A Survey of Topology Control in Wireless Networks

Hong-sheng CHEN, Bo CHEN* and Chun-hui WU

School of Computer Science and Technology, Hubei University of Science and Technology, Xianning 437005, China

*Corresponding author

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Abstract. Wireless Sensor Networks (WSNs)/Mobile Ad hoc Networks and Delay-tolerant Networks have many applications in recent years. Topology control is one of the most important research topics in wireless networks. It not only can prolong the lifetime of the network but also reduce the signal interference. Therefore, the research of topology control is of great significance. This paper analyzes and summarizes the main directions and research results of topology control problem of wireless networks in recent years, at the same time classifies and summarizes the topological control solutions in wireless sensor / mobile ad-hoc networks and delay tolerant networks, finally, points out the shortcomings and future research directions.

Introduction

With the rapid development of electronic technology, wireless sensor/ad hoc networks and delay tolerant networks have been widely used in our daily life and work, especially in the harsh environment where the network infrastructure is unavailable, such as mine monitoring, environment monitoring, battlefield reconnaissance, underwater monitoring, coastal and border protection, target tracking, and so on. However, due to the limited onboard energy, sensor nodes are easily to failure in harsh environment, which may lead the network damaged. Thus, how to save energy and prolong the life cycle of the network while ensuring network connectivity is very important.

Topology control can solve above problem. The aim of topology control is to maintain the topology of the network with least energy cost while ensuring network connectivity, throughput and coverage. Thus topology control can extend the life cycle of the network and can reduce signal interference. Due to its own characteristics in the sensor network, it can control the energy consumption by adjusting its transmit power, it can also save energy by adjusting the state of the sensor, such as sleep or activity, can also cluster all nodes by clustering algorithm, rotation select the cluster head node, through the cluster head node communication between the entire network to achieve data transmission. However, there are several performance metrics and factors that must be considered in topology control: Performance metrics include connectivity, coverage, throughput, etc. Considerations include limited energy, limited bandwidth, dynamic topology changes, and unstructured (Wireless mobile ad hoc and delay tolerant networks), intermittent connections (delay tolerant networks) and scalability.

Connectivity: It refers to the nodes of the networks can communicate with each other freely. Connectivity includes single-connectivity, double-connectivity and multi-connectivity. The more connectivity, the more robust the network.

Coverage: It refers to the coverage of the network, especially in the sensor network refers to the scope of monitoring or detection, which plays an important role in the decision-making. The higher of the coverage the decision-making effect will be better.

Throughput: It refers to the data transmitting capability of the entire network in the unit of time. Suppose the target region is a convex region, the throughput of each node is $\lambda$ bits / s, in the ideal case, there is the following relation (1):
\[ \lambda \leq \frac{16AW}{\pi\Delta L} \text{bit/s} \]  

(1)

\( W \) is the highest transfer rate of the node, \( A \) is the area of the target region, \( \Delta \) is a constant greater than zero, \( \pi \) is the pi, \( L \) is the average distance from the source node to the destination node, \( n \) is the number of nodes, \( r \) is the transmission radius of the ideal spherical radio transmission model.

Limited energy: Compared with the other electronic devices, the sensor is very small, low cost, easy to deploy, but its energy is limited, only through limited battery power supply equipment. Of course, there are solar energy. But it is restricted with the environmental and technical constraints, thus most of the current sensor is still battery-powered. As soon as the energy is exhausted, the sensor will be failed, so it is very important to save energy during topology control in network.

Limited bandwidth: The bandwidth of wireless networks is limited due to their own reasons, such as IEEE 802.11 and ZigBee, which are commonly used nowadays, and their upper limits are only 54Mb/s and 250Kb/s, respectively. In practical applications, the maximum bandwidth that can’t achieved the theoretical value due to signal interference caused by simultaneous communication. Therefore, it is very important to maintain proper transmission load in network topology control.

Dynamic Topology and Unstructured: In general, communication devices in wireless networks (such as WSN) are randomly deployed in a certain region, so the communication links between them may be unstable, especially in harsh environment. For ad-hoc and delay-tolerant networks, many devices are mobile, and the topology of the entire network is dynamically changing with time-varying. Therefore, it is very important to topology control in the network by setting related parameters.

Intermittent connection: Compared with the wired channel, the communication reliability of the wireless channel is poor, and the communication quality is affected by external environmental factors. Therefore, in wireless ad hoc networks and delay tolerant networks, communication between devices is intermittent due to real-time dynamic movement of communication devices. Thus, how to maintain a topology to ensure the data can be transmitted to the destination node with minimum energy cost under intermittent communication conditions is a challenging issue in topology control.

Scalability: Depending on the scenario considered, WSNs might be composed of several thousands of sensors. Thus, the scalability of the proposed topology control is suitable for large-scale sensor networks.

**Topology Control Classification**

Currently, a lot of researchers focus on topology control in wireless networks, and obtained the remarkable results. The methods of topology control may be divided into the following categories: power adjustment based, power mode based, connected dominating set based, hybrid structure based (including combing power adjustment based and connected dominating set based, power mode based and connected dominating set based), topology control based on connected dominating set can also be subdivided into geometry based and clustering based.
Power Adjustment

The method of power adjustment refers to reduce the energy consumption of transmitting data by adjusting the power of nodes instead of transmitting data with maximum power. The nodes cooperate with each other to adjust the power to find a suitable transmission power to form a connected network. In practice, only a limited number of power values per node can be adjusted, for example, Mica 2 supports 30 different power values and Telos nodes only have 8 different power values. However, in these limited power values, it is also possible to design the algorithm to adjust the power of nodes to minimize the total energy consumption while ensuring network connectivity. MECN[2], SMECN[3] and COMPOW[4] are all through power adjustment to reduce energy cost. These methods are all improve the throughput of the network, reduce the energy cost and signal interference.

Power Mode

The sleep scheduling method uses the features that the wireless node network interface has different power modes to save energy. Each node has four power modes: sleep, monitor, transmit and receive. The transmit and receive modes consume much higher energy than the sleep mode[5], continuous monitoring is also consume a lot of energy. Therefore, the state of the redundancy monitoring nodes can be switched to sleep state to save energy. This feature has been used in topology control to optimize power consumption and extend network lifetime without reducing network capacity and affecting connectivity.

GAF[6] conserves energy by identifying nodes that are equivalent from a routing perspective and then turning off unnecessary nodes, keeping a constant level of routing fidelity. STEM[7] algorithm is for managing power at the distributed system level, rather than just at the individual node level. This distributed algorithm determine which set of sensor nodes will be tasked with a given user query and which sensor nodes will remain in an idle state conserving power. ASCENT[8] builds on the notion that, as density increases, only a subset of the nodes are necessary to establish a routing forwarding backbone. In ASCENT, each node assesses its connectivity and adapts its participation in the multi-hop network topology based on the measured operating region.

Above methods are all through scheduling power mode to reduce energy consumption.

Connected Dominating Set

A dominant set refers to a subset of the graph that satisfies the following conditions: every node outside this subset has at least one immediate neighbor belonging to the dominant set. The connected graph consisting of dominant nodes is called Connected Dominance Set (CDS), which reduces the communication load and energy. Generally, wireless network can be modeled as a graph, thus topology control problem is converted to find the minimum connected dominating set. But this problem is NP-Hard. Therefore, many researches focus on this problem. Connected dominating set can also be subdivided into geometry based and clustering based.

1) Clustering Based

The main idea of clustering based topology control is to select a node set in the network to construct an efficient hierarchical topology. Many cluster methods use the CDS to build virtual backbones.

PACDS[9] is a method of calculating power-aware connected dominating set for topology control. ECDC[10] is a novel energy efficient distributed connected dominating set algorithm based on coordinated reconstruction mechanism is presented to further prolong the network lifetime and balance energy consumption. TMPO[11] is a distributed topology management algorithm that constructs and maintains a backbone topology based on a minimal dominating set (MDS) of the network. According to this algorithm, each node determines the membership in the MDS for itself and its one-hop neighbors based on two-hop neighbor information that is disseminated among neighboring nodes.
2) Geometry Based

Geometry based topology control have been widely used in wireless networks, especially in WSNs and Ad hoc networks.

Literature [12] and [13] proposed a topology control algorithm for each node to establish its own local minimum spanning tree based on the energy consumption weighted graph, and used it to save the neighbor nodes in the hop node of the tree node in order to adjust the network topology. Angand C W and Tham C K [14] propose an algorithm, iMST, that attempts to maximize average channel utilization by reducing interference. Literature [15] propose a family of structures, namely, k-localized minimum spanning tree (LMSTk) for topology control and broadcasting in wireless ad hoc networks.

Above methods are all geometry based topology control in WSNs and Ad hoc networks, but in DTNs, the research of topology control is less, that’s because the topology of DTNs is dynamic changing with time-evolving. Huang M et al[16-18] study the topology control problem in a predictable DTN, where the time-evolving network topology is known a priori or can be predicted. They first model such time-evolving network as a directed space-time graph that includes both spacial and temporal information. The aim of topology control is to build a sparse structure from the original space-time graph such that 1) the network is still connected over time and supports DTN routing between any two nodes; 2) the total cost of the structure is minimized. Chen et al[19-21] also proposed topology control for PDTNs based on Probability and spanning tree, they also proved this problem is NP-Complete, and proposed heuristic algorithms, and they are all efficiently in energy cost and connectivity.

Hybrid

Hybrid approach refers to the use of two or more methods in combination to achieve topology control, for example, combining the cluster structure and power adjustment can reduce power consumption better.

SPAN[22] is a power saving technique for multi-hop ad hoc wireless networks that reduces energy consumption without significantly diminishing the capacity or connectivity of the network. CLUSTERPOW[23] aims to increase the network capacity by increasing spatial reuse. They provide a simple and modular architecture to implement CLUSTERPOW at the network layer. LEACH[24] is a clustering-based protocol that utilizes randomized rotation of local cluster based station (cluster-heads) to evenly distribute the energy load among the sensors in the network.

Table 1 is the performance comparison of above topology control algorithms in terms of time complexity, information complexity, distributed, connectivity, and mobility.

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Time Complexity</th>
<th>Information Complexity</th>
<th>Distributed</th>
<th>Connectivity</th>
<th>Mobility</th>
</tr>
</thead>
<tbody>
<tr>
<td>MECN</td>
<td>O(V^3)</td>
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<td>Yes</td>
<td>High</td>
<td>Low</td>
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<tr>
<td>SMECN</td>
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<td>Yes</td>
<td>High</td>
<td>Low</td>
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<tr>
<td>COMPOW</td>
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<td>No</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>GAF</td>
<td>not provided</td>
<td>O(V)</td>
<td>No</td>
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<td>Low</td>
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<tr>
<td>STEM</td>
<td>not provided</td>
<td>not provided</td>
<td>Yes</td>
<td>Low</td>
<td>No Mobility</td>
</tr>
<tr>
<td>ASCENT</td>
<td>not provided</td>
<td>not provided</td>
<td>Yes</td>
<td>Low</td>
<td>No Mobility</td>
</tr>
<tr>
<td>PACDS</td>
<td>O(\Delta^2)</td>
<td>O(n \Delta)</td>
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<td>High</td>
<td>Low</td>
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<tr>
<td>ECDS</td>
<td>O(n)</td>
<td>O(n)</td>
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<tr>
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<td>High</td>
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<tr>
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</tr>
<tr>
<td>SPAN</td>
<td>O(n)</td>
<td>O(n)</td>
<td>Yes</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>CLUSTERPOW</td>
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<td>O(Pn)</td>
<td>No</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>LEACH</td>
<td>O(n)</td>
<td>O(n)</td>
<td>Yes</td>
<td>Low</td>
<td>Low</td>
</tr>
</tbody>
</table>
Insufficient and Future Research Direction

According to the current research, there are many challenging problems in the topology control of wireless networks, especially in DTNs:

1) How to construct a more efficient random DTNs model;
2) How to design an efficient distributed algorithm to find the communication link between each pair of nodes to achieve topology control;
3) How to get network topology information accurately

Conclusion

In this paper, we survey the topology control in wireless networks, summarizes the main directions and research results of topology control problem of wireless networks in recent years, and point out some future research directions.

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