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A Survey on Analytical Modeling and Mitigation Techniques for the Energy Hole Problem in Corona-Based Wireless Sensor Network

Hadi Asharioun · Hassan Asadollahi · Tat-Chee Wan · Niyayesh Gharaei

Abstract Wireless sensor networks (WSNs) have attracted much attention in recent years. In the many-to-one WSNs, the nodes located around the sink relay the data from other sensor nodes, which depletes their energy more quickly, resulting in energy holes and hot spot areas. When an energy hole appears, data cannot be sent from other sensors to the sink even though most of the sensors still have energy. In this paper, we generally classified the schemes proposed for solving the energy hole problem. In addition, we investigated the basic mathematical modeling of network connectivity and coverage, energy consideration, and optimum width of coronas in the corona-based WSNs.

Keywords Sensor network · Homogeneous · Heterogeneous · Lifetime · Energy hole

1 Introduction

A wireless sensor network (WSN) (see Fig. 1) comprises several low-power sensors located within a field, functioning in an unattended environment. These sensors are able to communicate with each other and send data to external base station (BS). Sensor nodes are tiny and

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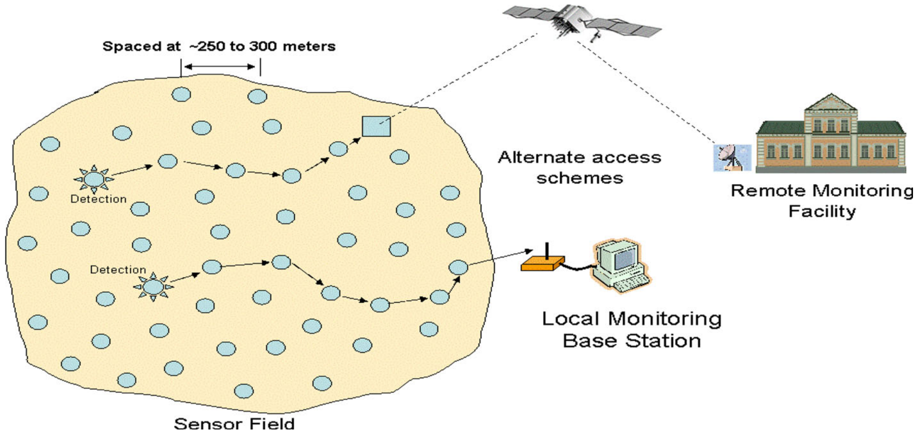


Fig. 1 A sensor network topology

have limited processing and computing properties, and they are commonly equipped with batteries with restricted power capacity. Thus, energy productivity is a very significant issue in scheming a topology. In the multi-hop transmission (also called many-to-one) architecture, nodes consume an unbalanced amount of energy and behave as data originator and data router in the network.

The sensor nodes that are closer to the sink/CH dissipate more energy compared to others. Thus, they die earlier and create energy holes, or hot spots [1]. On the other hand, if multi-hops are not used and all sensors transmit data directly to the sink, the nodes deployed farthest from the sink die much faster than those deployed closer to the sink due to long transmission distance. In any region, due to dense deployment, more sensor nodes may overlap, which increases the hardware cost. Therefore, dense deployment is another reason for the creation of holes problem in WSNs. When energy holes are created, they partition the network in such a way that it cannot provide a full coverage on the field. This causes a considerable reduction in the network lifetime. As a result, it is necessary to propose methods and techniques to avoid the energy hole problem in WSNs. The current examples of such techniques include the use of a mobile sink, transmission range control, and a non-uniform node deployment strategy [2].

The aim of energy hole avoidance is to circumvent or delay the formation of energy hole in order to prolong the network lifetime [2]. Removing energy holes increases the network lifetime, as does the use of energy-efficient designs for the network layers. The following five layers constitute WSN protocols: physical, data link, network, transport, and application. They are designed for coverage, localization, synchronization, data aggregation, data compression, security and storage. Designing and implementing efficient algorithms and communication protocols for these protocols can increase the total network lifetime. Increasing the lifetime of networks is one of the most critical challenges in designing a WSN. Network lifetime depends on factors such as the energy model, protocols and architecture of the network, channel characteristics, data collection method, and how lifetime is defined [3].

In addition, there are relationships between factors such as the network lifetime, sensors coverage, the number of alive nodes, network connectivity, application quality of service requirement, and the energy holes problems (see Fig. 2) and Fig. 3 shows the approaches for prolonging WSN lifetime. The figure shows that the network lifetime can be increased by

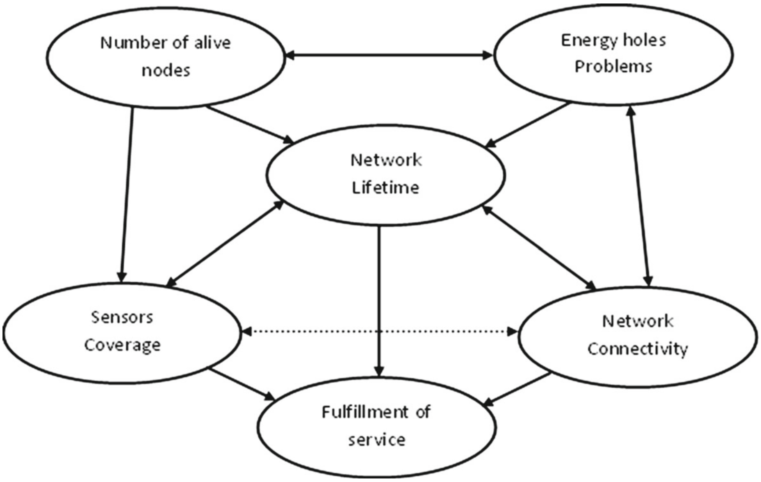


Fig. 2 Relationship among WSN parameters

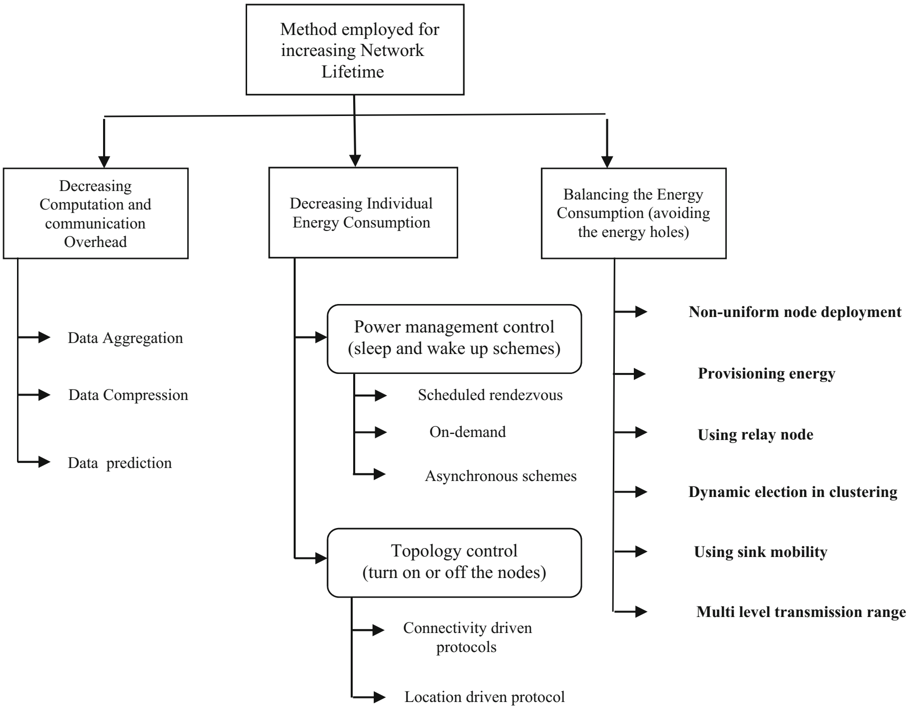


Fig. 3 Methods employed for increasing network lifetime

decreasing individual energy consumption, increasing initial energy, decreasing computation and communication overhead, and reducing the energy holes problem.

Node energy consumption has a direct effect on the network life time. Initial energy of the battery, sensing energy, transmission energy, reception, and electronic energy consumption depend on factors such as modulation, digital coding, filtering and spreading of the signal [4] most of which are related to other branches of science (e.g. physics, chemistry, and electronic engineering). In the network communication science branch, duty-cycling approaches are solution for increasing an individual sensor nodes [5]. Duty-cycling approaches are divided into two groups: topology control and power management control issues. In the topology control protocols, the number of active nodes are minimized while the network topology adapts dynamically based on needs of the application. As a result, topology control protocols prolong the network lifetime [6]. There are two main categories for classification of the topology controls, i.e. location driven protocols and connectivity driven protocols. In location driven protocols, the location of nodes are known and the protocols determine which node to be turn on or off. In connectivity-driven protocols, the protocol activates or deactivates the nodes dynamically to fulfill the network connectivity or coverage of sensing [7]. Another technique for conserving the energy of the nodes is using the sleep and wakeup schemes. Implementation of the protocols usually is on the MAC protocol layer and sometimes on the other layers (e.g. network or application). Sleep and wakeup protocols are divided into three categories: scheduled rendezvous [8], on-demand, and asynchronous schemes [9].

Computation and communication overhead reduce the network lifetime and solving the problem needs designing a protocol layer with low overhead. There are many energy efficient MAC protocols [10–13]. [13] that classify many routing protocols for prolonging the network lifetime. To reduce data communication overhead, many methods such as data aggregation [14], data compression [15,16], and data prediction [5] have been proposed.

Other the main techniques for increasing the network lifetime is mitigating the energy holes. This paper reviews previous studies that addressed routing challenges in WSNs, network lifetime, and the taxonomy of the energy hole problem. It also reviews methods of determining the optimal corona size in corona-based WSNs. The main goal of this literature review is to evaluate existing methods proposed to avoid energy holes and highlight the gaps in these methods.

The remainder of this paper is organized as follows: Sect. 2 gives an overview of the Mitigating Energy Hole Schemes in a WSN. Section 3 compares the energy hole schemes. Section 4 gives an overview of related mathematical. Finally, Sect. 5 concludes the paper.

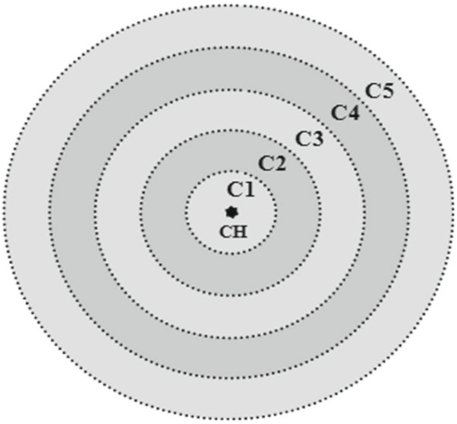
2 Mitigating Energy Hole Schemes

WSNs are designed to sense a phenomenon, either uniformly throughout the whole field or at specific locations (as in target tracking applications) [17]. Sensor nodes relay sensing data to the sink or cluster head (CH). Consequently, the nodes deployed near the sink relay more data than those farther from the sink. This architecture is known as many-to-one network and can be analyzed based on the corona-based model (see Fig. 4). In such networks, the nodes located within the network's inner coronas run out of energy, while those situated within the outermost coronas still have energy [2]. Corona-based models are discussed in the next chapters.

Li and Mohapatra [3] initiated the study on the energy hole problem in a large many-to-one sensor network. They described the energy hole in a corona model and defined the per node traffic load and the per node energy consumption rate (ECR). They proved that nodes in inner coronas consume energy much faster and have shorter lifetime. They developed a mathematical model to analyze the energy hole problem and proved that hierarchical deployment and data compression had a positive effect on a uniformly-distributed sensor network.

Summarizes some of the methods used to mitigate the energy holes problem. In corona-based WSNs, energy holes appear in the inner coronas. One technique for increasing the network lifetime is to avoid the development of energy holes. Most of these techniques can

Fig. 4 A many-to-one network consisting of five coronas



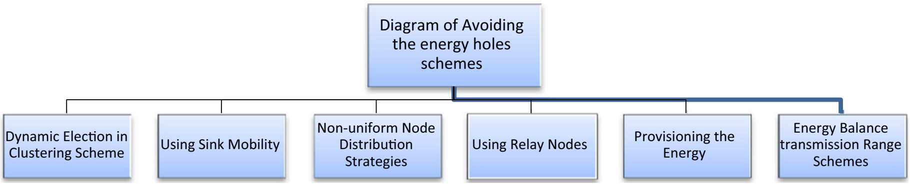


Fig. 5 Methods used to avoid the energy holes problem

be modeled using a corona-based model, which is a static model. However, WSNs that use clustering methods usually are not analyzed using a corona-based model because in clustering techniques, CHs rotate among the sensor nodes dynamically (Fig. 5).

The techniques that can be modeled based on the corona-based model to solve the energy hole problem are nodes distributions strategies, transmission range control, usage of sink mobility, and adding relay nodes. In addition, by optimizing the parameters that affect the energy hole problem and the network lifetime, these problems can be mitigated. Parameters that impact on the network lifetime include the number of coronas, the width of each corona, the node distribution strategy, the node transmission range, and the network area.

In this section, the techniques that can be employed to solve the energy hole problem are presented in detail. The sensor nodes deployment in Mitigating Energy Hole Schemes can be classified into homogenous and heterogeneous node deployment. In the homogenous node deployment, all the nodes are the same. The heterogeneous node deployment proposed by Jae-Joon et al. [18] refers to the deployment of nodes with different transmission ranges, different initial energy values, and different sensor coverage.

2.1 Dynamic Election in Clustering Scheme

One way to save energy and prolong the network lifetime is to use multi-hop transmissions to transmit data from the sensor nodes to the sink. For large-scale sensor networks, however, the clustering method is more appropriate [19]. In this method, each sensor node forwards data to its CH; after aggregation, the CH sends data to the sink. Transmission from the sensors to the CH or from the CH to the sink eider can occur directly or multi-hop method [20].

There are several objectives for using clusters in WSNs, including network connectivity, load balancing, and fault tolerance. When the clustering method is used, a CH is chosen from

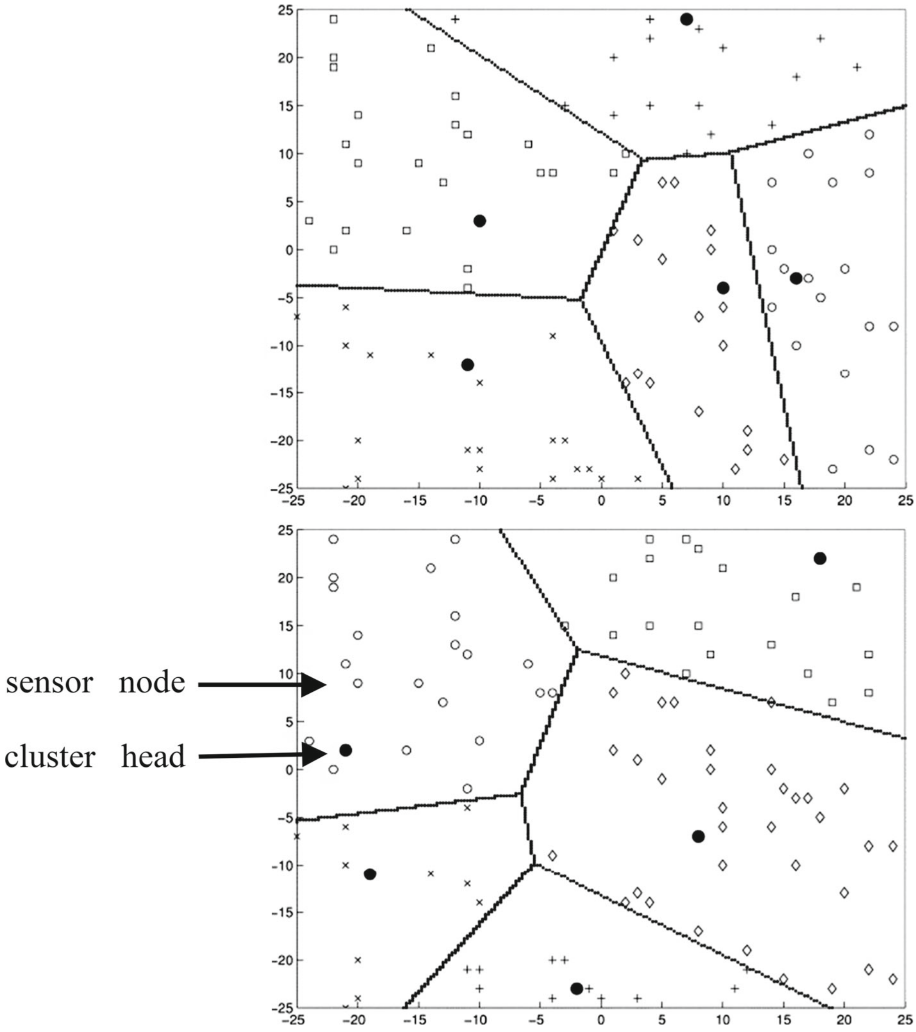


Fig. 6 Dynamic cluster formation during two different rounds of LEACH

among the deployed sensors [21,22]. To balance energy consumption, the CH role can be rotated among the sensor nodes within the cluster [21,23]. Thus, dynamic clustering methods can be used to address energy efficiency issues [20]. In dynamic clustering, the nodes are able to organize themselves into local clusters in which a node plays the role of CH and other nodes send data towards the CH. Nodes that are designated as CH receive data from other cluster members and then transmit the data to the BS. Thus, a CH consumes more energy than other nodes. After consuming all of its energy, the CH can no longer operate, which means that all of the surrounding nodes lose their communication capability. To overcome this problem, the positions of CHs with a high level of energy should be randomized to avoid running out of energy.

In the LEACH protocol [21], from time to time, the nodes designated as CH become regular nodes and other nodes become CH in order to balance the depletion of energy (see

Fig. 6). This technique, has been used in scenarios wherein only one-hop communication exists from each head to sink within a small square area.

In the HEED protocol [24], the multi-hop mode of transmission is used. To lower the communication cost in a rectangular network, the node degree and remaining energy are used to select the CHs. SAPC protocol proposed by Bekara, Laurent-Maknavicius [25] is known as a static cluster-based aggregation protocol in which the cluster-head nodes are recognized as the aggregators. ESPDA [26] is another type of cluster-based protocols. It first employs a sleep-active coordination protocol to avoid redundancy in the process of data transmission during intra cluster communication. The network coding proposed by Fragouli et al. [27] is another promising technique for data aggregation in clustering-based WSNs that can improve the performance of the sensor network. Soro and Heinzelman [28] introduced an unequal clustering size model for network organization. Among CH nodes, it can result in more uniform energy dissipation and, finally, it can lead to increased network lifetime. This approach can be used in both heterogeneous and homogeneous sensor networks.

2.2 Using Sink Mobility

The use of mobile sinks is another way to avoid energy holes. Luo and Hubaux [29] examined why there was more data pressure on nodes situated near the sink compared to those placed far away from the sink, resulting in higher energy consumption for the nodes closer to the sink. Mobile sinks were proposed as a solution to the uneven energy consumption problem. They maintained that the use of a mobile sink could result in a steady distribution of load among nodes by evenly distributing the task of forwarding data among all nodes. A number of researchers have developed mobile sink protocols.

Bi et al. [30] introduced an autonomous movement strategy known as the half-quadrant-based moving strategy (HUMS). Marta and Cardei [31] designed a localized and distributed mobile sink movement algorithm, and Wu and Chen [32] attempted to integrate a mobile sink and a static one when designing a WSN. [31], authors demonstrated that mobile sinks could extend the network lifetime 3.48 times more than static sinks.

Despite the advantages of mobile sinks, their application has introduced new problems to routing protocols. For example, the temporal changes in which nodes perform certain functions make routing of mobile nodes difficult. Therefore, many researchers have focused on routing protocols for WSNs [33–35]. Luo et al. [36] proposed a routing protocol to support sink mobility and reduce the packet loss that could take place when sink movement occurred. Gatzianas and Georgiadis [33] introduced a distributed algorithm that selected the routing paths to the mobile sink in a way to prolong the WSN lifetime.

2.3 Non-Uniform Node Distribution Strategies

There are two strategies for node deployment, namely random uniform deployment and non-uniform deployment. Nodes in the non-uniform deployment strategy, nodes are usually deployed manually. In case of various applications, the manual deployment is not possible to be adopted because of two reasons; firstly, it is significantly a time-consuming process; and secondly, the area wherein the network is located may be too harsh to be accessible for human being. However, the deterministic placement can be applied to those environments where, firstly, a small to medium number of devices are involved and, secondly, it is easily accessible for human being. Table 1 summarizes the studies that have used the non-uniform node deployment strategy.

Table 1 Summary of non-uniform node deployment works

	Sub-balanced energy	Consider coverage/ connectivity	Random node deployment	Other
Liu and Mahapatra [42]			✓	The nodes located closer to the sink are placed closer together.
Yunhuai et al. [38]			✓	Power-aware non-uniform distribution scheme
Xiaobing et al. [39]	✓		✓	Using geometric proportion
q-Switch [2]	✓		✓	Proposing new routing strategy (i.e., q-switch routing)
Strategy I [41]	✓	✓	✓	Using different sensor sensing ranges in outermost corona
Strategies II and III [41]	✓	✓		Using manual node deployment

Liu and Mahapatra [37] proposed a non-uniform strategic placement scheme of the sensor nodes to be used in a linear network. They provided a necessary distance between the adjacent sensor nodes to obtain a specified lifetime. In this system, the nodes located closer to the sink were placed closer together. Yunhuai et al. [38] conducted a research on a number of strategies that could be adopted to deploy the nodes, but, at the same time, they suffered from the energy holes problem. They introduced a scheme of power-aware non-uniform distribution. In this scheme, more nodes were located closer to the sink to provide sufficient energy for greater demand because of packet forwarding. The node deployment was done through a proposed distribution function. To ensure the energy balance, the energy depletion was done simultaneously for the whole sets of the nodes located with an equal distance from the sink.

Xiaobing et al. [39] utilized a non-uniform mode for the node distribution to examine the problem of energy holes within the networks in its theoretical aspects, and introduced the strategy of non-uniform node distribution in which a geometric proportion was employed for making change in ratio of density of the nodes situated in the adjacent layers. This guaranteed the highest level of efficiency in the consumption of energy. In this strategy, the least number of nodes needed in the upper neighboring layer was used as a base for determining the number of nodes for a layer. However, they did not discuss the minimum number of nodes needed for the layer located in the farthest point from the sink in order to maintain the coverage and connectivity. Similar to study of Jarry et al. [40], this study used unrealistic assumptions when evaluating uniform deployment of nodes. Xiaobing et al. [2] used their proposed node deployment in another research. They introduced a new non-uniform node distribution strategy in order to obtain a nearly-balanced depletion of the energy within the network. In each corona, they set the number of nodes and derived the ratio between ith coronas and the node densities within the adjacent $(i + 1)$th for energy holes problem. Finally, a q-Switch Routing algorithm was proposed; it was a distributed shortest path routing algorithm that was tailored for the proposed non-uniform node distribution strategy.

Ferng et al. [41] proposed three new strategies of non-uniform node distribution for the energy holes problem. Strategy I could achieved completely the energy balance through arranging more areas in outermost corona so that the sensor nodes could cover bigger area and have a longer sensing/transmission range in comparison with those sensor nodes located within other coronas. Strategy II achieved the longest network lifetime. Among these strategies, Strategy III needed the least number of sensor nodes. Then, the performance was examined through simulation and analytical approaches.

Atiq Ur et al. [43] introduced deployment strategies in which the sensor nodes were located in Gaussian fashion, which attempted to moderate energy hole around the sink. It reduced the residual energy through minimizing the chance of the energy holes to be formed closer to the sink. Liu et al. [44] used mixed-routing strategy for balancing energy consumption among nodes both within the different coronas and within the same coronas.

2.4 Provisioning the Energy

The use of heterogeneous sensor nodes can help to overcome the energy hole problem [18]. Different types of heterogeneous methods have been proposed, including the deployment of nodes with different transmission ranges, different initial energy, and different sensors coverage. Provisioning more energy for the nodes deployed in a hot spot place can mitigate the energy holes problem. Table 2 summarizes different energy provisioning strategies.

Hou et al. [45] evaluated the design problems involved in energy provisioning and relay node placement. They first formulated the problem as a mixed-integer nonlinear programming problem, and then they derived a heuristic algorithm for solving it. Sheldon et al. [46] sought ways to deploy the network so that the workload could be evenly distributed, which would allow the overall network behavior to degrade smoothly. Assuming that the sensors were evenly deployed within the monitored area, they designed a system in which a set of more powerful nodes was designated for data relaying, and they selected sub-regions for the deployment of the relaying nodes at a calculated density.

Iranli et al. [47] evaluated how to assign the initial energy levels and positions to the relay nodes and how to place nodes in clusters assigned to the individual relay nodes with the propose of prolonging the lifetime of a two-level WSN. Esseghir et al. [48] and Lian et al. [49] studied specifically the non-uniform initial energy distribution. This idea involves differentiating the sensor nodes with different initial energy levels based on the workload. For nodes with a higher workload, the initial energy should be set to a higher level. However, employing this strategy is not simple because producing and deploying the sensor nodes is very difficult [2,50].

Halder et al. [51] attempted to develop a non-uniform location-wise predetermined node deployment strategy. They used the principle of non-uniform node distribution to ensure the energy consumption balance and extend the network lifetime. Finally, they carried out extensive simulations to verify the energy consumption balance of their scheme and the extension of the network

2.5 Using Relay Nodes

The use of relay nodes in the network significantly affects the lifetime and connectivity of WSN systems. Table 2 summarizes different relay node and energy provisioning strategies. Quanhong et al. [52] and Wang et al. [53] evaluated the optimal relay node deployment using a minimum number of relay nodes that had connectivity and lifetime limitations. Quanhong et al. [52] investigated how device provisioning affected the usable lifetime of a system. They

Table 2 Summary of relay nodes/energy provisioning strategies

References	Summery (for relay nodes and energy provisioning)
Bhardwaj et al. [59]	They studied a multi-hop sensor network and minimized the amount of energy consumed when transmitting a data packet between a source node and a destination node
Mhatre and Rosenberg et al. [60]	They described the proportionality between the number of regular sensors and the square of the number of CHs in clustered WSNs
Hou et al. [45]	The authors designed problems involved in energy provisioning and relay node deployment. they did not calculated the maximum energy required
Esseghir et al. [48] and Lian et al. [49]	They studied specifically the non-uniform initial energy distribution. This idea involved differentiating the sensor nodes with different initial energy levels based on the workload. However, they did not calculate the maximum energy required
Ammari and Das [61]	They proposed a sensor deployment strategy based on energy heterogeneity whit a goal that all the sensors can deplete their energy at the same time
Halder et al. [51]	The authors attempted to develop a non-uniform location-wise predetermined node deployment strategy. They used the principle of non-uniform node distribution to ensure energy balancing and extend the network lifetime
Lin et al. [62]	They focused on the cost

proposed a device provisioning framework in accordance with hierarchical communication architecture. Based on the application scenario, device provisioning strategies can be either random or deterministic. Quanhong et al. [52] compared the contemporary approaches for random and deterministic device provisioning and discussed the open issues in each category. However, their study did not involve the corona-based model.

Kenan et al. [54] reported that the way relay nodes were deployed in a network significantly affected the lifetime and connectivity of WSNs. They examined the influences of random deployment strategies on lifetime and connectivity. They discussed the biased ECR associated with the uniform random deployment and the way it could result in deficient energy consumption and reduced network lifetime. To solve this problem, they proposed two novel strategies for random deployment of nodes, namely hybrid deployment and lifetime-oriented deployment. Hybrid deployment was an attempt to reconcile lifetime extension and connectivity, whereas lifetime-oriented deployment could be used to balance the energy consumption of the relay nodes, which would lead to prolonging the system lifetime. However, this scheme could not establish enough connectivity to the relay nodes when the system contained a relatively small number of relay nodes. In their study, Kenan et al. [54] considered both multi-hop and single-hop communication models. They combined simulated evaluation and theoretical analysis to find the appropriate trade-off between connectivity and lifetime extension to address the relay node deployment problem. They also provided guidelines indicating how to effectively deploy relay nodes in a large-scale heterogeneous WSN. Kenan et al. [54] also used relay node deployment density functions to find a solution to the problem of the biased energy consumption rate and expand the system lifetime. Their assumption was that sensing fidelity was guaranteed by the sensor node deployment strategy.

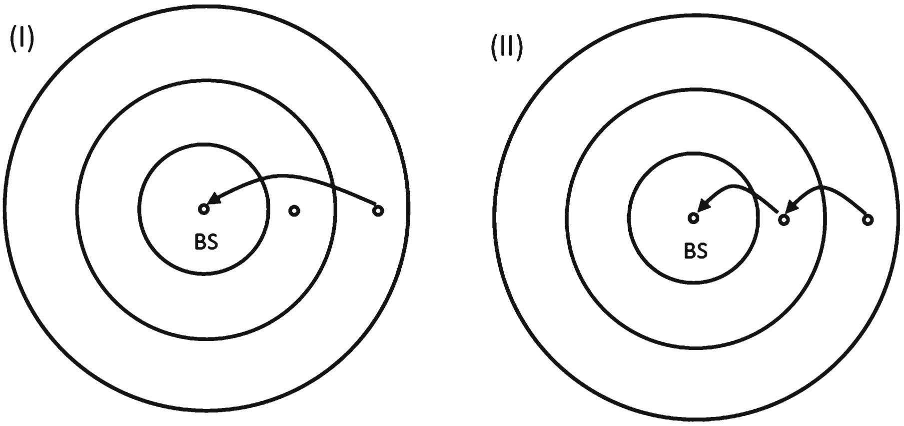


Fig. 7 Transmission protocols: (**I**) direct transmission; (**II**) hop-to-hop

Cooperative communications involve both the source-destination pair and relay nodes; the latter are used to transmit signals by relaying the signal from the source to a predetermined destination. Jing et al. [55] and Jiucai et al. [56] introduced a node deployment scheme for balancing the energy consumption within cooperative sensor networks. However, this scheme was limited because it required manual node deployment. Additionally, many other relay node deployment strategies exist for non-corona-based WSNs [57,58].

In Freng et al. [43] studied heterogeneity of sensor coverage in corona-based WSNs. They identified the minimum number of sensor nodes required for full coverage of the corona, and they showed that completely balanced energy depletion could be achieved for EPND and GND. They also introduced three new strategies for non-uniform node distribution. Strategy I achieved complete energy consumption balance through providing more sensor nodes in the outermost corona; thus they covered more area and had a longer sensing/transmission range compared with the sensor nodes located within other coronas. Energy-balanced transmission schemes are other examples of heterogeneous methods, which are discussed below.

2.6 Energy-Balanced Transmission Range Schemes

Energy-balanced transmission range schemes are a type of energy-balanced schemes. Controlling the transmission range helps to overcome the energy hole problem. Many researchers have attempted to find a solution to the energy-balanced transmission schemes in WSNs.

Many researchers have attempted to solve the problem of energy-balanced data propagation in WSNs. Energy-balanced transmission controls the transmission range in order to mitigate the energy hole problem. Examples of such schemes are described below.

Researchers have investigated energy-balanced mechanisms using the same slice model for which two periods of time are defined. During the first period, the sensors transfer data to the sink in a direct way, whereas during the second one, the sensors send data to the sensors that belong to the next slice (Fig. 7: transmission protocols: (I) direct transmission; (II) hop-to-hop). The network lifetime is calculated based on the ratio of multi-hop to direct sending of data [63–65].

Considering the energy consumption for single-hop and multi-hop communication to the sink, Perillo et al. Mhatre and Rosenberg [60] proposed an alternate mode between multihop and single-hop to achieve energy consumption balance. They calculated the optimization of network lifetime in a linear programming problem. But the authors only consider that nodes use up their energy without thinking of using energy efficiently to collect useful data.

Bhardwaj and Chandrakasan [66] provided upper bounds for the sensor network lifetime. A given topology has various routes through which the packets originating from a node can be transferred to a particular destination node. These routes may include varied paths, and a given node does not necessarily have direct communication with its one-hop neighbor. In such cases, the node may directly transmit the packet to another node situated two or more hops away, and thus it requires more energy. As the number of nodes increases, the number of paths through which a packet can be transferred between source and destination increases exponentially.

Mhatre and Rosenberg [60] examined sensor networks consisting of two different types of sensors: regular sensors and CH sensors with higher energy. The former utilized either single-hop or multi-hop communication to transfer data to the respective CHs, which had the same transmission radius with a smaller energy budget. The latter had a higher level of energy and could be used as CHs for the regular sensors. These sensors aggregated the received data prior to sending them, thus the required energy was proportional to the number of incoming reports. The challenge with this type of system is defining the parameters in such a way that both types of sensors run out of energy simultaneously. If this can be accomplished, the network lifetime is extended and the network total cost is minimized. The network total cost is calculated as the cost of building the sensors plus the energy consumed by them combined into a linear function. In both types, there should be a fixed total number of sensors. From their study, Mhatre and Rosenberg [60] concluded that for $n = 2$ (path loss power), multi-hop communication was not beneficial. Essentially, they did not prove that the use of hops of equal length was necessarily optimal. Their results were based on minimization of the energy in a critical ring, and it is noteworthy that other rings may not be critical.

Olariu and Stojmenovic [67] proposed a method for mitigating energy holes and maximizing network lifetime that involved uniform reporting and distribution based on power-adjusted transmission and corona network division. Leone et al. [68] studied the problem of energy-balanced data propagation in WSNs, and they extended and generalized previous studies by applying adaptive energy assignment. To address the data-gathering problem, they proposed that the sensors should sense the data and then transfer them to a single sink. This process can occur by either sending the data directly to the sink or transferring the data via a multi-hop scheme. These two data transfer methods consume different amounts of energy. Protocols for energy balancing typically balance the energy consumption of the sensors through calculating suitable ratios of neighboring and direct transmission.

These kinds of energy-balanced transmission schemes are based on the probabilistic data propagation algorithm. Charilaos et al. [69] hybridized multi-hop and single-hop transmission to achieve a balanced state of energy consumption among all of the sensor nodes. Both [67] and [69] divided the sensor network into concentric circular rings. In the former, all sensors had the same ratio of the number of multi-hop and single-hop transmissions; whereas in the latter, the ratios differed among sensors. Charilaos et al. [69] also introduced a ring model and proposed a probabilistic data propagation algorithm to balance the energy consumption of the sensors in the network, which was characterized by a uniform event generation rate and uniform node deployment.

Jarry et al. [70], authors used the probabilistic data propagation algorithm proposed by Charilaos et al. [69] to explore the relationship between energy balance and life-span maximization. However, they found that none of the schemes described above could balance energy consumption of the nodes present in the same slice or prolong the network lifetime. They stated that the mode of routing data to the sink played a significant role in the energy

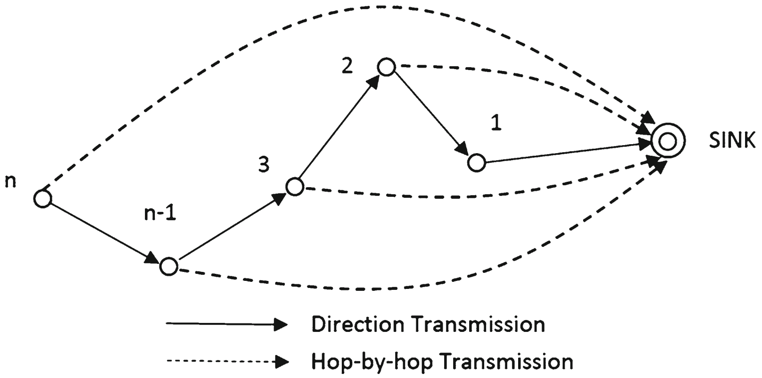


Fig. 8 A general chain network composed of n sensor nodes

consumption imbalance that affected the network lifetime. To solve this problem, they proposed an algorithm based on the mixed routing strategy. It enabled a sensor node to select one of two paths to transmit the data to the sink. One path transferred data through adjacent nodes (multi-hop), whereas the other one sent data directly to the sink (single-hop). Two parameters were important for choosing the path: the node's residual energy and the number of hops situated between the node and the sink. However, this algorithm includes the unrealistic assumption that events occur uniformly. Furthermore, it does not guarantee the energy consumption balance, although it may extend the network lifetime.

Jarry et al. [70] showed that among all of the energy-balanced routing strategies, they evaluated one that caused the flow of data transmission to be maximized within the network. More links within a network means that the data flow may be reduced (Fig. 8). This result demonstrates that the energy-balance mechanism can optimize the data flow within the network. In an independent study, Giridhar and Kumar [71] obtained similar results using linear programming tools.

Other studies have attempted to prolong the WSN lifetime using different transmission schemes [72] or managing each sensor's status in an inactive or active mode [73]. Zhang et al. [74] investigated how to balance energy consumption in a linear data-gathering sensor network. They took into consideration the energy consumed for both data receiving and data transmission. Powell et al. [75] designed an optimal data propagation algorithm that was aimed to maximize the network lifetime. It used a spreading technique to balance the energy consumption of the sensors in the same slice.

Song et al. [76] introduced a corona model improved with levels for analysis of the sensors with the adjustable transmission ranges within a circular multi-hop deployed WSN that had been modeled as the concentric coronas. In this model, it was assumed that, in each corona, there was an optimal transmission range of the sensors, which was a decisive factor for optimizing the network lifetime after the deployment of the nodes. Song et al. [76] showed that searching for the optimal transmission ranges of the sensors was a multi-objective optimization problem. In other words, they proved the non-deterministic hard problem. Thus, the authors proposed a distributed algorithm and a centralized algorithm to assign the sensors' transmission ranges in each corona for various node distributions. These two algorithms not only lowered the searching complexity but also obtained the near-optimal solution.

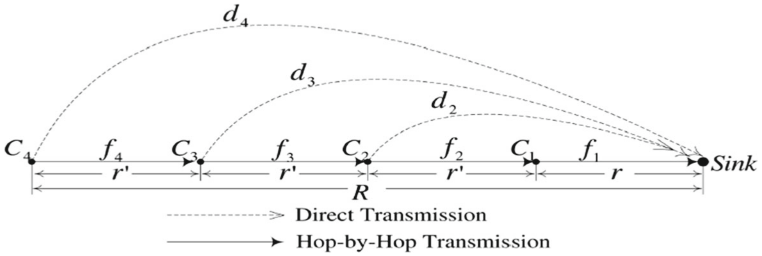


Fig. 9 Mapping the network onto a linear model

Ammari and Das [77] proposed three different solutions for solving the energy hole problem. The first involved adjusting the communication range of the sensors. This solution mitigated the energy hole problem to some extent, but it also limited the size of the fields. To overcome this problem, another deployment strategy based on energy heterogeneity was developed. All nodes located within a particular distance from the sink had an equal amount of energy initially, whereas the nodes deployed at two different distances had different amounts of energy. The heterogeneity property was applied so that all nodes could run out of energy at the same time. Finally, Ammari and Das [77] introduced a localized energy-aware Voronoi diagram-based data forwarding protocol that considered the nodes as homogeneous items and the sink as a mobile entity. The nodes selected a suitable forwarder node based on its closeness to the sink and residual energy. This method of selecting the forwarder nodes keeps the energy balanced. The mobility of the sink is the main weakness of this strategy, as the nodes require additional energy to keep track of the sink.

Haibo and Hong [78] balanced the energy consumed by nodes in a network by deploying the data-gathering sensors uniformly, and their goal was to maximize the network lifetime. They formulated the energy consumption balancing problem as an optimal transmitting data distribution problem and combined the mixed routing strategy and corona-based network division together with data aggregation. They first introduced a localized zone-based routing scheme to guarantee that energy consumption was balanced among all nodes in each corona (Fig. 9). They then introduced an offline centralized algorithm with time complexity to solve the transmitting data distribution problem.

Leone et al. [68] proposed an abstract model of energy dissipation that combined a random walk with rigorous performance analysis techniques. Two effective distributed algorithms were analyzed using both simulation and measurement tools. The first algorithm could be executed quickly and was easily implemented. The assumption was that sensors had a priori knowledge about the rate of data they generated. The sink collected all data and processed them to calculate the relevant value for the protocol parameter, and this value was then transmitted to the sensors, which computed their individual optimal ratio of neighboring and direct transmissions. The second algorithm elicited the information about the data transfer paths (i.e., multi-hop or direct) by observing the data paths and thus avoided the need for a priori knowledge of the data rate generated by the sensors. This algorithm was designed based on stochastic estimation, and thus it could be adapted to environmental changes.

Azad and Kamruzzaman [79] proposed the topology control approach wherein the nodes collaboratively adjusted their transmission power and then created an appropriate network topology aiming at balancing the energy consumption of the network. However, the sensor nodes required high transmission power to construct the topology. This feature severely

Table 3 Summery of Azad and Kamruzzaman's work

Method name	Abbreviation	Explanation
MH transmission	Multi-hop transmission	Traditional multi-hop method
FHS	Fixed hop size	The sensor nodes forward their data in the number of rings, equal to the proposed hop size
SVHS	Synchronous variable hop size	Varying the hop size over the time
H-AVHS	Heuristic-AVHS	The inherent energy is exploiting.
H-SVHS	Heuristic-SVHS	Usage deployment pattern among the sensor nodes for varying hop
AVHS	Asynchronous variable hop size	Each corona employs set of optimal hope size and duty cycles over time associated on it

limited the implementation of this approach. The authors formulated the network limitation maximization (NLM) problem as a balanced energy consumption minimization issue, and they proposed that the solution to the problem involved calculating the optimal number of coronas for maximization of the network lifetime.

Azad and Kamruzzaman [79] also separated the transmission distance presented in the conventional multi-hop scheme into two discrete parts: the hop size and the ring thickness. They analyzed energy and traffic distribution among the sensors and then identified how the critical ring shifted with hop size and how energy usage changed. They then introduced a transmission scheme and determined the optimal hop size and ring thickness by formulating the network lifetime as an optimization problem. You can see summery of Azad and Kamruzzaman's work in Table 3.

Chen et al. [80], authors used cooperative communication to solve energy hole problem and prolong the network lifetime in WSNs. They designed a cooperative transmission strategy in which each node helped its relay node forward the data using the cooperative multi-input single-output method. This strategy allows the energy in the nodes located close to the sink to be shared with the nodes deployed farther away. This way, it balances the energy consumed in the network. To identify the optimal state of power allocation among the cooperative nodes, they studied the optimization problem in terms of maximization of the network lifetime and minimization of the energy consumption. They found that the proposed cooperative transmission strategy efficiently alleviated the energy hole problem and provided a longer network lifetime compared with traditional non-cooperative transmission strategies in which the nodes forward the data via a hop-by-hop approach through the single-input single-output method. In addition, the new strategy's power allocation was shown to be more effective in the minimization of the energy hole problem, prolonging the network lifetime, and reducing the energy consumption. Their method did not require manual deployment of sensors because the node distribution could be arbitrary, and due to the cooperative communication, the power limitation was relaxed. In Thanigaivelu and Murugan [81], authors proposed a K-level-based transmission-range scheme designed to obtain energy balance throughout the network. They used the controlled region selection strategy in which the sensor nodes determined their possible next hops based on the K value (where K denoted the number of corona level jumps). Among the next nodes available, the one that had the maximum amount of residual energy was selected as the next hop. This technique avoided random selection and repetition of a node as the next hop node, which could occur in the normal fixed transmission range scheme. Using this level-based transmission range scheme, a new set of next hop nodes was

Table 4 Summary of studies conducted using multi level transmision range

	Corona-based model	Determine direct: indirect ratio	For outdoor environment	Other
Bhardwaj and Chandrakasan [66]			✓	
Guo et al. [63]		✓		Only for leaner communication
Mhatre and Rosenberg [60]	✓		✓	Hybrid model
Liu et al. [65]	✓		✓	
Olariu and Stojmenovic [67]	✓	✓	✓	Pre-determined transmission rang
Charilaos et al. [69]	✓	✓		
Jarry et al. [70]	✓	✓		
Zhang et al. [74]		✓	✓	
Ammari and Das [77]	✓	✓	✓	Combine with Sink mobility
Haibo and Hong [78]		✓	✓	Focused on data compression
Song et al. [76]	✓	✓	✓	With different sensing range
Azad and Kamruzzaman [79]	✓	✓	✓	
Chen et al. [80]	✓	✓	✓	Using more than one transceiver
Thanigaivelu and Murugan [81]	✓	✓		

chosen in the renewal phase (i.e., a new K value was selected each time). A summary of important approaches using multi level transmission range is presented in Table 4.

3 Comparison of Energy Balancing Methods

Table 5 shows the advantages and disadvantages of the energy balancing methods that have been described in this paper. Dynamic methods have high complexity algorithm; however, their cost (number of nodes or battery) is low because these methods do not need more nodes to balance the energy consumption. In this case, it would not be possible to obtain the complete balance of energy consumption and maximum lifetime, and there is no any specific model to provision the energy for obtain maximum lifetime. The methods which provision energy can use heterogeneous nodes with different capacity of battery, thus the nodes should be deployed non-uniformly. Therefore, these methods cannot be used in unattended environments. The use of relay nodes can have a significant effect on mitigating the energy hole problem; however, they increase the cost of network. The relay nodes can deploy randomly or manually. Definitely, random deployment is more practical than manual deployment, but with manual deployment, we can use efficiently extra relay nodes to obtain maximum lifetime. The use of multi transmission range can reduce the energy consumption of interior coronas so that it can balance the energy consumption in the coronas. These methods usually are impractical because the most real sensor nodes do not have varied transition rang. Using the optimal

Table 5 Comparison of the energy balancing methods

The energy balancing method	Advantages	Disadvantages
Dynamic clustering	Homogeneous, random node deployment	High overhead algorithm,
Sink mobility	High-effect on the energy holes	High complex of the routing algorithms
Nodes distributions strategies		
Homogeneous	Low cost, Homogeneous nodes	Manual node deployment
Energy provisioning	Can be used for maximization of the network lifetime	Manual node deployment, high cost / energy
Using relay nodes	Can be used for maximization of the network lifetime	Manual node deployment, high cost / energy
Heterogeneity on sensor coverage	Few number of nodes	Manual node deployment
Transmission range control		
Hybrid of Multi-hop and single hop	Simple algorithm; can be used in multi-hop and corona-based networks	Low effect on the energy holes problem
Probabilistic data propagation	Simple algorithm, distributed	No feasibility
K-level transmission ranges	Can be used for sensor with limited transmission range	No feasibility
Combination of several methods	High-effect on the problem	High complexity, no feasibility

number of coronas in each above method can mitigate the energy hole problem because, in this case, transmission range is optimized.

4 Related Mathematical Review

In this section, the mathematical analysis related to the energy hole problem in corona-based WSNs is presented. This section takes into consideration the basic mathematical equations of corona-based WSNs for proving and analyzing the research proposed methods regarding the energy hole problem. This section also includes the energy consideration of the corona-based WSNs, optimum width of coronas in the network, and the network connectivity and coverage.

4.1 Energy Considerations in the Coronas

Using Manish Bhardwaj [82] model, the energy dissipated when sending a bit of data over distance d was $E_{Tx} = E_{elec} + \alpha d^n$, and the energy consumption for data reception was $E_{rx} = E_{elec}$. Here, α is the energy dissipated in the op-amp in data transmission and n is the path loss exponent that indicates the rate at which the path loss increases with distance [83]. The value of n depends on the specific environment. For example, in free space, $n = 2$.

In some environments, such as buildings, stadiums, and other indoor environments, the path loss exponent can reach values in the range of 4–6. Finally, E_{elec} is the electronic energy, and it depends on factors such as digital coding, modulation, filtering, and spreading of the signal.

The definition of network lifetime used in this study is as follows: the network lifetime ends as soon as the first node die [84]. Before determining the optimal number of coronas in the network, the energy consumption of the nodes in the coronas must be considered. Consequently, only the energy consumption of innermost corona should be obtained:

Only the lifetime of the nodes in C_1 is considered instead of the total network lifetime. Thus, the lifetime of the interior corona is used to calculate the network lifetime. The energy consumption in C_1 is required to calculate the lifetime of C_1. According to [82], the key energy parameters needed for this calculation are the energy required to transmit one bit over a distance d (E_{Tx}), the energy needed to receive one bit (E_{rx}), and the energy required to sense one bit (E_d).

In this model, it is assumed that there are M nodes in the network and N_1 nodes in C_1. Based on these assumptions, all of the packets in the network relay data from C_1 to the sink. If each node generates and transfers l bits in one unit of time, then, using the result of the research conducted by Xiaobing et al. [2], the energy consumption in C_1 is:

$$E_1 = l\left[N_1 E_{Tx} + \sum_{j=2}^{k} N_j\left(E_{Tx} + E_{rx}\right)\right] \tag{1}$$

where E_{Tx} and E_{rx} are the transmission and reception radii energy for communication of one bit, respectively, l signifies the number of nodes in a packet, N_1 denotes the number of nodes in innermost corona, M is the number of nodes in the network, and E_d stands for the sensing energy in C_1. An energy model is used similar to one described in [82], and E_{Tx} and E_{rx} take the following form:

$$E_{Tx} = E_{elec} + \alpha d^n \tag{2}$$

$$E_{rx} = E_{elec} \tag{3}$$

where E_{elec} represents the electric energy consumed by transmission of one bit, which depends on factors such as filtering, digital coding, modulation, and spreading of the signal; α denotes the energy consumption in an op-amp for transmission;d is the distance between the transmitter and the receiver, and n signifies the path loss exponent related to a specific field. If the network has k coronas, then $R = R_{area}/k$, where R denotes the width of each corona and R_{area} denotes Network radius then:

$$E_{Tx} = E_{elec} + \alpha \frac{R_{area}^{n}}{k^n} \tag{4}$$

Now that the energy consumption of each sensor and the average energy consumption in $C1$ have been obtained, the optimal number of coronas in the network can be determined.

4.2 Optimum Number of Hops

Bhardwaj et al. [59] studied a multi-hop sensor network and determined an upper boundary for the network lifetime through minimizing the amount of energy consumed when transmitting a data packet between a source node and a destination node. To accomplish this task, they used an optimum number of relay nodes. However, this approach cannot be applied to cases

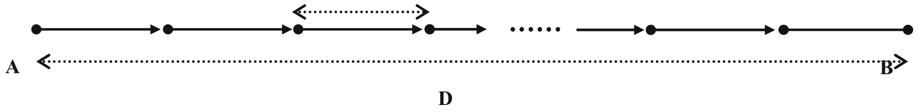


Fig. 10 Introducing K-1 relay nodes between A and B to reduce energy needed for transmitting a bit

in which a receiver node is centralized in a given region since it does not consider that the closer the nodes are to the receiver, the more packets they must relay. An optimum number of hop (K_{opt}) to communicate between each radio transmitter at A and a receiver at B with distance of d (see Fig. 10). The optimum number of corona (C_{opt}) as follows:

$$C_{opt} = K_{opt} = \left\lfloor \frac{R_{area}}{d_{char}} \right\rfloor or \left\lceil \frac{R_{area}}{d_{char}} \right\rceil \tag{5}$$

d_{char} that is called characteristic distance is resulted from the following formula:

$$d_{char} = \sqrt[n]{\frac{2E_{elec}}{\alpha(n-1)}} \tag{6}$$

where n is the path lost exponent and α signifies energy dissipated in the transmit op-amp (including op-amp inefficiencies). For example, in free space with the parameters set as: $E_{elec} = 50\, nJ/bit$, $\varepsilon_{fs} = 10$ pJ/bit/m^2, d $=$ 500 m, the optimum number of hop to communicate between transmitter and receiver is 5.

4.3 Number of Nodes in the Coronas

It is assumed that there are M nodes in the network/cluster and N nodes have been deployed in the Coronas 1. Furthermore, it is assumed that the nodes are uniform in the area. Then, $\mathrm{N} = \mathrm{M}/\mathrm{C}_{\mathrm{opt}}^2$ where $\mathrm{C}_{\mathrm{opt}}$ is the number of coronas in the network/cluster.

$$M\pi d_{char}^2 = N\pi \left(d_{char} C_{opt}\right)^2 \Rightarrow N = \frac{M}{C_{opt}^2} \tag{7}$$

The nodes are deployed uniformly; therefore, the number of nodes in each corona, compared to innermost, is

$$N_i = (2i-1)\, N_1 \tag{8}$$

where N_1 denotes the number of nodes in innermost corona and N_i is the number of nodes in the ith corona. The equation is proved clearly from the area of each corona using the following formula:

$$Area_{coronai} = (2i-1) Area_{corona1} \tag{9}$$

4.4 Optimal Number of Coronas

Olariu and Stojmenovic [67], authors determined the optimal number of coronas for using with random uniform node deployment; though, a similar formula for non-uniform node deployment is not available. Several numerical algorithms have, however, been used to determine the optimal number of coronas in certain situations. For example

They studied multi-hop and single-hop transmissions to identify the optimal number and sizes of coronas (with different widths). In their study, the corresponding transmission radii depended on the network radius. They calculated the optimal network radius around the sink that could balance the energy consumption of all sensors in the network. In their system, all of the sensors had the same multi-hop to single-hop transmission ratios. Azad and Kamruzzaman [79] viewed the network lifetime as an optimization problem, and they proposed a transmission scheme that included an optimal hop size and ring thickness from Olariu's formula [85]. In another study, Wang and Jing [86] posited that the circle network should be divided into multiple coronas, and they introduced an optimal number that could be calculated using an approximate formula.

Mhatre and Rosenberg [62], authors described the proportionality between the number of regular sensors and the square of the number of CHs. By analyzing two modes of communication between the BS and the sensors, they concluded that for path loss = 2, multi-hop communication was useless. Multi-hop communication would be more applicable in situations in which each CH sits at the center of a circle divided into concentric rings of equal width. Based on the assumption that multiple hops have roughly equal lengths, Mhatre and Rosenberg [62] calculated the optimal forwarding distance for each hop. However, they did not prove that it was optimal to have hops with equal length. To obtain these results, they minimized the energy in a critical ring; at any given time, only one critical ring existed. Mhatre et al. [87] also calculated the optimum node intensity and node energy that could guarantee at least T units of lifetime and, at the same time, ensure a high probability of connectivity and coverage. They also attempted to reduce the overall network cost. In their study, lifetime was defined as the number of successful data gathering trips (or cycles) that could occur until the coverage and/or connectivity terminated.

Li et al. [88] studied uniformly distributed sensor networks and discussed the unequal clustering strategy and the associated theoretical issues. They also introduced a method to build an optimal clustering architecture with the goal of minimizing the energy consumed by sensor nodes. The results of many simulation experiments showed that this method was able to prolong the network lifetime.

In non-uniform node deployment, numerical algorithms can be used to determine the optimal number of coronas for a given system. Haibo and Hong [78] attempted to maximize the network lifetime of a system of uniformly-deployed data gathering sensors through balancing the energy consumption of nodes situated in different coronas. They set up the problem as an optimal transmitting data distribution issue. To solve this problem, they combined the concepts of mixed routing, corona-based network division, and data aggregation. They first used a localized zone-based routing scheme to guarantee balanced energy consumption of the nodes within each corona. They then applied an offline centralized algorithm with time complexity to solve the transmitting data distribution problem. The goal of this approach was to find the optimal number of coronas that can maximize the network lifetime, and this number was computed offline using the simulated annealing algorithm. In another study, Xiaobing et al. [2] used the uniform Eq. [67] as the basis for their non-uniform node deployment strategy. Ferng et al. [41] calculated the minimum number of sensor nodes needed in a corona to achieve full coverage of the corona. They also calculated the optimal transmission ranges of this method.

For a system with uniform node deployment, Mhatre and Rosenberg [89] reported an optimal transmission distance and proposed. Based on the proposed formula, the optimal number of coronas (K_{opt}) in a corona-based WSN with uniformly-distributed nodes is:

$$K_{opt} = round\left(\sqrt[n]{\frac{\alpha\,(n-2)}{4E_{elec}}} \times R_{area}\right) \tag{10}$$

where E_{elec} represents the electric energy consumed by transmission of one bit; n signifies the path loss exponent related to a specific field; α denotes the energy consumption in an op-amp for transmission and R_{area} denotes Network radius.

4.5 Connectivity and Coverage in Corona-Based WSNs

A network of sensors is connected if at least one path exists between each pair of nodes within the network. Primarily, connectivity depends on the presence of paths, thus it is affected by changes in the network's topology, which can occur due to factors such as physical attacks, node failure, and mobility. These occurrences may result in loss of links, network partitioning, node isolation, re-routing, and upgrading of the paths.

Ensuring that the conditions necessary for area coverage and node connectivity are met is crucial to providing effective sensing coverage of the network's area and proper multi-hop communication for the nodes. In [90], it was investigated how coverage and connectivity of a network would be affected if unreliable nodes were deployed along the grid points. They evaluated the Poisson process intensity, and p were defined as each node's reliability probability. The equation used to obtain the probability of connectedness of nodes and area coverage is as follows [87]:

$$\Pr\left(\text{network is connected and covered}\right) \geq 1 - \left(\frac{1}{\gamma \mathrm{r}}\right)^{2} \mathrm{e}^{-\pi\theta^{2}\mathrm{pr}^{2}\lambda} \tag{11}$$

To use successfully multi-hop communication for nodes in corona-based WSNs, the minimum conditions that allow node connectivity must be met. Gupta and Kumar [91] studied the conditions needed for node connectivity (with and without coverage) when sensor nodes were randomly deployed. They reported that when n sensor nodes were deployed randomly within an area and each node had a transmission range R, the probability of node connectivity could be calculated as follows:

$$\Pr\left(\text{Connectivity}\right) \geq 1 - 1 - \mathrm{ne}^{-\pi \mathrm{nr}^{2}(\mathrm{n})} \tag{12}$$

In [79], the above-mentioned relationship is normalized for n sensor nodes located over a sector with an area $\frac{1}{2}\pi R^2$ (instead of per unit area). When the desired probability for network connectivity is set to be at least P_{con}, the minimum transmission range required by each sensor, represented as $r_{con} = r(n)$, is given by:

$$r_{con} \geq R\sqrt{\frac{\theta}{2\pi n} log \frac{2\pi n}{\theta(1 - P_{con})}} \tag{13}$$

In sensor networks, a high density of nodes means that they cannot be completely isolated from each other. It has been clearly proved that sensor nodes should be well connected to each other; however, this architecture does not necessarily prevent the network topology from changing or the network from getting smaller because of sensor node failures. Moreover, connectivity may depend on random distribution of nodes.

To assess the efficiency of a WSN, sensor coverage for the particular field must be determined. The quality of monitoring in WSNs depends greatly on the application being used. Applications such as target tracking may require a higher level of coverage to track the target accurately, whereas an application such as habitat or environmental monitoring can tolerate a lower degree of coverage. To achieve a higher degree of coverage, multiple sensors are needed to monitor the same location to collect more reliable data [92]. Ferng et al. [41] gives the minimum number of sensor nodes needed in corona Ci for full coverage as:

$$A = 2\cos^{-1}\left(\frac{(b_1^{opt})^2 + \left(\sum_{j=1}^{i} w_j\right)^2 - s_1^2}{2b_1^{opt}\sum_{j=1}^{i} w_j}\right) \tag{14}$$

$$N_i^{min} = \left\lceil \frac{360^\circ}{A} \right\rceil \tag{15}$$

where b_1^{opt} is the optimal position, k signifies the number of coronas, N_i^{min} denotes the minimum number of nodes in corona i required for coverage, and w_i represents the width of corona i.

5 Conclusion

This paper described the energy hole problem and reviewed techniques designed to mitigate this problem in corona-based WSN. The review focused on energy-balancing methods and analytical research in this field. We presented a general classification of existing energy hole problem schemes. The energy hole problems in the corona-based WSN are classified into six categories: using dynamic clustering node, non-uniform node deployment, sink mobility, relay node, provisioning the node, and the use of multi-level transmission rang.

In addition, we investigated the basic mathematical modeling of network connectivity and coverage, energy consideration and optimum width of coronas in the corona-based WSN so that these issues can be used in solutions to the energy hole problem.

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