Overview of Topology Control in Wireless Sensor Networks

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Abstract

Topology control is one of the most importance issues in performance optimization for wireless sensor network. It can prolong network lifetime, reducing radio interference, ensuring network connectivity and coverage. In this survey paper, we discuss the design object of topology control, study the different network topology models and graph models which used in topology control, typical topology control algorithms are also analyzed through the angle of power control and sleep scheduling. Finally, we summarize the present situation and problems which still remained to be solved.

Keywords: Wireless Sensor Networks, Topology Control, Topology Structure, Topology Algorithm

1. Introduction

Wireless sensor networks (WSNs) has gained worldwide attention in recent years. These sensors are small, with limited processing and computing resources, and they are inexpensive compared to traditional sensors. These sensor nodes can sense, measure, and gather information from the environment and based on some local decision process, they can transmit the sensed data to the user. Smart sensor nodes are low power devices equipped with one or more sensors, a processor, memory, a power supply, a radio, and an actuator. The applications of WSNs range from important social issues such as environmental and habitat monitoring, traffic control, emergency scenarios, and health care, to economical issues such as production control and structure monitoring[1-6].

Topology control is one of the most fundamental problems in wireless sensor networks. Firstly, topology control is of great importance for prolonging network lifetime; Secondly, topology control can reducing radio interference, increasing efficiency of MAC(media access control) protocols and routing protocols; Thirdly, topology control can ensuring network connectivity and coverage, increasing quality of network services; Finally, topology control can improving network performance.

This paper analyses network and graph models involved in design topology control, discusses topology control mechanism in WSNs, summarizes current work, relevant evolution and challenges.

The rest of the paper is organized as follows: Section 1 describes the design objectives. Section 2 discusses the network models in designing the different topology control algorithms. Section 3 describes the graphs usually used in topology control. Section 4 reviews the topology control mechanism about power control and state scheduling. Section 5 presents the problems and future research in topology control. Finally, we conclude this survey in Section 6.

2. Design object

Design objectives of topology control variation with the different application of WSNs. In the section, we introduce the design objectives which we generally consideration.

A. Network Coverage

Coverage is a method for evaluating the QoS of WSNs. In network coverage, the most important factor is network sensing capability of physics world [7]. The problems of coverage can be divided into district coverage, point coverage and barrier coverage [8]. If each point in the object district is monitored by \( k \) sensors, the network is called \( k \)-coverage. In 1-coverage, each point in object district is required to be monitored by a sensor.

B. Network Connectivity

WSNs is a large-scale network, sensory data need to be sent to sink through multiple hops, this
requires topology control must proves the connectivity of network. If at least \( k \) sensors are taken out and network becomes disconnected, the network is called \( k \)-connectivity, topology control must prove the network is 1-connectivity. Power control and state scheduling must ensure network connectivity which is the basic require of topology control.

C. Network Lifetime

The lifetime of WSNs is generally limited by the battery lifetime of the sensor nodes. Maximize the network lifetime of a power is certainly one of the most important design objectives for WSNs, lifetime can be defined as the duration time which percentage of dead nodes below a threshold. It also can be defined as the measure of network QoS, current topology control mechanisms use power control and state scheduling to minimize energy consumption and prolong network lifetime.

D. Network Throughput

Assume object district is a bulge district, the throughput rate is \( \lambda \) bit/s. In perfect condition, we have following equation[9]: \( \lambda \leq \frac{16AW}{\sqrt{\pi}Lnr} \), where \( A \) is the area of object district, \( W \) is the fastest transmission rate of nodes, \( \pi \) is circumference ratio, \( \Delta \) is a constant which is greater than zero, \( L \) is the average distance from original node to object node, \( n \) is the number of nodes, \( r \) is radio radius.

E. Topology Properties

In fact, it is very difficult to judge whether network topology is good or not according to design objectives, when design the scheme of topology control (especial power control), we always pursuit excellent topology properties such as connectivity, symmetry, planarity, extensibility and so on.

F. Energy Consumption

Since sensor node is very easy to failure, if energy of some nodes are depleted before the others, energy holes may appear in the sensing coverage or the sensor network may become disconnected. Some mechanisms strive to balance energy consumption among the sensors by round robin operation.

3 Modeling of WSNs

In this section, in order to analysis topology control mechanism, several important components of system model such as topology structure, energy consumption and lifetime modeling are introduced.

A. Topology Structure

According to function and structure arrangement, WSNs can be classified as flat network, hierarchical network and hybrid network. It is very important to study and exploit the effective, practicality network structure, because topology structure is very crucial to design network protocol.

Figure 1 shows the structure of flat network. In flat network, all nodes are considered to be same nodes and perform the same functionalities. The topology structure is simple, easily maintenance, and has good robustness, however the structure has no management central, it adopts self-organize cooperate algorithm to form network, and the algorithm is relatively complicate. Figure 2 shows the structure of hierarchical network. Hierarchical network includes top layer and underlay. Top layer have many backbone nodes, underlay have many ordinary nodes. Flat network structure is used between backbone nodes and ordinary nodes. The topology structure is very easy to management, and has advantage of expansibility, however it needs more expensive hardware. Figure 3 shows the structure of hybrid network. Hybrid network is integration of the above two structures, flat network structure is used between backbone nodes and backbone, or used between ordinary nodes and ordinary nodes. Hierarchical network structure is used between backbone nodes and ordinary nodes. Hybrid network structure has superior function than others structure. However, it need more expensive hardware.
B. Modeling Energy Consumption

In WSNs, energy consumption is one of the most important issues because each sensor node has a limited energy level. If all nodes in a dense sensor network become involved in sensing, redundancy will be increased and this will lead to consumption of unnecessary energy. Thus, it is fundamental to model the node energy consumption accurately.

Network lifetime is directly related to the sensors lifetime and in other words the energy dissipated in the sensor nodes. The consumed energy in sensors includes the energy required for sensing, receiving, transmitting and processing of data. The total consumed energy is usually dominated by the required energy for data transmission. Two cases may be considered for the transmission mode of the nodes in the network. In the first case, nodes transmit with a fixed transmission power. This usually results in a fixed transmission range. In the second case, nodes use a mechanism to adjust their transmission power based on their distance to the next hop or the sink. Hence, the required energy for a packet transmission in sensor $i$ can be modeled as $e(d_i) = l(e_i d_i^\alpha + e_o) = kd_i^\alpha + c$ [10], where $l$ represents the packet length in bits, $d_i$ denotes the distance between sensor $i$ and the next hop, $\alpha$ represents the path loss exponent, $e_i$ shows the loss coefficient related to 1bit transmission and $e_o$ is the overhead energy due to the sensing, receiving and processing for the same amount of data, $k = le_o$ and $c = le_o$ represent the loss coefficient and the overhead energy for a packet transmission respectively. The path loss exponent depends on the local terrain and is determined by empirical measurements. The typical value of $\alpha$ for WSNs is from 2 to 4.

C. Lifetime Modeling

Lifetime of WSNs is defined as the time after which certain fraction of sensor nodes run out of their batteries, resulting in a routing hole within the network. The lifetime modeling of WSNs study here applies to any definition of the network lifetime.

For a WSNs with total non-rechargeable initial energy $\epsilon_0$, the average network lifetime $T$, measured as the average amount of time until the network dies, is given by $T = (\epsilon_0 - T_o)/(P_c + \lambda T_r)$, where $P_c$ is the constant continuous power consumption over the whole network, $T_o$ is the expected wasted energy (i.e. the total unused energy in the network when it dies), $\lambda$ is the average sensor reporting rate defined as the number of data collections per unit time, and $T_r$ is the expected reporting energy consumed by all sensors in a randomly chosen data collection. The lifetime formula provides a quantitative characterization of key components that affect network lifetime under a general network setting. Specifically, a lifetime maximizing protocol should aim at reducing the average wasted energy $T_o$ and the average reporting energy $T_r$.

The above formula can be easily extended to include other energy consumption sources. For example, to include the energy consumed in network maintenance, we obtain the following formula via a derivation similar to that given above. $T = (\epsilon_0 - T_o)/(P_c + \lambda T_r + \eta T_m)$, where $\eta$ is the maintenance rate.
of the network which shows how often the maintenance is performed, and $T_m$ is the expected energy consumed in a randomly chosen network maintenance.

4. Graphs in topology control

Network topology can be represented by the graph, graph models used in WSNs are usually based on proximity graph theory or probability graph theory. This section introduces various proximity graph and probability graph models which represent local connections between sensor nodes in WSNs. Figure 4 shows the structure of graph model.

![Graph Model Diagram]

**Figure 4.** Structure of graph model

**A. Unit Disk Graph (UDG)**

In geometric graph theory, a unit disk graph is the intersection graph of a family of unit circles in the Euclidean plane. That is, we form a vertex for each circle, and connect two vertices by an edge whenever the corresponding circles cross each other.

For WSNs, circles represent the communication range of a sensor node and if two or more circles sufficiently cross one another than there is communication link between sensor nodes. UDG model is used extensively to calculate interference and capacity of WSNs.

**B. Yao Graph and Undirected Yao Graph**

Given a set $N$ of points in the plane, and an integer $k \geq 6$, the Yao Graph of parameter $k$ is the directed graph $YG_k = (N, E_k)$ defined as follows. At each node $u \in N$, divide the plane into $k$ equally sized cones originating at $u$. Denoting by $c_u^1, ..., c_u^k$ the cones for node $u$, we have that $(u, v) \in E_k$ if and only if there exists cone $c_u^i$ such that $v$ is the closest neighbor of $u$ in $c_u^i$.

Undirected Yao graph Given a set $N$ of points in the plane, and an integer $k \geq 6$, the Undirected Yao Graph of parameter $k$ is the graph $UYG_k = (N, E_k)$, where $(u, v) \in E_k$ if and only if either edge $(u, v)$ or edge $(v, u)$ is in $YG_k$.

Normally in WSNs sensor nodes are deployed with omnidirectional antennas but in some case it uses directional antennas where this model well captures the directionality.

**C. Relative Neighborhood Graph (RNG) and Gabriel Graph (GG)**

Let $S$ be a set of $n$ points in $\mathbb{R}^d$. The relative neighborhood graph of $S$, denoted RNG($S$), is a graph $(S, E)$, where a pair of points $(p, q) \in E$ if and only if $d(p, q) \leq \max\{d(p, z) \cap d(q, z) / d(p, q)\}$.

Here $d(\ldots)$ is the Euclidean distance. In other words, $(p, q)$ is an edge of RNG($S$) if the lune of $p$ and $q$ defined as the set of points $\lambda(p,q) = \{z \mid d(p, z) < d(p, q) \cap d(q, z) < d(p, q)\}$ does not contain any point of $S$.

Given a set $N$ of points in the plane, the Gabriel Graph (GG) of $N$ is the graph $GG = (N, E)$ such that $(u, v) \in E$ if and only if the circle that has segment $\overline{uv}$ as diameter does not contain any other point of $N$ in its interior.

In real network, interference due to neighboring nodes is reality and one has to consider those details in modeling of network connectivity. One of the ways to overcome this interference problem is by making underlying network topology as planner graph. RNG and GG are the two graphs with...
provide such a microscopic constrain that produces the planner graph at macroscopic level. The graphs consider interference of neighboring nodes while defining the connectivity of network. In WSNs when transmission power is proportional to the square of the distance, GG graph is a effective topology in energy saving. 

D. Random Graphs and Geometric Random Graphs (GRG)

A well-established theory that at first glance seems useful in the analysis of WSNs properties is the theory of random graphs. In this theory, a graph is formed by inserting a certain number of edges between random nodes in the graph. Unfortunately, random graph theory cannot be directly applied in the investigation of WSNs properties since a fundamental assumption in this model is that the probabilities of edge occurrence in the graph are independent, which is not the case in the context of WSNs. While traditional random graph theory is not very useful in the theoretical analysis of fundamental WSNs properties, a more recent and still-in-development applied probability theory turns out to be very useful to this purpose: the theory of Geometric Random Graphs (GRG). The theory of GRG can be seen as an extension to the traditional random graph theory in which the graph is not considered as an abstract entity (set of nodes connected by a number of edges), but as a geometric entity (set of points in the d-dimensional space, connected on the basis of a proximity relation). In a typical GRG model, a set of n points is distributed in a d-dimensional region $\mathbb{R}$, and asymptotic properties of the resulting node placement for $n \to \infty$ are investigated.

The theory of GRG has been used in several recent papers to study fundamental WSNs properties, such as the critical transmitting range for connectivity and k-connectivity, the critical neighbor number, and the cost of the optimal solution to the RA and WSRA (Weakly Symmetric Range Assignment) problem.

5. Relative works

The studies of topology control mechanism is mainly focus on the objectives of how to prolong the network lifetime and can be classified as power control and state scheduling. Table 1 summarizes the different algorithm of topology control and exhibits a comparison. Figure 5 shows the taxonomy of topology control mechanism.

![Figure 5. Taxonomy of topology control mechanism](image)

5.1 Power control

A. Power control combined with routing protocol

Power control is a complex problem, Kirousis et al. simplified it as the problem of transmission range assignment. Regard $N = \{u_1, \ldots, u_n\}$ is the point set which can represent the position of nodes in $d$ dimension, $r(u_i)$ is the transmission radius of node $u_i$. The problem of range assignment is to make transmission power minimum. In one dimension, transmission range assignment can be solved in multinomial time while it is NP-hard in two and three dimensions. The COMPOW (Common Power) protocol [11] is the first proposal appeared in the literature that explicitly deals with different node transmit power level. Narayanaswamy et al. consider a relatively simple setting in which all the network nodes are forced to use the same transmit power level. Since all the nodes are forced to use the same power level, a single, faraway node can cause a generalized power level increase. To solve this problem, Kawadia and Kumar release the assumption of using a common power level, and define a protocol for joint topology control and routing that induces an implicit power-level-based clustering on the nodes which is called CLUSTERPOW (Cluster Power) [12]. The CLUSTERPOW protocol displays many similarities with the simpler COMPOW protocol. As in COMPOW, every node in the network
maintains separate routing tables, one for each power level. Routing table $RT_i$, referring to power level $P_i$, is maintained by exchanging hello messages at power level $P_i$. When node $u$ has to send a message to node $v$, it calculates the minimum power level needed to reach node $v$: it is the minimum level $P_i$ such that $RT_i$ contains an entry for node $v$. Then, the packet is sent using this minimum power level. This process of calculating the minimum power level needed to reach the destination is repeated at each intermediate node in the route from the source to the destination. The main problem of CLUSTERPOW is expending to large.

B. Power control based on nodes degree

Ramanathan et al. proposed LMA and LMN algorithms based on nodes degree [13]. The basic idea is give the upper limit and lower limit of nodes degree, every node adjust transmission power, and each node degree falls between the upper limit and lower limit. However the algorithms can not guarantee the network connectivity.

C. Power control based on direction

Wattenhofer et al. proposed CBTC (Cone-based Topology Control) protocol algorithm[14] to ensure the network connectivity. The basic idea is set the transmission power level of node $u$ to the minimum value $p_u$, such that $u$ can reach at least one node in every cone of width $\rho$ centered at $u$.

In other words, a node must retain connections to at least one neighbor in ‘every direction’, where parameter $\rho$ determines the granularity of what is meant by ‘every direction’. The algorithm need the reliable direction information, so it is very crucial to acquire the angle of arrive. Nodes should be equipped with multiple directional antennae, and this requires high cost for sensor nodes.

D. Power control based on proximity graph

Li and Hou proposed two representative algorithms based on proximity graph theory, Directed Relative Neighbourhood Graph (DRNG) and Directed Local Minimum Spanning Tree (DLMST) [15]. All nodes use maximum transmission power to form the topology graph $G$, and find proximity graph $G'$ according to some criterion, each node decides its transmission power in order to communicate with the farthest neighbourhood. Both algorithms can guarantee the network connectivity, and have good capability in average transmission power and node degree. However, power control based on proximity graph generally requires accurate location information.

5.2 State scheduling

Power control prolong network lifetime through lower transmission power of nodes without consider energy consume and coverage redundance during detection. In fact, the receiving and idle modes may require as much energy as transmitting ,and coverage redundacy also consumes much energy. Only all of the nodes are in sleep mode can reduce energy consume greatly. State scheduling mechanism is quite effective for high density networks and event-driven networks.

If all nodes are considered to be same type and performs same functionalities for entire network life cycle, the network named flat network or non-hierarchical network, otherwise named hierarchical network. Several state scheduling algorithms are stated as follows:

A. State scheduling in flat network

The basic idea of state scheduling in flat network is each node control the conversion between work status and state status. Each node is not belong to a certain cluster, and is not influenced by cluster head .

Kumar et al. proposed a simple state scheduling algorithm which we call Randomized Independent Sleeping (RIS) [16]: Time is divided into periods. At the beginning of a period, each node independently decides whether to remain awake for this period (with probability $p$) or go to sleep (with probability $(1-p)$). With this approach, the expected lifetime of the network can be increased by a factor close to $1/p$. RIS uniform duty cycle and balances the energy consumption in the network, however it requires strict time synchronization.

Berman et al. presented Maximization of Sensor Network Life (MSNL) in [17], formulated the state scheduling problem as a network lifetime maximization problem with constraints on sensing coverage. When nodes are in transition mode, monitor district can not be covered by active nodes and transition nodes, the mode will be changed into active mode immediately, otherwise changed into sleep mode. MSNL requires accurate location information, and neighborhood nodes will enter into the sleep mode simultaneously.
Wu et al. introduced a Lightweight Deployment-Aware (LDAS) without location information in [18]. It is very difficult to confirm whether sensing areas of a node is covered by other nodes without location information. Wu think even all nodes are in active state, it also very difficult to guarantee full coverage for a given deployment area. So LDAS is only adapt to the condition of node distribution uniform.

Cerpa and Estrin proposed an Adaptive Self-Configuring Sensor Networks Topologies (ASCENT) to maintain a data delivery [19]. In ASCENT, each node assesses its connectivity and adapts its participation in the multi-hop network topology based on the measured operating region. ASCENT neither can ensure network connectivity nor ensure uniform energy consumption.

Ye et al. developed a protocol called Probing Environment and Adaptive Sensing (PEAS) suitable for high-density sensor [20]. In PEAS, each node has three status: sleeping, probing and working. Firstly nodes are in the status of sleeping, when sleeping timer overflow, nodes enter into working status, and broadcast detecting message as a certain transmission radius, if a node receives acknowledge, it will enter into sleeping status, otherwise it will enter into probing status until energy deplete. PEAS can provides asymptotic connectivity.

Wang et al. proposed a Coverage Configuration Protocol (CCP) [21], the basic idea is maximize the number of sleeping nodes under the condition of K-coverage and K-connectivity. When transmission radius is two times of sensing range, if network K-coverage a bulge region, then the network must be K-connectivity. CCP can ensure the network connectivity through transmission range. Xing et al. proposed integrate CCP with SPAN[22]. In SPAN, nodes adaptive become backbone nodes or enter into sleeping status, sleeping nodes revival period to determine themselves whether become backbone nodes or not, backbone nodes also determine themselves whether quit or not. SPAN only keeps the original connectivity of network while it cannot configure the network to the designated connectivity.

B. State scheduling in hierarchical networks

In hierarchical network, nodes are divided into cluster heads and form the backbone network, the key technology of state scheduling in hierarchical network is cluster.

Heinzelman et al. proposed Low-Energy Adaptive Clustering Hierarchy (LEACH) [23]. LEACH takes a hierarchical approach and organizes nodes into clusters. Within each cluster, nodes take turns to assume the role of a cluster head. The cluster head node sets up a schedule and transmits this schedule to all nodes in its cluster. LEACH assumes that cluster nodes start the cluster setup phase at the same time and remain synchronized thereafter. LEACH requires strict time synchronization, and does not ensure uniform distribution of cluster heads.

Deng et al. proposed a Linear Distance-based Scheduling (LDS) [24]. LDS is an algorithm based on cluster which adapt to high density network, LDS only considers sleep scheduling within cluster and assumes cluster architecture is already exist. LDS can not ensure uniform energy consumption.

Xu et al. proposed a geographical adaptive fidelity (GAF) algorithm [25]. Each GAF node uses location information to associate itself with a virtual grid, where all nodes in a particular grid square are equivalent with respect to forwarding packets. Nodes in the same grid coordinate with each other to determine who will sleep and how long. Nodes periodically wake up and trade places to accomplish load balancing. In GAF any node in adjacent grid can communicate with each other. GAF requires accurate geographic locations and a high standard for node sensors. GAF neither considers the near distance between nodes in real network can represent the problem of direct communication between nodes, nor ensures the uniform energy consumption.

Deb et al. proposed a topology discovery algorithm (TopDisc) based on minimum dominating set (MDS) in graph theory [26]. TopDisc utilize color to distinguish node status and solve the problem brought by the form of backbone network topology structure. TopDisc afford three color and four color algorithm to label node status. Other TopDisc algorithm gives a new method to choose cluster head, the algorithm can make nodes form cluster structure rapidly in network which deployed many nodes, and build cluster tree relationship between cluster head. However the hierarchical network is not very flexible, the algorithm neither consider die of nodes and join of new nodes nor consider remain energy and geography location.

Younis and Fahmy presented Hybrid Energy-Efficient Distributed Clustering (HEED) [27]. HEED does not rely on the scale of networks, and forms clustering by constant iteration. HEED comprehensive takes lifetime, extendibility and load balance into account, and does not require peculiar requirements for deployment and capability of nodes. Although HEED execution does not require synchronization, nonsynchronization will have serious impact on clustering quality.
6. Problem and future research directions

The researches of WSNs topology control have made many progresses, researcher draw many lessons from Ad Hoc, and put forward many topology control algorithms according to the characteristic of WSNs. However many problems about the algorithms still exist, such as mathematic models are too ideal without consider the problems in practice application; Lack definitude and practicality algorithm about topology problem; Lack efficient measure about network performance; Position of topology control in protocol stack has not been make certain; Researches lack persuasive experiment results.

In order to solve the above problems, future research directions should put emphases on the following themes: Evaluate mechanism of communication link quality and selecting policy of neighbour nodes; Set up self-adaptive policy of topology structure; Study topology control scheme toward application-oriented.

In conclusion, the trend of topology control research in WSNs is application-oriented, various mechanism intermingling, self-adaptive and robustness. Under the condition of network connectivity and coverage to improve communication efficiency and prolong network lifetime.

7. Conclusion

Topology control is the key technology and hot topic in WSNs. In this survey paper, we try to cover the spectrum of topology control in WSNs, from basic theory to topology control mechanism, finally we highlight the challenges in WSNs and point out some future research.

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9. References


