Topology Control for Wireless Sensor Networks with Irregular and Dynamic Radio Coverage

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Abstract

A critical issue in wireless sensor networks is represented by the limited availability of energy within sensor nodes. An effective approach for energy conservation is scheduling sleep intervals for extraneous nodes, while the remaining nodes stay active to provide continuous service. Most previous solutions assumed a perfect radio condition with a static, circular coverage. However, in real situations, radio signals are very dynamic and irregular in their coverage. This is especially true for wireless sensor networks, which usually employ low quality radio modules to reduce the cost. Assuming no location information is available, we approach the problem in this paper from two aspects: space and time. We present a topology control algorithm, termed OTC, for sensor networks with consideration of radio irregularity and dynamic radio coverage. It uses two-hop neighborhood information to select a subset of nodes to be active among all nodes in the neighborhood. Each node in the network selects its own set of active neighbors from among its one-hop neighbors. This set is determined such that it covers all two-hop nodes. OTC is evaluated against a well-known algorithm from the literature, namely Span, through realistic simulations using TOSSIM. The results show that under dense deployment and irregular and dynamic radio coverage, our algorithm outperforms Span.

Keywords: Radio Irregularity, Topology Control, Simulations, TinyOS and TOSSIM.

1. Introduction

Wireless sensor networks use low power radio transceivers due to the stringent constraints on battery capacity. As a result, radio transmission with wireless sensors is unreliable. Furthermore, propagation patterns are irregular and unstable causing very dynamic radio coverage. Radio irregularity is inherent in every wireless sensor network that it should be constituted in its protocol or algorithm design. Radio irregularity is proven to have significant impact on both the routing layer and the MAC layer [1, 2]. Due to the direct impact on the upper layer protocols, many services, such as localization, routing and tracking are required to be resilient to the irregular and dynamic radio propagation and to include mechanisms to deal with the problems caused by the irregular and dynamic radio propagation patterns. To the best of our knowledge, this is the first attempt to design and evaluate a topology control algorithm for wireless sensor networks with consideration of irregular and dynamic radio coverage. Compared to the diversified solutions produced for topology control in sensor networks, research on radio coverage still has considerable room for improvement. Radio coverage is an indispensable element of many sensor network systems. One well-known but largely ignored issue is radio irregularity. It has been known for years that radio patterns are not regular [3-6], but researchers still continue to develop, simulate and analyze sensor network protocols that utilize a simplified theoretical radio coverage model [7], in which the radio coverage boundary is represented by a circle (a sphere in 3D) centered by a sensor. We acknowledge that the results
based on this simplifying assumption could reveal high-level insights, but that such assumption often lead to the all-too-common problem that solutions developed by simulation and analysis do not work as expected in the real world. Our work is motivated by the fact that it is difficult to accurately characterize in-situ coverage areas with theoretical models. For example, environmental impacts (e.g. obstacles) can severely affect radio characteristics, causing irregular, non-uniform and dynamic radio propagation patterns at different sensor nodes. Since irregularity is a common issue in sensor networks, it is unwise for developers to continue ignoring this reality.

In this paper, with the help of an extension to the DOI radio model proposed in [8], we explore the impact of radio irregularity on topology control performance. Among the algorithms we evaluated, we found that radio irregularity has a significant impact on topology control algorithms (for instance, Span performs worse in the presence of radio irregularity). Thus, we investigated our proposed solution OTC to deal with radio irregularity in wireless sensor networks. We evaluated OTC in simulations, and our results demonstrate that OTC copes well with radio irregularity due to its clever neighbor discovery mechanism.

The rest of this paper is organized as follows. In section 2, we briefly describe related radio model research found in recent literature. Section 3 describes the design and implementation of OTC in depth. The simulation environment, system parameters and performance metrics are discussed in section 4. We present the simulation results in section 5. Finally, we conclude the paper in section 6.

2. Related Work

The phenomenon of the radio irregularity has been known for a long time. Several researchers have already shown extensive evidence of radio irregularity in wireless communication. Their main focus on these studies: a) To observe and further quantify such phenomena [4, 9, 10]; b) To clarify and demonstrate the weakness of the use of the common disk model in existing evaluations [9, 11], and c) To develop other algorithms that are less dependent on the commonly assumed radio coverage [12]. However, research on a realistic model for the radio range irregularity is still at its infancy. In [8], the authors introduced an irregular radio model termed degree of irregularity (DOI). This model assumes an upper and lower bound on the radio propagation range. When a neighboring node is beyond the upper bound, then it is out of the communication range, and when it is within the lower bound, the node is guaranteed to be within communication range. If the distance between a pair of nodes is between these two boundaries, the communication is dependent on the actual radio range in that direction, and three scenarios are possible: 1) symmetric communication, 2) asymmetric communication, and 3) no communication. In this model, the DOI metric is used to denote the irregularity of the radio coverage. It was originally defined as the maximum range variation per unit degree change in the direction of radio propagation. As shown in Fig. 1, when the DOI is set to zero, there is no range variation, and the communication range is a perfect circle. However, when we increase the DOI value, the communication range becomes more and more irregular.

![Figure 1. Degree of irregularity.](image)

The DOI model is a good start to model signal irregularity. However, this model does not take the environment into account, and it usually results in undetermined and abrupt changes of range values in all directions. Since the DOI model is based on an absolute communication range, it assumes that within the inner range, the signal is very strong and can always be received correctly, while beyond the outer range there is no signal at all. This binary assumption is not true in reality. For example, in Fig. 2 (a), the DOI model assumes that there is no interference between nodes B and C. However, in reality, there are no such clear boundaries, and the communications of nodes do interfere with each other. The DOI model only models an absolute range based on the distance, and determines whether one node can hear another node only by comparing their distance with the sender's communication range. With such a binary decision, it cannot deal with interference. In addition, with the DOI model, it is difficult to build a mathematical model for the performance analysis of upper layer protocols.

In [1, 2], the authors explained some notable causes of radio irregularity namely: non-isotropy, continuous variation and difference in transmit power. They extended the DOI model by also considering the radio interference among devices. The Radio Irregularity Model (RIM) is based on experimental results made with a pair of Mica2 motes.
the energy model and the DOI factor together. They redefined DOI in the RIM model as the maximum received signal strength percentage variation per unit degree change in the direction of radio propagation. DOI values are then calculated accordingly. RIM is a general radio model which can reduce to the isotropic model when the DOI value is zero. It also reduces to the DOI model when there is no interference among nodes. Compared to the DOI model, the RIM model takes into account the radio transmit power, power loss, the background noise, and the interference among different communication signals. The difference can be further illustrated with an example.

![Figure 2. Communication interference in DOI and RIM radio models. (a) No interference in the DOI model in this co-location of three nodes and (b) Interference in the RIM model](image)

In Fig. 2 (b), the RIM model allows node B’s signal to propagate beyond its communication range to reach node C, even though it is not strong enough for node C to receive it as a valid packet. This weak signal from node B acts as one source of background noise around node C. In this case, node C may not be able to receive packets from node A, if the received signal is not stronger than the product of the Signal-Noise Ratio (SNR) value and background noise level of node C.

From above, it is obvious that there are different ways of defining a node’s neighbors, such as by using geographic location information of the neighbors (i.e. DOI radio model) or by comparing signal strength. In our implementation, we chose to focus on RIM model as our radio model. The received signal strength is used as the determining factor, and the interference is handled by the MAC layer in TOSSIM. We believe that the DOI model is non-realistic as it is based on the distance only, and does not take into account the environment factor (i.e., transmit power, path loss, background noise and interference). Although, the radio coverage of a node is irregular and dynamic, as assumed in this paper, we can still consider a neighbor that reportedly receives at the smallest signal strength (i.e. RADIO-RX-THRESHOLD) as right on the border of the radio coverage. In our simulation, nodes send their packets with certain transmit power, RADIO-TX-POWER. All other nodes compute the path loss according to the path loss model and check whether the final signal strength is larger than the receiver sensitivity, RADIO-RX-THRESHOLD. A node can receive the packet if the received signal strength is above this threshold. Thus, each one-hop neighbor of a node can use this rule to decide if it is a neighbor of that node.

3. The OTC Topology Control Algorithm

In this section, we focus on how topology control can deal with radio irregularity to ensure its correct behavior. This is critical as such an algorithm generally makes redundant nodes to sleep, and any incorrect operation may result in network partitions. Now, we describe OTC in detail and how it deals with the radio issues.

3.1. Overview

In OTC, a subset of nodes forms a multi-hop forwarding backbone to preserve the connectivity of the underlying sensor network, while the remaining nodes are forced to sleep as they are redundant. It only keeps a node awake if it is absolutely essential for maintaining connectivity. Redundant nodes spend more time in the sleep state, as they no longer carry the burden of forwarding data at this time. OTC employs a load balancing strategy to balance energy consumption, whereby the backbone role is rotated among nodes. OTC runs above the link and physical layers, and supports the routing protocol. This structure allows OTC to exploit the power-saving feature of the link layer protocol, while still being able to influence the routing process.

To support its functions, OTC contains three elements: a mechanism for neighbor discovery, a mechanism for role alternation and a mechanism for selecting the active nodes in the network. These elements are described in detail further.

3.2. Discovery Mechanism

Our algorithm is a distributed algorithm that uses local broadcast messages to discover and react to changes in the network topology. The OTC algorithm is designed specifically for a static multi-hop wireless sensor network. Each node must detect the neighbor nodes with which it has a symmetric link. Each node periodically broadcasts a HELLO message as illustrated in Fig. 3. Upon exchanges of HELLO messages, a node can gather information about its neighborhood and its two-hop neighborhood. Each node builds a list of its all neighbors and active neighbors, and for each neighbor, its active neighbors. Such information must be refreshed periodically to detect the changes in the topology. Each node updates its local knowledge about its neighbors with each received HELLO message.
Each node maintains a neighbor table, describing the neighbors and the two-hop neighbors. Such information is considered valid for a limited period of time, and must be refreshed periodically to remain valid. Expired information is purged from the neighbor table.

### 3.3. Selection of Active Nodes

OTC selects a group of active nodes from all nodes in the network. Active nodes stay awake continuously and perform multi-hop packet routing within the sensor network. Other nodes remain in power-saving mode, and periodically check if they should wake up and exchange their roles with the active node. Each node in the network selects a set of nodes from its one-hop neighborhood. This set of selected neighbor nodes is called its active list. This set is selected such that the node is able to reach all its two-hop neighbors via the active list, see Fig. 5. The active list of \( x \), denoted as \( A \), is then an arbitrary subset of the one-hop neighborhood of \( x \) which satisfies the following condition: every node in the two-hop neighborhood of \( x \) must have a path towards \( x \). For the seed node, the sink randomly chooses one of its neighbors to initiate the process. The selection then sequentially progresses in a breadth-first manner towards the rest of the network.

The selection of the seed node can depend on its available energy and node degree. A node with more residual energy and higher node degree can be selected as seed node. Once a node has its one-hop and two-hop neighbor information, it can then select a minimum number of one-hop neighbors which covers all its two-hop neighbors.

### 3.4. Role Alternation

In OTC, a node can be in one of three states: sleep, listen and active. Figure 5 shows the state transition diagram of a node. Initially, all nodes start out in the listen state. When in the listen state, a node turns on its radio and exchanges HELLO messages to gather information about its neighborhood. In addition, when a node enters the listen state, it sets up a timer \( T_l \). When \( T_l \) expires, if the node did not receive an announcement message from its neighbor nodes, the node enters the active state. If before \( T_l \) expires, the node receives a WITHDRAWAL message (i.e. its node ID is not found in the sender’s active list) from its neighbors, then the node turns off its radio and moves into the sleep state, or if the node received a JOIN message (i.e. its node ID is found in the sender active list), then the node moves into active state and broadcast its own active set.

![State transitions of a node in OTC](image)

When the node enters the active state, it sets a timeout value \( T_a \) to determine how long it should stay active. After \( T_a \) expires, the node moves back into the listen state. A node in the active state periodically checks if it should turn its radio off, and move into the sleep state. This decision is based on the following eligibility rule; it checks whether every pair of its neighbors can reach each other within two hops. A node delays its withdrawal announcement with a randomized backoff delay. When the backoff delay timer expires, the node reassesses its withdrawal eligibility. If the withdrawal is still valid, it announces its withdrawal (i.e. sending an announcement message with status field value is set to non-active) and transits to the sleep state. When transiting to the sleep state, a node cancels all timers, sets the sleep timer \( T_s \) and turns off its radio. A node in the sleep state returns to the listen state after an application dependent sleep time \( T_s \).
4. System Parameters and Performance Metrics

The implementation is carried out on the TOSSIM simulation environment [13]. We compared the performance of our proposal with Span, one of the most widely cited algorithms. The summary of the simulation environment is shown in Table 1. RADIO-TX-POWER is the initial signal strength of a node. For all simulation results in this paper, each experiment is repeated 5 times on different network topologies and a 95% confidence interval is obtained. The scenario that we have used in our simulation experiments consists of a 300m x 300m square area. In each run, we placed the sink in the left-corner of the simulated region. The number of nodes is varied from 20 to 100 nodes. In our scenario, all sensor nodes sample the environment and generate a data message every 10 s.

Table 1. Details of the simulation

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulator</td>
<td>TOSSIM</td>
</tr>
<tr>
<td>RADIO-TX-POWER</td>
<td>10 dBm</td>
</tr>
<tr>
<td>RADIO-RX-THRESHOLD</td>
<td>-75 dBm</td>
</tr>
<tr>
<td>PROPAGATION-PATHLOSS</td>
<td>FREE-SPACE</td>
</tr>
<tr>
<td>MAC-PROTOCOL</td>
<td>B-MAC</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>15.2 kb/s</td>
</tr>
<tr>
<td>Payload size</td>
<td>57 bytes</td>
</tr>
<tr>
<td>Terrain</td>
<td>300 m x 300 m</td>
</tr>
<tr>
<td>Simulation Time</td>
<td>10,000 s</td>
</tr>
</tbody>
</table>

In the following experiments, we have adopted a number of metrics to evaluate the performance of the algorithms. These performance metrics are defined as follows:

- **Packet delivery ratio (%)**: the percentage of received data packets at the sink.
- **Average latency (ms)**: the average delay of a packet from any source to the sink.
- **Average hops**: the average number of hops a packet takes to travel from the source to the sink.
- **Average number of active nodes**: the average number of active nodes over simulation time.
- **Network throughput (kbps)**: the amount of data received at the sink within the simulation time.
- **Total energy (J)**: total consumed energy by all nodes in the network, excluding the sink.

The network is studied for two types of radio irregularities, namely irregularity in coverage space and irregularity in time. In order to simulate radio irregularity, we consider the following system parameters in this paper.

**Degree of irregularity in space**: in TOSSIM, nodes send their packets with certain transmit power, RADIO-TX-POWER. All other nodes compute the path loss according to the path loss model and check whether the final signal strength is larger than the receiver sensitivity, RADIO-RX-THRESHOLD. A node can receive the packet if received signal strength is above this threshold. We use free space model as the path loss model. The path loss is directly proportional to the logarithmic value of distance, and is computed as follows [14]:

\[
\begin{align*}
(1) \text{pathloss} &= 0 \\
(2) \text{valueForLog} &= 4.0 \times \pi \times \text{distance} / \text{waveLength} \\
(3) \text{pathloss} &= \text{pathloss} + 20 \times \log_{10}(\text{valueForLog}), \\
&\quad \text{if valueForLog} > 1.0
\end{align*}
\]

To simulate irregularity, we define DOI as the maximum percentage of the original path loss, plus an additional path loss as shown below:

\[
\begin{align*}
(4) \text{doiValue} &= \text{rand}[0,1] \times \text{DOI} \\
(5) \text{temp} &= \text{doiValue} \times \text{pathloss} \\
(6) \text{pathloss} &= \text{pathloss} + \text{temp}
\end{align*}
\]

The value of DOI controls the final path loss, thus controlling success rate of the data packets received by a node. As the DOI value is increased, the radio coverage becomes more irregular.

**Degree of irregularity in time**: irregularity of radio coverage can also depend on time as demonstrated in the testbed experiments as discussed in section 3. The radio coverage of a node remains the same for a certain period of time and then changes (i.e. we repeat above steps 3-6 to generate different pathloss value and thus, obtain different signal strength). We use this parameter to control changes in the radio coverage of the nodes.

5. Simulation Results

In this section, we present our main findings. We discuss results from an extensive performance evaluation of our implementation of OTC and the benchmark algorithm Span.

5.1. Radio Irregularity in Spatial Coverage

Changing DOI may affect certain network properties that ultimately affect network performance. To appreciate how such properties are influenced, an initial set of simulation experiments is performed. Two measures are used to capture network properties, namely **stable region** and **normalized node degree**. Stable region represents the area wherein the signal is...
strong and can always be received correctly. Beyond this area there are two cases: (a) the communication is asymmetric, or (b) there is no signal at all and there is no communication. Normalized node degree is defined as the number of neighbors normalized against the number of neighbors when DOI is zero. Figures 6 and 7 show the effect of changing DOI values on the stable region and the number of neighbors. When DOI less than 0.2, the radio signal propagation is almost perfect, and all nodes are within the stable region of a sender. When DOI is 0.2, almost 50% of the radio range in the 60-m radio coverage is irregular, and it gets worse at higher DOI values. When DOI is 0.4, the irregularity created by such a DOI is very high and the stable region around a sender is only about 10 m. When DOI is greater than 0.2 the network connectivity is badly affected with almost 50% of the neighbors are in the unstable region. As can be seen from the graphs, stable region and normalized node degree of a node gets smaller with increased irregularity, and hence the stable neighbors stored in the neighbor table are typically closer to the node. As a result, we need to select more forwarding nodes to cover the whole network and this incurs more hops/delay to deliver the data packets to the sink.

Table 2. Environment for irregularity in space

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Nodes</td>
<td>100</td>
</tr>
<tr>
<td>DOI</td>
<td>0.005 - 0.4</td>
</tr>
</tbody>
</table>

Figure 8 shows the effect of changing DOI values on both OTC and Span. Figure 8 (a) compares the algorithms in terms of their total energy usage. Here, we considered the energy used by all nodes in the network except the sink. It is apparent that both schemes experience almost linear energy increase with the increase in DOI value when DOI greater than 0.1. Figure 8 (b) compares the algorithms in terms of the number of active nodes selected. The average number of active nodes is computed across different election rounds. It is clear that when we increase the DOI
value, both schemes select more active nodes. This is because the stable region of a node gets smaller with increasing irregularity, and hence the stable neighbors stored by OTC and Span are typically closer to the node. As a result, both schemes need more hops and forwarding nodes to cover the whole network. We observed that OTC provides a significant amount of savings beyond Span, because OTC keeps fewer number of nodes active at any point in time. In OTC, each node is allowed to exchange messages with its neighbors only twice, and then must decide which links to keep. While in Span nodes communicate with each other continuously, they use local HELLO messages to propagate topology information, but it does not depend on them for correctness: when HELLO messages are lost (e.g., due to interference), Span elects more active nodes. Figure 8 (c) depicts the packet delivery ratio for the schemes for different DOI values. As can be seen from the graphs, as the DOI is increased, both schemes experience a drop in the delivery ratio and increase in the number of lost packets. In other words, as we decrease the stable region around the sender, the probability of unsuccessful delivery increases.

In order to investigate the impact of topology control on delay, we compared the average time needed to deliver a packet to the sink. Figure 8 (d) shows the average latency as a function of irregularity in space. Note that we considered only packets that successfully reach the sink in the results. Figure 8 (e) shows the average number of hops a message takes to travel from the source to the sink with respect to the irregularity in space. As can be seen from the graphs, with more hops in the path we experience a significant (nearly doubled) increase in the latency. As the DOI is increased, both schemes experience an increase in the average hops as well as latency. We can however observe from the graphs that OTC has fewer average hops and latency than Span. This is because Span incurs more collisions as seen in Fig. 8 (c) and packets have to travel through longer path to reach the sink.

We also investigated the algorithms' effect on network throughput. Figure 8 (f) shows the throughput with respect to the irregularity in space. As expected, network throughput decreases for both algorithms. It is interesting to note though that our algorithm performs better than Span, while using fewer number of active nodes. OTC outperforms Span as it exhibited better delivery ratio as seen from Fig. 8 (c).

5.2. Radio Irregularity in Time

Table 3 shows only the unique parameters for these set of experiments. We fixed DOI at 0.2, and varied the radio-stable interval from 40 to 350 seconds. Other
settings are same as in table 1. In Fig. 9 (a), it is apparent that OTC conserves more energy with the increase in radio stability. When the radio-stable period is increased, sleeping nodes in OTC will have more time in this energy saving mode before they wake up again and exchange their roles with the active nodes. In Span, the number of selected active nodes increases with radio-stable period as shown in Fig. 9 (b). That is because Span needs longer time than OTC to converge, and thus, Span exhibits an increase in consumed energy. It is evident that OTC provides a significant amount of savings beyond Span, because OTC keeps lesser number of nodes active at any point in time. Figure 9 (c) shows the average number of hops as a function of number of nodes in the network. It is apparent that Span experiences increase in number of hops with the increase in radio-stable period. This is because Span selects more forwarding nodes and thus incurs more collisions. On the other hand, OTC experiences a slight decrease in number of hops with the increase of radio-stable period.

As shown in Fig. 9, increasing stability of the radio coverage improves the performance of our algorithm. The reason is because each node in OTC collects information about its one-hop and two-hop neighbors. A node uses this information to select its set of active neighbors. Thus if the radio coverage does not change for a long period of time, the coverage information remains valid for a longer period. In contrast, if the radio coverage changes very frequently, the communication between senders and receivers may not be reliable.

6. Conclusion

Since the presence of radio irregularity in wireless sensor networks is common and mostly has an ill-effect on network performance, it definitely makes this factor a crucial protocol design variable. As a concrete example to show the effect of radio irregularity on a specific scheme, we investigated a distributed topology control algorithm, termed OTC, for wireless sensor networks. It adaptively elects a subset of nodes to be active from the network pool of nodes, and periodically rotates their roles. Active nodes form the routing backbone and forward data packets toward the sink, while redundant nodes transit to the power-saving mode. In order to evaluate OTC, it is benchmarked against a well-known and comparable algorithm, namely, Span. We proved that, radio irregularity has a significant impact on topology control. For example, the number of selected active nodes increases with increasing degree of irregularity in space. As the effective radio range of a node becomes smaller with increasing degree of irregularity, the number of neighbors of a node reduces. With the increase in the number of active nodes, the collisions in the network increases too. OTC has shown almost stable performance under dynamic radio coverage. This is because OTC stores information about one-hop and two-hop neighbors. Nodes in OTC discover and react to changes in the neighborhood by exchanging HELLO messages. Our simulation results show that under dense deployment and irregular radio coverage, our algorithm outperformed Span in terms of packet delivery, packet loss, throughput, average latency and energy usage.

10. References

[8] He, T., Huang, C., Blum, B.M., Stankovic, J.A., and Abdelzaher, T. "Range-free location schemes for large scale


