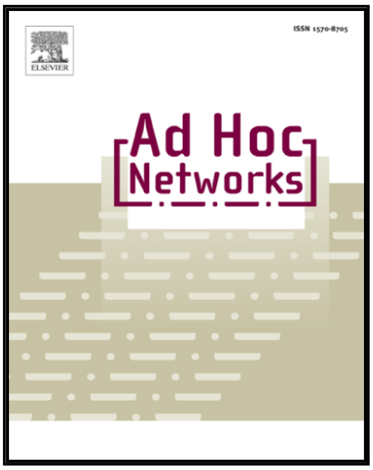
Accepted Manuscript



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PII:	S1570-8705(18)30436-0
DOI:	10.1016/j.adhoc.2018.07.003
Reference:	ADHOC 1703

To appear in: *Ad Hoc Networks*

Received date:	1 August 2017
Revised date:	2 May 2018
Accepted date:	2 July 2018

Please cite this article as: Azzedine Boukerche, Peng Sun, Connectivity and Coverage based Protocols for Wireless Sensor Networks, *Ad Hoc Networks* (2018), doi: 10.1016/j.adhoc.2018.07.003

Connectivity and Coverage based Protocols for Wireless Sensor Networks

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Abstract

A wireless sensor network (WSN) consists of a group of energy-constrained sensor nodes with the ability of both sensing and communication, which can be deployed in a field of interest (FoI) for detecting or monitoring some special events, and then forwarding the aggregated data to the designated data center through sink nodes or gateways. In this case, whether the WSN can keep the FoI under strict surveillance and whether the WSN can gather and forward the desired information are two of the most fundamental problems in wireless sensor networks that need to be solved. Therefore, preserving network connectivity while maximizing coverage by using the limited number of energy constrained nodes is the most critical problem for the deployment of WSNs. In this survey article, we classify and summarize the state-of-the-art algorithms and techniques that address the connectivity-coverage issues in the wireless sensor networks.

Keywords:
Network connectivity, fault-tolerant, area coverage, wireless sensor networks.

1. Introduction

Wireless sensor networks (WSNs) have gained a considerable attention in the recent years [1, 2]. The development of modern sensing and wireless communication technologies have greatly promoted the development of energy-

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efficient micro sensing equipments with both sensing and wireless communication abilities, which is the furtherance of developing WSNs [3].

The objective of the deployment of the WSN is to monitor a given field of interest (FoI) or keep a given target under strict surveillance. However, due to the limited size and battery capacity, both computational and communication capacities of the sensor nodes are limited [4]. Hence, in order to achieve the expected objective, multiple sensor nodes need to cooperate. Typically, a large-scale WSN that consists of thousands of sensor nodes is deployed to cover a given FoI by either random or deterministic method. The connected WSNs can accomplish many complicated tasks. Moreover, by exploiting the communication capacity of the sensor nodes, the WSN can consist a wireless communication network to transmit the gathered data which eliminates the dependency of the complicated wired communication backbone that is hard to be deployed in the remote area. Moreover, by exploiting its ease-deployment property, the WSN is widely adopted in very broad applications, e.g., the surveillance of military activities, boundary control, and industrial and agricultural monitoring, etc [5].

As aforementioned, the existing deployment strategies of WSNs are categorized into two main classes: the deterministic ones and the random ones. For the deterministic method, the deployed position of each sensor node is predefined for a specific FoI. It can achieve the system objective more efficiently. However, if the WSNs are deployed in the remote area and the environment can be very hazardous to the human safety, e.g., the battlefield, volcano, etc, the manual/deterministic deployment strategies of WSNs may not be adopted. In this case, the random deployment strategies of WSN could be an applicable option, e.g., paradropped by the airplane. Then, the deployed WSN needs to automatically work for weeks or months. During the working period, the battery replacement may not be applicable [3]. Hence, the energy preserving problem has to be considered when the WSN-based system is being designed. In order to prolong the lifetime of the network, utilizing the WSN in an energy efficient method is essential to facing the strict energy constraint in sensor nodes [6].

Furthermore, there are another two important factors that affects the deployment of an efficient WSN, i.e., find optimal node deployment/area coverage strategies and efficient connectivity control techniques. Once the nodes are deployed, they need to sense and detect the desired events from the given FoI, and then generate corresponding data for the detected events. Therefore, it is important to keep the required coverage degree of the deployed WSN which can guarantee that any given point in the FoI can be monitored by the desired number of sensor nodes. Besides the coverage problem, maintaining the network connectivity is another important issue that needs to be considered to implement the WSNs. Usually, the connectivity of the WSNs is defined as the ability of each sensor node to find a path to reach the designated gateway/data sink. If there are no available routes from a sensor node to the data sink, the data collected by that node cannot be processed. Hence, keeping network connectivity is a key issue to implement the deployed WSN-based systems. Further, as summarized in [3], the network connectivity and coverage can be regarded as an evaluation metric of Quality-of-Service (QoS) in the WSNs to determine that whether the given FoI is under strict surveillance and whether the detected/gathered information can be forwarded and processed successfully. Therefore, how to maintain network connectivity while maximizing coverage by using the minimum number of resource-constrained nodes is a critical problem.

As previously mentioned, the WSN is utilized to monitor an FoI and forward the detected data to sink. We note that coverage without connectivity is meaningless in the WSNs. So, we consider that the functionality of a WSN system is fully kept if and only if the system keeps required connectivity while the FoI is fully covered. If the system keeps its connectivity while losing coverage in certain areas, we consider the system has the partial functionality, because the connected WSN can still forward the gathered data to the data sink through the existing route, even though some of the sensing areas are not covered by the system. However, if the system cannot preserve its connectivity, even though the FoI is fully covered, the WSN cannot forward gathered data, and then loses its functionality. Consequently, we consider that keeping connectivity of a WSN is fundamental to implement a WSN.

In this survey, we investigate the network connectivity and coverage problems. The rest of the survey is organized as follows: in Section 2, the notion of coverage and connectivity will be firstly introduced. Section 3 discusses various techniques that consider the connectivity problem in WSNs and other related research areas. Further, several fault-tolerant/failure-resilient techniques are described. Then, in Section 4, we summarise multiple techniques that are designed for the joint connectivity and coverage problem under an integrated framework. In Section 5, under different assumptions about the communication range, we introduce the existing research efforts related to the node deployment/area coverage strategics. Finally, in Section 6, we conclude this survey and demonstrate open problems in this area.

2. Preliminaries

The research efforts proposed for addressing the connectivity and coverage issues in WSNs are based upon a lot of theories and assumptions. The basic concepts of connectivity and coverage have an essential role for understanding this issue. In this section, we describe the category of sensor nodes, sensing models and communication models.

2.1. The classification of node

The sensor nodes are the basic units that compose a WSN and are produced in small size with the built-in sensing and wireless communication models. Basically, the sensor nodes can be categorized based on their mobility, i.e., the static node and the mobile node. Besides the aforementioned basic functionalities, the mobile node has limited mobility that is constrained by its battery's limited energy. Due to the unstable nature of the wireless communication and the limited battery capacity, the node/link failure cannot be avoided. A WSN may be separated into multiple disconnected subgroups or lose coverage for certain areas (i.e., coverage holes generated) in furtherance of these node/link failures. In this situation, the mobility of the nodes could be triggered to move to the uncovered area and fix the detected coverage hole in the system [6].

Besides the classification based on the node's mobility, the sensor nodes can be also categorized by their sensing techniques, e.g., the optical sensor nodes [7] and the sensor nodes equipped with directional sensing antenna [8]. Moreover, since the data aggregated by a WSN have to be forwarded to the processing center, some nodes, that are located closer to the data sink, not only monitor their vicinities but also serve as *relay/intermediate nodes* for other far located nodes.

2.2. Sensing model

Based on the observed physical phenomena and experimental results, two common sensing models are widely used to theoretically analyze the performance of a WSN. The first one is *the binary disc model* that is a kind of Boolean model, in which the probability of detecting an event is one within the sensor's sensing range R_s, otherwise it is zero. This model can be mathematically represented as follows:

$$p(s_i, P) = \begin{cases} 1, & d(s_i, P) \leq R_s \\ 0, & d(s_i, P) > R_s \end{cases} \tag{1}$$

where $p(s_i, P)$ is the probability that point P can be sensed by sensor s_i, and $d(s_i, P)$ is the distance between P and sensor s_i.

However, the binary disc model is too simple to capture the complex and realistic characteristics of the real world. In order to overcome this weakness, by considering the measure of the uncertainty in the sensing detection, a more realistic model, *the probabilistic sensing model*, is proposed and can be calculated as follows:

$$p(s_i, P) = \begin{cases} 1, & d(s_i, P) \leq R_s - R_e \\ e^{-\omega\alpha^\beta}, & R_s - R_e < d(s_i, P) \leq R_s + R_e \\ 0, & d(s_i, P) > R_s + R_e \end{cases} \tag{2}$$

where $\alpha = d(s_i, P) - (R_s - R_e)$. ω and β are parameters that affect the probability of detection when a point is located in $[R_s - R_e, R_s + R_e]$. $R_e < R_s$ is the parameter used to reflect the uncertainty of the sensing range [6].

Howbeit, all of them are too ideal to capture all the features of the real world, since they all assume that the sensing area is a disc. We call them as uniform sensing models. Yet, in reality, sensing range is affected by many factors, such as the obstacles and the weather conditions. The uniform sensing models (USM)-based algorithms may not achieve the desired performance because of the potential errors of coverage measurement caused by the environmental factors. Therefore, the irregular sensing range can be regarded as a more realistic sensing model. In [9], by considering the irregular sensing range caused by obstacles, the authors proposed an intersection point method (IPM) to capture the characteristics of an irregular simple polygon sensing area. Further, in [10], the authors proposed an irregular sensing range detection model (RDM)-based on a revised α-shape algorithm.

2.3. Communication model

Similar to the sensing model, multiple communication models are also proposed to mathematically model the complex characteristics of the wireless communication channel. The simplest model is *the protocol model* in which two nodes can communicate with each other iff they locate in each other's communication range R_c.

Further, in order to capture other disruptive physical characteristics of the wireless channel (e.g., the multiple path fading, and the interference, etc.) rather than only the diminishing effect of the transmission distance, the authors in [11] modeled wireless channels incorporating these effects and called the model as *the physical model*. Let Pt_i denote the transmission power of the node s_i in the node set $\mathcal{X}$. Then, by considering the ambient noise power level N_0, the SINR of the received signal emitted by node s_i can be calculated by

$$\frac{\dfrac{Pt_i}{\Big(d(s_i, s_j)\Big)^{\alpha}}}{N_0 + \displaystyle\sum_{k\in\mathcal{X}, k\neq i} \dfrac{Pt_k}{\Big(d(s_k, s_j)\Big)^{\alpha}}} \geq \delta_{min} \tag{3}$$

where δ_{min} is the minimum acceptable SINR that is necessary for node s_j to achieve successful receptions and decoding. The signal power decays with distance r as $\frac{1}{r^{\alpha}}$. α is always assumed to be $\alpha > 2$ [11].

Moreover, based on the graph theory, the *graph-based model* is proposed, in which the nodes are considered as vertices in the graph, and the communication link between any pair of them is considered as an edge that connects two vertices.

Similar to the sensing model, the communication range is also affected by the deployed environment. For instance, in a power-constrained WSN, the wireless communication links dramatically degrade when temperature increases [12]. Hence, the heterogeneity of the communication range (i.e., radio irregular) should be considered to formulate a more realistic communication model. In [13, 14], the authors proposed a new type of carrier sensing model to capture the features of the radio irregular.

$$Pr_i = Pt_i - L(i) + f(i) \tag{4}$$

where Pr_i and Pt_i are the receiving power and the transmission power of the signal, respectively. $L(i)$ is the function denotes the path loss. $f(i)$ is the given channel fading function.

3. The connectivity in WSNs and related issues

As aforementioned, the connectivity is critical for WSNs. For the guaranteed and reliable data transmission, the consideration of the fully-connected network is necessary. Meanwhile, the intensive node deployment scenario is always adopted, and the node scheduling scheme is implemented to periodically switch the ON/OFF state of nodes in turn to reserve the limited energy of each node. Hence, in [15, 16], it's clear that the connectivity only requires that any active node (i.e., the node in ON state) has to have at least one available path to communicate with the data sink, while coverage requires all locations in the coverage region be within the sensing range of at least one active node. Once the configuration of sensor nodes is accomplished, nodes organize a connected network to send detected data back to the gateway/data sink. Therefore, one of the research directions is, how to achieve/maintain the required system-wide connectivity, and a lot of related research work has been proposed in recent years. Basically, these conditions are derived based on the intensive deployment of nodes. Furthermore, in order to analyze the connectivity issue of WSNs, the notion "k-connectivity" needs to be considered, i.e., k-connectivity means that the network can keep its connectivity by removing at most k-1 nodes from itself. Obviously, a network with k-connectivity ($k \geq 2$) has much better fault tolerance/resilience than a network with only 1-connectivity. Since the nodes in a WSN may fail randomly which are caused by battery depletion or wireless interference, preserving the k-connectivity is critical for WSN and can improve the survivability of a WSN. Li *et al.* [17] provided a good survey on connectivity and coverage in WSNs.

We can categorize the existing related work on the connectivity in WSNs into: 1) *Deriving critical conditions for the connectivity*; 2) *Theoretical analysis of network component failures problem*; 3) *Fault tolerance and recovery related work*; 4) *Failure-resilient/fault-tolerant WSN design problem.* In the following parts of this section, we will present all these categories in detail.

3.1. Critical conditions for the connectivity

In this category, researchers tried to discover the critical conditions for achieving desired connectivity in a certain area, i.e., node density λ, communication range R_c, etc. We summarised some of related work in Table 1. In this table, n denotes the number of deployed nodes and $\pi R_c^2 = (\log n + c(n))/n$ [11]. *Unit disk/square area* denotes the size and the shape of the deployment area. *Un-reliable/reliable* represents whether the deployed nodes do have/do not have the node failure probability. All the listed approaches are derived based on the assumptions of 1) the fix communication range and 2) the random node deployment strategy.

3.2. Theoretical Analysis of Network Component Failure Problem

Due to the unstable nature of the wireless communications, the network component (e.g., node/link) failures in WSNs cannot be avoided. Their

		Connectivity degree	Comm. model	Assumptions	Derived conditions
critical conditions for R_c	[11]	asymptotically connected	Phys.	Static, reliable ; uniform distribution; unit disk area;	iff $c(n) \to \infty$, system is asymptotically con.; Critical condition: $R_c = \sqrt{\frac{\log n}{\pi n}}$
	[18]	1-connected & 1-coverage	Prot.	Static, un-reliable; uniform distribution; unit square area	Critical condition to achieve both cov. and con. is : $R_c^2 p(n) \sim \frac{\log n}{n}$, where $p(n)$ is the node activity probability
	[19]	1-connected & 1-coverage	Prot.	Static, reliable; poisson distribution; $R_c = R_s$; node density is λ; square area (size=A)	As $A \to \infty$, conditions for cov.: full-cov.: $R_c = \sqrt{\frac{(1-\epsilon)\ln A}{\pi\lambda}}$ un-cov.: $R_c = \sqrt{\frac{(1+\epsilon)\ln A}{\pi\lambda}}$ As $A \to \infty$, condition for con.: un-con.: $R_c = \sqrt{\frac{(1-\epsilon)\ln A}{\pi\lambda}}$
critical node density λ_c	[20]	asymptotically connected	Phys.	static, reliable; unit disk area	Min. No. of neighbors: $\Theta(\log n)$ asymptotically con.: $5.1774 \log n$ asymptotically dis-con.: $0.74 \log n$
	[21]	1-connected	Phys.	static, un-/reliable; unifrom/poisson dist.; node failure prob. p	$\lambda_c = \frac{2}{\sqrt{3}(\frac{P_t}{N_0 d_{min}})^{2/\alpha}}$ un-con.: $q_f < 0.1603$ $q_f = \begin{cases} e^{-(\frac{3\sqrt{3}}{2}\lambda R_c^2)(1-p)} & poisson \\ p^{\frac{3\sqrt{3}}{2}\lambda R_c^2} & uniform \end{cases}$
	[22]	1-connected & 1-coverage	Prot.	static, reliable; linear network or an area with size A;	Linear network: as length $L \to \infty$ con.: $n = (1+\epsilon)\frac{L}{R_c}\log\frac{L}{R_c}$ un-con.: $n = (1-\epsilon)\frac{L}{R_c}\log\frac{L}{R_c}$ For an area with size A: $n =$ $(1+\epsilon)\frac{2V+\sqrt{A}}{V}\frac{\sqrt{A}}{R_c}\ln\frac{\sqrt{A}}{R_c} \sim \frac{A}{V}\ln A$

Table 1: Summary of the related work on deriving the critical conditions for achieving required connectivity and coverage degree.

failures or misbehaviors can put additional burden on neighboring nodes and may even cause them to fail if the resulting energy consumption exceeds a given threshold. If this happens recursively, the cascading failure may occur [23]. In this case, many research efforts are proposed to cope with this issue in order to maintain the functionality of the WSN. We summarize these research efforts in three main fields:

1. *Research about the survivability of different network topologies*: For instance, the authors in [24] tested the resilience of the networks in the topologies following Exponential (*Erdös − Rényi* model) and Power-Law (scale-free model) distributions, which represent homogeneous and inhomogeneous networks, respectively. The authors concluded that both of the tested networks were separated into small unconnected clusters due to an attack on only a few nodes in the system. The scale free networks were more robust than the exponential networks in the random failure case. Based on these conclusions, it is clear that network topologies also need to be considered as an essential factor when we design an applicable WSN.
2. *Mathematical modeling of cascading failures in different types of practical networks, such as power grids, transport networks and WSNs*: In [25], the authors designed a mathematical model for the cascading failure in the complex network which was based on local load distributions; this model can be easily adopted in WSNs. As an improvement, in [26], the authors designed a "probabilistic" region failure model to evaluate the reliability of a given wireless network.
3. *Research about cascading failures in interdependent networks*: In [23], the authors showed that cascading failures often happened in a mixed power grid and wireless networks, i.e., the power grid supplies power to the WSN system and the WSN transmits the essential monitored data and the control messages for the power grid. Accordingly, the wireless node failures can be triggered by the loss of power stations and in turn the control messages cannot be transmitted. Consequently, more power stations connected to the grid may lose functionality. Based on the presented simulation results, the authors concluded that even a small percentage of nodes in the system losing their function could cause a whole network failure. Since these results are obtained from some general types of networks, WSN-based networks are also expected to have the same behavior. In [27], the authors analysed the human ini-

tiated cascading failures in the inter-dependent societal infrastructures (i.e. transport network and communication network), which again led to similar results.

3.3. Failure Recovery Approaches

There are three main classes of approaches focusing on the network component failure recovery, namely protection schemes, restoration schemes, and hybrid ones. Protection schemes reserve backup resources in advance and can be classified into two categories: proactive protection and reactive protection. On the contrary, restoration schemes are triggered only after a failure is detected and then they start to discover the available resources. The hybrid schemes resort to restoration when the protection fails. Here, we discuss both the protection scheme and the restoration scheme in detail.

3.3.1. The protection scheme

In the protection scheme, between any given source and destination pair, two (or more) link-disjoint paths are selected. The source node transmits the data through all of the selected paths. If there is a link on one of these paths facing the link failure, the destination can still receive the data from the other redundant paths. Currently, most of proposed protection schemes are designed to be 1+1 (i.e., one primary path plus one redundant path) protection schemes. Further, the protection schemes can be classified into two categories: *the proactive protection* and *the reactive protection*. The main difference between these two classifications is that, in the proactive protection, the data are transmitted to the destination through all the selected paths at the same time. Hence, this activity needs at least as twice as many resources, which is hard to realize. In reactive protection, there are a primary path and a backup path. The backup path is not used until a failure occurs.

The proactive protection: For example, in [28], the authors proposed a multi-path transport protocol based on a carefully designed network coding scheme that encoded a set of enhancements to TCP data. However, many of the existing coding schemes are designed to face the maximum number of failures. In this case, if the failure process had high standard error (i.e., the difference between the average number of failures and the maximum number is large), the system transmission capacity would be wasted and the throughput would be degraded. In order to overcome this limitation, the authors in [29] proposed a coding scheme to face the average number of failures.

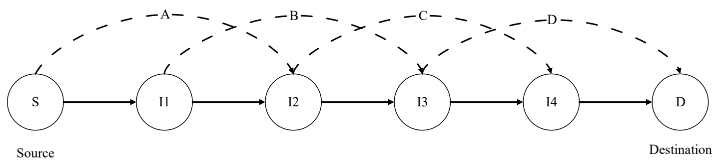


Figure 1: Illustration of the Rapid and Reliable Routing Mesh Protocol

The reactive protection: Many routing protocols claim that they can recover the node (link) failures (or disconnections) without introducing high overhead. Existing routing approaches can be roughly classified into two categories: topology-based and position-based.

Topology-based protocols do not assume that each node can determine its position. Without requiring the nodes' location information, the topology-based protocols adopt the global flooding technique to distribute either topology information (e.g., DSDV [30]) or queries (e.g., AODV [31], DSR [32], etc). In order to reduce the delay and enhance the reliability, Javadi *et al.* [33] proposed a multi-path routing protocol that utilized the mesh connectivity of a wireless network by which one primary path and multiple mini-path are selected between a source and a destination. As shown in Fig. 1, the primary path (solid line) is used to connect the source and destination. Whilst the secondary paths (dash line) are selected by connecting pairs of intermediate nodes on the primary path. Multiple copies of data are transmitted through mini-paths and primary path simultaneously. The redundant copies are used to cope with the potential link failure and failures of the intermediate nodes that are located on the primary path. The excessive congestion on the network that may be caused by the redundant data transmission can also be avoided by routing them along these mini-paths. Since the Topology-based protocols have to adopt the global flooding to distribute either topology information or queries, it suffers from limited scalability.

By assuming that each node can determine its location, position-based protocols achieve better efficiency and scalability than topology-based ones [34]. Based on the different number of location servers that are adopted to store each node's location, different position-based protocols are addressed. The Grid Location Service (GLS) is presented in [35], where a small number of nodes are required to store each node's location information. In GLS, each node only needs to update its location information at a limited number of nodes without flooding the whole network. In turn, the location inquiries are limited to a reasonable overhead. Consequently, the authors show that the GLS achieves a good balance between the reliability and the working load. The authors also show that in a small network, GLS tolerates intermittent node disconnections well. However, as shown in [36], in large networks, GLS's fault-tolerance greatly degrades. Li *et al.* [37] propose a reactive protection scheme to achieve the desired robustness of the wireless network. Both primary paths and disjoint backup paths are discovered by the proposed scheme discovers. Whilst, the partial bandwidth for backup paths are reserved. In order to take advantage of network coding, the path overlapping allocation of backup paths is considered for different receivers. Moreover, the robust multi-path rate-control and bandwidth reservation problem for scalable video multi-cast streaming is taken into account when possible link failures of the primary paths exist. In [38], authors proposed a fault-tolerant technology to support emergency information transmission in WSNs by selecting alternative path after detecting a fault.

The aforementioned protection schemes exploited the multi-path property of the WSNs and increased the robustness of the WSNs to the unexpected transmission failures based on the link/node failure. But, this kind of schemes is achieved by using more transmission resources (wireless channels) and more frequent channel switching. Due to the limited number of the wireless channels and ineluctable channel switching delay, this kind of schemes is difficult to be adopted in a practical WSN.

3.3.2. The restoration approach

Restoration approaches are more capacity-efficient (resource-efficient) than protection schemes. Because the restoration scheme does not need to reserve the transmission resources for the working data flows. The restoration approach is triggered by the detected failure, and it switches data flows from the failed path to a backup path dynamically. Many data flows can share the links which will be used in a backup route.

The authors in [39] present a restoration scheme to keep the network connectivity, in which local and global restorations are used. The objective of this scheme is to minimize the ripple effect of the system component failure, which means the scheme limits the recovery area locally for the failure. Further, Jiang and Xue in [40] proposed a joint routing, channel assignment and scheduling algorithm to face the jamming happens in the wireless networks. The authors used a greedy scheduling algorithm to schedule both jamming traffic and regular traffic. Also, they adopted both global and local restoration to achieve desired tradeoff between the restoration latency and the network throughput after restoration. In order to quantitatively evaluate the impact of jamming attacks during and after restoration, the authors also defined two performance degradation indices, the transient disruption index and the throughput degradation index. This work can be easily extended to WSN. Another link recovery scheme can be found in [41]. This work describes an autonomous network reconfiguration system (ARS) that enables a multi-radio wireless networks to autonomously recover from local link failures while preserving their performance. Then, based on the generated configuration changes, the system cooperatively reconfigured network settings among local nodes. Similar work can be found in [42, 43].

However, since the restoration introduces delay in the recovery process, the capacity-efficiency and the recovery speed must be balanced. Existing restoration algorithms can be categorized as dynamic or pre-planned. In dynamic ones, the backup path is recomputed by using the message flooding. Even though they can have quick responses to face frequent failures, this kind of algorithms introduces high cost of resource usage and a larger delay. On the other hand, the pre-planned algorithms can recover from the failure more quickly but are not so robust to various failures.

3.4. Failure-resilient/Fault-tolerant WSNs Design Problem

In the recent years, several studies have been dedicated to the design of failure-resilient networks. For example, in [44], the authors designed a model to measure the cascading failure based on the given component failure probability in a network, such as WSNs. In this proposed model, the traffic load on the faulty node is redistributed to its neighbours. This activity increases the traffic load of its neighbors and the new total traffic load may exceed the given threshold value and cause a new node failure. When this process keeps going, the cascading failure happens. As an improvement, in [26], the authors designed a "probabilistic" region failure model to capture the key features of a region failure and applied it for the reliable assessment of wireless networks.

Further, based on the failure probability, multiple algorithms are designed to improve the robustness of the network. For example, there is a number of existing work that aims at improving the robustness and survivability of WSN systems by designing a new routing and channel assignment algorithms. The authors in [45] designed a graph-based routing approach to construct reliable routing graphs which satisfied the given reliability requirements. In this scheme, the intermediate devices on the path can be pre-configured with multiple neighbors to help transmitting packets without using a fixed path starting from a given source. Another robust routing algorithm is designed by Xiang in [46]. In this work, a deadlock-free routing scheme for meshes is proposed based on a new virtual network partitioning scheme, called channel overlapping. This algorithm is designed for an n-dimensional virtual network, but WSNs can adopt it by reducing the dimensions to two or three. Similar design can be found in [47]. In [48], the authors proposed a scheme to achieve the desired robustness and load balance of wireless networks by channel assignment and router selection. But this scheme is again purely centralized and thus lacks scalability and agility. In [49], authors designed a new sensing technique to improve the accuracy of the wireless channel condition measurement. Based on this technique, the wireless sensor networks could make a more accurate decision for the routing and channel assignment. So, the reliability of the system could be improved. Other related work can be found in [50].

Also, some approaches have been proposed to improve the system reliability by carefully designing the connectivity or topology of wireless networks. Paper [51] addresses the problem of fault tolerant deployment of wireless ad-hoc networks. Based on the pre-assumed transmission range, the authors propose a scheme to calculate the probability that a given network is k-connected. Based on the intensive deployment, in [52] the redundant sensor nodes are used to cope with the random working nodes failure. Following the similar idea of deploying redundant nodes, a distributed algorithm is proposed in [53]. By deploying a calculated necessary number of extra nodes in the given network, the objective of fault-tolerant topology control can be achieved. However, due to the limited space and cost constraint, adding redundant nodes to a deployed WSN may not always be an acceptable solution. Another fault-tolerant topology control algorithm is presented by Li and Hou in [54], in which a spanning subgraph is computed by each node. If a pair of vertices is not k-connected, an extra edge will be added between these two vertices. The authors further prove that the resulting global network is k-connected. In [55], by considering the mobility of nodes, the author shows the mobility resilient topology control protocols. The author classifies the topology control protocols into two types. 1) In this case, the topology is built and maintained by each node based on its own knowledge about its neighbors. According to its own requirements, each node adjusts its transmission power level locally. The algorithm presented in [54] belongs to this category. 2) Unlike nodes in the first type of protocols that need to maintain a topology, in the second type, based on some given criteria, the nodes only maintain a number of neighbors located in their vicinities, e.g., [56]. The first type of protocols is more complicated than the second type, since the reconfiguration procedure is triggered every time when any link/node misses from the original topology graph, otherwise the topology may be disconnected. Due to the movements of the nodes, the requirements of maintaining the topology (i.e., Minimum Spanning Tree) trigger the algorithms much more frequently than that in the static networks. In the contrast, the second type of algorithms (i.e, [56]) only needs to maintain a required number of neighbors in a specific area, which is much easier than the first type algorithms. Consequently, even the algorithm in [54] is very efficient for static network, it does not suit the mobile scenario. For static wireless network, a distributed algorithm is addressed in [57] to preserve the k-connectivity of the network while minimizing the possible power consumption. By collecting location and maximum power information from all nodes located in a node's surrounding area, the node adjusts its transmission power levels for these nodes to ensure that it can reach all these nodes through k optimal vertex-disjoint paths. Some more work can be found in [58, 50].

4. Integrated connectivity and coverage

In the previous section, we mainly focus on the connectivity and related survivability issues of WSNs. It is the foundation that we deploy WSNs to achieve its main objective that is to monitor the FoI or detect the desired data. While, the coverage determines whether the FoI is under strict surveillance or not. So, in this section, we will summarize the related work on integrated connectivity and coverage problem in WSN, i.e., 1) effects of the ratio R_c/R_s, and 2) research efforts on preserving connectivity and coverage.

4.1. Effects of the ratio R_c/R_s and related research efforts

Finding the relationship between the sensing range R_s and communication range R_c is the foundation for designing the node deployment strategy. As shown in Fig. 2, if $R_c < R_s$, even though the system is fully covered by the minimum number of sensor nodes, the system loses connectivity.

In [16], the authors for the first time proved the sufficient condition for 1-coverage implying 1-connectivity was $R_c \geq 2R_s$. Based on this result, when we design a WSN system, we can focus on the node deployment strategy

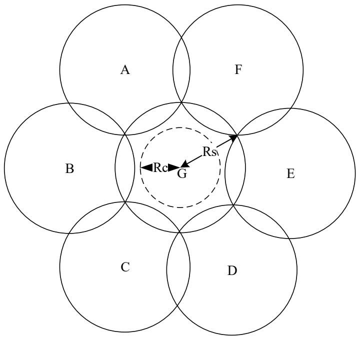


Figure 2: Illustration of the relation of R_c and R_s

and eliminate the connectivity problem by assuming $R_c \geq 2R_s$. Whilst, the authors in [59] individually derive the same result. Further in [60], the authors provide three conditions to achieve k-coverage and k-connectivity as follows: 1) Given a connected network graph while assuming that $R_c \geq 2R_s$, if the coverage is completely preserved after the node scheduling, the connectivity of the resultant network is still preserved. 2) Given a connected network graph and $R_c < 2R_s$, if the coverage is completely preserved after the node scheduling, there still exists a probability that the resultant network loses its connectivity. 3) Given a k-connected network graph and $R_c \geq 2R_s$, if the k-coverage is completely preserved after the node scheduling, the k-connectivity of the resultant network is definitely preserved. This research study is important for applications that require a higher degree of coverage and connectivity. Many existing surveys discussed the existing approaches proposed for coping with the integrated coverage and connectivity problem in WSNs based on this research work, such as [17, 61].

However, the $R_c \geq 2R_s$ condition cannot always be guaranteed in the real world. Therefore, many other research approaches had been proposed to address the node deployment pattern design based on the different ratios of $\frac{R_c}{R_s}$. We summarized some of the related work in Table 2. Generally, the related work can be categorized by the number of dimensions (i.e., 2D or 3D), and the types of deployment patterns (i.e., regular geometrical tessellation or lattice). In the following, we will present the summarised related work in detail.

Based on the assumption of different value of R_c/R_s, many research efforts focus on designing the node deployment strategies to minimize the number of deployed nodes while achieving the desired performance. As shown in

No. of Dims.		Connectivity & coverage degree	Types of deployment	Ratio of $\frac{R_c}{R_s}$	Deployment pattern
2D	[62]	1-connected & 1-coverage	Regular tessellation	$\frac{R_c}{R_s} < 1$, $\frac{R_c}{R_s} = 1$ $1 < \frac{R_c}{R_s} \leq \sqrt{3}$ $\frac{R_c}{R_s} > \sqrt{3}$	Shown in Fig. 3
	[63]	1-connected & 1-coverage	Regular tessellation	$\frac{R_s}{R_c} \leq 0.658$	Triangular pattern
				$0.658 < \frac{R_s}{R_c} \leq 0.8772$	Square pattern
				$\frac{R_s}{R_c} > 0.8772$	Hexagonal pattern
	[64]	m-connected & k-coverage $m \geq 1$ & $k \geq 1$	Regular tessellation	$\frac{R_c}{R_s} < 1$ $\frac{R_c}{R_s} = 1$ $\frac{R_c}{R_s} > 1$	Adopts the same patterns in [63]
	[65] [66]	k-connected & 1-coverage ($k \leq 6$)	Regular tessellation	$k = 3$: $1.0459 \leq \frac{R_c}{R_s} < \sqrt{2}$	Flattened hexgon ($edge = R_c$)
				$\frac{R_c}{R_s} = \sqrt{2}$	Rectangle with side length $2R_c$ and R_c
				$\sqrt{2} < \frac{R_c}{R_s} < \sqrt{3}$	Parallelogram with side length $2R_c$ and R_c. Bigger inner angle (BIA): $2\arcsin\frac{R_c}{2R_s}$
				$\frac{R_c}{R_s} \geq \sqrt{3}$	Parallelogram with side length $2\sqrt{3}R_c$ and $\sqrt{3}R_c$. BIA: $2\pi/3$
				$k = 4 : 1.3903 \leq \frac{R_c}{R_s} \leq \sqrt{2}$	Rectangle with side length $2R_c$ and R_c
				$\sqrt{2} < \frac{R_c}{R_s} < \sqrt{3}$	Parallelogram with side length $2R_c$ and R_c. BIA: $2\arcsin\frac{R_c}{2R_s}$
				$\frac{R_c}{R_s} \geq \sqrt{3}$	Parallelogram with side length $2\sqrt{3}R_c$ and $\sqrt{3}R_c$. BIA: $2\pi/3$
				$k = 5$: $\frac{R_c}{R_s} \leq \sqrt{2}$	Rhombus
				$\sqrt{2} < \frac{R_c}{R_s} < \sqrt{3}$	Rhombus with BIA: $2\arcsin\frac{R_c}{2R_s} \in [\frac{\pi}{2}, \frac{2\pi}{3}]$
				$\frac{R_c}{R_s} \geq \sqrt{3}$	Rhombus with BIA: $2\pi/3$
3D	[67]	1-connected & 1-coverage	Regular tessellation, based on Kelvin's conjecture and Kepler's conjecture	$\frac{R_c}{R_s} \geq 1.7889$	Truncated octahedral cell
				$1.4142 < \frac{R_c}{R_s} < 1.7889$	Hexagonal prism or rhombic dodecahedron
	[68]	k-connected	Lattice deployment pattern	$k = 1, 2$: Eq. (6)	Shown in Fig. 5
				$k = 3, 4$: Eq. (7)	Shown in Fig. 6

Table 2: Summary of the related work proposed on the node deployment pattern design based on the ratio of $\frac{R_c}{R_s}$

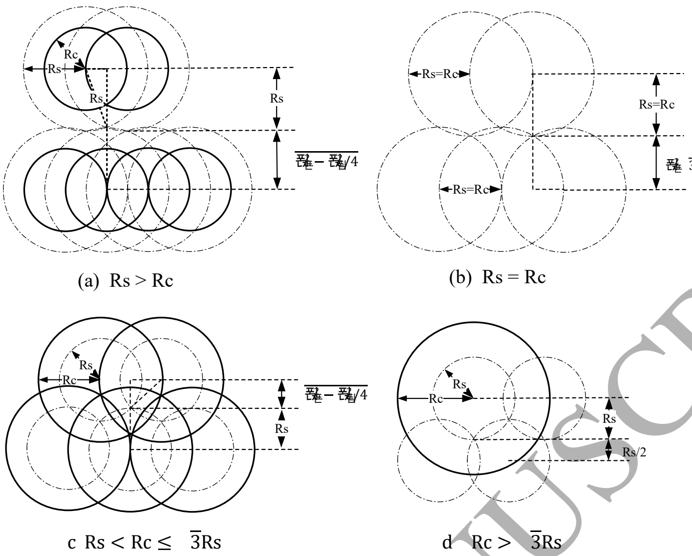


Figure 3: Illustration the different node deployment methods

Fig. 3, authors in [62] designed different sensor deployment methods in 2D area based on the assumption of $R_c \leq \sqrt{3}R_s$ and $R_c > \sqrt{3}R_s$. Moreover, in the lattice WSNs, following the given deployment pattern, the sensor nodes are deployed to the desired locations in a deterministic manner. In order to achieve both full sensing coverage and full connectivity in a WSN, in [63], the authors conclude that: the triangular pattern, square pattern and hexagonal pattern could be the optimal with condition $R_s/R_c \leq 0.6580$, $0.6580 < R_s/R_c \leq 0.8772$ and $R_s/R_c > 0.8772$, respectively.

$$A = \begin{cases} min(2R_s^2, R_c^2), & square \\ min(\frac{3\sqrt{3}}{2}R_s^2, \frac{\sqrt{3}}{2}R_c^2), & triangular \\ min(\frac{3\sqrt{3}}{4}R_s^2, \frac{3\sqrt{3}}{4}R_c^2), & hexagonal \end{cases} \quad (5)$$

where A is the size of each pattern. The Fig. 4 depicts the example of these three patterns. Further, in [64], the authors adopted these three patterns to achieve k-coverage in m-connected WSNs.

In 3D space, based on the Kelvin's conjecture, the Kepler's conjecture and the Voronoi tessellation, in [67], Alam and Haas prove that the truncated octahedral cell is the best deployment pattern that can achieve the best coverage and connectivity among multiple patterns (i.e., cube, hexagonal

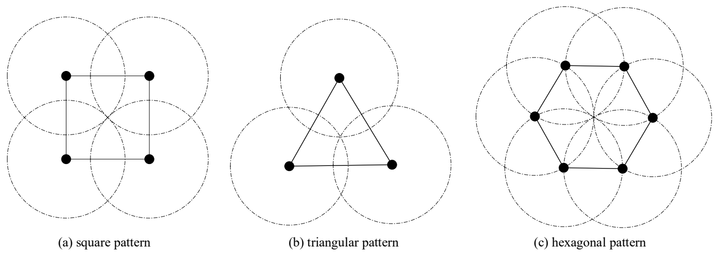


Figure 4: Illustration of the square, the triangular, and the hexagonal pattern

prism, and rhombic dodecahedron), if $R_c/R_s \geq 1.7889$. While, if $1.4142 < R_c/R_s < 1.7889$, the hexagonal prism and the rhombic dodecahedron are the best patterns.

Further, Zhang *et al.* [68] designed a set of node deployment patterns to achieve k-connectivity ($1 \leq k \leq 4$) and full-coverage, and proved their optimality under different ratios of R_c/R_s, among regular lattice deployment patterns. The results can be summarized as follows:

1) In 3D space, as shown in Fig. 5, the optimal pattern for achieving 1- or 2-connectivity and full coverage is given by

$$Opt_{1,2} = \begin{cases} \Lambda_{2-1} & if\ \frac{R_c}{R_s} < \frac{4}{3} \\ \Lambda_{2-2} & if\ \frac{4}{3} \leq \frac{R_c}{R_s} < 12/\sqrt{9+32\sqrt{3}} \\ \Lambda_{2-3} & if\ 12/\sqrt{9+32\sqrt{3}} \leq \frac{R_c}{R_s} < 2\sqrt{3}/\sqrt{5} \\ \Lambda_{2-4} & if\ \frac{R_c}{R_s} \geq 2\sqrt{3}/\sqrt{5} \end{cases} \tag{6}$$

2) As shown in Fig. 6, the optimal pattern among regular lattice patterns for achieving 3- or 4-connectivity and full coverage in 3D space is given by

$$Opt_{3,4} = \begin{cases} \Lambda_{4-1} & if\ \frac{R_c}{R_s} < \frac{4}{3} \\ \Lambda_{4-2} & if\ \frac{4}{3} \leq \frac{R_c}{R_s} < 2\sqrt[3]{2}/\sqrt{3} \\ \Lambda_{4-3} & if\ 2\sqrt[3]{2}/\sqrt{3} \leq \frac{R_c}{R_s} < 2\sqrt{3}/\sqrt{5} \\ \Lambda_{4-4} & if\ \frac{R_c}{R_s} \geq 2\sqrt{3}/\sqrt{5} \end{cases} \tag{7}$$

4.2. Research efforts on preserving connectivity and coverage

As aforementioned, one of the primary objectives of WSNs is to provide full coverage of a given FoI as long as possible. Many tasks (i.e., targets tracking or boundary surveillance) require full coverage of FoI at any time.

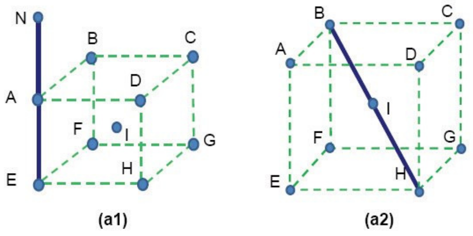


Figure 5: Lattice patterns that achieves 1 or 2-connectivity and full coverage [68].

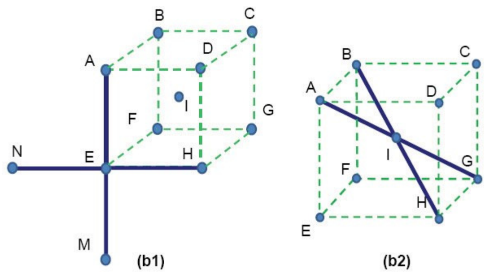


Figure 6: Lattice patterns that achieves 3 or 4-connectivity and full coverage [68].

In this case, how to guarantee/preserve the connectivity of a WSN while achieving full coverage is critically important. Many approaches are proposed to address this integrated issue.

In order to determine the degree of the coverage and connectivity, some researchers tried to derive discriminants for locally determining coverage-connectivity. For example, in [69], by assuming $R_c \geq 2R_s$, Huang *et al.* derived a distributed method for the self-testing of coverage-connectivity: In the 2D plane, if there is no nodes located in the same location, then the whole area is k-covered iff each sensor in the network is *k-perimeter-covered* ([70]). Further, depending on this criterion, the k-coverage and k-connectivity problem is determined by: the deployed sensor network is k-coverage and k-connected if any sensor in the system is k-direct-neighbor (i.e., the sensor can communicate with its neighbors directly) perimeter-covered. Then, a sensor-sleeping scheduling protocol, that combines with a transmission power control protocol to reduce energy consumption, is proposed. In [71], the authors developed a maximum connected load-balancing cover tree (MCLCT) algorithm to achieve full coverage as well as base station-connectivity of each sensing node by dynamically forming load-balanced routing cover trees. A recent work, that shares the similar idea, can be found in [72].

Within an intensive network, Liu *et al.* [73] proposed a distributed node scheduling scheme without using location information. Accordingly, based on the theoretical analysis of the detection probability, each node in the system randomly chose a subset to join and each subset could keep required network coverage intensity t of the sensing area. Then, based on the minimum-hop-count routing scheme and broadcasted control information, the authors adopted random scheduling for sensing coverage and then turned on extra sensor nodes to keep network connectivity if necessary.

Moreover, many studies have exploited the mobility of sensors to improve the quality of coverage and connectivity. Authors in [74] presented a relative neighborhood graph (RNG)-based connectivity preservation scheme. By assuming that the initial system is connected, the mobile sensor nodes move in the calculated direction and distance (limited by the communication range of the sensor) to approach the required system coverage. During the movement, the connectivity between each pair of connected nodes is preserved. Simultaneously, longer communication links are replaced by the multiple shorter links (by adding intermediate relaying nodes) to balance the transmission energy consumption of the system. As an improvement, the authors in [75] adopted the similar idea to deploy the mobile sensor while avoiding the obstacles in the FoI.

In [76], Le *et al.* designed an environment-learning-based phenomenon monitoring system in which the sensor nodes could move to the optimal positions which was selected based on the information iteratively learned about the environment. Because nodes' movements consume a large portion of the constrained energy in sensors which will further shorten the lifetime of the WSN. Consequently, the question, "*how to minimize the movements of mobile nodes while achieving desired coverage and connectivity in WSNs*", needs to be solved. In [77], authors for the first time addressed the challenges of this problem. The authors defined this problem as a mobile sensor deployment (MSD) problem and coped with it by solving two sub-problems, i.e., the Target COVerage (TCOV) problem and the Network CONnectivity (NCON) problem.

Further, in [78], the authors analyzed the coverage and the network connectivity in 3D space. Based on the Reuleaux tetrahedron, the authors also defined the network connectivity $\kappa(G)$ of a given Graph G and showed that $12.024\alpha^3 k \leq \kappa(G) \leq \frac{R_c V^{2/3} k}{0.422 r_0^3}$, where $\alpha = R_c/R_s$ and $k \geq 4$. However, the authors blurred the geodesic distance and the Euclidean distance. Especially, R_s and R_c were measured in Euclidean distance. Also, the calculation for the boundary condition was done under the ideal assumption for the node failure, and the authors did not consider the randomness of the node failure.

5. The coverage in WSNs

As aforementioned, the WSN is utilized to monitor an FoI. Achieving a desired coverage for the FoI is the sufficient condition to achieve this objective. According to [79, 80], the coverage is defined as whether any point in the FoI is covered by a certain number of sensor nodes. Moreover, coverage problem has attracted a great deal of research attention and many approaches have been proposed, e.g., the node deployment strategies for coping with coverage, and the node scheduling schemes for extending the lifetime of WSN while preserving coverage, etc. In the following parts of this section, we will firstly categorize the coverage problems and then survey the research efforts proposed to cope with them.

5.1. Classification of Coverage

Firstly, we demonstrate the classification of the coverage deployment strategies. According to the existing research efforts, there are three main criteria that are used to classify the coverage problem, i.e., the coverage objective, the knowledge of location information, and the mobility of nodes. The detailed classification will be listed as follows.

5.1.1. According to the coverage objectives

In order to efficiently deploy a WSN, we need to know the objectives, which need to be detected/monitored, before the deployment of a WSN. Accordingly, based on the different objectives, the coverage problems can be categorized into three types as follows:

- *Full/blanket coverage*: The full/blanket coverage is defined as that the whole area of a FoI needs to be under strict surveillance which means any point in FoI should be sensed by n sensor nodes ($n \geq 1$). Subject to the cost constraint, the minimized number of sensor nodes should be deployed.

- *Targets coverage*: Unlike the full coverage that requires the whole FoI under monitoring, targets coverage only requires to monitor some specific targets or points in a given area. In order to ensure the efficient coverage, targets coverage always adopts a deterministic manner to deploy sensor nodes.

- *Path/barrier coverage*: We can consider the path coverage as a specific case of targets coverage with which all the target points are located on a path. The objective of path coverage is to detect the potential intruders. For instance, the boundary surveillance is a task that requires path coverage.

5.1.2. According to the deployment type

The knowledge of location information is another important criterion to classify the coverage problems.

- *Deterministic Deployment*: In this case, the sensor nodes are deployed in a deterministic manner. The location for each sensor node is predetermined by the given node deployment strategy. Coverage in art gallery problem [81] can be considered as the deterministic coverage, since the positions of all the guards are predetermined. Normally, this kind of problem is solved by the computational geometry.

- *Random Deployment*: since the WSNs are always deployed in the remote area and the environment can be very hazardous to the human safety, e.g., the battlefield, volcanos, etc. The manual/deterministic deployment strategies of WSNs may not be adopted [3]. Consequently, the random coverage is introduced. In this type of coverage, the sensor nodes are randomly deployed in a FoI (i.e., paradropped by airplane) without any predefined information about nodes' locations and network topology. In the 2D plane, the probability theory and geometric method are commonly adopted to analyse and solve the random deployment [79].

5.1.3. According to the mobility of nodes in WSNs

As aforementioned, there are two types of nodes in WSNs, i.e., static nodes and mobile nodes. Based on the mobility of the nodes in WSNs, the existing approaches can be classified into two main categories: static coverage and dynamic coverage. In order to ensure the required coverage, the dense deployment is usually adopted if the sensor nodes are stationary [73]. While, by considering the mobility of nodes, the mobile nodes are used to recover the coverage hole in FoI or move to optimal location by which the network coverage and efficiency can be improved.

There are many surveys that have been proposed for the coverage problem. In the rest of this section, we survey the existing research efforts on the coverage/node deployment problem based on the number of dimensions of the WSN deployed environment, i.e., coverage in 2D and 3D, respectively. In each part, we classify the published approaches based on the techniques adopted by themselves.

5.2. Coverage in 2D

In this section, we do surveys for the research approaches proposed for 2D coverage. As aforementioned, coverage is normally considered as the evaluation metric of the QoS in WSNs. Naturally, a question, how to measure the coverage performance in WSN, is raised. To answer this question, the notion k-coverage is introduced. It measures the degree of coverage by determining that whether any given point in the FoI is covered by at least k $(k \geq 1)$ sensor nodes. In order to determine the coverage level of the system, the simplest logic is to determine the coverage degree for each sub-domain (i.e., separated by the coverage disks of different sensors) one by one. However, the computational complexity of this direct method can be $O(n^2)$ in the worst case, where n represents the number of sensor nodes.

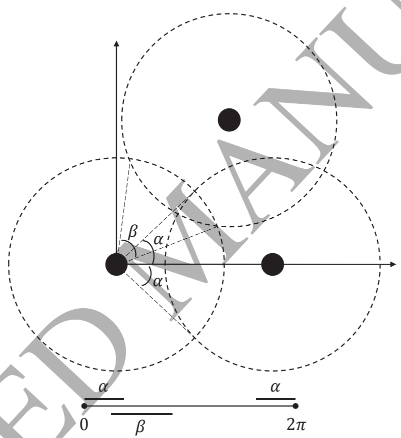


Figure 7: Illustration the determination process of the perimeter coverage

In order to reduce the computation complexity of the k-coverage problem, by assuming $R_c \geq 2R_s$, the authors in [70] present a notion called perimeter-covered, by which the k-coverage for the FoI is determined by checking whether each sensor is k-perimeter-covered or not. By this way, each sensor node can determine the k-perimeter-covered locally with the computational complexity $O(d \log d)$, where d is the maximum number of neighbours of a sensor and $d \ll n$. Consequently, the total computational complexity of determining k-coverage for a FoI can be reduced to $O(nd \log d)$. As shown in Fig. 7, an example of how to determine the perimeter-coverage of a sensor's perimeter is presented. Based on the assumption of the unit disk sensing range, the authors randomly deploy an intensive WSN to cover the FoI where no sensors are located in the same position. For each sensor node, by communicating with its own connected neighbours, it can compute the covered radian of its sensing perimeter and label the arches in $[0, 2\pi]$ segments. Then, based on the labeled results, the perimeter-coverage of each node can be determined. Moreover, the authors prove that as long as the perimeters of sensors are sufficiently covered, the whole area is sufficiently covered. Similar work can be found in [71].

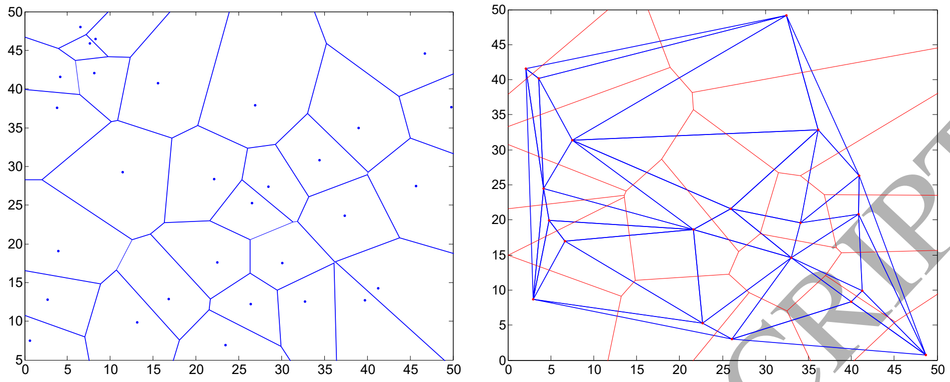
In [82], by considering the user-defined objectives (i.e., k-coverage, required event's detection probability, etc.), Fei *et al.* present a dynamical sensor selection scheme based on a so-called Partially Observable Markov Decision Process (POMDP). In POMDP, k sensors are selected in each time interval to preserve the required area coverage. The system performance can be adjusted by changing the reward function of POMDP as well as the parameters of the coverage model to facing different users' requirements. Moreover, in [83], the authors provided the optimal k-coverage deployment patterns for $4 \leq k \leq 9$.

Besides the related work mentioned above, many of research approaches are derived based on the computational geometry. In the following part of this section, we do survey the existing approaches based on the computation geometry in 2D plane.

5.2.1. Computational Geometry

One of the most famous 2D coverage problems is the *Art Gallery problem* [84]. The objective of this problem is to ensure that for any point in the room can be monitored by at least one camera/guard. Usually, this problem is solved by the computational geometry theory. Since the objective of the Art Gallery problem is same with the coverage problem, the solutions of Art Gallery problem can be adopted to solve the 2D coverage problem. While, in [85], the authors address that the solutions for the Art Gallery problem are only efficient in the 2D plane. In 3D space, it is NP-hard problem. The authors in [85] presented a discussion on computational geometry, i.e., Voronoi Diagram and Delaunay Triangulation.

Voronoi diagram: The Voronoi diagram is one of the most important models that are used by the node deployment approaches which are designed based on the computational geometry theory. In WSNs, a Voronoi cell is defined as a convex polygon in the FoI that is covered by a sensor and formed by all the points in the FoI that consider the sensor is the closest one in the system, which is shown in Fig. 8(a).



(a) Illustration of Voronoi diagram (b) Illustration of Delaunay triangulation

Figure 8: The Voronoi Diagram and the Delaunay triangulation of a set of two-dimensional points. The Delaunay triangulation is represented by blue lines

Many research efforts adopt the Voronoi diagram model to cope with two types of coverage problems: 1) For a given FoI and a set of nodes, how to design a time efficient scheme to determine whether the system can achieve a predetermined coverage degree (i.e., $k \geq 1$) or not. 2) In a given FoI, by giving a set of nodes, what's the maximum coverage degree k that could be achieved. For instance, the authors in [86] solve both questions. The authors firstly present an algorithm to reduce the computational complexity of the k-coverage determination process to $O(n \log n + nk^2)$, which is better than $O(nd \log d)$ proposed by [70]. Moreover, the authors propose another algorithm to determine the maximum coverage level that can achieve $O(n^3)$ and $O(n^4)$ running time in 2D and 3D case, respectively. Similar to [70], since the proposed approaches are centralized, their scalability is limited. It may not be able to be implemented in a large WSN. As an improvement, based on the distributed/localized Voronoi diagram construction algorithm, the authors in [87] introduce a region coverage algorithm and a fully sponsored coverage algorithm without requiring the global locations information. Based on the directional antenna technique, each node determines whether its Voronoi cell is fully covered or not by locating all its one-hop neighbors. Further, based on the coverage state, the fully sponsored redundant sensors can switch to off-duty state to save energy.

Besides the stationary WSN, some research work also tries to exploit the mobility of the sensor node. In [88], the authors adopt the Voronoi diagram to detect the coverage holes in the system and further present three mobile node deployment schemes, i.e., the VEC (VECtor-based) protocol, the VORonoi-based Algorithm (VOR), and the Minimax algorithm. More clearly, based on the so called virtual force (i.e., calculated based on the average distance between each pair of nodes in a WSN), if the Voronoi cell of one of a pair of closely located nodes is not fully covered, the corresponding node will be pushed to move farther from the other node. The movement distance varies in these three algorithms. In VEC, the distance is given by $[d_{avg} - d(s_i, s_j)]/2$, where d_{avg} is the pre-computed average distance between two nodes. Unlike VEC by which the nodes are moved by a computed distance, in order to cover the maximum hole area, the greedy VOR moves the node to its farthest Voronoi vertex, if a coverage hole is detected in its cell. However, this kind of movements may generate new coverage hole. Consequently, the Minimax is proposed to achieve balance between VOR and VEC.

In the above work, the authors consider the random network with a predetermined number of nodes. However, in reality, most of random networks are intensively deployed. There are redundant sensor nodes deployed in the system. As aforementioned, due to the constrained energy in WSN, the redundant nodes should be recognized and switched to inactive. Accordingly, Cărbunar *et al.* [89] investigate the problem of detecting and eliminating redundancy in a sensor network with a view to improving energy efficiency, while preserving the network's coverage. Instead of using the original Voronoi diagram, the proposed work adopted the so called Multiplicative Weighted Voronoi Diagram (MWVD) in which the Euclidean distance is replaced by an assigned weight. The authors use the MWVD to detect the coverage hole and further examine the effects of switching the redundant nodes inactive. The simulations demonstrate that the promising results can be achieved by the proposed work. Another redundant nodes scheduling scheme designed based on the Voronoi diagram is presented by Boukerche and Fei in [87].

So far, we can see that the Voronoi diagram can be adopted to solve the mobile node deployment and the energy efficient system design problem, separately. Furthermore, some approaches are proposed to investigate the integrated problem. Since the node's lifetime is constrained by the limited battery energy, the movements of the node can dramatically reduce the node's lifetime by consuming a large amount of energy. As a result, the aforementioned work, that assumes a WSN consisting of mobile nodes, may not be able to be adopted in a practical system. Hence, the WSN consisting of both static and mobile nodes is a more practical option. Accordingly, based on the Voronoi diagram, a bidding protocol is proposed in [90]. The basic idea is that the static nodes detect the coverage hole and calculate a bidding price based on the size of the hole. Accordingly, based on the bidding price calculated by static nodes (i.e., measure of the coverage hole size), the mobile nodes move to the optimal location through multiple movements. However, the multiple movements may consume a large amount of energy. Hence, in order to overcome this limitation, in [90] the same authors improved their bidding protocol by designing a so called proxy-based bidding protocol, by which the mobile nodes only take virtual movements during the bidding process and move to the final destination after the bidding processing accomplished. By this way, as shown in the presented simulation results, the movement distance can be reduced by up to fifty percent while achieving the same coverage.

Delaunay Triangulation: The Delaunay triangulation is another well-known diagram that is widely adopted in many research efforts. In computational geometry, the Delaunay triangulation maximizes the minimum angle of all the angles of the triangles in the triangulation and is formally defined as [91]: For a set P of points in a plane, a triangulation $DT(P)$ such that no point in P is inside the circumcircle of any triangle in $DT(P)$. The Delaunay triangulation can be easily drawn from a Voronoi diagram by connecting two nodes that the edge between them is perpendicular to the corresponding Voronoi cells' boundaries. As addressed in [87], most of the existing distributed algorithms cannot efficiently construct either the Voronoi diagram or the Delaunay triangulation. For example, Li *et al.* in [92] presented a distributed best coverage algorithm based on the Delaunay Triangulation with running time $O(nlogn)$, which has the same complexity of the centralized algorithm proposed in [93].

Besides the area coverage problem, the computational geometry can be also adopted to solve the barrier/path coverage problem. Recall the definition of the barrier/path coverage, we know that it can be considered as a specific case of target coverage. Ideally, the deterministic manner could be the optimal option for the deployment of WSN to coverage a path/barrier. However, in reality, due to the complexity of the real geographical surface, most of the WSNs are randomly deployed. As a result, the desired path coverage may not be ensured. Consequently, in a random WSN system with a given node density, finding the best- and worst-coverage path is ultimately useful in the network design stage to determine that whether a desired path coverage can be achieved or not. The authors in [94] define the maximal breach path and the maximal support path to model the worst- and best-coverage path, respectively. Depending on the definition of the Voronoi diagram and Delaunay triangulation, we know that the boundaries of Voronoi cells are the sets that contain all the nodes that locate farthest away from the sensor nodes. While, in contrast, the edges of Delaunay triangles are the set that contains all the nodes that locate closest to the sensors. Accordingly, a heuristic is proposed by the authors. The maximal breach path is built by connecting the boundaries of the corresponding Voronoi diagram. On the other hand, the maximal support path is formed by the edges of the given Delaunay triangles.

5.2.2. Other topics in 2D coverage

Virtual-force-based coverage: By considering the mobility of the sensor node, in order to cope with the integrated random coverage and node movement problem, the notion of virtual force algorithm (VFA) is proposed to improve the coverage of a random network with an initial deployment. The VFA algorithm is developed based on the idea of the potential field introduced in [95]. In [96, 97], the authors investigate a virtual-force-based coverage in a heterogeneous random network. In the proposed work, the nodes in the system can compose different clusters and the VFA is implemented in the cluster headers. Similar to the VOR [88], if any two nodes are located too close to each other, the VFA computes a corresponding virtual force that pushes these two nodes to the optimal positions. The authors demonstrate that the coverage of the original network can be improved. However, the proposed algorithm highly relies on the sub-global location information that is stored in cluster heads. As a result, the performance of this approach in the homogeneous network is doubtful, since the nodes in homogeneous network may not have the global information. In [98], both VFA and triangle deployment pattern are adopted to adjust each sensor's position and sensing range to maximize the coverage degree of the deployed WSN.

Clustering algorithms: As aforementioned, the dense deployment of WSNs is widely used in practice. In this case, switching each redundant node to inactive individually is a potential solution for the energy conservation, e.g., the node scheduling schemes we mentioned above. Another alternative solution is to separate the whole system into multiple clusters/sub-groups, and each cluster can achieve the guaranteed system coverage. The different clusters work in an alternative way. Consequently, the energy in the off-duty clusters can be conserved. In turn, the system lifetime is extended. This kind of clustering problem can be solved by maximizing the number of the disjoint clusters in the system. In [99], Slijepcevic and Potkonjak presented a heuristic scheme called the most constrained-minimally constraining heuristic to cope with this problem. In the proposed work, the maximum number of clusters is generated by using the minimum number of sensors to form each cluster. The limitation of this approach is that each sensor needs to cover a large area. This may consume more energy to maintain longer sensing range and communication range. A similar heuristic method called MC-MIP is proposed in [100] to compute the maximum number of disjoint set covers. Zou *et al.* [101] presented an efficient active nodes selection scheme in the dense deployed network to build clusters based on the notion of connected dominating set (CDS). In the proposed work, the active nodes are selected to achieve the largest surveillance area while keeping the system connectivity for routing and information dissemination. The authors proved that the proposed coverage-centric active nodes selection problem is NP-complete. The authors in [102] proposed an algorithm to connect the deployed sensors as multiple well defined clusters in which the gateway nodes without the energy-constraint were selected to work as cluster-heads. By balancing the load among these gateways, the total energy consumption would be reduced. The authors in [103] proved a good survey on the clustering algorithms.

Energy efficient related research efforts: Currently, sensor nodes are normally powered by their built-in batteries. Hence, the lifetime of a WSN is directly affected by the lifetime of the nodes in the system. Due to the limited capacity of the battery, energy is the most critical constraint for developing a sustainable WSN. Therefore, the conserving energy/extending battery life is very important in designing a sustainable WSN system. To cope with this problem, many research approaches have been proposed. For instance, over the past few years, various research efforts have addressed important issues such as channel assignment (or spectrum sensing), routing [104, 105, 106, 107] (or topology control [108, 109]), and scheduling [110, 111], with the aim of increasing the capacity of these networks. Additionally, efficient solutions for minimizing overall network energy consumption [108], or for maximizing the efficiency of nodes' energy usage and the network's overall energy utilization [112, 110], have also been discussed in the literature. However, due to the limited capacity of the battery, the lifetime of the non-rechargeable battery-powered WSN is still limited. Hence, the energy efficiency related design is still a hot topic of the research.

Besides the topics we mentioned above, there are still some other interesting topics related on the coverage problem. For example, in [113], the authors present a kind of behavioral pattern, named Target-based Association Rules (TARs). TARs are developed to predict the location of the undetected events. Three different data preparation mechanisms (i.e., Al-Node, Schedule-Buffer, and Fused-Schedule-Buffer) for accumulating the data needed for extracting TARs have been proposed. The authors in [114] analyzed the coverage degree in the path coverage problem. While, Kaiwartya *et al.* [115] compared performances of several sensor deployment patterns for the precision agriculture.

5.3. Coverage in 3D

Currently, intensive research efforts have been proposed to cope with the coverage problem in the 2D plane. However, the assumptions in the 2D coverage may not capture all the requirements of the practical deployment of WSNs in real work. Accordingly, based on the more reality assumptions, the 3D coverage problem needs to be considered. Moreover, the computational complexity of the 3D deployment strategies can be increased exponentially, since the factors in the third domain need to be considered.

In [116], the authors extend their work about the k-coverage [70] from the 2D plane to the 3D space. In the proposed work, each sensor node can sense a sphere with a radius that equals to its sensing range. Similar to the criterion for determining the perimeter-coverage [70], based on the condition $R_c \geq 2R_s$, the authors prove that the whole space is k-covered when all the sensing spheres are all with k-coverage. An algorithm with time complexity $O(nd^2 \log d)$, where d is the maximum number of sensors whose sensing ranges may intersect a given sensor's sensing range, is then presented to determine whether a sphere is k-covered or not based on the *geodesic distance*. This algorithm can be fully distributed so that each sensor can determine its own coverage with time $O(d^2 \log d)$.

Moreover, some research efforts tried to solve the 3D coverage problem by discovering the optimal deployment patterns. Alam and Haas tried to solve this issue directly based on the Kelvin's Conjecture and Kepler's Conjecture in [117]. They proved that, by using the Voronoi tessellation of 3D space, the truncated octahedral pattern could be the optimal option for the node deployment strategy. Zhang *et al.* in [68] also derived the best deployment patterns in 3D space, as well as analyzing the relation of R_s and R_c under different conditions. Unlike considering the sensors as the center of each pattern [117], the authors considered the sensors as the vertices in their work.

In [78], Ammari and Das also analyzed the K-coverage and connectivity in 3D space. Based on the Reuleaux tetrahedron, the authors derived the critical condition of R_s and R_c for keeping both connectivity and coverage. However, as aforementioned, the authors blurred the geodesic distance and the Euclidean distance in their analysis and did not consider the randomness of the node failure. Some more related work can be found in surveys [6, 3].

6. Open problems and Conclusion

Before concluding this survey, we introduce some of open problems in the real world.

6.1. Open problems in the real world

In this article, we surveyed the existing research efforts on connectivity and coverage problem in WSNs. Most of them are developed based on the ideal assumptions or conditions of the wireless channel. However, in reality, besides the distance, many other factors may affect the sensing and communication range, such as the real geography environment, communication jamming and even the temperature. For example, in a low power WSN, the capacity of wireless communication links dramatically degrades when temperature increases [12]. Hence, the design of WSNs from the lab and theory to the real world is essential. In the following, we present some of the opening problems related to deployment of WSNs in the real world.

6.1.1. Irregular sensing range

In order to efficiently and accurately analyze the performance of WSNs, an accurate sensing model is necessary. So far, many sensing models have been proposed, and they vary from the simplest binary disc model to more realistic probabilistic sensing model. However, most of them are too ideal to capture all the features of the real world, since they are all designed based on the assumption that the sensing area is a disc (i.e., unit-disk and non-unit-disk). We call them as disk-based sensing (DBS) model. Yet, in reality, sensing range is affected by many factors, such as the obstacles and the weather conditions. The DBS-based algorithms may not achieve the desired performance because of the potential errors of coverage measurement caused by the environmental factors. Therefore, the irregular sensing range should be considered to approach a more realistic sensing model. However, there are only a few research approaches that can be found in this area, e.g., RDM [10], IPM [9], radio irregular [13, 14].

6.1.2. Energy harvesting (EH)-based sensor networks

As aforementioned, the limited battery energy is one of the most critical constraints of WSNs. Besides the aformentioned clustering algorithms and energy efficient design, fortunately, another potential solution of building semi-permanent/long-term and sustainable WSNs is to enable sensor nodes to harvest renewable energy [118], e.g., wind, solar energy, ambient wireless (electromagnetic) energy, etc. For example, authors in [119] addressed this issue. First, the authors considered the quality-aware target coverage in an energy harvesting sensor network by introducing a new coverage metric that could accurately measure the coverage level/degree, and formulating a coverage maximization problem that took both sensing coverage quality and network connectivity into consideration. Further, they proposed a method for handling energy prediction fluctuations during the monitoring period. In [120], the author also considered adopting renewable energy in wireless networks. In this work, the author theoretically analyzed the residual energy changing process of the battery in the wireless node. Then, based on presented theoretical results, a distributed heuristic scheme was proposed to prolong the working time of the wireless node.

Currently, we can roughly categorize the existing EH-based approaches into three classes:

- ***MAC layer control schemes***: Due to the spatiotemporal fluctuation of the renewable energy, the available energy of EHNs remains uncertain. Hence, improving the utilization of the residual energy of energy-harvesting-node (EHN), while achieving required system performance (e.g., transmission delay, packet delivery ratio, etc.), is still vital in EH-aided WSNs. In order to explore the available energy of EH wireless nodes more efficiently, authors in [121] designed an asynchronous collision avoidance scheme depending on the hop-count information. Further, in [122], a deadline-constrained packet scheduling algorithm was presented for the EH-aided wireless network, in which, by considering both required transmission deadlines and the currently available energy in the EHN, the energy efficiency was achieved by dynamically adjusting the data transmission rate.

- ***EH-aided topology control scenarios***: Since the renewable ambient energy (e.g. solar energy, wind, etc.) is not always uniformly distributed in a given area/space, the gathered energy of different EHNs may be different. For example, a node with direct sunshine can gather much more energy than a node located in the shadow of a tree. Hence, a strategy for balancing the energy consumption of different parts of a deployed WSN is critical. In [123], Tan *et al.* addressed this problem. First, the authors modelled this problem based on the ordinal potential game, and proved the existence of a Nash equilibrium. Then, a polynomial-time topology control scheme was proposed to achieve the Nash equilibrium. Accordingly, EHNs that harvested more energy took more data forwarding tasks, while the EHNs with less energy could reduce the energy consumption by using a shorter link to send data. Consequently, the lifetime of the EH-WSN could be extended. Further, in [124] and [125], authors considered the topology control in the EH-assisted cognitive WSN. Both approaches tried to improve the energy efficiency of the system based on the spectrum sensing techniques, by which the spectrum resources of the primary users could be explored. Hence, the EH sensor nodes could schedule their data transmission more dynamically, which in turn, improved the energy efficiency of the system.

- ***Wireless charger or data relaying node deployment strategies***: In [126], a hierarchical packet forwarding scheme was presented. Data paths from each sensor to the data sink can be established based on the selection rules of the presented EH relaying nodes, and the energy consumption of data transmission could also be reduced. Similar work can be found in [127, 128]. Unlike other approaches that adopted solar energy, the authors of [129] adopted the electromagnetic energy harvesting technique in their design. In the presented work, the authors analyzed and solved the minimum-cost deployment problem for both co-located and separated cases of data sink and energy supplying nodes, in order to improve energy efficiency while minimizing the number of energy supplying nodes. Meanwhile, in [130], the authors investigated the mobile energy charger routing problem in the cluster-based WSN. Based on the locations of the cluster heads and the residual energy level, the mobile charger calculated the moving path independently. Meanwhile, the system-wide energy balance was further achieved by bilateral-trading between cluster headers with the higher levels of residual energy and those with lower levels.

6.1.3. Geographic Surface coverage in WSNs

As aforementioned, the coverage is a fundamental problem in WSNs. Existing studies on this topic focus on 2D ideal plane coverage and 3D full space coverage. However, the geographical surface of a targeted FoI in reality is much more complicated than the ideal assumption in the theoretical analysis. Hence, most of existing approaches may not able to implement in the real world. In [131], the notion of surface coverage is presented. In the surface coverage, the FoI is the real complex geographic surface and sensor nodes can be only deployed on the surface. The authors proposed three approximation algorithms to cope with this kind of coverage problems.

6.1.4. Underwater acoustic sensor networks

Moreover, deployment of sensor networks in underwater environment is another interesting research direction. Due to the trend of under-ocean exploration, real-time monitoring or long-term surveillance of the under-ocean environment, e.g., real-time monitoring for under-ocean oil drilling, is imperative. Underwater wireless sensor networks can provide an optimal option, and have recently attracted intensive attention from researchers. Nevertheless, terrestrial WSNs have been well investigated and solved by many approaches that rely on the electromagnetic/optical transmission techniques. Deploying an applicable underwater wireless sensor network is still a big challenge, because the ocean water is a special medium with unique properties, which prevent the electromagnetic/optical transmission techniques from being adopted. Hence, the acoustic transmission techniques become the optimal choice. In [132], the problem of dynamic coverage within the Autonomous Underwater Vehicle (AUV)-based wireless sensor networks (AWSNs) in underwater environment is addressed. The underwater node deployment is similar to the original 3D coverage. However, the effects of the ocean water (e.g., underwater fluid motions, the reflection and refraction of the ocean water, etc.) need to be considered in the underwater sensing system design.

6.1.5. Coverage problem in the UAV-based WSNs

Recently, the Unmanned Aerial Vehicle (UAV) technique has been widely adopted in both military and civilian applications. Since the UAV also equipped the sensing and communication equips, it can be also considered as a sensor node with high mobility. So, an attracting research problem can be defined as the integrated coverage of UAV-based WSNs (UWSNs) and the geographic surface coverage. The emerging UWSNs could be a practical option to cope with the aforementioned surface coverage problem. Because the UAV can scan the FoI at a high altitude which is not constrained by the geographic surface limitation. Meanwhile, the development of the UAV techniques further prompts the deployment of the UWSNs. The authors in [133] present a Fast Path Planning with Rules (FPPWR) algorithm to improve the data collection efficiency of the UAV. Moreover, the authors in [134, 135] theoretically analyzed the target tracking and dynamic coverage problem in the UWSNs, respectively. In [136], the authors provide a survey on UAV-based wireless communication systems.

6.2. Conclusion

Connectivity and coverage are two of the most important issues in WSNs, which can be considered as the sufficient conditions to utilize a WSN. Many research efforts have been proposed to cope with these problems. In this survey, firstly, we briefly introduced the basic knowledge on the notions of connectivity and coverage. Then, we summarized the research efforts proposed for addressing the connectivity problem, and then listed the critical conditions to keep system connectivity. Since the connectivity is affected by the node/link failures, we also did a survey for the research work related to the failure-resilient/fault-tolerant WSNs design problem. Further, we summarized the existing approaches addressed integrated connectivity and coverage problem. Based on the proposed conditions for keeping connectivity while preserving coverage, we described the research efforts proposed for coverage problem in the final.

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