# A Survey on Topology issues in Wireless Sensor Network

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**Abstract:** *Topology issues have received more and more attentions in Wireless Sensor Networks (WSN). While WSN applications are normally optimized by the given underlying network topology, another trend is to optimize WSN by means of topology control. A number of approaches have been invested in this area, such as topology directed routing, cooperating schemes, sensor coverage based topology control and network connectivity based topology control. Most of the schemes have proven to be able to provide a better network monitoring and communication performance with prolonged system lifetime. In this survey paper, we provide a full view of the studies in this area. By summarizing previous achievements and analyzing existed problems, we also point out possible research directions for future work*.

**Keywords:** Wireless sensor networks, Topology, Sensor holes, Power control, Power management

## 1. Introduction

Wireless Sensor Networks (WSNs) have become an emerging technology [1] that has a wide range of potential applications including environment monitoring, object tracking, scientific observing and forecasting, traffic control and etc.. A WSN normally consists of a large number of distributed nodes that organize themselves into a multi-hop wireless network and typically these nodes coordinate to perform a common task.

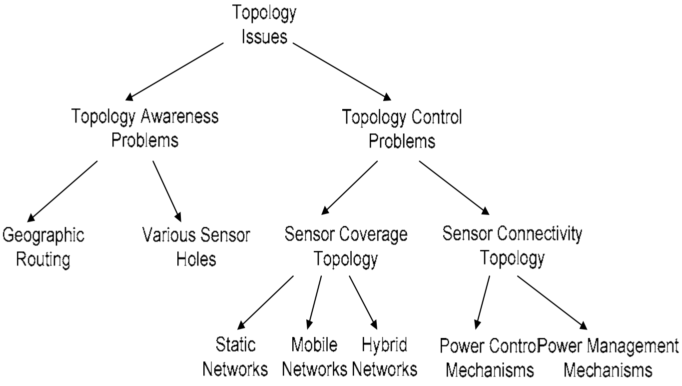
To achieve a lasting and scalable WSN design, the following aspects have to be carefully taken into account in the design stage:

- *Energy conservation*.
- *Limited bandwidth*.
- *Unstructured and time-varying network topology*.
- *Low-quality communications*.
- *Operation in hostile environments*.
- *Data processing*.
- *Scalability*.

Several solutions have been proposed in the literature which addresses at least some of the above issues. In particular, great efforts have been devoted to the design of energy efficient message delivery and data retrieving methods. With the awareness of the underlying network topology, more efficient routing or broadcasting schemes could be achieved. Furthermore, the network topology in WSNs can be changed by varying the nodes' transmitting range and adjusting the wake/sleep schedule of all nodes. Therefore, further energy can be saved if the network topology can be maintained in an optimal manner.

In this survey, we focus on the topology related issues in WSNs. We first give our topology in Section 2, followed by topology awareness problems in the next Section. In Section 4, we introduce existed topology control approaches for both sensor coverage topology and sensor connectivity topology. The article concludes with a summarization of the study and the outline of future research directions.

**Figure 1**. A Taxonomy of topology issues in WSNs



## 2. Topology Issues, the Taxonomy

Topology issues have been extensively studied in WSNs. In this section, a coherent taxonomy is organized and depicted in Figure 1. We divide the topology issues into two categories: Topology Awareness Problems and Topology Control Problems.

Topology Awareness Problems include geographic routing problems and sensor holes problems. Geographic routing uses geographic and topological information of the network to achieve optimal routing schemes with high routing efficiency and low power consumption. Various sensor holes, such as Jamming holes, sink/black holes and worm holes, may form in a WSN and create network topology variations which trouble the upper layer applications. For examples, intense communication may cause jamming holes which will fail to deliver message to exterior nodes. Sink/Black holes and worm holes are caused by nodes exhausted around sink node or pretended sinks or by malicious nodes. If sensor holes issues are not treated carefully, they will create costly routing table and exhaust the intermediate nodes rapidly.

Topology Control Problems can be further divided into two categories: Sensor Coverage Topology and Sensor Connectivity Topology. The coverage topology describes the topology of sensor coverage and is concerned about how to maximize a reliable sensing area while consuming less power. The connectivity topology on the other hand is more concern more about network connectivity and emphasizes the message retrieve and delivery in the network. Two kinds of mechanisms have been utilized to maintain an efficient sensor connectivity topology: Power Control Mechanisms and Power Management Mechanisms. The former controls the radio power level to achieve optimized connectivity topology and the later maintains a good wake/sleep schedule.

# 3. Topology Awareness Problems

## 3.1 Geographic Routing

Geographic routing approach relies on greedy forwarding to route packets based on nodes’ local information on the network topology.

Karp et al. [22] propose the Greedy Perimeter Stateless Routing (GPSR) for MANETs. The protocol starts in greedy forwarding mode, and assumes the location information of sensor nodes can be obtained by supporting systems [6, 30]. GPSR recovers from local maximum position by using perimeter rouging mode and the right-hand rule.

Kranakis et al. [24] propose the Compass Routing algorithm and FACE-1 algorithms that guarantees the destination is reached even when local minimum phenomenon occurs in greedy forwarding. Similar to the work in [24], Bose et al. [5] propose the FACE-2 routing algorithm. In contrast to GPSR, routing in FACE-2 is done through the perimeter of the Gabriel Graph (CG) formed at each node. It also modifies the FACE-1 so that the perimeter traversal follows the next edge whenever that edge crosses the line from the source to destination. Obviously, the downside of FACE-2 is that it consumes more energy in the perimeter nodes.

As an extension to the compass routing algorithm, Kuhn et al. [25] introduce deterministic fall back mechanism to get back in the greedy mode from the perimeter routing mode without necessarily exploring the complete face boundary. In [12], Douglas et al. proposed a probabilistic solution called Intermediate Node Forwarding (INF). Negative Acknowledgment (NAK) packet has been adopted to provide feedback to the source about packet drops in this approach.

Li et al. in [27] propose an active message transmission by relaying scheme for communication in a disconnected mobile ad-hoc wireless network. The protocol relays messages using mobile agents by moving nodes appropriately to complete a routing path in a disconnected network. For WSNs, the proposed protocol can avoid routing holes due to sparse deployment or node failures but will fail to achieve any significant results if the routing holes are formed. Yu et al. [48] proposed Geographic and Energy Aware Routing (GEAR) to route a packet toward a region of interest. GEAR works well if the region to be covered is a small fraction of the total area. The efficiency drops quickly when the area of interest increases.

TABLE 1 summarizes the proposed geographic routing schemes and exhibits a comparison.

**TABLE 1**

| *Protocol* | *State maintained* | *Topology adaptive fault tolerance* |
|---|---|---|
| GPSR [22] | Location info and the whole planar graph (RNG or GG) | Right-hand rule in perimeter mode to round the voids |
| Compass Routing [24]<br>FACE II [5]<br>GOAFR+ [25] | Location info and the whole planar graph (GG) | Face routing on planar graph to avoid routing holes |
| INF [12] | Location info | Active NAKs and source initiated repair |
| Active Message Relay [27] | Location info | By node movement to reach disconnected neighbors |
| GEAR [48] | Location info and learned and estimated cost values | Learned and estimated cost for energy efficient geographical routing, and limited flooding in region |

## 3.2 Hole Problems

For most of the geographic routing schemes, a routing hole consists of a region in the sensor network, where either nodes are not available or the available nodes cannot participate in the actual routing of the data due to various possible reasons. In order to prevent the infection to the packet delivery by sensor holes, the geographic routing schemes described in Table 1 do not provide methods to detect and localize the holes. Fang et al. [14] provide a theoretical work on determining sensor holes in which so-called *stuck node* is defined and an algorithm called *BOUNDHOLE* is proposed to find the holes utilizing the strong stuck nodes.

Li and Liu [26] study an application specific scenario for the underground monitoring in coal mine. They propose a topology maintenance protocol SASA, which claims to rapidly detect the structure variation during underground collapse by regulating the mesh sensor network deployment and formulating a collaborating mechanism based on the regular beacon strategy for sensors. The so-called *edge nodes* outline the sensor hole and report it to the sink. To the best of our knowledge, the SASA protocol is the first work which relates the topology variation to the actual geographical changes.

Wood et al. discuss jamming hole in [42]. A jamming hole circumvents the ability of nodes in a specific area to communicate/sense so that a virtual hole emerges. Wood et al. propose a JAM protocol to detect and map jammed regions in a sensor network. The detection part of the protocol applies heuristics based on available data, e.g. bit-error rates etc., to distinguish jamming from normal interference. The JAM protocol assumes that the location information and unique ID is known to each node.

Sink/Black holes and worm holes are gradually formed due to sensor node power exhausted and the possible denial of service attacks in the network. The sink hole is characterized by intense resource contention among neighboring nodes of the malicious node for the limited bandwidth and channel access [41]. Worm hole is another kind of denial of service attack [18]. It is formed when a malicious node causes nodes located in different parts of networks to believe that they are neighbors, which result in incorrect routing convergence.

Karlof et al. [21] analyze the resilience of various routing protocols and energy conserving topology maintenance algorithms against sink holes. They showed that popular routing protocols like directed diffusion, rumor routing and multi-path variant of directed diffusion etc. are all vulnerable to sink holes attacks. For geographical greedy forwarding algorithms it is more difficult to create sink holes because in this case a malicious node has to advertise different attractive locations to different neighbors in order to qualify as next hop. Wood et al. in [41] identified a number of possible defenses against the sink holes. In the authorization solution, only authorized nodes can exchange routing information with each other. The solution is not scalable due to high computation and communication overhead. Also, public key cryptography is not feasible in sensor networks given the capacities and constraints of the sensor devices.

# 4. Topology Control Problems

## 4.1 Sensor Coverage Topology

We break this family of problems into small categories: Static Network, Mobile Network and Hybrid Network.

### 4.1.1 Static Network

For a static sensor network, proposed approaches have different coverage objectives. We introduce these approaches separately.

***Partial Coverage***

In [45], Ye et al. propose PEAS, which extends WSN system functioning time by keeping only a necessary set of sensors working in case the node deployment density is much higher than necessary. PEAS protocol consists of two algorithms: Probing Environment and Adaptive Sleeping. In PEAS protocol, the node location information is not required as a pre-knowledge. Cao et al. [8] develop a near-optimal deterministically rotating sensory coverage for WSN surveillance system. Their scheme aims to partially cover the sensing area with each point eventually sensed within a finite delay bound. Their assumption is that the neighboring nodes have approximately synchronized clocks and know sensing ranges of each other.

***Single coverage***

For single coverage requirement, Zhang et al. [49] have proposed the Optimal Geographical Density Control (OGDC) protocol. This protocol tries to minimize the overlap of sensing areas of all sensor nodes for cases when $Rc \geq 2Rs$ where Rc is the node communication range and Rs is the node sensing range. OGDC is a fully localized algorithm but the node location is needed as a pre-knowledge.

***Multiple coverage***

Wang et al. [40] present the Coverage Configuration Protocol (CCP) that can provide flexibility in configuring sensor network with different degrees of coverage. The CCP protocol needs node location information as assistance. Huang et al. [19] propose polynomial-time algorithms to verify whether every point in the target area is covered by at least the required number of nodes. The authors suggest a central controller entity that can collect the details of insufficiently covered segments and dispatch new nodes to supplement. However, this centralized approach lacks scalability. Yan et al. [44] propose a distributed density control algorithm based on time synchronization among the neighbors. A node can decide its on-duty time such that the whole grid still gets the required degree of coverage.

### 4.1.2 Mobile Network

Wang et al. [39] study the deployment schemes for movable sensors. Given an area to be monitored, the proposed distributed self-deployment protocols first discover the existence of coverage holes in the target area then calculate the target positions and move sensors to diminish the coverage holes. Voronoi diagrams [2, 13]are used to discover the coverage holes and three movement-assisted sensor deployment protocols VEC, VOR and Minimax are designed.

Howard et al. [17] and Heo et al. [16] study the sensor network in the viewpoint of virtual forces. In [17], nodes only use their sensed information to make moving decisions. It is a cost effective and no communication among the nodes or localization information is needed. For the DSS (Distributed Self-Spreading) algorithm proposed in [16], sensors are 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.

### 4.1.3 Hybrid Network

The coverage scenario with only some of the sensors are capable of moving has been under active research, especially in the field of robotics for exploration purpose. The movement capable sensors can help in deployment and network repair by moving to appropriate locations within the field to achieve desired level of coverage.

Batalin et al. [3] suggest a combined solution for the exploration and coverage of a given target area. The coverage problem is solved with the help of a constantly moving robot in a given target area. The algorithm does not consider the communications between the deployed nodes. All decisions are made by the robot by directly communicating with a neighbor sensor node. Wang et al. [38] address the single coverage problem by moving the available mobile sensors in a hybrid network to heal coverage holes.

A comparison of different sensor coverage approaches are listed in Table 2. As you can see from the table, most of the proposed approaches need node location information as assistance and the unit-disk model is widely adopted as a simplification of the node transmitting model.

**TABLE 2**

| ***Category*** | ***Approach*** | ***Proposed Solution*** | ***Main Assumptions*** | ***Characteristics*** |
|---|---|---|---|---|
| Static Network | Partial Coverage | PEAS [45] | Power dynamic adjustment | Distributed sleeping schedule |
| | | Rotating coverage[8] | synchronized clocks, sensing range | Distributed sleeping schedule, guarantee finite delay bound |
| | Single Coverage | OGDC[49] | Location info, uniform sensing disk | Residual energy consideration |
| | | Sponsored Area[36] | Location info. | Sector based coverage calculations |
| | | Extended-Sponsored Area[20] | Location info, synchronized clock | Uniform disk sensing model |
| | Multiple Coverage | CCP[40] | Location info | Configurable degree of coverage. |
| | | k-UC, k-NC[19] | Location info | Non-unit disk model supported |
| | | Differentiated [44] | Location info, synchronized clock | Grid based differentiated degree of coverage |
| Mobile Networks | Computational Geometry | VEC, VOR, Minmax [39] | Location info | Localized, Scalable, Distributed. |
| | | Co-Fi [15] | Location info, Nodes predict its death | Single coverage based. Residual energy considerations. |
| | Virtual Forces | Potential Fields[17] | Range and bearing | Scalable, Distributed. No local communication required. |
| | | DSS[16] | Location info | Scalable, Distributed. Residual energy based. |
| Hybrid Networks | Single Mobile sensor | Single Robot[3] | Location info | Distributed. No multi-hop communications. |
| | Multiple Mobile Sensor | Bidding Protocol[38] | Location info | Voronoi diagram is used for single coverage requirement. |

## 4.2 Sensor Connectivity Topology

### 4.2.1 Power Control Mechanisms

The goal of power control mechanisms is to dynamically change the nodes' transmitting range in order to maintain some property of the communication graph, while reducing the energy consumed by node transceivers because they are one of the primary sources of energy consumption in WSNs. Power control mechanisms are fundamental to achieving a good network energy efficiency. Power control is studied in homogeneous and non-homogeneous scenarios which can be distinguished by examine if the nodes have the same transmitting range or not.

For homogeneous network, the CTR (Critical Transmitting Range) problem has been investigated in theoretical ways as well as practical viewpoints. Narayanaswamy et al. [29] present a distributed protocol, called COMPOW that attempts to determine the minimum common transmitting range needed to ensure network connectivity. They show that setting the transmitting range to this value has the beneficial effects of maximizing network capacity, reducing the contention to access the wireless channel, and minimizing energy consumption. Santi and Blough [34] investigate through simulation the tradeoff between the transmitting range and the size of the largest connected component in the communication graph. The experimental results presented show that, in sparse two and three-dimensional networks, the transmitting range can be reduced significantly if weaker requirements on connectivity are acceptable: halving the critical transmitting range, the largest connected component has an average size of approximately $0.9n$. This means that a considerable amount of energy is spent to connect relatively few nodes.

Non-homogeneous networks are more challenging because nodes are allowed to have different transmitting ranges. The problem of assigning a transmitting range to nodes in such a way that the resulting communication graph is strongly connected and the energy cost is minimum is called the Rang Assignment (RA) problem, and it was first studied in [23]. The computational complexity of RA has been analyzed in [10, 23]. It is shown to be NP-hard in the case of 2D and 3D networks. However the optimal solution can be approximated within a factor of 2 using the range assignment generated in [23]. An important variant of RA has been recently studied is based on the concept of symmetry of the communication graph. Due to the high overhead [28] needed to handle unidirectional links in routing protocols or MAC protocols which are naturally designed to work under the symmetric assumption, Symmetric Range Assignment (SRA) shows more practical significance. However, Blough et al. [4] show that SRA remains NP-hard in 2D and 3D networks, and it even incurs a considerable additional energy cost over RA. We can refine SRA to WSRA (Weakly Symmetric Range Assignment) which weakens the requirement that the communication graph contains only bidirectional links by allowing the existence of the unidirectional links but requiring the symmetric subgraph of the communication graph resulting from RA connected. In the released WSRA problem, only marginal effect on the energy cost has been induced while the desired symmetry property has been kept. Two polynomial approximation algorithms for WSRA have been introduced by Calinesc et al. [7].

A lot of power control approaches have been proposed which try to design simple and practical protocols that build and maintain a reasonably good topology. Rodoplu and Meng [33] 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. Pan et al. [31] consider a two-tired Wireless Sensor Network (WSN) consisting of sensor clusters deployed around strategic locations and base-stations (BSs) whose locations are relatively flexible.

### 4.2.2 Power Management Mechanisms

Power management is concerned of which set of nodes should be turned on/off and when, for the purpose of constructing energy saving topology to prolong the network lifetime. It can utilize information available from all the layers in the protocol stack.

In GAF approach [43] proposed by Xu et al., nodes use location information to divide the field into fixed square grids. The size of each grid stays constant, regardless of node density. Nodes within a grid switch between sleeping and listening mode, with the guarantee that one node in each grid stays up so that a dynamic routing backbone is maintained to forward packets. (Fig. 21 gives the example of virtual grid)

Chen et al. [9] propose Span, a power saving topology maintenance algorithm for multi-hop ad hoc wireless networks which adaptively elects coordinators from all nodes to form a routing backbone and turn off other nodes' radio receivers most of the time to conserve power.

Schurgers et al. [35] proposed STEM approach, which exploits the time dimension rather than the node density dimension to control a power saving topology of active nodes. They switch nodes between two states, "transfer state" and "monitoring state". Data are only forwarded in the transfer state. In the monitoring state, nodes remain their radio off and will switch into transfer state to be an initiator node on event detected. The extended study on combining STEM and GAF shows the potential of further power saving by exploiting both time dimension and node density dimension.

**TABLE 3**

| ***Protocols*** | ***Mechanism type*** | ***Mobi/Static*** | ***Synchronization*** | ***Location info*** | ***Distributed*** |
|---|---|---|---|---|---|
| Span[9] | Power management | Static | None | No | Yes |
| Asynchronous Wakeup protocol [50] | Power management | Static | None | No | No |
| Power saving protocol [37] | Power management | Mobile | None | No | Yes |
| GAF[43] | Power management | Mobile | None | Yes | Yes |
| STEM[35] | Power management | Static | None | No | Yes |
| S-MAC[46] | Power management | Static | Yes | No | Yes |

Zheng et al. have studied asynchronous Wakeup schedules for Wireless Ad Hoc Networks in [50]. They derive the theoretical limit of the wakeup schedule and prove that the lower bound is achievable by a constructive method. The proposed protocol needs optimal symmetric wakeup schedule function (WSF) design as a basis in the network initialization process.

Some MAC layer protocols [11, 32, 46, 47] are also proposed to maintain nodes sleep schedule and wake up nodes dynamically to create energy efficient network topological styles.

Table 3 summarizes the power management mechanisms, and gives us an in-depth knowledge of the characters of proposed mechanisms.

# 5. Conclusions and Future Research Directions

In this survey paper, we reviewed two major topology issues in WSNs, namely topology awareness and topology control. Topology awareness problems take the approach of constructing applications or upper protocols to conform the underlying topology. Typical approaches applied in this category do not actively consider improving the topology itself for the specific applications. Topology control mechanisms focus more on constructing an energy-efficient and reliable network topology and normally do not touch the concrete applications above the topology. So the first major question we raise is how to relate the topology control mechanism to the upper topology aware applications more tightly in WSNs.

For topology control problems, sensor coverage topology and sensor connectivity topology have been separately discussed in most of the literatures. However, while the sensing coverage topology represents the network sensing ability, the connectivity topology should as well maintained as a necessity for the successful information delivery, including queries, sensing data and control messages. How to construct an optimized coverage topology while maintaining efficient and low cost connectivity is not well understood and deserves further studies.

Power control and power management are two different types of topology controlling methods. The combination of the two has not yet well studied. We believe by integrating power control and power management, it is possible to provide noticeable improvements on network topology and efficiencies of energy usage. This is another interesting research topic for the researchers in the field.

In this paper, we present a comprehensive survey on topology issues for WSNs. We provide our classifications of the problems and approaches. Under this frame, we list, review and compare some classical works in the field. At last, we highlight the challenges in this topic and point out some future research directions.

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