,T\right) = \sum_{r\in R}\sum_{ij\in A} w_{ij}x_{ij}^r \tag{6}$$

where we denote by r a generic pair of nodes (i, j) and by R the set of all pairs of nodes and by $c(r,T)$ the shortest path cost between two nodes r on a tree T.

The objective function (6) minimizes the total routing cost computed over all the arcs and all the commodities. The minimization problem can be formulated as a multicommodity flow problem, where each commodity corresponds to a pair r of nodes. Let A be the set of directed arcs obtained by adopting two directed arcs for each edge of E in both directions. Therefore, two arcs ij and ji and commodity $r = (u,v)$, equal to the flow x_{ij}^r which traverses the arc ij from u to v. In order to force the variable x_{ij}^r to be 0 or 1, we add continuity constraints in a node u for the commodity r

$$\sum_{j:uj\in A} x_{uj}^r - \sum_{k:ku\in A} x_{ku}^r = 1 \qquad \forall r = (u,v) \in R,\ \forall u \in V,\ u < v. \tag{7}$$

We made also the following constraint that guarantees the balance of the flow in the transit nodes for the pair r.

$$\sum_{j:ij\in A} x_{ij}^r - \sum_{k:ki\in A} x_{ki}^r = 0 \qquad \forall r = (u,v) \in R,\ \forall i \in V \setminus \{u,v\}. \tag{8}$$

Let y_e for $e \in E$ be a binary variable which is equal to 1 if the edge e belongs to a tree, 0 otherwise. To send the flow related to the commodity r only on an edge of the tree, we introduce the constraint

$$x_{ij}^r + x_{ji}^r \le y_e \quad \forall e = ij \in E,\ \forall r \in R \tag{9}$$

With this notation and setting, the flow-based formulation is the following:

$$\begin{aligned}
\min_x \quad & J\left(x\right) = \sum_{r\in R}\sum_{ij\in A} w_{ij}x_{ij}^r \\
\text{subject to :} \quad & \sum_{j:uj\in A} x_{uj}^r - \sum_{k:ku\in A} x_{ku}^r = 1 \\
& \forall r = (u,v) \in R,\ \forall u \in V,\ u < v \\
& \sum_{j:ij\in A} x_{ij}^r - \sum_{k:ki\in A} x_{ki}^r = 0 \\
& \forall r = (u,v) \in R,\ \forall i \in V \setminus \{u,v\},\ u < v \\
& x_{ij}^r + x_{ji}^r \le y_e \quad \forall e = ij \in E,\ \forall r \in R \\
& \sum_{e\in E} y_e = n - 1 \\
& x_{ij}^r \ge 0, \quad \forall r = \{u,v\} \in R,\ ij \in A
\end{aligned} \tag{10}$$

During the past few years there has been intensive activity aimed at showing that particular problems are NP-complete. Whenever a problem is found to be NP-complete, we know that it is not isolated or unique but instead is linked to a large number of classical hard problems. Such a discovery should lead all but the most confident and optimistic of us to despair of obtaining a polynomial-time algorithm for such a problem. The usual method of showing that a problem is NP-complete is to check that the problem is NP and then to show the reduction of the considered problem to a known NP-complete problem. The proposed model (10) belongs to the class of multicommodity flow problems as described previously. Thus, as proved in [35], we can show the reduction of the problem (10) to the satisfiability problem arising in elementary mathematical logic and known to be NP-complete (see [35] and the references therein).

Following the operating principle of GAF, we will consider that the nodes participating in the routing will take a flow value equal to 1, while the nodes in the sleep state will take the value 0. The following subsection describes this operating principle used in detail.

5. Algorithms

Heuristic approaches have received great deal of attention in the literature, as in many applications a good solution has to be determined with very low computation times. Heuristic approaches are needed in these cases due to the complexity of the problem. This part describes some points including active node selection, data aggregation that is based on cooperative agents, and the time complexity of the proposed heuristic algorithm.

5.1. Active Node Selection. In basic GAF, only one node in each grid cell is activated to behave as an active node. Active nodes are responsible for routing data to the BS via multihop data routing. The data importance is an essential criterion

Import Data.
Initialize the constants α, β, p and *threshold*.
for $k \in [|1, n_G|]$ **do**
  Initialize the list of the node of important Data $ListImportance(k) \longleftarrow \emptyset$.
  Initialize $X \longleftarrow \emptyset$
  for $i \in G(k)$ **do**
    Compute $w_i \longleftarrow \alpha d(i, s) + \beta E_r^t(i)$
    if $|ActualData(i) - OldeData(i)| > threshold$ **then**
      $ListImportance(k) \longleftarrow \{ListImportance(k), i\}$
      $w_i \longleftarrow w_i + p$
    end if
    for $j \in [|1, i-1|]$ **do**
      if $w_j < w_i$ **then**
        $t \longleftarrow X(i)$
        $X(i) \longleftarrow X(j)$
        $X(j) \longleftarrow t$
      end if
    end for
  end for
  $Active(k) \longleftarrow \{X(i) : 1 \leq i \leq \#ListImportance(k)\}$
end for

Algorithm 1: Active nodes selection.

that should be considered for data routing. However, the GAF protocol activates only one node for each grid cell without considering the data importance. In our approach, the active node selection is based on the following:

(i) Residual energy (E): This key parameter allows agents to maximize the lifetime of their network by participating in routing only if the value of this parameter is sufficiently high. We consider the ratio between the remaining energy E_r^t at time t and the maximum energy E_i of the sensor at the time of its deployment, as illustrated in this equation:

$$E = \frac{E_r^t}{E_i}. \tag{11}$$

(ii) Information importance (I): This parameter depends on the type of application. We assume that information is more important if the difference between the new information and the old information exceeds a certain threshold.

(iii) Minimum distance to the BS.

Thus, a network grid cell may have more than one active node: the principal active node and one or more active member nodes. This efficient selection process improves the network performance and allows important data to reach the BS. To improve the routing of the GAF protocol, we consider a cooperative agent method in which an active node or an active member node can be selected as a cooperative agent. We use Algorithm 1 to generate active nodes in each grid. Our proposed model is aimed for a whole class of this type of problems. In order to make it general, the weights α and β are arbitrarily chosen according to the decision maker considering his needs and objectives. Moreover, from a theoretical point of view, concerning the existence and the convergence of these algorithms, it is enough that these two constants are positive.

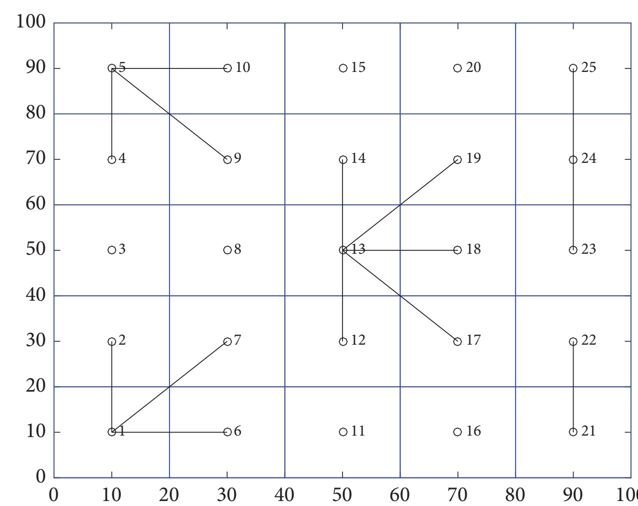

Figure 4: Geometric interpretation of the set of possible receiving nodes for some typical sending nodes.

Algorithm 1 returns the set of active nodes in each grid and then we can define the set of edges of the graph N as given in Figure 4 and Table 1.

The second step consists of the optimal cooperation process. We use a heuristic algorithm based on the identification of a set of nodes around where the solution can be built. This end is called the core of the network [36]. Based on opportunely weighted-out degree values, we classify the nodes in several levels. The external levels represent

Table 1: The set of all possible receiving nodes for given sending nodes.

Grid of sending active nodes	Possible receiving grids
(i, j), $1 < i, j < nG$	$(i-1, j)$, $(i-1, j+1)$, $(i, j+1)$, $(i+1, j)$, $(i+1, j)$.
$(i, 1)$, $1 < i < nG$	$(i-1, 1)$, $(i-1, 2)$, $(i, 2)$.
(i, nG), $1 < i < nG$	$(i, nG+1)$, $(i+1, nG)$, $(i+1, nG)$.
(nG, j), $1 < j < nG$	$(nG-1, j+1)$, $(nG+1, j+1)$.
$(nG, 1)$	$(nG, 2)$.

the outlying nodes and the internal levels represent the core nodes, that is, the central nodes of the tree to be reconstructed. Once the nodes have been assigned to the different levels, a network reduction is operated to build the core of the network. A successive phase builds a tree starting from the core. The algorithm adds the nodes belonging to the successive levels to the current core at each iteration. The tree solution thus determined is finally optimized by a local search procedure. The main phases of the algorithm and the related procedures are described as follows.

5.2. Data Aggregation Based on Cooperative Agents. In this subsection, we present a data aggregation approach based on cooperative agents. This approach will be applied in the GAF routing protocol. The amount of energy consumed during communication is higher than that consumed for the sensing and processing tasks. To overcome this problem, we propose a new technique to reduce the number of packets communicated in the sensor network. Our novel approach aims to perform local data processing before the data are transmitted to the BS. The main aim of this work is to propose an efficient data aggregation approach based on a multiagent system. Thus, a large data volume can be transmitted to the BS on the basis of a global view of the sensing area. In this work, an agent is implemented in each sensor node to exploit routing information to establish a local view and thus maintain a knowledge base. Each agent can decide, in accordance with a given strategy and in a completely decentralized way, whether it wants to cooperate with another agent. When a sensor senses information about its environment, its agent decides whether that information is important. If so, it initiates aggregation by sending a cooperation request packet to its direct neighbours to invite them to participate in the current aggregation session. Each neighbour agent decides to cooperate or not in accordance with the strategy described in the next section. If an agent decides to participate in the cooperation process, it sends the information collected by its sensor node to the agent that sent the cooperation request. If the agent receiving the cooperation request is selected to be used as a gateway by the requester, then it directly sends a request for cooperation to its immediate neighbours while waiting to receive the data aggregated by the requesting agent. When the requesting node receives information from its direct neighbours, it concatenates that information and eliminates redundancies before sending the result to its gateway. This procedure is repeated until the aggregated data reach the BS.

We propose a data routing protocol with partial aggregation, meaning that only active nodes or active member nodes can participate in data aggregation. Before making the data transmission decision, each active node requests routing cooperation when necessary. The following steps are used to accomplish the objective of finding the optimal path.

Phase 1 (cooperation strategy and core generation). We define the cooperation strategy by considering several parameters of the decision-making process, such as the level of importance of the collected information, the residual energies, and positions of nodes in the network and the degrees of the nodes. The cooperation decision depends on the values of these parameters. For example, when a node has only a small amount of power, it may refuse to participate in the routing of certain information or any information when its battery level is critical. Thus, it saves its energy to be used only for sensing and transmitting its own information. The considered cooperation parameters are described as follows:

(i) Density (D): This parameter enables the identification of dense areas in the network and areas where there are few sensors. When a node has a very large number of neighbours, it consumes energy very quickly, and it is assigned a higher priority for finding a cooperating neighbour than that of another node with a lower degree.

(ii) Position (P): We define three position types for the sensor nodes in the network: normal, border, and critical. We consider that the position of a sensor node is critical if it serves as a relay between two parts of the network. In addition, it represents a gateway in our gridded network. In this case, active nodes will be critical nodes. A sensor has a border position if it is located at an extremity of its grid cell. The remaining nodes have normal positions because they have more neighbours and do not represent network gateways.

We compute the shortest path tree for each node in the graph N using one of the well-known algorithms (see, for example, Dijkstra's and Prim's shortest path algorithms [37, 38]). Then, on the basis of these shortest path trees, we build a directed network $N'(V, A')$ where V is the set of nodes of network N and A' is the set of directed arcs, so that two arcs ij and ji exist for each edge $ij \in E$ in N. We compute the weights w_{ij} and w_{ji} of the origin/destination pairs that use the edge ij in all the shortest path trees, going from i to j or from j to i using the following equations:

$$w_{ij} = w_E\left(E_i^T + E_j^R\right) + w_D\left(\frac{1}{D_i} + \frac{1}{D_j}\right) + w_P\left(P_i + P_j\right) + w_I\left(I_i + I_j\right) \tag{12}$$

Equation (12) represents the cooperation coefficient as calculated using the parameter values E, D, P, and I, where these parameter values are associated with the weights w_E, w_D, w_P, and w_I, respectively. These parameters constitute the set of new arc weights of N'. If $w_{ij} = 0$, then the arc ij does not exist. If w_{ij} has a low value, the corresponding arc is used by few o/d pairs. If w_{ij} has a high value, the corresponding arc is in many o/d pair paths. Each node in N' has an indegree (resp., outdegree), i.e., the number of arcs entering (resp., exiting) a node. These degrees can be weighted with the parameter w_{ij}, thus generating the weighted indegree d_k^{in} and outdegree d_k^{out} for a node k:

$$d_k^{int} = \sum_{i:ik\in A'} w_{ik}, \qquad d_k^{out} = \sum_{i:ki\in A'} w_{ki}. \tag{13}$$

The nodes with a low weighted outdegree can be assumed as candidates to be leaves of the tree. The nodes with a high weighted outdegree can be assumed as candidates to be core nodes of the tree.

We use these quantities to classify the nodes in successive levels with an increasing weighted outdegree. On the basis of this classification the algorithm removes from N' all the nodes with the lowest d_k^{out} and all the arcs entering and exiting them, thus generating a reduced network N''. The same reduction is performed on N'' thus generating a new reduced network, until a core node or a set of core nodes with the same weighted outdegree is determined. We use Algorithm 2 for the network reduction to find the core node.

Initialize $V' \longleftarrow V$.
for $k \in V$ **do**
  Compute the shortest path tree $T(k)$.
  for $ij \in T(k)$ **do**
    Compute $w_{ij}^{T(k)}$ using the equations (12).
  end for
end for
for $ij \in A$ **do**
  $w_{ij} \longleftarrow w_{ij}^{T(k)}$
end for
$l = 0$
repeat
  $l \longleftarrow l + 1$
  for $k \in V'$ **do**
    $d_k^{out} \longleftarrow \sum_{j\in V'} w_{kj}$
  end for
  $d^{min} \longleftarrow \min_{k\in V'} d_k^{out}$
  $L(l) \longleftarrow \left\{k \in V' \mid d^{min} = \sum_{j\in V'} w_{kj}\right\}$
  $V' \longleftarrow V' \setminus L(l)$
  for $k \in L(l)$ **do**
    $NodeLevel(k) \longleftarrow l$
  end for
until $V' = \emptyset$
$l_m \longleftarrow l$

Algorithm 2: Network reduction using cooperation strategy.

Phase 2 (tree building [36]). The tree building starts from the core node. We add nodes to it using the node classification defined above. We select the node j of the level adjacent to the core that has the maximum weighted indegree, and we connect it to the core, using an edge ij corresponding energy consumed as a selection criterion. We repeat this procedure for all the nodes of the same level. In this way the core is enlarged with the nodes of this level. The procedure continues, adding the nodes of the successive levels, adjacent to the current enlarged core, following the same selected rule above. The procedure is repeated until the nodes of all the levels have been added to the initial core thus generating a tree. The tree building operation is effectuated using Algorithm 3. A local minimization procedure has been developed to improve the obtained solution. In order to explain it we have to define the following settings. Let $T(V, E_T)$ be the tree solution obtained in Phase 2 and let $S \subset V$ be the core of T, which is a node or a set of nodes. As k is a node of T there is only one chain connecting k to the core S. Therefore, we can remove the edge kf, $kf \in E_T$, incident in k and belonging to this chain to split the tree T into two subtrees, $T_1(V_1, E_{T_1})$ and $T_2(V_2, E_{T_2})$, where V_1 and V_2 are two node subsets constituting a partition of V such that $k \in V_1$ and $S \subset V2$. Recall that $L(l)$ indicates the set of nodes belonging to the generic level l, sorted by decreasing value of the weighted indegree, and that l_m is the core level. Starting from the first node in $L(l_m)$, indicated as $g \in V$, we perform the splitting of T related to g, as described above, and we consider all the edges connecting g to the nodes of V_2 able to restore the connection of the tree. Each edge generates a different tree with its related tree objective function value. If T^* is the best tree obtained by adding the edge gj, $j \in V_2$ to restore the connection, if $C(T^*) < C(T)$ we update our solution substituting the removed edge gf with the edge gj. This operation is repeated for all the nodes in the level l_m, following the above defined ranking. The procedure is repeatedly iterated from level $l_m - 1$ to level 1 and then from level 1 to $l_m - 1$, until no solution improvement can be achieved. This procedure is attained by using Algorithm 4.

5.3. Time Complexity of the Proposed Algorithms. In this subsection, let us denote by m the number of edges in the network and by n the number of vertices. In the following

```
Initialize T ⟵ ∅, E_T ⟵ ∅, l_1 ⟵ l_m.
repeat
    Maximum ⟵ 0
    l_2 ⟵ l_1
    repeat
        for k ∈ L(l_1) : k ∉ T do
            CurrentNode ⟵ 0
            if T = ∅ then
                T ⟵ T ∪ {k}
            else
                for j ∈ T : n_jk > 0 do
                    if Maximum < n_ij then
                        currentNode ⟵ k
                        EdgeToAdd ⟵ jk
                        Maximum ⟵ n_jk
                    end if
                end for
                if CurrentNode ≠ 0 then
                    Break
                end if
            end if
        end for
        l_2 ⟵ l_2 − 1
    until CurrentNode ≠ 0
    T ⟵ T ∪ {CurrentNode}
    E_T ⟵ E_T ∪ {EdgeToAdd}
    l_max ⟵ l
    if L(l_1) ⊂ S then
        l_1 ⟵ l_1 − 1
    end if
until T=V
```

Algorithm 3: Tree building and solution improvement.

results, we describe the time complexity of the proposed algorithms.

Lemma 1. *The time complexity of Algorithm 2 is* $O(n^2)$.

Proof. Algorithm 3 is engendered by two fundamental steps:

(i) The computation of the shortest path tree $T(k)$ for each point $k \in V$. Using, for example, the Dijkstra Algorithm, it is well known that the execution time of this method is $O(m + n\log n)$. We refer to [37–42] for more details about this and other methods.

(ii) Finding the argument of minimal weighted indegree and classification of the vertices in different levels. For typical serial sorting algorithms good behavior is $O(n\log n)$, with parallel sort in $O(\log^2 n)$, and bad behavior is $O(n^2)$.

Other instructions of the algorithm are executed in $O(n)$ in the first iteration, and this estimate decreases in the next iterations. For n sufficiently large, we get the desired estimate. □

Lemma 2. *The time complexity of Algorithm 3 is* $O(n^2)$.

Proof. Let ν_i for $i = 1, \ldots, m$ the number of vertices in the level $L(i)$. The time complexity to enlarge the core to the nodes of the level adjacent is $O(\nu_1^2)$ since this operation includes sorting rules. In the same way for the successive levels $L(i)$ for $i = 2, \ldots, m$, the time complexity is $O(\nu_i^2)$. By definition of the level $L(i)$, for $i = 1, \ldots, m$, we have $\sum_{i=1}^{m} \nu_i^2 = n^2$. This achieves the demonstration. □

Lemma 3. *The time complexity of Algorithm 4 is* $O(n^2)$.

Proof. For each edge kf to be removed, let $\theta(kf)$ be the number of edges in (V_1, E_{T_1}) and (V_2, E_{T_2}) as given in Algorithm 4. We define $\Theta(T) = \sum_{kf\in E} \theta(kf)$. Since $\theta(kf) \le 8$ (see Table 1), we have $\Theta(T) \le 8n$. Let T^* be the new tree constructed by removing the edge kf and replacing it by an edge gj as described in Algorithm 4. If $C(T^*) < C(T)$, it is easy to check that $f(T)$ decreases by at least 1 at each iteration. Taking into account the execution of the conditions $C(T^*) < C(T)$, the desired estimate is achieved. □

Finally, we get the time complexity of the proposed method.

Theorem 4. *The time complexity of the combination of Algorithms 2, 3, and 4 is* $O(n^2)$.

6. Simulations and Results

To evaluate the performance of our cooperative agents GAF (CAGAF) protocol, we compared it with basic GAF. The comparison was evaluated on the basis of the energy consumed, the data importance, and the number of dead nodes. Table 2 shows the simulation parameters.

Figure 5 shows the solution obtained after the refinement of the local search. Figures 5(b), 5(d), and 5(f) are given to illustrate the importance of data in different cases which shows the significant move of data during the run of our programs in order to reach the BS while Figures 5(a), 5(c), and 5(e) show the corresponding optimal path selection, where another node is activated in the same grid if the data collected are considered as important data.

The simulation results in terms of the energy consumption, data importance, and the number of dead nodes are shown below. Figures 6, 7, and 8 show, respectively, the comparison graphs of the energy consumption, the number of dead nodes, and the important data collected between the basic GAF (BGAF) and our proposed CAGAF protocol. Figure 6 shows the impact of the cooperative agents on energy consumption. It seems clear from this figure that, with the smart selection of active nodes with considering maximum residual energy, distance to the base station and the data importance as criteria of interest help in decreasing the energy consumption. Our cooperative strategy is based on the following parameters. The residual energy allows agents to participate in routing only if their energy is sufficiently high, unlike in the previous version considered for comparison, namely, basic GAF. The density enables the identification of

```
l = l_m
repeat
  for k ∈ {k ∈ V : NodeLevel(k) = l} do
    for kf ∈ E_T do
      Remove the edge kf.
      Set (V_1, E_T1) the tree containing k.
      Set (V_2, E_T2) the tree containing the core nodes.
      for g ∈ V_1 do
        for j ∈ V_2 do
          T* = (V, E_T1 ∪ E_T1 ∪ {gj})
          if C(T*) < C(T) then
            T ⟵ T*
          end if
        end for
      end for
    end for
  end for
  l ⟵ l − 1
until l > 0
```

Algorithm 4: Local minimization.

Table 2: Simulation parameters.

Communication Range	Number of Nodes	Number of Grid Cells	Initial Energy	Packet Size
100 × 100	100	3 × 3	0.5 J	500 bytes

dense areas in the network to minimize the traffic routing in our proposed protocol relative to that in basic GAF. The definition of the position type for each sensor allows our approach to achieve a global view of the normal, border, and critical zones, allowing other agents to be activated if necessary. The information importance is also an important parameter in our CAGAF protocol. And the heuristic method is used to find an optimal path in terms of energy to transmit data collected until reaching the BS. The consideration of these parameters in our new enhanced version of the GAF protocol has a direct impact on energy consumption, as shown in Figure 6, which proves that our protocol is very efficient compared with basic GAF. Our enhanced CAGAF protocol permits the optimization of energy consumption during communication, thus extending the network lifetime.

Figure 7 shows the number of dead nodes as a function of the total number of nodes. We observe that the number of dead nodes decreases in CAGAF protocol. The number of dead nodes is higher in the GAF protocol because the network nodes consume more energy due to the routing process between adjacent grid cells. Packets are routed through all adjacent grid cells, which increases the number of active nodes responsible for data routing. Therefore, the number of dead nodes has the highest value. By contrast, CAGAF results in a decreased number of dead nodes compared to GAF because of its improvement; our approach achieves a further reduction in the number of dead nodes due to the efficient active node selection process, which considers the factors of energy level and data importance. In this protocol, each network grid cell may have more than one active node to account for the network density. Each grid cell may thus exploit additional active member nodes for data cooperation. Moreover, the proposed approach is based on a cooperative agents strategy in which data packets are aggregated efficiently.

Figure 8 shows the important data collected by the basic GAF (BGAF) and the CAGAF protocol. It seems clear that the CAGAF protocol detects all the important data during the execution of the simulation, which explains the apparition of the CAGAF protocol graph close to 100%, compared to the basic version BGAF that does not consider this parameter.

7. Conclusion

In this paper, we have proposed the enhanced energy-efficient routing protocol CAGAF, which improves data aggregation through the use of cooperative agents in a WSN. Unlike in the previously proposed protocol in which the active node selection process is based on random selection, in our approach, active nodes are selected based on the information importance, the maximum remaining energy, and the minimum distance to the BS. The routing process in our approach is based on cooperative agents communication, where the agents are selected on the basis of the following parameters: the residual energy, the density, the position type of each sensor, and the importance of the

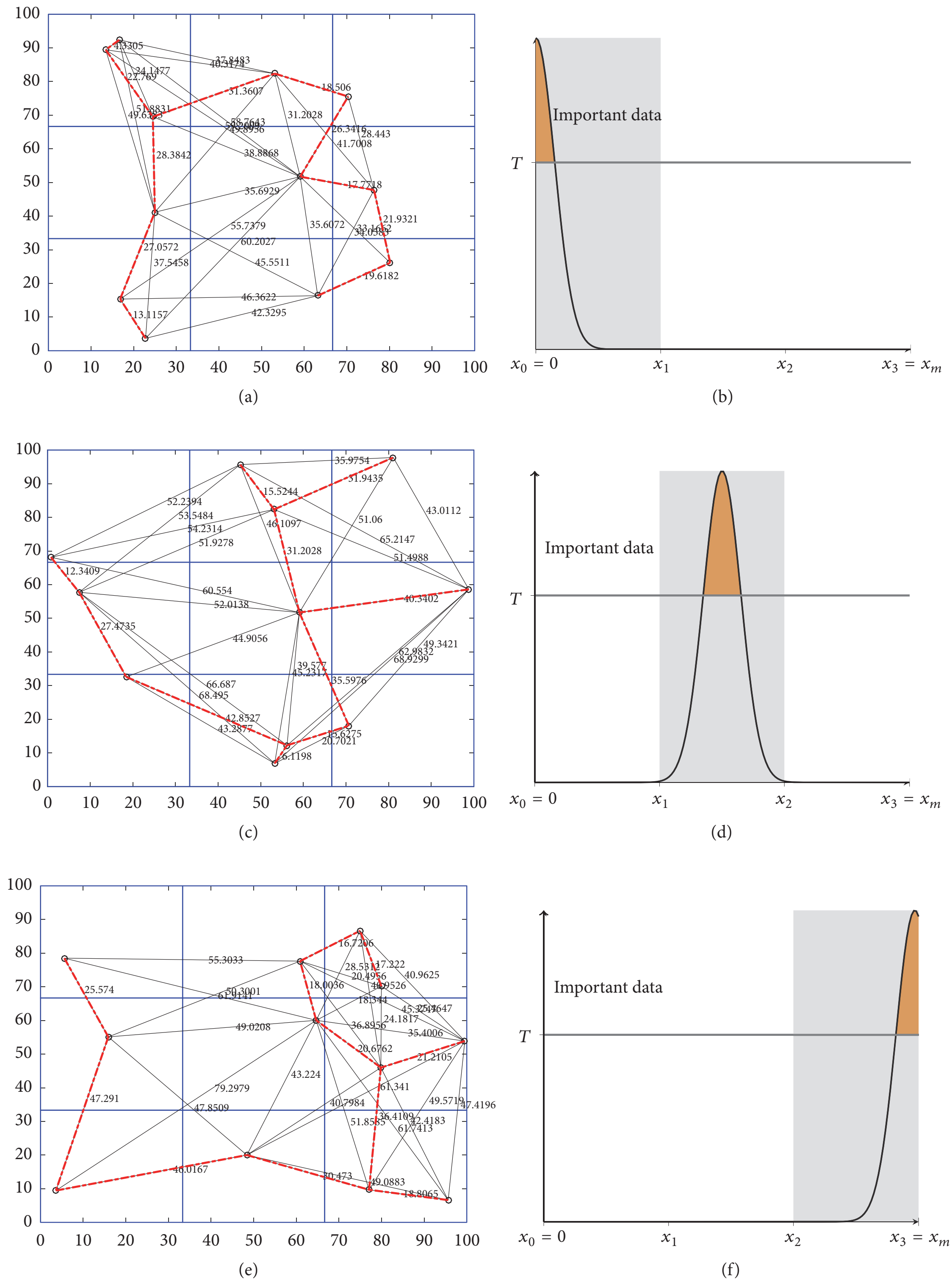

FIGURE 5: Examples of minimum routing trees, active nodes selection, and data important illustration in different cases.

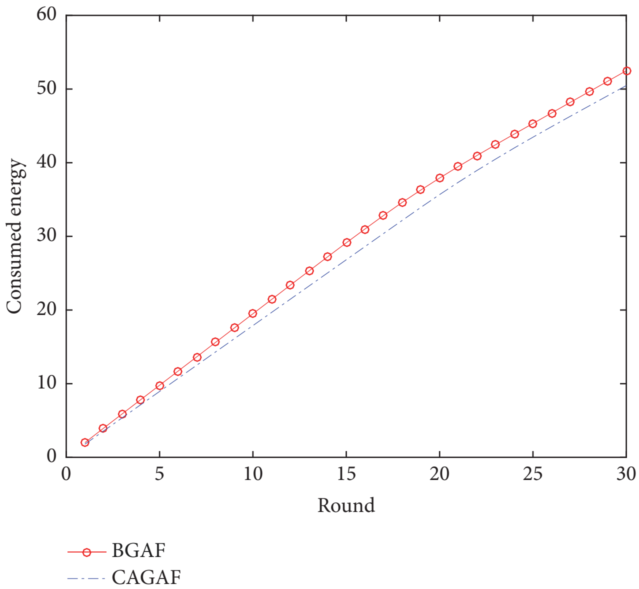

Figure 6: Energy consumption during rounds.

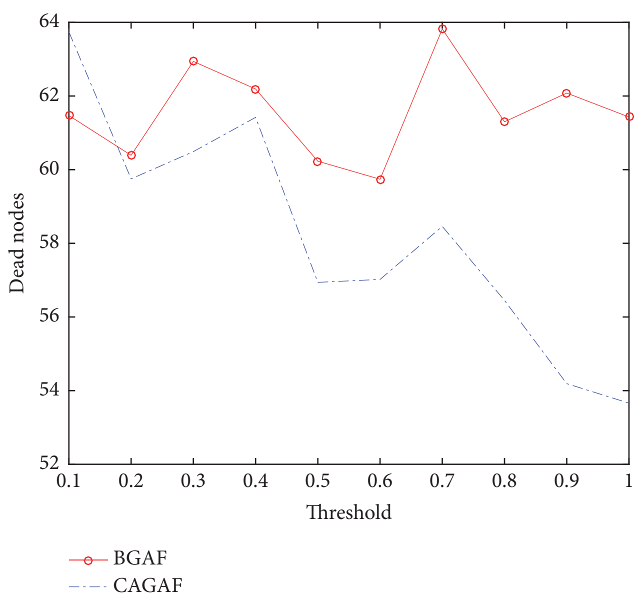

Figure 7: Number of dead nodes in BGAF and CAGAF in terms of threshold.

information. Then, a heuristic method is used to design an optimal routing path to transmit data collected until reaching the BS. Simulation results prove that our protocol is more efficient than basic GAF in terms of energy consumption, data importance, and the number of dead nodes.

Data Availability

The datasets analysed during the current study are available from the corresponding author on reasonable request.

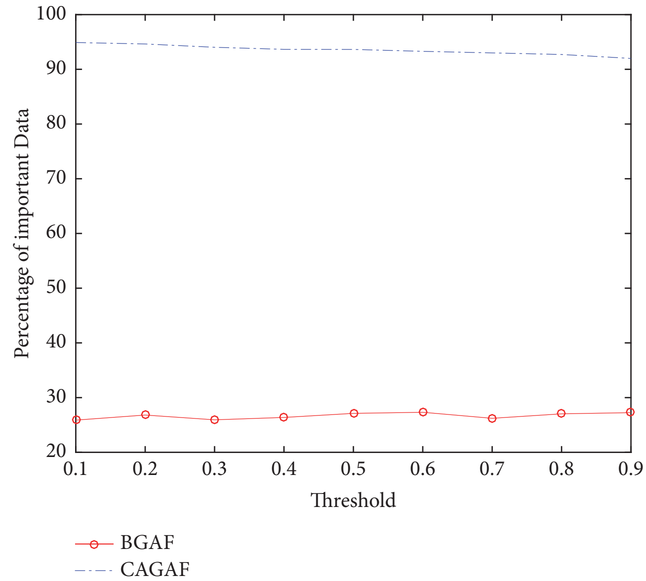

Figure 8: Percentage of important data collected by BGAF and CAGAF in terms of threshold.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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