A Survey on Topology Control in Wireless Sensor Networks: Taxonomy, Comparative Study, and Open Issues

Topology control techniques for wireless sensor networks are systematically classified into two categories, namely, network coverage and network connectivity. The relevant basic principles, state of the art, and future research directions are summarized in this paper.

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ABSTRACT | The wireless sensor network (WSN) technology spawns a surge of unforeseen applications. The diversity of these emerging applications represents the great success of this technology. A fundamental performance benchmark of such applications is topology control, which characterizes how well a sensing field is monitored and how well each pair of sensors is mutually connected in WSNs. This paper provides an overview of topology control techniques. We classify existing topology control techniques into two categories: network coverage and network connectivity. For each category, a surge of existing protocols and techniques are presented with the focus on blanket coverage, barrier coverage, sweep coverage, power management, and power control, five rising aspects that attract significant research attention in recent years. In this survey, we emphasize the basic principles of topology control to understand the state of the arts, while we explore future research directions in the new open areas and propose a series of design guidelines under this topic.

KEYWORDS | Connectivity; coverage; topology control; wireless sensor networks (WSNs)

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I. INTRODUCTION

Past several years have witnessed a great success of wireless sensor networks (WSNs). As an emerging and promising technology, WSNs have been widely used in a variety of long-term and critical applications, including event detection [18], [35], [59], [92], [105], target tracking [28], [74], [103], environment and habitat monitoring [36], [63], [77], localization [96], [101], [102], safety navigation [14], [17], [49], and so on. A sensor network usually consists of hundreds even thousands of sensor nodes, which are typically self-organized in a multihop fashion. By working together, sensor nodes coordinate to finish a common task.

To achieve a sustainable and scalable WSN design, researchers and engineers have made great efforts toward consideration of following several aspects.

- *Energy conservation*. Compared with competing high-end technologies, e.g., personal computer, personal digital assistant, etc., sensor networks are known to be low cost, miniature, and easily deployed. These attractive merits, however, imply that resources available to each individual sensor node are severely limited. Although it is highly possible that constraints on hardware will disappear as fabrication techniques advance, the energy problem remains to be the victim of Moore's law since more transistors consume more power naturally. On the other hand, the battery capacity only doubles within 35 years according to [43]. To close the gap between the limited energy supply and the increasing demand of the sustainable sensor network deployment, energy conservation needs to be considered carefully in the network design.

- *Limited bandwidth*. Similar to other wireless multi-hop networks, WSNs are also characterized by the limited bandwidth available to each sensor node. Theoretical bandwidths in industrial standards, like IEEE 802.11 and Zigbee, can be up to 54 Mb/s and 250 kb/s, respectively, nonetheless the achievable performance is much worse in practical situations, mainly due to the radio interference caused by simultaneous communications. Thus, a major task in the WSN design is to keep the network traffic carrying capacity at a reasonable level, even in the presence of dense sensor node deployments.
- *Unstructured and time-varying network topology*. In principle, sensor nodes in the network might be arbitrarily placed in the field; hence, the underlying topology graph that represents communication links between nodes is usually unstructured. Furthermore, due to node mobility and/or hardware failure, the network topology may vary as time goes by. Consequently, it is important to configure serials of networking parameters appropriately.
- *Low-quality communications*. Communications over wireless channels are, in general, not reliable compared with those over wired channels. Moreover, the quality of communications is strongly impacted by environmental factors that can be time varying. Since WSNs are likely to be deployed in harsh environments, the low communication quality might be a direct consequence in most cases. In this scenario, how to achieve an efficient communication over such a low-quality channel needs to be well addressed.
- *Scalability*. Depending on the specific application requirement, WSNs could be composed of tens, hundreds, even thousands of sensors. Thus, the scalability of the proposed protocols used in the sensor network is also a critical issue.

The original mission of WSNs is to monitor the target field and detect the occurrence of important events. Due to the stochastic nature of events and environmental parameters, every point in the field needs to be carefully surveilled, i.e., the field should be covered by sensor nodes well enough to capture events and report environmental parameters. On the other hand, with the system deployment cost and scalability under consideration, it is not practical to make the field covered by sensor nodes with extraordinarily high density. As a consequence, one primary problem for WSNs is to achieve an appropriate coverage by sensor nodes in the network. It determines the quality of the service that can be provided, the underlying topology that can be constructed, and the scalability that the system can achieve.

Once a sensor network is deployed, system operators must know the network condition from time to time. To this end, plenty of networking services serve as a bridge between the network and system operators, such as flooding, data collection, information aggregation, time synchronization, and so on. Unlike wired networks, the major challenge is how to efficiently support these subtle services on top of lossy wireless communication channels with only limited bandwidths. In particular, great efforts have been devoted to such a problem. With an appropriate transmission range of each sensor node and dedicated algorithms, efficient networking services can be provided. Moreover, the energy can also be largely saved by adjusting sensors' active/sleep schedules, leading to a long lifetime of the system. The essence of those operations is to maintain good connectivities of pairs of communicating sensor nodes temporally and spatially.

Thus, it is important to control the coverage and connectivity to satisfy aforementioned design considerations. As a result, a fundamental operation of WSNs is topology control that characterizes how well a sensing field is monitored and how well each pair of sensors is mutually connected in the network.

In this survey, we will conduct a thorough overview on the topology control issues in WSNs. In Section II, we propose a taxonomy to classify existing topology control issues. In Section III, we introduce topology coverage problems in detail, and in Section IV, we review connectivity problems under both spatial and temporal controls. Additionally, we explore relevant open issues in Sections III and IV as well. In the end, we point out several WSN design guidelines, conduct a set of case studies, and summarize this survey in Sections V–VII, respectively.

II. TAXONOMY

Topology control issues have been extensively studied in WSNs. Essentially, coverage and connectivity are two performance metrics mainly investigated in existing literatures.

Coverage refers to the surveillance map of the target field, which emphasizes the sensors' placement positions and cooperations among sensors. From the system's point of view, i.e., the networking perspective, people are particularly interested in the quality of coverage, as it directly represents how capable the network can perform. To quantify the coverage quality, various benchmarks are used in terms of the granularity of coverage.

- *The highest granularity*: Every point in the target field should be always monitored by sensors, which we characterize as blanket coverage. Blanket coverage offers the best coverage quality and the system benefits from the most instant response of any event occurred in the network. However, such a coverage style largely increases the costs of the system deployment and maintenance.
- *The medium granularity*: Every path crossing the network should be monitored by the network,

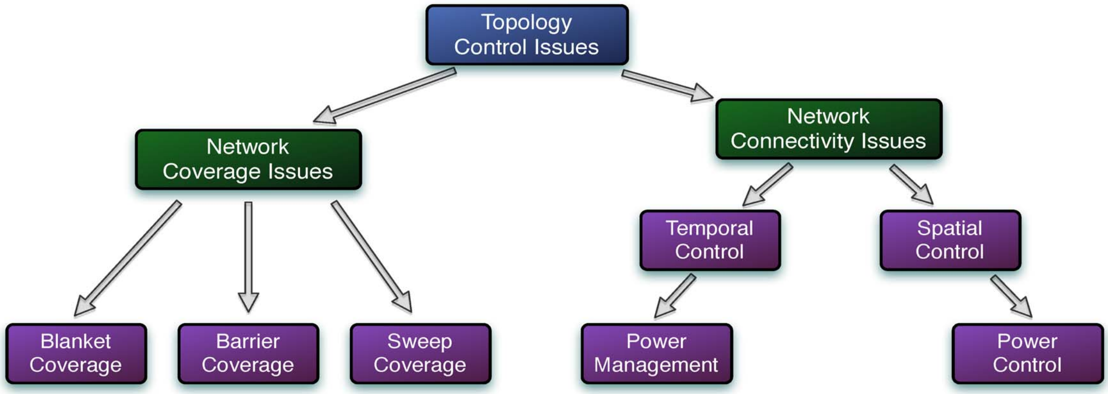

Fig. 1. ***Taxonomy of topology control issues in WSNs.***

which we characterize as barrier coverage. Barrier coverage ensures that any intruder who aims to pass through the network can be guaranteed to be detected. However, such a type of coverage incurs detection delay. Moreover, if the movement path does not cross the network, the intruder cannot be guaranteed to be reported.

- *The lowest granularity*: The network is not necessarily connected and the system can tolerate certain event detection delay. In this case, the target field can be covered by a sparse network composed of mobile sensors, which dramatically reduces the costs of the system deployment and maintenance. We characterize the last type as sweep coverage.

On the other hand, if taking a fine look at the topology of WSNs, i.e., the sensor's perspective, people normally focus on how well sensors are mutually connected in the network topology. *Connectivity* relates to the message retrieve and delivery in the network. When a sensor node works, its connectivity to other sensors can be studied from two aspects.

- *The temporal domain*: Due to the energy saving purpose, sensor nodes usually switch between the active state and the sleep state. It is clear that such a switching phenomenon decides the connectivity of two neighboring sensor nodes. In the temporal domain, people need to study how to step up an optimal active/sleep schedule to achieve good connectivities of sensors in the network.
- *The spatial domain*: The current sensor motes commonly support multiple energy levels. Under different energy levels, the transmission range varies. Recent literatures have shown that the optimal energy level does not usually reside on two power extremes, but instead on some value in between. In the spatial domain, people need to investigate the policy to configure the energy level of each sensor to optimize mutual connectivities.

Therefore, in this section, the taxonomy of topological issues can be organized hierarchically, as depicted in Fig. 1. Basically, topology control issues can be divided into two categories: network coverage and network connectivity, as discussed before.

A. Network Coverage

As mentioned before, network coverage describes how well the target field is monitored by the sensor network, and the concerned problem is how to achieve a reliable sensing area that satisfies certain application requirements while consuming less power. According to different coverage granularities (representing different application requirements) discussed above, network coverage can be further divided into three categories: *blanket coverage*, *barrier coverage*, and *sweep coverage*.

- Blanket coverage focuses on the sensing coverage of every point in the field. More precisely, each field position needs to be covered by at least one sensor node. In general, if every point in the field is covered by at least k sensors, where $k = 1, 2, 3, \ldots$, the resulting blanket coverage is denoted as k-blanket coverage. Blanket coverage is also known as *full coverage*. Note that, in the literature, the full coverage may not necessarily require to cover every point in the field. Instead, the k-coverage can be achieved over a set of points only. Such discrete point coverage may have more efficient solutions [83], while the traditional area coverage is more applicable. In this survey, we focus on covering every point in the field for blanket coverage.
- In barrier coverage, people are interested in each crossing path, which is defined as a path that crosses the complete width of the belt-region-like field. Similar to k-blanket coverage, k-barrier coverage requires that every crossing path intersect the sensing region(s) of at least k sensor node(s).

- In sweep coverage, whenever an event occurs, the sensor node that detects this event becomes a point of interest (POI) and records the sensory data in its local memory. Sweep coverage requires that the locally recorded information be collected by some mobile devices within certain delay bound.

B. Network Connectivity

In network connectivity, two types of mechanisms have been utilized to maintain an efficient sensor connectivity topology: power management mechanisms (i.e., the temporal control) and power control mechanisms (i.e., the spatial control).

- The former one works by maintaining a good active/sleep schedule of each sensor node to prolong the system lifetime while keeping almost equivalent system capability in the topological sense.
- The latter one woks via controlling the sensor communication radio power level to achieve optimized connectivities among sensor nodes.

In the next two sections, we will review existing techniques designed for topology control in detail and explore relevant open issues.

III. NETWORK COVERAGE ISSUES

The first step in deploying a WSN is to determine what we are attempting to monitor, as reported in [64]. Typically, we would monitor an entire area, or look for a breach among a barrier, or watch a set of POIs.

A. Blanket Coverage

As aforementioned, the coverage of an entire field refers to blanket coverage, in which every single point of the network should be within the sensing range of at least one sensor node. To achieve such a goal, blanket coverage has been studied in *static*, *mobile*, and *hybrid* networks. Different types of networks are named according to the motion ability of involved sensor nodes, which are introduced to trade off between the network lifetime and the cost of the network management.

- In static networks, no sensor can move. This kind of networks is easy to deploy but suffers the energy hole issue, shortening the network lifetime [89].
- In mobile networks, all sensors can move. This type of networks largely increases the cost of sensor nodes and the complicity of the protocol design; nevertheless, the network lifetime can be prolonged dramatically.
- Hybrid networks combine advantages of both static and mobile networks.

In any types of networks above, to further reduce the deployment cost, it is always better for us to deploy the minimum number of sensor nodes within a field so that blanket coverage can be ensured. In this section, we introduce existing techniques in static, mobile, and hybrid networks separately.

1) *Static Network*

a) Single coverage: The basic requirement in blanket coverage is to guarantee the single coverage, i.e., each position in the field must be covered by at least one sensor node. To this end, Zhang and Hou [99] have proposed the optimal geographical density control (OGDC) protocol. This protocol tries to minimize the overlap of sensing areas of all sensor nodes for the case when $R_c \geq 2R_s$, where R_c is the sensor node communication range and R_s is its sensing range. The algorithm starts with all sensor nodes initially in the "UNDECIDED" state. A sensor with sufficient power will be randomly chosen to start the process of node selection. This selected sensor node broadcasts a power-on message, checks power levels of all receivers of its power-on message, and verifies whether the target field is covered by all "DECIDED" sensors. If the target field has not been fully covered yet and enough power is available at a power-on message receiver side, this receiver node becomes the neighbor of the previously selected sensor node, sets its own state to be "DECIDED," and broadcasts the power-on message again. This process continues until the field is completely covered by sensors. OGDC is a fully distributed algorithm, while the location information of each sensor node needs to be known in advance.

The issue of coverage with different sensing capacities is addressed by Tian and Georganas [78]. They discuss the topology control for both homogeneous and heterogeneous sensing ranges. Each sensor node tries to discover whether its sensing area has been fully covered by its neighbors (sponsors). If so, this sensor node turns off its radio. To avoid the possibility of multiple neighbors turning off radios simultaneously, resulting in a coverage hole, sensor nodes execute a random backoff algorithm before going to sleep. This algorithm has been further extended and improved by Jiang and Dou [42].

b) Multiple coverage: In order to improve the system reliability, generally, the multiple coverage is required in real systems, i.e., each position in the field must be covered by at least two sensor nodes. In this case, Wang *et al.* [85] present the coverage configuration protocol (CCP) that can provide flexibility in terms of the granularity of the sensor network configurations. By this protocol, systems can self-configure for different degrees of coverage. The authors further prove that for boundary nodes whose sensing range intersects with the network boundary, the desired connectivity is equal to the degree of coverage, while for internal nodes, the desired connectivity is twice the degree of coverage under the constraints that $R_c \geq 2R_s$. Each deployed sensor node runs the K_s-coverage eligibility algorithm. Given a requested coverage degree k_s, a sensor node is scheduled to sleep if every location within its coverage range has already been K_s covered by the active nodes in its neighborhood. For cases when $R_c < 2R_s$, CCP guarantees neither the connectivity nor the coverage. The CCP protocol needs the node location information to assist as well.

Huang and Tseng [40] propose a series of algorithms to verify whether every point in the field is covered by at least the required number of sensor nodes. Algorithm $k - UC$ deals with the unit sensing disk case and algorithm $k - NC$ deals with the nonunit sensing disk case. The proposed algorithms require the location information of each deployed node. The authors suggest a centralized controller entity that can collect the details of insufficiently covered segments and dispatch new nodes to supplement. However, this centralized approach fails to meet the scalability requirement.

Yan *et al.* [95] propose a distributed density control algorithm, which is capable to provide the differentiated coverage based on different requirements in different parts of the deployed sensor network. The algorithm relies on the time synchronization between neighboring sensors. In the initialization phase, nodes exchange their location information and synchronize with their neighbors. In the sensing phase, which comprises several rounds with equal time duration, each node divides its whole sensing area into grids and advertises its reference point, start time, and stop time, defined with respect to that reference point. Each node sorts its neighbors that cover a particular grid in ascending order in terms of their reference points in one round. Based on the obtained time sequence, one sensor node can decide its on-duty time such that the whole grid still gets the required degree of coverage. The results from all the covered grids are merged to find the adopted duty schedule for the node.

In [67], network coverage has been studied with the consideration of the impact from sensor node distributions. Peng *et al.* investigate the impact from both analytical and experimental aspects. In addition, they propose a distribution-free protocol, which does not rely on the probability distribution of sensor node locations and yield good estimations of network coverage. Yan *et al.* [94] also introduce an optimization technique for the sensing overage in WSNs.

In real systems, even the deployment of a WSN is carefully performed; sensors may still be displaced due to human or environmental factors. In [81], Vu and Zheng thoroughly discuss the impact of location uncertainty on the coverage properties in WSNs. They introduce the concept of max Voronoi diagram (VD) and propose a polynomial algorithm to overcome the uncertainty issue. The algorithm introduced in [81] can ensure the worst case k-coverage by determining the minimum sensing radius.

The coverage protocols discussed so far are all based on the typical disc model. However, Xing *et al.* [91] demonstrate that such a simple sensing model fails to capture the stochastic natural in wireless networks. To achieve a more realistic sensing model, Xing *et al.* [91] thoroughly study the coverage problem under the data fusion model and explore its fundamental performance limits. In addition, the scaling laws between coverage, network density, and signal-to-noise ratio (SNR) are derived. It has been shown that the data fusion model can dramatically improve the sensing coverage compared with the traditional disc-based model.

In real systems, coverage requirements may change according to the system operator's need basis. However, it is usually hard to support multiple aforementioned protocols in one system. To this end, Gu *et al.* [31] introduce a unified sensing coverage architecture, which can support various protocols by merely configuring two system parameters. In addition, a two-level coverage protocol, uScan, is proposed under this coverage architecture. Compared with existing protocols, uScan can approach the optimal performance in a batter way.

So far, we have introduced plenty of protocol-level solutions for blanket coverage in static networks. In the literature, there are also some theoretical results, such as [8] and [9]. In [9], an interesting phenomenon called pattern mutation is observed, which can be used to explore the joint optimization between network coverage and node connectivity. In [8], Bai *et al.* find the optimal patterns that can achieve multicoverage in any 2-D plane using Voronoi polygons.

2) Mobile Network: Wang *et al.* [82] aim to achieve a sensor deployment for mobile sensors that maximizes the sensor coverage with short delay, short movement distance, and low message complexity. Given an area to be monitored, the proposed distributed self-deployment protocols first discover the existence of coverage holes in the target area based on the sensing service. Once a coverage hole is discovered, the protocols calculate the target positions and move sensors there to diminish the coverage holes. Voronoi diagrams [5], [29] are used to discover the coverage holes, and three movement-assisted sensor deployment protocols VEC, VOR, and Minimax are proposed, based on the principle of moving sensors from the densely deployed areas to the sparsely deployed areas. A node needs to know the location information of its neighbors to construct its own Voronoi diagram. The diagram partitions the whole space into Voronoi polygons. Each polygon has a single node with the property that every point in the polygon is closer to this node than any other node.

Ganeriwal *et al.* [30] propose a protocol called Co–Fi that uses mobile sensors to repair the coverage hole resulting from the energy depletion in a deployed sensor network. Co–Fi works in four phases. In the initialization phase, every node learns about its sensing neighbors and calculates its own coverage region. In the panic request phase, a dying node requests to update the network topology. In the panic reply phase, sensing neighbors of the dying node respond to this request and inform the dying node with their residual energy and the mobility cost needed for the target location, as shown in Fig. 2. In the

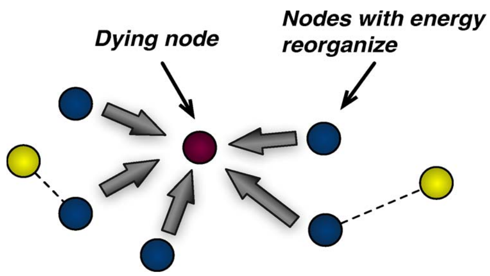

Fig. 2. *Mobile nodes salvage the coverage holes.*

decision phase, the dying node chooses the node with the maximum utility as succession.

Howard *et al.* [39] and Heo and Varshney [37] try to study the sensor network in the viewpoint of virtual forces. In [39], sensor nodes are treated as virtual particles, and the virtual forces due to potential fields repel the nodes from each other and obstacles. The authors assume that each sensor is capable of determining the range and bearing both its neighbor nodes and the obstacles. In this approach, nodes only use their own sensory information to make the decision. No communication among the nodes or localization information is needed. For the distributed self-spreading (DSS) algorithm proposed in [37], sensors are assumed to be randomly deployed initially. They start moving based on partial forces exerted by the neighbors. The forces exerted on each node by its neighbors depend on the local density of deployment and on the distance between the node and the neighbor.

Recently, researchers have become interested in the problem of approaching the k-coverage using moving sensor nodes. Initially, sensor nodes are randomly distributed in the network and the sensing range of each node can be turned online. The design objective is to satisfy the k-coverage requirement using those mobile nodes. In [48], Li *et al.* propose the Load bAlancing k-Area Coverage through Autonomous Deployment (LAACAD) approach for balancing the sensing workload (prolonging network lifetime) and guaranteeing k-coverage by leveraging the convex optimization techniques. In [34], Han *et al.* further address the mobile coverage problem by taking advantage of directional antennas.

3) Hybrid Network: In hybrid networks, only some sensors are capable of moving. The mobile sensors can repair the coverage failure by moving to appropriate locations within the field to achieve the desired level of coverage.

Batalin and Sukhatme [12] propose a combined solution for both the exploration and the coverage of a given target field. The coverage problem is solved with the help of a constantly moving robot in a given area. The mobile robot first performs the network deployment in the target field as it explores the unknown environment. The deployed nodes then guide the robot based on their local measurements, to so far poorly covered areas. The mobile robot, using its local sensing data and the recommended direction acquired from a deployed sensor node, decides about its future direction for exploration. If the robot does not receive a direction beacon when it has traveled a predetermined distance in one direction, it deploys a new sensor node to improve the local coverage of the local area. The algorithm does not consider the communications between the deployed nodes. All decisions are made by the robot through directly communicating with a neighboring sensor node.

Wang *et al.* [33] address the single coverage problem by moving the available mobile sensors in a hybrid network to heal coverage holes. The static sensors detect their local coverage holes by using Voronoi diagrams. The mobile sensors also calculate coverage holes formed at their current positions, if they decide to move to new positions. The static sensors bid for the mobile sensors based on their size of the coverage hole. A mobile sensor compares the bids and decides to move if the highest bid received has a coverage hole size greater than the new hole generated in its original location due to its movement. The bids are broadcast locally up to two hops.

4) Summary of Blanket Coverage: Based on the discussions in this section, key features of aforementioned blanket coverage protocols are tabulated in Table 1. To sum up, the trend of protocol designs for the static coverage migrates from the single coverage to multiple coverage, since the latter one can provide a better quality of coverage. In the category of mobile networks, geometric computations and potential fields are wildly used in the protocol design. Moreover, most of protocols can perform in a distributed manner. In hybrid networks, both one and multiple mobile sensor node(s) can achieve the requirement of the blanket coverage. One common assumption that is made in most of these designs is that the location information of each sensor node is available, and location-free protocols are rare. Although great efforts have been made to blanket coverage, we find that this topic can be further explored by investigating the coverage versus network lifetime issue as follows.

Since every position in the field needs to be monitored in blanket coverage, to reduce the deployment and maintenance costs, the general policy to place sensors of aforementioned protocols or algorithms is deploying the minimum number of sensor nodes within a field, while a variety of system requirements can be achieved. As a matter of fact, such a sensor deployment policy usually results in a sparse topology in the network.

Compared with a peer dense network in the same field, with a larger sensing range, each sensor node in the sparse network collects more sensory data in general. Sensory data in WSNs normally need to be transmitted back to the base station or the sink node in a wireless multihop fashion. As a result, the traffic density circulated at each sensor node of the sparse network is raised compared with a dense network. On the other hand, according to the

Table 1 Comparative Study of Blanket Coverage Protocols

Protocols	Category	Approach	Major Assumptions	Key Characteristics
OGDC [99]	Static	Single Coverage	Location info., Uniform sensing disk	Residual energy consideration
Sponsored Area [78]	Static	Single Coverage	Location info.	Sector based coverage calculations
Extended-Sponsored Area [42]	Static	Single Coverage	Location info., Time synchronization	Uniform disk sensing model
VD [81]	Static	Multiple Coverage	Binary sensing, Disc coverage	Uncertainty sensor placement, k-coverage guarantee
uScan [31]	Static	Two level	Location info., Time synchronization	Unified coverage architecture
VEC, VOR, Minmax [82]	Mobile	Computational geometry	Location info.	Localized, scalable, distributed
Co-Fi [30]	Mobile	Computational geometry	Location info, nodes predict their deaths	Single coverage based, Residual energy considerations
Potential Fields [39]	Mobile	Virtual Forces	Range, bearing	Scalable, Distributed, No local communication required
DSS [37]	Mobile	Virtual Forces	Location info.	Scalable, Distributed, Residual energy based
Single Robot [12]	Hybrid	Single mobile sensor	Location info.	Distributed, no multi-hop communications
Bidding Protocol [33]	Hybrid	Multiple mobile sensors	Location info.	Voronoi diagram is used for the single coverage requirement

recent measurement study [58], the routing structure to deliver the in-network traffic is relatively stable. Therefore, in a sparse network, a large volume of traffic will be transmitted, following relatively stable routing paths. Along these routing paths, sensors close to the sink node must carry much more traffic compared with remote sensor nodes. Consequently, the energy consumption in the network suffers a severely unbalanced distribution, which will dramatically shorten the network lifetime.

Thus, we refer to the coverage versus network lifetime issue as open issue 1 in this survey, in relation to how to trade off between the coverage performance and the network lifetime.

B. Barrier Coverage

Barrier coverage originates from the boundary detection problem [24], [104] in some real applications, such as detecting intruders crossing the border of two countries. In principle, barrier coverage requires that the system can detect any moving path crossing a belt region monitored by sensors. Barrier coverage has been studied from both deterministic and probabilistic aspects [64].

Using the results from percolation theory, Liu and Towsley [54] study the barrier coverage problem for the first time in sensor networks of a strip shape in the 2-D plane. Essentially, the following problem is addressed in the network defined above: Does a giant sensor cluster to percolate the given barrier-like network exist? In addition, if the width of the strip network is only finite, the authors calculate the probability to detect an intruder when this intruder crosses the strip. As unveiled in [72], the strength of barrier coverage that is the number of disjoint barriers fails to be obtained in [54].

Kumar *et al.* [47] propose a set of algorithms to determine whether a region is k-barrier covered. Wang and Cao [86] study the barrier coverage problem in camera sensor networks. In [47], Kumar *et al.* further verify that such an answer cannot be given by using local information only. Then, two types of deployments are studied in this work. With the optimal deployment pattern, the authors discuss how to achieve k-barrier coverage when sensors are deployed deterministically. On the other hand, the authors also consider to achieve barrier coverage with high probability when sensors are deployed randomly. Moreover, two kinds of coverage are introduced in [47]: weak and strong barrier coverages illustrated in Fig. 3. Compared with blanket coverage, both kinds of coverage largely

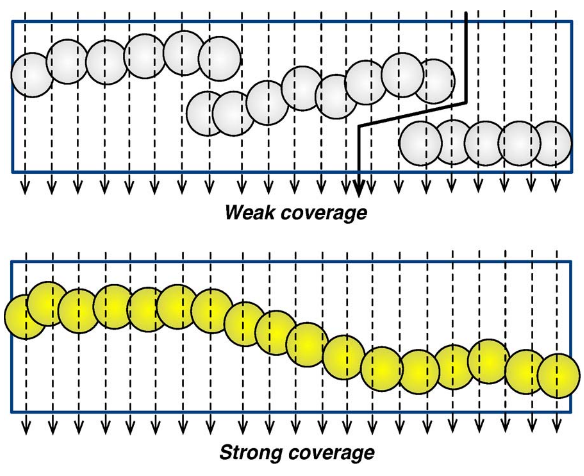

Fig. 3. *Weak coverage versus strong coverage.*

reduce the number of sensors that need to be placed in the network. In the end, critical conditions for weak-barrier coverage are derived in [47]. Based on this result, one can compute the minimum number of sensors needed to provide the weak-barrier coverage with high probability in a given belt region. Unfortunately, critical conditions for strong-barrier coverage are missing in [47].

Focusing on the strong-barrier coverage, Balister *et al.* [10] and Chen *et al.* [21] conduct a comprehensive study on this problem. In [10], Balister *et al.* introduce new techniques to derive reliable density estimates for finite regions, including thin strips. Then, they apply the proposed techniques to solve the open problem of deriving reliable density estimates for achieving barrier coverage and connectivity in thin strips, in which sensor nodes are deployed as a barrier to detect moving objects and phenomena. Protocols proposed in [10] are completely distributed. On the other hand, the localized barrier coverage protocol (LBCP) is proposed in [21], which is also sufficiently distributed and can provide near-optimal performance in terms of the network lifetime. As a result, LBCP can ensure barrier coverage most of the time.

Previous works, such as [10] and [21], have shown how to construct sensor barriers to detect intruders moving along restricted crossing paths in rectangular areas. The authors present a complete solution in [53] to this problem for sensors that are distributed according to a Poisson point process. In particular, they present an efficient distributed algorithm to construct sensor barriers on long strip areas of irregular shape without any constraint on crossing paths. Additionally, they guarantee that intruders cannot cross the strip undetected no matter how they choose their crossing paths. To this end, the authors make two main contributions in [53] that provide theoretical foundations and practical algorithm for the construction of strong barriers in a sensor network. Specifically, they obtain the critical conditions for strong barrier coverage in a strip sensor network, filling the gap in understanding of the critical conditions for barrier coverage.

Studies in [53] are based on the assumption of the Poisson point process. To further reduce such an assumption, Saipulla *et al.* discuss barrier coverage with a line-based deployed WSN, as shown in Fig. 4. In [72], the authors claim that the line-like deployment might represent a more realistic sensor placement model in many applications. In this work, a tight low bound for the existence of barrier coverage under line-based deployments is derived. Additionally, the authors find that sensor deployment strategies have direct impact on the barrier coverage of a WSN. The results demonstrated in this work show that barrier coverage of the line-based deployments significantly outperforms that of the Poisson model when the random offsets are relatively small compared to the sensor's sensing range.

So far, barrier coverage has been mainly discussed based on the typical unit disk sensing model. Such a simple model facilitates the barrier coverage design and study so that the optimal deployment patterns can be obtained and analyzed. However, as unveiled in [91], such a simple sensing model fails to capture the stochastic nature of wireless communication channels. Usually, the event detection in WSNs is a stochastic process, which is determined by many practical factors: geometric distance, SNR, etc. As a pioneering work, Xing *et al.* [91] utilize the data fusion model to increase the quality of coverage in blanket coverage. As a matter of fact, some probabilistic sensing models may serve as a better option to further investigate barrier coverage in WSNs. Thus, we characterize the realistic modeling issue as open issue 2 in this paper, relating to how to make probabilistic guarantees to design the optimal barrier coverage pattern by using more realistic sensing models.

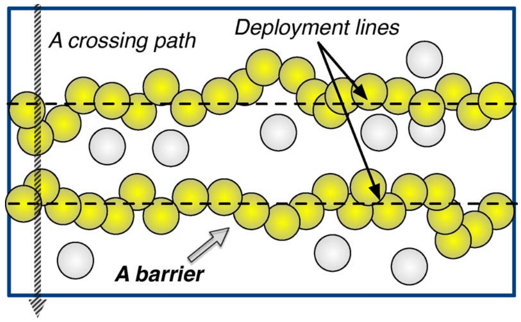

Fig. 4. ***Sensors are deployed in a rectangular area with two adjacent deployment lines.***

C. Sweep Coverage

Sweep coverage does not require continuous network coverage when the full coverage in the field cannot be achieved. Instead, it is enough to detect a series of POIs. The concept of sweep coverage initially comes from the context of robotics which mainly concerns the metric of coverage frequency, i.e., the frequency of the coverage of each point. Robots coordinate or randomly move in the field and deploy communication beacons in the environment to mark previously visited areas. Robots then make local decisions on their motion strategy through communications with those beacons.

Howard and Mataric [38] introduce an algorithm to deploy a mobile robot network to cover the entire region. Similar to static sensor networks, a robot sensor network is also composed of a set of sensor nodes that sense environments and process sensory data. The major difference is that sensors in the robot network have the motion capability. Similarly to [38], Rekleitis *et al.* [70] also tailor to deploy a mobile sensor network to cover the entire region.

Topological mapping is introduced to sweep the destination region by Wong and MacDonald [88]. The authors propose a topological coverage algorithm in this paper. In this proposal, the reachable surface is decomposed into multiple subregions.

Even under the mobile networking context, aforementioned sweep coverage mechanisms measure the efficiency of the coverage performance based on the total intersected areas covered by different sensors under some snapshot. In other words, such a measurement is static. Different from previous works, Batalin and Sukhatme [11] introduce the frequency coverage metric, measuring the coverage frequency of each position in the region, to address the dynamic coverage problem. They require all areas of free space in the field to be covered by sensors in as short a time as possible.

Although the sweep coverage problem has been extensively studied in the domain of robotics, the system performance will suffer a lot if aforementioned mechanisms are applied to WSNs [23]. It is because robots are highly intelligent with advanced hardware and software. On the contrary, due to the energy concern, sensor nodes are not highly integrated in most cases.

The work presented in [23] is reported to be the first one formally introducing the sweep coverage problem in WSNs. In WSNs, people are particularly interested in, within a given time span, how many sensors are needed to sweep several POIs instead of the entire network. In [23], Cheng *et al.* first mathematically define the above sweep problem encountered in WSNs as the min-sensor sweep-coverage problem and prove such a problem is NP-hard. Then, it has been shown that the min-sensor sweep-coverage problem cannot be solved in a better way than the 2-approximation, including the case of 2. Moreover, by assuming that all sweep periods are identical, the authors propose a centralized algorithm that can achieve a $2+\epsilon$ approximation. In the end, the distributed SWEEP (DSWEEP) algorithm is introduced to satisfy certain sweep requirements in a distributed manner.

In [23], each POI is assumed to be fixed in advance. By further relaxing such an assumption, Xi *et al.* [90] study the sweep coverage problem with dynamic POIs, in which POIs can be dynamically changed, e.g., appearing or emerging, anytime and anywhere. In [90], the relationship among information access delay, information access probability, and the number of required mobile sensor nodes is discussed first. Then, based on a virtual 3-D information potential map, a distributed algorithm is proposed to guide the movement of mobile nodes to achieve the sweep coverage in the network.

1) Summary of Barrier and Sweep Coverages: Based on the discussions in Section III-B and C, key features of aforementioned barrier and sweep coverage protocols are tabulated in Table 2. To sum up, the weak barrier coverage has been well studied from theory to practice. The current focus is on how to achieve strong barrier coverage by relaxing the constraints on the shape of the barrier and the process of point nodes.

In sweep coverage, Cheng *et al.* [23] have addressed how to ensure sweep coverage given a set of discrete POIs in the field. In addition, they further determine the metric of sweep coverage and study the applicability in this scenario. However, in real systems, it is hard to predict when and where an event might happen. In other words, POIs may not be always known in advance. By relaxing this assumption, Xi *et al.* [90] investigate the case, in which POIs are all dynamic, i.e., POIs can appear at any time and any position in the field. The most important performance metric in this more realistic network model is the relationship between the delay bound that can be achieved to detect all those POIs and the number of involved sensor nodes in the network. It quantifies the quality of the sweep coverage.

If there is only one dynamic POI in the field, the above performance metric has been well studied and its closed-form expression is given in [90]. In real systems, however, there may exist multiple POIs. To the best of our knowledge, the above performance metric has been studied only under two special cases in [90]: when the delay bound is extremely large or small. When the delay bound is moderate, its mathematical relationship is so far

Table 2 Comparative Study of Barrier and Sweep Coverage Protocols

Protocols	Category	Type	Major Assumptions	Key Characteristics
[47]	Barrier	k-barrier testing, barrier deployment	Deterministic deployment	NP-hard proof, critical conditions for weak coverage
[10]	Barrier	barrier deployment	High degree of connectivity	Strong coverage, distributed algorithm
[21]	Barrier	barrier deployment	Location info.	Strong coverage, distributed algorithm, near optimal performance
[72]	Barrier	barrier deployment	Poisson point process	Irregular shape barrier, strong coverage, critical conditions
[53]	Barrier	barrier deployment	Location info.	Line based barrier
[23]	Sweep	Theoretical analysis, protocol design	Fixed POI positions	Theoretical foundation, $2+\epsilon$ approximated algorithm
[90]	Sweep	Protocol design	Direction of a communicable node is known	Dynamic POI positions, information potential

unknown to the community. As mentioned in [90], the key point of this problem is to analyze all possible intersecting scenarios of different circular areas that may need the location information of each POI. Therefore, we refer to the delay bounded optimization issue as open issue 3, which relates to how to derive the mathematical relationship between the event collection delay bound and the number of sensor nodes needed in the network when the required delay bound is moderate.

IV. NETWORK CONNECTIVITY ISSUES

In this section, we will discuss network connectivity issues in topology control. As mentioned in Section II, solutions to these issues from both temporal and spatial domains will be reviewed in detail.

A. Power Management Mechanisms

In this section, we specify strategies to achieve network connectivity in the temporal domain. Research literature [26] and industrial specifications [1] have jointly shown that radio dominates the energy consumption compared with all other hardware components in sensor nodes (motes). We take the well-known TelosB mote [3] as an example to briefly verify this statement.

Table 3 summarizes the energy consumptions of some mainstream radios compared with the second most energy consuming hardware component, microcontroller, according to [26]. As TelosB motes are normally composed of MSP430F1611 (microcontroller) and CC2420 (radio), Table 3 shows that the working current of its radio is 28.8 times as much as that of its microcontroller. The similar phenomenon can be found at other types of sensor motes as well. In practice, radio is not always busy with communications. Instead, radio performs idle listening to assess the channel most of time. On the other hand, Table 3 reveals a remarkable energy consumption gap between the active state (i.e., Tx or Rx) and the sleep state of radios. According to these facts, power management is introduced to optimally schedule the active/sleep states of radio to avoid energy wastes.

To obtain an effective power management, three techniques are wildly adopted, called synchronized duty cycling media access control (MAC),[1] asynchronous duty cycling MAC, and hybrid MAC protocols. The basic idea of all three techniques is to avoid radio open all the time. Radio switches between the active state and the sleep state to prolong the lifetime of each sensor. The fundamental difference among these three techniques is whether a synchronized system time is needed. Synchronized and hybrid protocols normally require sensor nodes to be synchronized, at least locally synchronized among neighboring sensors. A surge of protocols have been proposed for time synchronization in WSNs. On the other hand, asynchronous protocols do not require any time synchronization among sensors.

Table 3 Energy Consumptions of Typical Radios and Microcontrollers (M-C: Microcontroller)

Radio	Rx/Tx (mA)	Sleep (μA)	M-C	Active (mA)
MC13192	37/30	1.0	ATmega128L	0.95
MC13202	37/30	1.0	ATmega1281	0.9
MC13212	37/30	1.0	ATmega2561	0.9
CC2420	18.8/17.4	1.0	MSP430F149	0.42
CC2430	17.2/17.4	1.0	MSP430F1611	0.5
CC2520	18.5/25.8	.05	MSP430F2618	0.5

1) Synchronized Protocols: S–MAC proposed in [97] by Ye *et al.* is reported as the first one to control sensor connectivity in the time domain by applying different communication strategies in different time slots. Compared with the traditional always-on method, the power consumption of each sensor node can be reduced by the periodic listen–sleep switch applied at each sensor node side. In S–MAC, every sensor node needs to set up a working schedule and exchange it with all its neighbors. Additionally, neighboring sensor nodes are locally synchronized to remedy their clock drift so that they could share a common working schedule, which is realized by periodically updating nodes' schedules by SYNC messages. Collision and overhearing avoidance are developed to further diminish power consumptions.

In S–MAC, nodes are usually deployed with an active time that can handle the highest (expected) message rate. Whenever the rate becomes lower, however, the configuration of the active/sleep schedule is not optimal and energy will be wasted on idle listening. To solve this issue, T–MAC [80] is proposed based on S–MAC. T–MAC adopts similar methods in S–MAC for collision avoidance and overhearing. The major difference is the mechanism in T–MAC to further reduce the energy consumption on idle listening by transmitting all messages in bursts of variable length, and sleeping between bursts. To maintain an optimal active time under various message rates, the duration of the active state is determined dynamically.

In S–MAC and T–MAC, each active/sleep schedule period consists of one active state and one sleep state. In the random wakeup schedule [32], the system time is first partitioned into periods. Then, each period is further divided into multiple time slots with equal length. During the system configuration phase, each sensor node randomly selects several slots in which it stays active. The remaining slots serve for the sleep state. The number

[1]In this section, the reviewed protocols may not be pure MAC layer protocols. Some of them are highly coupled with certain services on other layers. For example, Random wakeup schedule in [32] is tailored for the flooding service in WSNs. However, for the simplicity of the presentation, we still use the term "MAC protocols" to describe all scenarios.

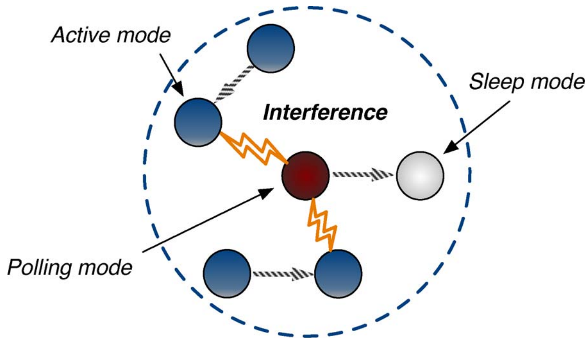

Fig. 5. *Interference between the wakeup plane and the transfer plane in the case of one frequency in STEM.*

of active slots over the number of sleep slots defines the duty cycle ratio.

2) Asynchronous Protocols: In the geographical adaptive fidelity (GAF) algorithm [93], sensor nodes use the location information to divide the field into fixed square grids. The size of each grid stays constant, regardless of node density. Nodes within one grid switch between sleeping and listening states, with the guarantee that one sensor node in each grid stays up so that a dynamic routing backbone is maintained to forward packets.

Chen *et al.* [22] propose Span, a power saving topology maintenance algorithm for multihop *ad hoc* wireless networks that adaptively elects coordinators from all nodes to form a routing backbone and turn off other nodes' radio receivers most of the time to save energy. By nodes locally electing coordinators and adaptively rotating their operating role between coordinator and noncoordinator, Span achieves four goals.

Schurgers *et al.* [75] propose the sparse topology and energy management (STEM) technique, which exploits the time dimension rather than the node density dimension to control a power saving topology of active sensor nodes. STEM switches nodes between two states: the transfer state and the monitoring state. Data are only forwarded in the transfer state. In the monitoring state, nodes keep their radio off and will switch into the transfer state to be an initiator node on a detected event. A special frequency band other than data transmitting frequency of a wakeup plane is designed for the initiator node to wake up its target node so that there is possible interference between the wakeup plane and the transfer plane. Fig. 5 illustrates the possible interference when only one frequency band is used.

Tseng *et al.* [79] first study asynchronous wakeup for power saving in mobile *ad hoc* networks. Mobile nodes develop their active slots for communications. Through the beacon window and the multihop traffic indication map window, sensor nodes achieve the neighbor discovery and the packet forwarding. By maintaining a dynamic network topology of active nodes in every time instance, the whole system achieves power saving, and thus prolongs its lifetime.

Zheng *et al.* have studied asynchronous wakeup schedules for wireless *ad hoc* networks [100]. They derive the theoretical limit of the wakeup schedule and prove that the lower bound is achievable by a constructive method. An asynchronous wakeup protocol based on the optimal symmetric block design has been proposed for slotted communication in the network.

Different from S–MAC and T–MAC, B–MAC [68] adopts the low-power listening (LPL) technique that does not try to explicitly synchronize neighboring nodes. Instead, LPL allows the receiver to sleep most of the time and only periodically sample the channel. Long preambles are used by senders to guarantee the receiver to get packets. A filter mechanism, called clear channel assessment (CCA), can help sensor nodes decide whether there is a packet arriving. Moreover, B–MAC provides an adaptive preamble sampling scheme to minimize the idle listening.

Similar to B–MAC, wise–MAC [27] also adopts the preamble sampling technique for the energy saving purpose. As discussed in B–MAC, at each access point, a preamble with the size equal to the sampling period is transmitted prior to every data frame to ensure that the receiver is awake when the data portion of the packet arrives. This technique offers a very low power consumption when the channel is idle, however, the disadvantages of this protocol are that the long preambles limit the throughput of the system and a large amount of energy consumptions in reception. Moreover, the energy consumption at the receiver side not only contains the intended receiver but also all other sensors overhearing this preamble. The major improvement of wise–MAC is to limit the preamble length, avoiding to transmit some unnecessary portion of the preamble. The preamble length in wise–MAC is dynamically determined, and the length is long enough for the intended receiver being woken up.

To address the issues of the long time waiting at the intended receiver side and overhearing in LPL, X–MAC [16] adopts a strobed preamble approach. Instead of transmitting a long preamble each time, in X–MAC, the sender sends out a series of preambles with a smaller size,

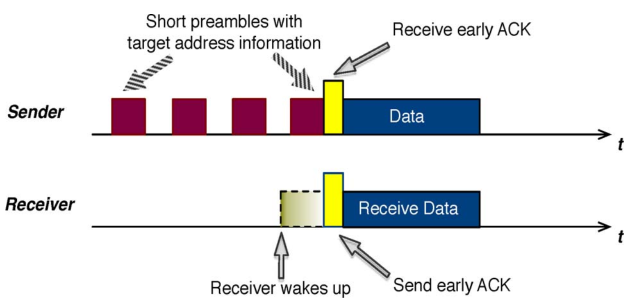

Fig. 6. *X–MAC.*

as shown in Fig. 6. Each short preamble contains an ID of the intended receiver. Furthermore, the sender inserts multiple pauses between two consecutive preambles. The stream of short preamble packets effectively constitutes a single long preamble. During each assess point, the sender listens to the medium. These artificially inserted gaps between any two short preambles enable the receiver to send an early ACK back to the sender. Once receiving the early ACK from the target sender, the sender immediately switches to transmit the data packet. If one sensor node, which is not the intended recipient, receives the short preamble, it returns to sleep immediately.

The design of C–MAC in [57] is parallel to X–MAC by the way of resolving the long time waiting issue and the overhearing issue when LPL is used. C–MAC avoids transmitting a traditional long preamble; instead, it sends a series of RTS prior to the data packet.

In all previous works, the sender needs to frequently transmit preambles to probe receivers. They are also known as sender-initiated protocols. Since the wireless channel is shared by all sensors in the network, when one sender probes the receivers, all other sensors within its transmission range cannot communicate. Such a method has a major drawback: extra energy and time are consumed unnecessarily. To overcome this issue, the receiver-initiated MAC (RI–MAC) protocol is proposed in [76]. In RI–MAC, once a packet is ready, the sender keeps active and waits silently until the intended receiver is explicitly signified by a short beacon. The major challenge of receiver-initiated protocols is that it is hard to support efficient flooding and multicasting services.

3) Hybrid Protocol: Different from synchronized and asynchronous protocols, the scheduled channel polling MAC (SCP–MAC) protocol [98] is a hybrid protocol combining the synchronized nature and the LPL technique together, which can reach extremely low duty cycle (e.g., 0.1%), while still achieving small latency. Whenever a sensor has a packet to send, it waits in the sleep state until the receiver starts to assess the medium. Then, the sender will send a short wakeup tone to inform the receiver. Before sending the tone, the sender performs a carrier sense within a predefined contention window, denoted as CW1. If the sender wins during the contention, it will inform the receiver by sending a tone; otherwise, it will go to sleep and repeat the same process the next time when the receiver polls the channel. After the sender wakes up the receiver, it enters the second contention window, denoted as CW2. The sender will send the data packet once it wins in the contention.

4) Summary of Power Management Mechanisms: Based on the discussions in Sections IV-A1–IV-A3, key features of aforementioned power management protocols are tabulated in Table 4. Table 4 shows that most protocols are distributed and location free, which are good attributes for practical deployments. Asynchronous protocols constitute the majority of existing power management mechanisms.

However, current power management mechanisms face a common problem: they are mainly designed to efficiently support different network services. Even for the same network service, different mechanisms may rely on different assumptions to work appropriately. The direct benefit of such a phenomenon is that people can obtain excellent system performance by choosing the dedicated technique or protocol based on particular application needs. In real implementations, however, it is not always beneficial. In practice, one WSN usually needs to support multiple network services. For instance, the current efforts to build a long-term large-scale WSN, GreenOrbs [2], needs to at least support data collection, data dissemination, diagnosis, localization, and so on.

If protocols are closely coupled with certain specific services, we need to integrate many of them to cover all desired services. Unfortunately, the experience from real developments teaches us that such complicatedly integrated systems are usually lack of scalability and of low efficiency. Thus, we refer to the unified framework issue as open issue 4 for protocol designers. More precisely, it

Table 4 Key Features of Power Management Protocols

Protocols	Year	Mobile/ Static	Category	Location Info.	Distributed	Major Characteristic
Span [22]	2001	Static	Asyn.	No	Yes	Routing backbone
GAF [93]	2001	Mobile	Asyn.	Yes	Yes	Grid-based division
Power saving protocol [79]	2002	Mobile	Asyn.	No	Yes	Beacon and MTIM windows
STEM [75]	2002	Static	Asyn.	No	Yes	State switching
Asyn. Wakeup protocol [100]	2003	Static	Asyn.	No	No	Symmetric block design
S-MAC [97]	2002	Static	Syn.	No	Yes	Fixed duty cycling
T-MAC [80]	2003	Static	Syn.	No	Yes	Adjusted duty cycling
B-MAC [68]	2004	Static	Asyn.	No	Yes	Low power listening
Wise-MAC [27]	2005	Static	Asyn.	No	Yes	Abbreviated preamble sampling
X-MAC [16]	2006	Static	Asyn.	No	Yes	Strobed preamble sampling
SCP-MAC [98]	2006	Static	Hybrid	No	Yes	Receiver tone approach
C-MAC [57]	2007	Static	Asyn.	No	Yes	RTS/CTS based preamble sampling
RI-MAC [76]	2008	Static	Asyn.	No	Yes	Receiver initiated approach

relates to how to design a unified framework for topology control to provide reasonable performance with multiple service needs. A pioneer work tailored for this open issue is [25]. The proposed A–MAC protocol unifies previous works and is able to efficiently support all desired services covered by previous designs. Dutta *et al.* [25], in a small part, touch upon the power management in topology control, and we believe that there will be large research space available for exploring highly integrated protocols to cover more components in topology control.

Another open issue in this section is related to the tradeoff between prolonging system lifetime with topology control and the achieved system performance. In Section IV, we have reviewed a bunch of low duty cycling MAC protocols, which have achieved a great success in prolonging the lifetime of the network while maintaining a good network connectivity. Many fundamental problems, however, are still not well understood, especially from the theoretical perspective. One typical question is as follows: Is it always beneficial to set an extremely low duty cycle in the network? Ye *et al.* [97] reveal that the average latency of S–MAC to exponentially collect data increases as the duty cycle decreases. The similar phenomenon has been reported in [32] as well. The essence of the power management techniques is to trade the performance of some system metric (e.g., connectivity and delay) for the system lifetime, i.e., the energy consumption. For some network operations, e.g., the basic flooding operation, since the energy consumption of each sensor is approximately linearly proportional to the duty cycle ratio, the overall benefit obtained in low duty cycle networks decreases exponentially as the duty cycle ratio decreases.

For open issue 5, referred to as the low duty cycle performance issue, we believe that it is important to mathematically analyze the power management mechanisms in low duty cycle networks. Such a theoretical research will bring us not only an in-depth understanding of fundamental tradeoffs in low duty cycle WSNs, but also insights on how the maximum network gain can be achieved.

B. Power Control Mechanisms

In Section IV-A, we have reviewed existing mechanisms to manage the radio's working schedule for the network connectivity purpose at the temporal domain. However, even though the active/sleep working pattern of a radio is given, the energy can be further saved at the spatial domain by adjusting its working power.

Table 5 provides a concrete example of CC2420 to demonstrate how energy consumptions vary under different radio working powers. Some typical working power levels and their corresponding energy consumptions are tabulated in Table 5. By such a fact, one natural question is: Is it wise to make radio work with the maximum working power all the time? Research literature later found that the answer is negative. The optimal transmission power is normally between zero and the maximum value. Its specific value can be decided by the power control based on the application requirement. Mahfoudh and Minet [60] summarize the goals to conduct the power control in WSNs as follows:

- reducing the energy consumption since the power grows at least quadratically with distance;
- reducing interference;
- improving spacial reuse and mitigating the MAC-layer medium contentions.

Table 5 Output Power Settings and Typical Current Consumption of CC2420

Power Level	TXCTRL Register	Output Power (dBm)	Current (mA)
31	0xA0FF	0	17.4
27	0xA0FB	-1	16.5
23	0xA0F7	-3	15.2
19	0xA0F3	-5	13.9
15	0xA0EF	-7	12.5
11	0xA0EB	-10	11.2
7	0xA0E7	-15	9.9
3	0xA0E3	-25	8.5

The essence of power control is to form proper connectivities among sensors in the network to reduce energy consumption and improve the network capacity. Problems, related to power control, are mainly studied in stationary networks with little attention on the node mobility as well. The most distinct attribute among proposed mechanisms is whether it is a homogeneous (i.e., nodes have the same transmission range) or heterogenous (i.e., nodes are allowed to choose different transmission ranges) approach.

1) Homogenous Approaches: For the homogeneous network, the critical transmitting range (CTR) problem has been widely studied to maintain sensor connectivities with less power consumptions. The CTR problem can be described as follows: suppose n nodes are placed in $R = [0, l]^d$, with $d = 1, 2, 3$. What is the minimum value of r such that the r-homogeneous range assignment for this placement is connected? The motivation to study CTR stems from the fact that, in many situations, the dynamically adjusted node transmission range is not feasible. Thus, in this scenario, setting the same transmitting range r for all the units is a reasonable choice, and the only option to reduce power consumption and increase network capacity is to set r to the minimum possible value that ensures connectivity.

The CTR problem has been investigated in both theoretical and practical viewpoints. The theory of geometric random graphs is utilized to analyze the CTR problem in a probabilistic manner. More precisely, it figures out the minimum value of r, providing connectivity with high probability. In the practical characterization, Narayanaswamy *et al.* [65] present a distributed protocol, called the common power (COMPOW) protocol, that attempts to determine the minimum common transmitting range needed to ensure network connectivity.

They show that setting the transmitting range to this value is beneficial to maximize the network capacity, reduce the contention to access the wireless channel, and minimize the energy consumption.

Bettstetter [13] analyzes the network connectivity under the assumption that some of the nodes have the transmission range $r1$, and the remaining nodes have the transmission range $r2 \neq r1$. Santi and Blough [73] investigate the tradeoff between the transmission range and the size of the largest connected component in the communication graph. The experimental results show that, in sparse 2-D and 3-D networks, the transmission range can be reduced significantly if weaker requirements on connectivity are acceptable: halving the critical transmission range, the largest connected component has an average size of approximately 0.9 n, which means that a considerable amount of energy is spent to connect relatively few nodes.

2) Heterogeneous Approaches: The nonhomogeneous network raises more general problems where nodes are allowed to have different transmission ranges. The problem of assigning a transmission range to nodes in a way that the resulting communication graph is strongly connected and the energy cost is minimum is called the range assignment (RA) problem, and it was first studied in [45].

Under the assumption that the transmission power is proportional to the transmission distance, the authors propose the broadcast incremental power (BIP) algorithm to achieve an energy-efficient broadcasting service in WSNs. The basic idea of BIP is to set up a minimum spanning tree (MST) in terms of power cost. More precisely, BIP transforms the network graph to a minimum energy broadcasting tree rooted at a given source. BIP executes in a round-by-round fashion and is generally controlled by a cluster. In addition, the computational complexity of RA has been analyzed in [66]. It is shown to be NP-hard in the case of 2-D and 3-D networks. However, the optimal solution can be approximated within a factor of 2, using the range assignment generated in [50].

An important variant of RA that has been studied is based on the concept of symmetry of the communication graph. Due to the high overhead [62] needed to handle unidirectional links in routing protocols that are originally designed for symmetric links, symmetric range assignment (SRA) demonstrates more practical importance. However, Blough *et al.* [15] show that SRA remains NP-hard in 2-D and 3-D networks, and it even incurs a considerable extra energy cost over RA.

Agarwal *et al.* [4] reveal the phenomenon of hitchhiking in wireless communications. Under the hitchhiking model, obtaining the optimal solution to construct the most energy-efficient topology is proven to be NP-complete in [4]. To solve this problem in practice, a distributed topology control with hitchhiking (DTCH) algorithm is proposed in [19] to achieve energy-efficient data dissemination with controlled power.

Adaptive transmission power control (ATPC) is proposed in [52] for the purpose of power control with the consideration of correlation between transmission power and received signal strength indicator (RSSI)/link quality indicator (LQI). Extensive empirical results in [52] show that link quality is significantly influenced by spatio–temporal factors, and that every link is influenced to a different degree in a real system. Based on this observation, the goal of ATPC is to achieve energy efficiency and guarantee the link quality between neighbors.

Rodoplu and Meng [71] present a distributed power control algorithm that leverages on location information to build a topology that is proven to minimize the energy required to communicate with a given master node. Li and Wan [51] introduce a more efficient implementation of the protocol which, however, computes only an approximation of the minimum energy topology. Ramanathan and Rosales-Hain [69] consider the problem of minimizing the maximum of node transmitting ranges while achieving connectedness. They also consider a stronger requirement of 2-connectivity of the communication graph.

Li *et al.* [50] introduce the local MST (LMST), a fully distributed and localized protocol aimed at building an MST-like topology. The authors show that: 1) the protocol generates a strongly connected communication graph; 2) the node degree of any node in the generated topology is at most 6; and 3) the topology can be made symmetric by removing asymmetric links without impairing connectivity. A distributed topology control protocol based on directional information called cone-based topology control (CBTC) is proposed by Wattenhofer *et al.* [87] and has been further extended to the case of 3-D space by Bahramgiri *et al.* [6] and implemented using directional antennas in [41].

MobileGrid proposed by Liu and Li [56] tries to keep the number of neighbors of a node within a low and high threshold centered around an optimal value. When the actual number of neighbors is below (above) the threshold, the transmission range will be increased (decreased), until the number of neighbors is in the proper range. However, no characterization of the optimal value of the number of neighbors per node is given and, consequently, no guarantee on the connectivity of the resulting communication graph is provided.

Some articles aim to provide basic theoretical analysis on power control problems with node mobility. The increased message overhead and nonuniform node spatial distribution induced by mobility makes the problem much harder. Nevertheless, some of the proposed practical power control protocol tries to deal with node mobility. An adaptation of the CBTC protocol to the case of mobile networks is discussed by Li and Wan [51], and it is shown that if the topology ever stabilizes and the reconfiguration protocol is executed, then the network topology remains connected. The protocol proposed by Rodoplu and Meng [71] also presents how it could be adapted to the mobile scenario. The power consumption is evaluated in the presence of a mobility pattern which resembles the random direction model. The MobileGrid [56] protocol, which is based on the *k*-neighbors graph, is explicitly designed to deal with node mobility.

So far, the topology issues are mainly discussed on the logic topology for WSNs. Few articles relate the logic network topology to some real environmental factors such as geographic structures, event territories, sample distribution, etc. Thus, open issue 6, referred to as the environment-aware topology issue, asks how we can further explore those relationships and construct more environment-aware sensor network topologies. We will probably achieve better energy conservation and work efficiency under such an adaptive architecture. For instance, we are able to relate the network topology to the event distributions such that data collection on the network topology is always optimized against the actual data generation. More environmental factors may be considered for further system optimization.

The term "topology" is used across this survey but we have not formally discussed its accurate meaning. Following the definition in wired networks, such as Internet and peer-to-peer networks, people normally use a graph to present the topology of a WSN. In the topological graph, vertices denote sensor nodes and edges stand for communication links between sensors. In practice, the topology of a sensor network is indispensable for both in-built protocols and system operators. After sensors exchange adequate information, we can know which pair of sensors mutually communicate and several types of associated information, such as the average RSSI value, the average packet reception ratio, the expected transmission times (ETX), and so on. With such information, how to derive the connectivity relationship and then the network topology remains not clear. So far, there are no standard answers to such a question, and researchers find that the way to describe topology seems highly related to the specific application. For instance, RSSI is usually not an accurate metric for the link quality in data routing while expected transmission times normally work better. For many topology control works, however, RSSI usually serves as the threshold to obtain communication links in the network topology. In addition, those link statuses vary from time to time. Thus, giving accurate and appropriate description of the underlying network topology remains an open issue, which we refer to as open issue 7, the topology description issue. We believe that addressing such an open issue helps to set up standard and uniform platforms to discuss topology related problems. Protocol designers will then be able to design universally applicable protocols.

C. Achieving Both Coverage and Connectivity

So far, the coverage and connectivity issues have been discussed separately in Sections III and IV. In the literature, however, the two problems can be related by the sensing range and the transmission range. In [7], Bai *et al.* discuss the connection between coverage and connectivity. In this work, the authors propose an optimal deployment pattern to achieve both full coverage and 2-connectivity, and prove its optimality for all values of r_c/r_s, where r_c is the communication range and r_s is the sensing range of sensor nodes. They also prove that, when $r_c/r_s<\sqrt{3}$, a previously proposed deployment pattern for achieving both full coverage and 1-connectivity can be optimally ensured. In the end, the authors compare the efficiency of some popular regular deployment patterns such as the square grid and triangular lattice, with respect to the number of sensors needed to guarantee coverage and connectivity. Later, Bai *et al.* further explore a new set of patterns when r_c is relatively smaller than r_s. In [9], an interesting phenomenon called pattern mutation is observed. Bai *et al.* find that the mutation occurs among the patterns for full coverage and 3-connectivity when $r_c/r_s = 1.0459$, among the patterns for full coverage and 4-connectivity when $r_c/r_s = 1.3903$, and among the patterns for full coverage and 5-connectivity when $r_c/r_s = 1.0406$ [9]. This is the first time that mutation in pattern evolution for achieving both full coverage and different orders of connectivity is discovered.

V. DESIGN GUIDELINES FOR TOPOLOGY CONTROL

After reviewing a surge of techniques and discussing a series of open issues for topology control in WSNs, we propose three design guidelines for the future theoretical study and protocol design on topology control issues.

A. Guideline 1: Proper Networking Model

The first design guideline is to validate appropriate networking models before the system design and analysis.

Networking models include the sensing model, the interference model, the node distribution model, the topology model, and so on. In the previous literature, many simple networking models, e.g., the unit disc sensing model, the exclusive interference model, and the uniform node distribution model, are wildly used to simplify the system design and the theoretical analysis. However, with the rapid advance of WSN techniques, the obtained system performances from real systems are usually complicated and far beyond what those simple networking models describe. Simple models fail to accurately capture the essence of real behaviors of the network. As a consequence, conclusions made from those simplified models may provide inaccurate or even misleading results in practice.

As mentioned in Section III, there have been pioneer research works following the guideline, such as [91], where a more realistic sensing model is used, and significant system performance improvement has been achieved. In line with open issue 2 and open issue 7, we propose the guideline of developing and using a proper networking model to study topology control problems. We believe that introducing a realistic and proper networking model brings additional challenges for the theoretical analysis and protocol design; nevertheless, it will ensure the research results more applicable to real situations.

The first design guideline can directly benefit the real-time and crucial-event monitoring applications, such as volcanic earthquake monitoring [55], building fire monitoring [84], bridge health monitoring [44], and so on. Due to the sophisticated physical features, aforementioned simple networking models fail to obtain desired performance in those applications.

B. Guideline 2: Balancing Coverage and Connectivity

The rationale behind guideline 2 is to carefully trade off between network performance and network lifetime, whenever people design topology control protocols.

After a WSN is deployed, people pay attention to its performance as it represents the quality of service provided by the network. In Section III, we have reviewed plenty of protocols aiming to achieve a good performance in the topology control with the minimum cost. On the other hand, it is also well known that WSNs are usually deployed in harsh or remote areas and the network lifetime is expected to be long enough, which triggers the study of power management and control mechanisms in network connectivity, as reviewed in Section IV. In summary, network coverage and network connectivity have contradicting focuses. The former one focuses more on the network performance and the latter one concerns more the network lifetime.

However, many topology control protocols cannot treat both aspects with balanced performance consideration. As veiled by open issue 1, the direct optimization or design objectives of most network coverage protocols are not to prolong the network lifetime. It is possible that excellent system performance can be achieved based on the proposed protocols; nevertheless, the system may not be able to consistently work for a long period. On the other hand, open issue 5 indicates a reversed situation, where the network performance is severely sacrificed to trade an excessively long system lifetime. We believe that guideline 2 can serve as a general rule to guide the design of sensor network topology control protocols for balanced coverage and connectivity performance. We may further consider open issue 6 in enabling the cross layer and integrated design for multipurpose optimization across network coverage, connectivity, system lifetime, etc.

The second design guideline can directly benefit the monitoring systems deployed in remote or harsh places, such as forest monitoring [63], underground environmental monitoring [46], and so on. This type of applications prohibits system operators frequently replacing the battery for each sensor mote. Therefore, the tradeoff between network performance and network lifetime needs to be carefully made by balancing network coverage and pairwise connectivity.

C. Guideline 3: Unified Framework for Different Service Demands

The third design guideline in topology control suggests the design of unified protocols that can support more network services at the same time. In practical systems, a WSN usually provides a set of different services according to different application needs. Moreover, some additional information might be needed for the system operator, such as the system diagnosis information. All those cooperations and information are closely coupled with various network services.

Most existing topology control protocols are designed particularly for certain network services, and excellent system performance can be obtained by selecting dedicated protocols for the desired network service. Therefore, one practical system needs to integrate multiple protocols to cover all demanding services, as shown in open issue 4. However, experiences from real system implementations, not limited to WSNs, teach us that complicatedly integrated systems are prone to losing the attributes of scalability and efficiency. On the contrary, the principle with a simplified design is usually applied in practice. Therefore, we believe that guideline 3 is significant for the system realization in WSNs. Following guideline 3, a WSN can work with the minimum number of protocols. More importantly, scalability and efficiency can be achieved simultaneously as well.

The third design guideline can directly benefit the large-scale monitoring systems, such as city-wise urban CO_2 monitoring [61]. This type of systems usually contains a large number of sensor motes (e.g., more than 1000 nodes). To guarantee the proper execution of the system, it not only runs the basic application program, but also it runs plenty of fine-grained diagnosis, data fusion, and structure management programs (e.g., layering, clustering). Thus, guideline 3 ensures that the number of protocols and the total amount of exchanged messages can be minimized. In light of this, the system robustness can be improved and the networking resources can be fully utilized.

VI. APPLICATION EXAMPLES

In this section, we discuss the practical importance of topology control based on three recent deployed sensor network systems.

A. Volcanic Earthquake Monitoring

The volcanic earthquake is a severe disaster. The volcanic eruption monitoring and the earthquake prediction are highly desired. Liu *et al.* [55] develop a system on the Tungurahua Volcano near Banos Ecuador for both monitoring and prediction purposes. In the system, the major challenge is that, compared with traditional expensive monitoring instruments, low-cost wireless sensor motes often have limited sensing capability, e.g., low SNR and narrow responsive frequency band. How do we satisfy the stringent sensing quality requirements?

In [55], Liu *et al.* find that existing sensing models yield poor monitoring quality due to the limited sensing capability of low-cost sensors and unpredictable dynamics of volcanic activities. Existing sensing models are too simple to reflect their sophisticated nature. Moreover, they are designed only for short-term monitoring due to the high-energy consumption of centralized data collection. Such observations fully demonstrate the importance of guideline 1, proposed in Section V. In the system, the authors propose a novel quality-driven approach to achieving real-time, *in situ*, and long-lived volcanic earthquake detection, which can achieve near-zero false alarm and missing rates and less than 1 s of detection delay [55].

B. Forest Monitoring

Forest is a valuable resource on Earth. In the forestry, researchers need the all-year ecological surveillance in the forest, collecting various sensory data, including temperature, humidity, illumination, and carbon dioxide titer. The collected information is utilized to support various significant applications, such as forest surveillance, forestry observation and research, fire risk evaluation, and succor in the wild.

In this application, as the sensor network is deployed in the forest, the system operator cannot frequently replace the battery for each sensor mote. On the other hand, the operator should obtain the newly collected data to understand the latest forest situation. Therefore, such a system demonstrates an urgent need to trade off between network performance and network lifetime, i.e., guideline 2 mentioned in Section V. Tailored to solving this issue, Challen *et al.* [20] propose a duty cycle adjustment scheme to balance the energy budget of each sensor node while ensuring efficient data transmission in the network.

C. Urban CO_2 Monitoring

Due to the continuous worsening of global warming, the carbon emission has drawn people's attention all over the world. One of the main causes of global climate deterioration is the over-emission of CO_2 [61]. Many developed countries have been required to reduce or limit the total volume of the CO_2 emission, so as to slow down the trend of global warming. As a result, an accurate and real-time measure of the CO_2 emission in urban areas has been highly desired recently.

In this application, the major issue is that, due to the scale of the system (e.g., more than 1000 nodes), it should support a bunch of concurrent services, such as data collection, parameter dissemination, link estimation, local data processing, and diagnosis, to guarantee that the entire network works properly [61]. The requirement demonstrates the importance of guideline 3, proposed in Section V. To avoid unnecessary sensor nodes' deployment and message exchanges, Mao *et al.* [61] propose efficient and effective approximation approaches based on the Steiner tree and prove that their scheme uses additional relay nodes at most twice the minimum.

VII. CONCLUSION

In this paper, we conducted a comprehensive survey on topology control issues in WSNs. We provided a taxonomy for the topology control techniques under this frame and reviewed existing works. Comparative studies have been conducted to investigate and evaluate different protocols. In the end, we also point out plenty of future research directions and useful design guidelines for topology control. ■

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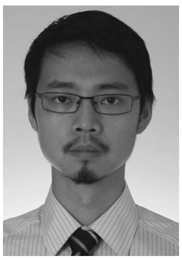

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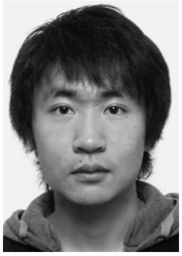

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