

Research Article

Topology Control Algorithm considering Antenna Radiation Pattern in Three-Dimensional Wireless Sensor Networks

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Received 22 January 2014; Accepted 21 May 2014; Published 12 June 2014

Academic Editor: Hannan Xiao

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Topology control is a key issue of wireless sensor network to reduce energy consumption and communication collision. Topology control algorithms in three-dimensional space have been proposed by modifying existing two-dimensional algorithms. These algorithms are based on the theoretical assumption that transmission power is radiated equally to the all directions by using isotropic antenna model. However, isotropic antenna does not exist, which is hypothetical antenna to compare the real antenna performance. In the real network, dipole antenna is applied, and because of the radiation pattern, performance of topology control algorithm is degraded. We proposed local remapping algorithm to solve the problem and applied it to existing topology control algorithms. Simulation results show that our algorithm increases performance of existing algorithms and reduces power consumption.

1. Introduction

The short sensing sensor ranges in a wireless sensor network result in a high density network, which causes many communication collisions. Some research has attempted to reduce communication collisions using a Medium Access Control (MAC) layer scheme, but there is a limit to the extent of collision reduction within the MAC layer. A physical layer scheme is the fundamental solution for reducing collisions by controlling the transmission range or transmission power. The topology control algorithm attempts to find the minimum transmission range while maintaining network connectivity within a network layer. As a consequence, collisions are greatly reduced and network efficiency is increased. This is done under the assumption that optimal throughput performance can be achieved when using the minimum transmission power that is required to maintain network connectivity. It seems reasonable because low transmission power reduces both interference and collision. So, traditional topology control algorithms focus on the network connectivity with the minimum transmission power. Topology control

finds a minimum transmission range; consequently, energy consumption is reduced. As a result, network lifetime is increased, which is one of the most important performance factors in wireless sensor networks.

Generally, topology control algorithms are performed in three steps. In the first step, each node collects neighbor information with maximum transmission range. The information is different to algorithm but generally contains node ID and position. After collecting the information, each node selects minimum neighbor nodes which are essential nodes to maintain network connectivity by performing topology control algorithms with neighbor information. In the last step, each node finds farthest nodes in the selected neighbor nodes and calculates the distance. Based on the distance each node sets its transmission range. As a consequence node position or distance information is a key factor in topology control algorithm. Most of the existing topology control algorithms assume that each node knows its exact location or relative location using Global Positioning System (GPS) or other localization technics. In this paper, we also assume that each node has its location information.

Numerous papers have appeared on topology control and most of the algorithms use graph theory in two-dimensional network. However, in the real network, sensor nodes are deployed in three-dimensional space. So lots of topology control algorithms cannot be used directly in the real network. Some researches proposed topology control algorithm in three-dimensional space by extending the existing two-dimensional algorithms. These algorithms are represented in the Section 2. However, all of these algorithms have a common assumption, which causes critical problem in the real network. The assumption is that sensor node uses isotropic antenna. The isotropic antenna is an ideal antenna that radiates its power uniformly in all directions. This means that each node has a transmission range of perfect sphere shape. However, in the real network, this assumption cannot be accepted. Most of the sensor nodes use dipole antenna which radiates its power nonuniformly. In this paper, we analyze the effect of antenna radiation pattern on the performance of topology control algorithm. Based on the analysis, we propose a simple method to enhance the topology control algorithms in the real network.

The rest of this paper is organized as follows. Section 2 presents current research related to topology control in two- and three-dimensional space. In Section 3, we introduce a difference between isotropic antenna and dipole antenna. In Section 4, we show the effect of dipole antenna in the real network. Our algorithm is proposed to enhance performance of topology control algorithm in the real network in Section 5. We evaluate the performance of our algorithm in Section 6 and conclude the paper in Section 7.

2. Related Works

2.1. Two-Dimensional Topology Control Algorithms. Numerous papers have appeared on topology control. Most of the topology control algorithms use graph theory to satisfy the network connectivity. In [1], the authors proposed a topology control based on a distributed minimum spanning tree (MST). In [2], the authors proposed a simple topology control which has realistic assumptions so it can be easily implemented in real networks. In [3], the authors proposed cone based topology control (CBTC) (α) where α is a degree of cone and $\alpha = 5\pi/6$ is the necessary and sufficient condition to preserve network connectivity. Unlike most of the topology control, algorithms [2, 3] do not require exact location information. For [2], only the link quality with neighbor nodes is required, while [3] uses only directional information, which can be obtained and more easily compared to the exact node location. Because a topology control algorithm reduces the transmission range to reduce interference and collision, the network connectivity is susceptible to node failures. Therefore, [4] proposes a fault-tolerant topology control algorithm, the fault-tolerant local spanning subgraph (FLSS_k). The FLSS_k algorithm is $k - 1$ fault-tolerant; that is, the failure of at most $k - 1$ nodes will not disconnect the network. These topology control algorithms focus on network connectivity because topology control

assumes that maximum network throughput is achieved using the minimum transmission range that satisfies network connectivity.

Recent papers have proposed solving both connectivity and throughput problems. In [5], the authors propose a distributed congestion aware topology control algorithm, Power Assignment for Throughput Enhancement (PATE). PATE introduces a cost function including traffic load, number of interference nodes, and MAC status to determine transmission power while maintaining network connectivity, so that the overall network throughput is increased. However, [5] has no analysis model for the network throughput performance. In [6], an adaptive topology control (ATC) algorithm is proposed that changes its exclusive area under different conditions. The authors also analyzed the expected throughput using the graph theory. Because ATC uses throughput based on the graph theory, the throughput cannot represent actual throughput model. In [7], the authors propose a centralized algorithm Spatial Reuse Maximizer (MaxSR) that combines a power control algorithm and topology control algorithm. The algorithm is based on the Signal to Interference plus Noise Ratio (SINR) model in the physical layer. However, MaxSR is a centralized algorithm so it is difficult to implement it in a real network and throughput is defined only in the physical layer so the MAC layer effect is not considered.

2.2. Three-Dimensional Topology Control Algorithms. Gabriel graph (GG) and relative neighborhood graph (RNG) are the most well-known graphs for topology control. GG and RNG can be used in three-dimensional networks easily as shown in Figure 1. GG removes link xy when there exists a neighbor node in the sphere associated with the diameter that has the two nodes x and y as endpoints. RNG removes link xy when there exists a neighbor node which is located within a transmission range of nodes x and y . Cone based topology control (CBTC) also can be applied to three-dimensional network by using 3D cones instead of sectors based on angles. However, there still remain issues to apply CBTC in three-dimensional networks.

3D-YAO is proposed in [8]. Authors extended YAO graph to three-dimensional algorithm by proposing partitioning method to find equal cones without intersection among each other. Because a topology control algorithm reduces the transmission range to reduce interference and collision, the network connectivity is susceptible to node failures. Therefore, [9] proposes a fault-tolerant topology control algorithm by expending CBTC. The authors show that running the proposed algorithm with $\alpha = 2\pi/3k$ is an upper bound for preserving k -connectivity in three-dimensional network. In [10], authors proposed adaptive topology control algorithm considering link qualities and interference based on 3D-YAO graph.

All of these algorithms have one common assumption that transmission range of node is perfectly sphere. However, in the real network, transmission range is not sphere because of the antenna radiation pattern. So, existing algorithms do not work efficiently in the real network. In this paper, we will

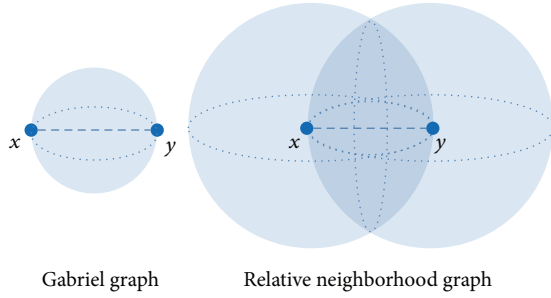


FIGURE 1: Gabriel graph and relative neighborhood graph in three-dimensional space.

show how the antenna radiation pattern causes problem and propose a simple algorithm to solve the problem.

3. Isotropic and Dipole Antenna

The isotropic antenna is an ideal antenna that radiates its power uniformly in all directions. It has no preferred direction of radiation. However, isotropic antenna does not exist. It is a hypothetical antenna to compare the real antenna performance. Figure 2 shows the radiation pattern of isotropic antenna. (a) shows radiation pattern on the azimuthal plane which is a parallel to the ground plane. (b) shows radiation pattern on the elevation plane which is a vertical plane. As shown in the figure, radiation power is always same regardless of any direction. The radiation pattern of isotropic antenna is perfectly sphere. So the radiation pattern is always circular to any plane.

On the other hand, dipole antenna is the simplest and most widely used in wireless sensor networks. The most common form of dipole antenna is the half-wave dipole, in which each of the two rod elements is approximately $1/4$ wavelength long, so the whole antenna is a half-wavelength long. According to the length of antenna, radiation pattern is different. Figure 3 shows the radiation pattern of half-wave dipole. In the azimuthal plane, the radiation pattern is the same as isotropic antenna. So in two-dimensional space, there occurs no problem even if we assume dipole antenna. However, in three-dimensional space, radiation pattern of dipole is different to isotropic antenna. As shown in Figure 3, radiation power on the elevation plane is different to each direction. So in three-dimensional space, dipole antenna assumption causes performance degradation. The detailed problem is presented in Section 4.

In general, there exists gain compared to isotropic antenna. According to the direction, the gain may be positive or negative. However, in this paper, we normalized the maximum dipole antenna gain to 0 dBi without loss of any generality. It makes us easily understand the effect of dipole antenna. In this paper we will use the normalized dipole antenna radiation unless noted otherwise. Figure 3 is also a normalized graph because the maximum power is the same as the power of isotropic antenna in Figure 2.

4. Problem according to Antenna Radiation Pattern

The main issue of dipole antenna is nonuniform power radiation. Because the power radiation is different according to the direction, transmission range and transmission power are not proportional. As a consequence, some receivers at the same distance cannot communicate with the same transmission power. Figure 4 shows the case. The figure shows the received signal strength (RSS) value when isotropic and dipole antennas are used. In the figure, transmitter node is located at $[25, 25, 25]$. A receiver node located at $[25, 25, 15]$ which is below the transmitter node. When isotropic antenna is used, RSS value of the receiver is approximately -71.6 dBm. However, when dipole antenna is used the receiver node cannot detect the signal because of radiation pattern of dipole antenna. On the other hand, a node located at $[15, 25, 25]$ has the same RSS value both with isotropic and dipole antennas. Because we assumed normalized dipole antenna, when a node is on the same azimuthal plane with transmitter node the RSS value is the same.

As we mentioned in Section 1, topology control algorithm finds a node's transmission range and power based on the distance information. When sender node sets its transmission range to 10 m, sender node should be able to communicate with node at $[25, 25, 35]$ if isotropic antenna is assumed. However, in the real network, sender node cannot communicate with the node because of the power radiation pattern of dipole antenna. This example is unrealistic in the real network, because topology control algorithm tries to find topology based on the collected neighbor information. Since a node at $[25, 25, 35]$ is not a neighbor node of sender node, sender node does not need to communicate with that node. However, RSS difference actually causes problem in topology control algorithm. For example, RSS value of a node at $[25, 35, 38]$ with isotropic antenna is approximately -84.9 dBm, which is almost 10 dBm higher compared with dipole antenna. When sender node sets its transmission range under the assumption of isotropic antenna, sender node cannot communicate the node at $[25, 35, 38]$ in the real network. Even if the sender node sets its transmission range enough to communicate the node, because actual transmission range is increased to the other direction, original topology which is found by topology control algorithm is changed. As a result, topology becomes complex and topology control algorithm cannot find efficient topology.

The problem can be represented by using simple equation. Assume that topology control algorithm uses the following path-loss model to find transmission range, which is widely used model to represent wireless channel:

$$P_{rx} = P_{tx} - PL(d),$$

$$PL(d) = PL(d_0) + 10n \log_{10} \left(\frac{d}{d_0} \right) + X_{\sigma}. \quad (1)$$

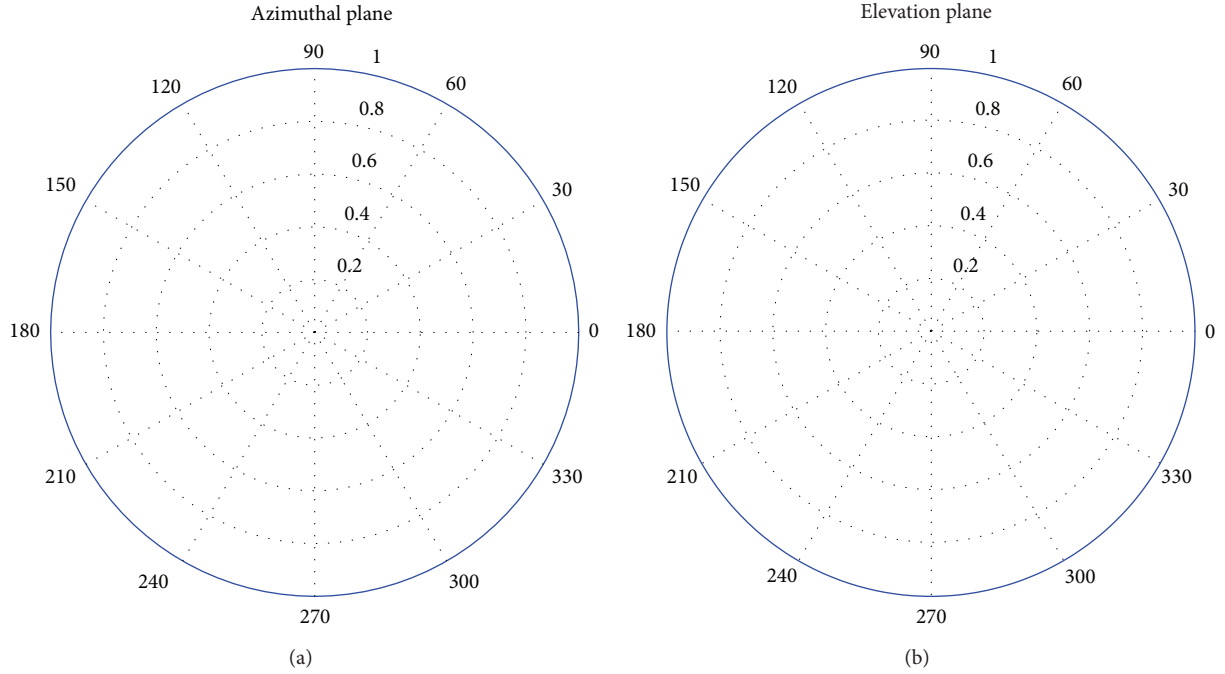


FIGURE 2: Radiation pattern of isotropic antenna.

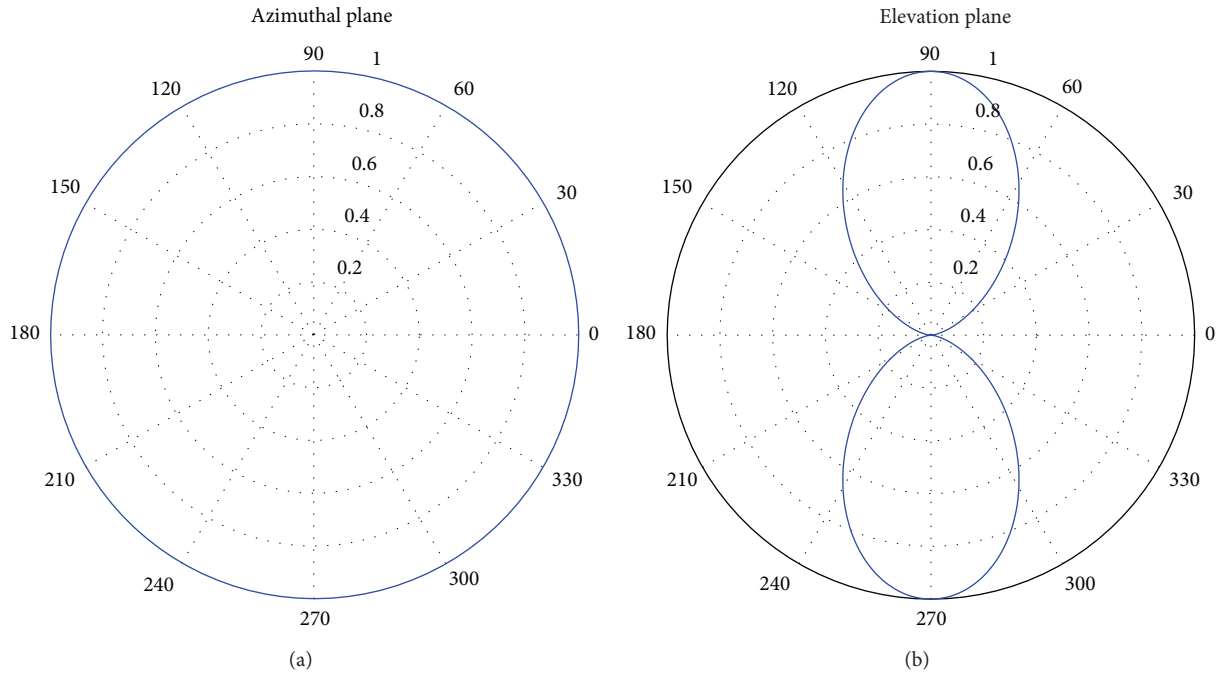


FIGURE 3: Radiation pattern of dipole antenna.

In (1), P_{rx} is a receiver power at the receiver node, P_{tx} is a transmission power at the transmitter node, d is a distance between transmitter and receiver, n is a path-loss exponent, d_0 is a reference distance, $PL(d_0)$ is a path loss at the reference distance d_0 , and X_σ is a Gaussian random variable with mean zero, which represents shadow fading.

Assume that minimum receiver sensitivity at the receiver node is P_{target} . Then we can represent a transmission power as a function of transmission range r . Consider

$$P_{tx} = P_{target} + PL(d_0) + 10n \log_{10} \left(\frac{r}{d_0} \right) + X_\sigma. \quad (2)$$

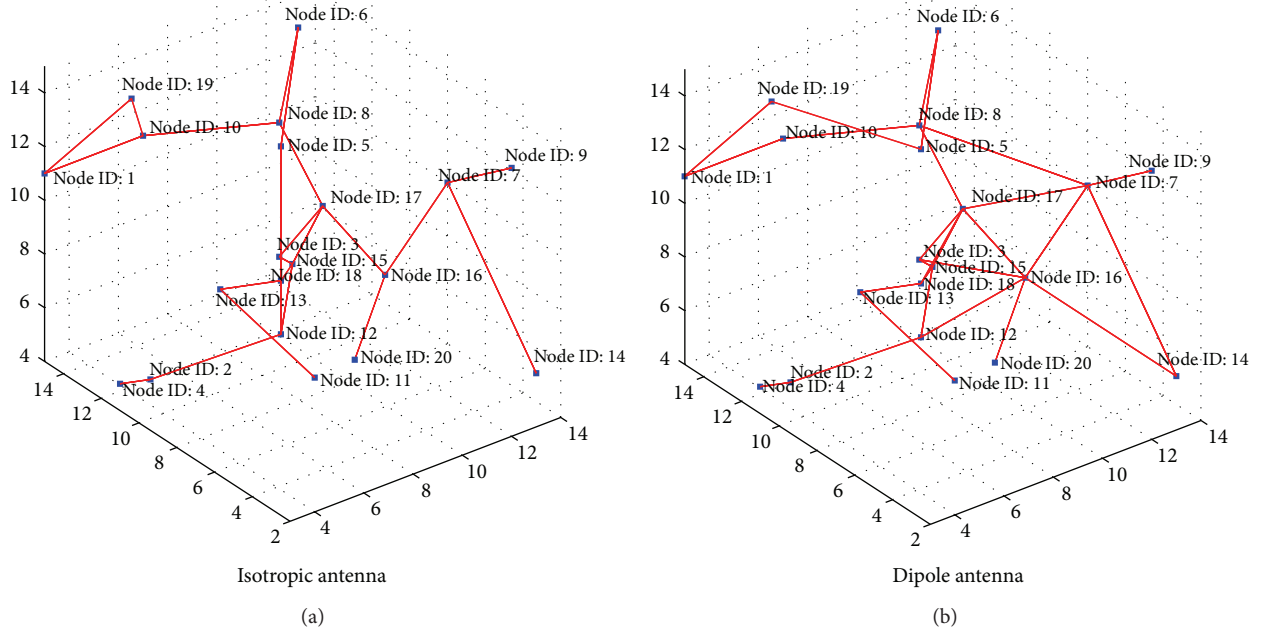


FIGURE 5: Comparison of topology under the assumption of isotropic and dipole antenna.

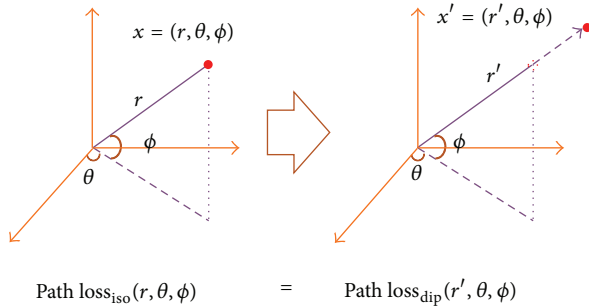


FIGURE 6: Concept of local remapping algorithm.

The simplest method is to measure the antenna gain before node deployment. Because all sensor nodes have same antenna, only one measurement is required to apply our algorithm. Based on the measurement data, the gain should be installed to sensor nodes. Another method is to estimate antenna gain in the real network environment. Topology control should collect its neighbor information with maximum transmission power. When a node collects its neighbor information, the node can estimate antenna gain. Because each node knows distance from neighbor node and transmission power of other nodes (maximum transmission power), antenna gain can be estimated with path-loss model in (1). However, this method has estimation error caused by channel shadow fading term, that is, X_{σ} . So the algorithm should be performed several times to reduce estimation error. In

the simulation, we assumed that antenna gain is measured and each node knows exact normalized dipole antenna gain.

6. Simulation Results

We simulated our algorithm using the physical parameters shown in the Table 1. Most of the parameters are obtained from the IEEE 802.15.4 specification [11]. The receiver sensitivity of the IEEE 802.15.4 specification at 2.4 GHz frequency is -85 dBm and the maximum transmission power is -10 dBm. We set the path-loss exponent to 3.3, the reference distance of the path-loss model is 8 m, and PL(8 m) is 58.5 dB, which comes from the IEEE 802.15.2 specification [12]. The constraints are based on a 2.4 GHz center frequency. We used half-wave dipole antenna, which is widely used in wireless sensor networks.

Figure 7 shows the example network with isotropic and dipole antenna. (a) shows topology found by MST algorithm with isotropic antenna. (b) shows MST topology with dipole antenna. As shown in the figure, dipole antenna causes additional links and it makes complex topology. However, when our algorithm is applied, the topology becomes simpler and with almost the same complexity as isotropic antenna case. The topology found by remapping algorithm is considerably different to isotropic antenna case, because our algorithm runs over the virtual distance calculated by (4) and (5).

We applied our algorithm to MST, GG, and RNG. CBTC is not considered in our simulation because of radiation pattern of dipole antenna. CBTC finds a closest node in each sector. But dipole antenna radiates little power to the

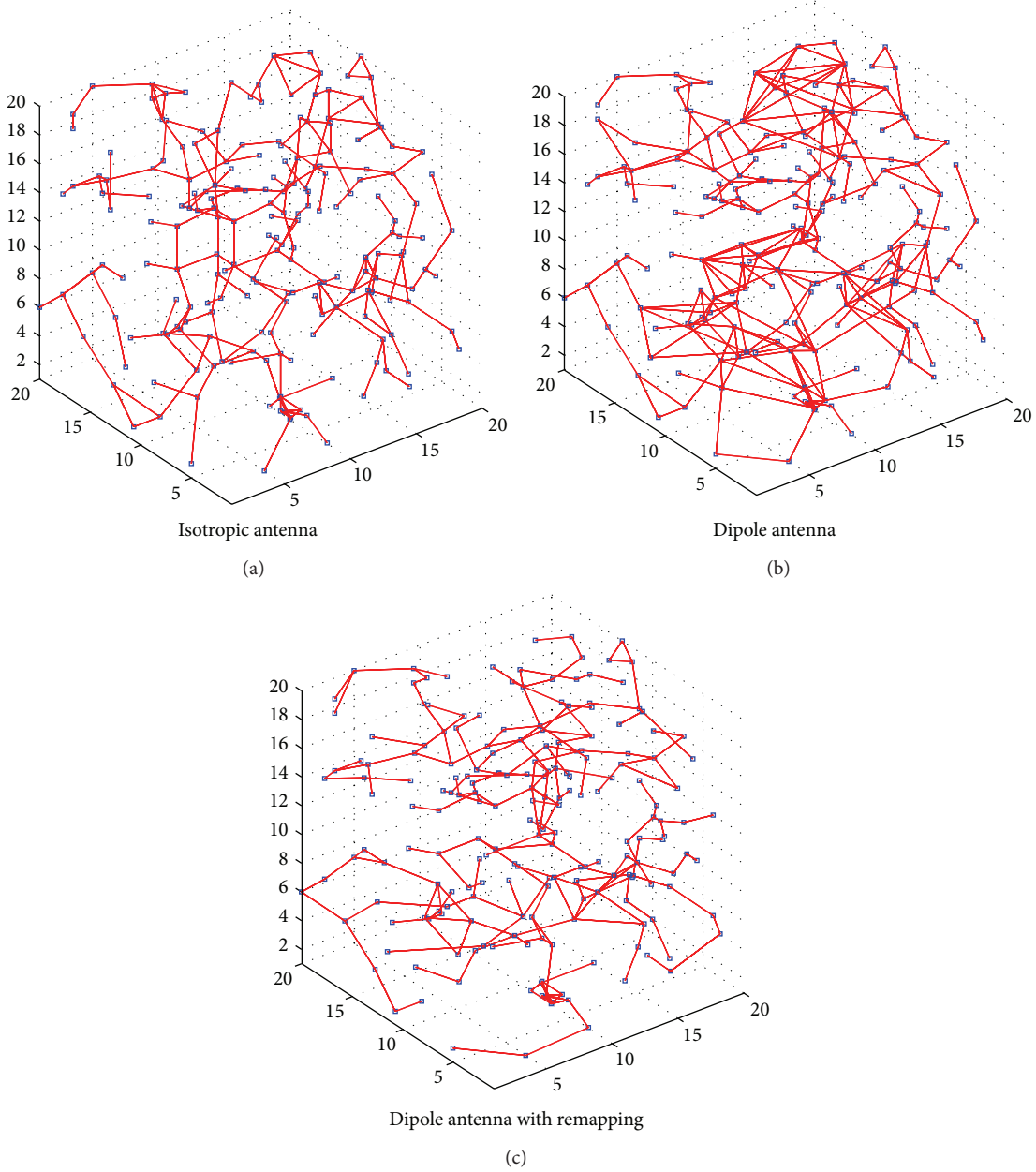


FIGURE 7: Example network topology with proposed algorithm.

TABLE 1

Parameter	Value
Network size	50 m × 50 m
Path-loss exponent	3.3
Receiver sensitivity	-85 dBm
Reference distance	8 m
Path loss at reference distance	58.5 dBm
Maximum transmission power	-10 dBm (approximately 50 m)

upper and lower side. As a result, CBTC tends to use maximum transmission range because CBTC cannot find any

neighbor nodes in some sectors with dipole antenna. So CBTC algorithm shows poor performance when dipole antenna is used.

Figure 8 shows average node degree with various topology control algorithms. In the graph, square marker represents isotropic antenna, cross marker represents dipole antenna, and triangle marker represents dipole antenna with local remapping case. As shown in the figure, there exists large node degree gap between isotropic antenna and dipole antenna when topology control is not applied. This result means that there exist some areas that cannot be covered with dipole antenna which can be covered with isotropic antenna. Because of the gap, existing three-dimensional topology

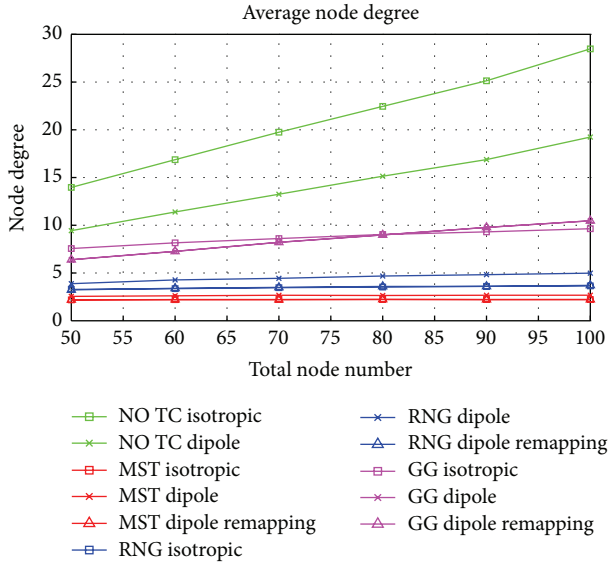


FIGURE 8: Average node degree of various topology control algorithms.

control algorithms under the assumption of isotropic antenna cannot operate efficiently in the real network.

Because there exists relationship between MST, RNG, and GG, MST shows minimum average degree and GG shows large average degree. In MST and RNG algorithm, our local remapping algorithm operates well and the node degree is almost the same with isotropic antenna. However, in GG algorithm, our algorithm does not work properly and it is shown well in Figure 9. Figure 9 shows the power consumption of total nodes in the network. As shown in the figure, when local remapping algorithm is used with GG algorithm, power consumption does not reduce unlike other topology control algorithms. For example, MST algorithm with local remapping algorithm reduces power consumption more than 50% compared to that without local remapping algorithm. However, power consumption of GG with local remapping is the same as dipole antenna case. It is caused by the algorithm characteristic of GG topology control algorithm. GG removes unnecessary link between two nodes when there exists a neighbor node in the sphere associated with the diameter that has the two points as endpoints. The criterion is checked by using a distance from a virtual point, which is center of two nodes. Because our local remapping algorithm relocates neighbor node's position, the virtual point also moves and as a result GG algorithm cannot operate well. So our algorithm can be applied to the algorithms that use virtual point to decide topology such as GG. However, most of the algorithms do not use virtual point to find topology so our algorithm can be applied to various existing topology control algorithms.

Figure 10 shows average node degree as height of network volume increases while network node density is maintained. The simulation is performed on $50\text{ m} \times 50\text{ m}$ network and height is increased to show the influence of dipole antenna. In the simulation, average node degree is almost constant

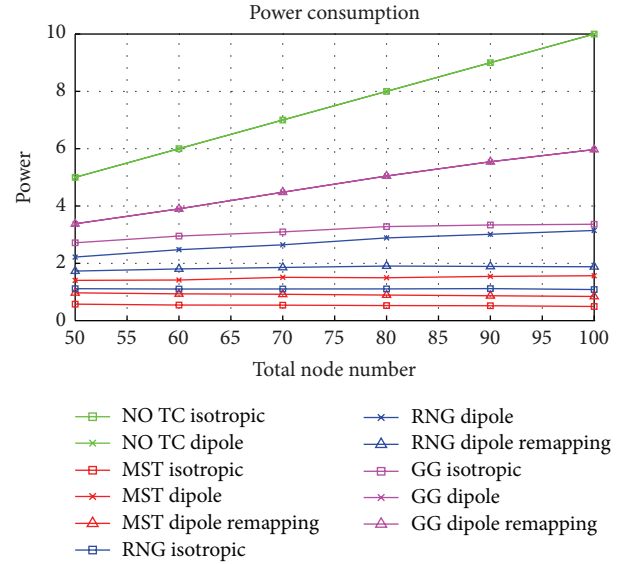


FIGURE 9: Average power consumption of various topology control algorithms.

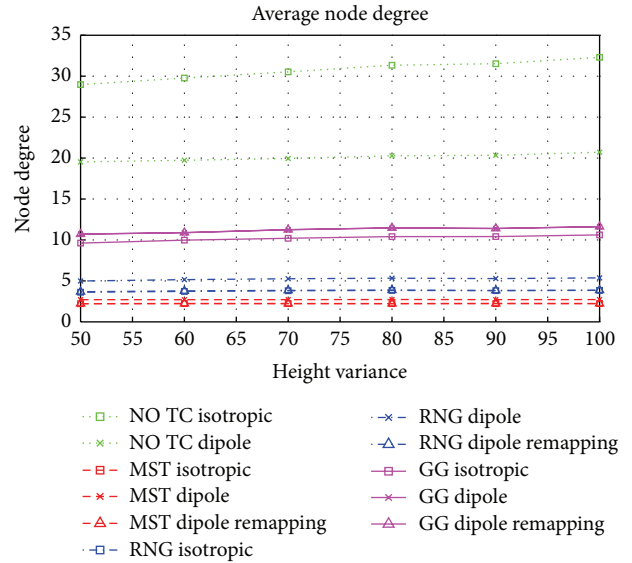


FIGURE 10: Average node degree as height of network volume increases.

regardless of network height as shown in Figure 10 because we maintained node density constantly.

While average node degree is maintained constantly, power consumption of whole network is increased as network height increased as shown in Figure 11. When dipole antenna is applied, power consumption increment ratio is much higher than when isotropic antenna is applied, which is shown in Figure 12. This is because radiation pattern of dipole antenna is not a sphere. Because dipole antenna radiates little power to the upper and lower side, power consumption increases as height of network volume increases. When our local remapping algorithm is applied the increment ratio is

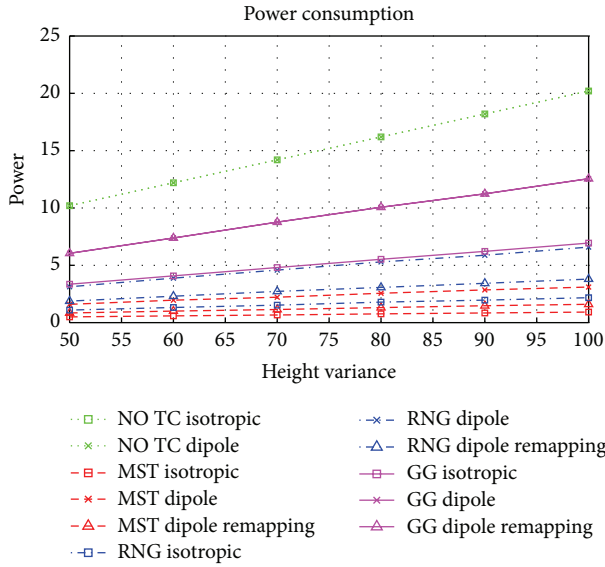


FIGURE 11: Average power consumption as height of network volume increases.

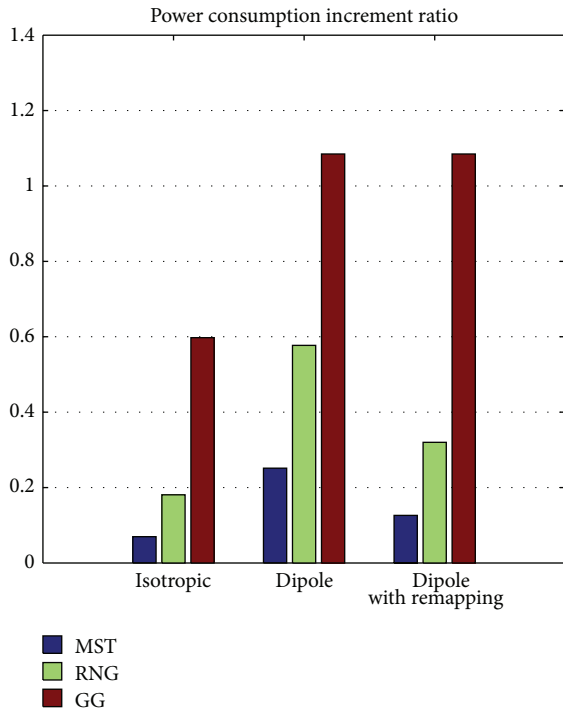


FIGURE 12: Power consumption increment ratio as height of network volume increases.

decreased, but still higher than isotropic. As a consequence, when sensor nodes are deployed in three-dimensional space, it is better to deploy sensor nodes as flat as possible. If network height is much longer compared to surface side length, sensor nodes should be rotated 90 degrees to reduce power consumption caused by dipole antenna radiation pattern.

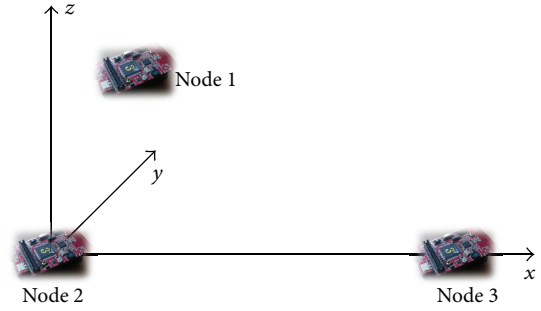


FIGURE 13: Experiment topology.

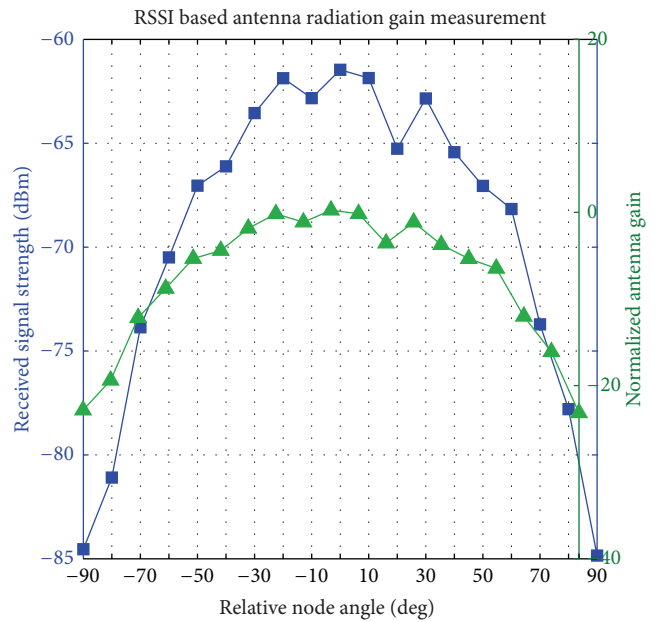


FIGURE 14: Antenna gain measurement using receiver signal strength.

7. Experiments

We tested our algorithm in the real network. Because of limited node number, our experiment is composed of very simple topology as shown in Figure 13. There are three nodes in the network. Two nodes (node 2 and 3) are located in the ground (x - y plane) and last node is located at the upper side of node 2. The distance between nodes 1 and 3 is same as the distance between nodes 2 and 3. Also nodes 1, 2, and 3 are located on the x - z plane.

We used micaz based modified sensor node. The sensor nodes have PCB antenna which shows almost the same radiation pattern with dipole antenna. The sensor node uses CC2420 RF chipset and the chipset provides variable output power from -25 dBm to 0 dBm. Because we do not have measurement equipment for the radiation pattern, we analyzed received signal strength to calculate antenna gain of

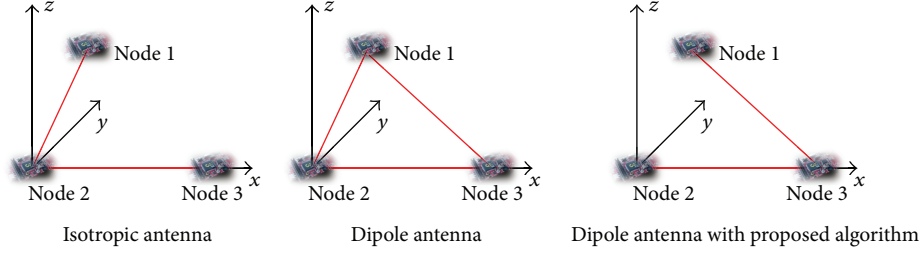


FIGURE 15: Experiments results.

antenna by using (1) and (4). From these equations, we can get an antenna gain equation as follows:

$$\begin{aligned}
 A_{\text{dipole}}(\theta, \phi) &= P_{\text{tx}} - P_{\text{rx}}(\theta, \phi) - \text{PL}(d_0) - 10 \cdot n \cdot \log\left(\frac{r}{d_0}\right) - X_{\sigma}. \quad (7)
 \end{aligned}$$

By taking expectation on both sides of (7), we can remove shadow fading term, that is, X_{σ} . The equation is as follows:

$$\begin{aligned}
 E[A_{\text{dipole}}(\theta, \phi)] &= P_{\text{tx}} - P_{\text{rx}}(\theta, \phi) - \left\{ \text{PL}(d_0) + 10 \cdot n \cdot \log\left(\frac{r}{d_0}\right) \right\}. \quad (8)
 \end{aligned}$$

Because we can control transmission power, relative angle, and node distance between two nodes, we can measure antenna gain of sensor node. But we need to know sum of path loss at the reference distance ($\text{PL}(d_0)$) and path-loss exponent (n). We set the value as same value as $P_{\text{tx}} - P_{\text{rx}}(0, 0)$. Then we can get a normalized dipole antenna gain, $G_A(\theta, \phi)$ because maximum gain of dipole antenna $G_A(0, 0)$ becomes 0 dBm. In our testbed, because all nodes are placed on the x - z plane, we measured antenna gain while fixing θ to 0. The measurement result is shown in Figure 14.

In the graph, x -axis shows the relative node angle. The transmitter node is fixed and receiver node is moved as changing relative angle from -90 to 90 degree while maintaining node distance. Left y -axis shows the received signal strength at the receiver node. Right y -axis shows antenna gain calculated based on the receiver signal strength. Theoretically, antenna gain at -90 and 90 degrees should be $-\infty$. However, the measured antenna gain is approximately -22 dBm. This is because there exist a multipath fading and other environmental factors. We measured our result in the open space to minimize other environmental factors. But sensor nodes are placed on the ground, and multipath from the ground is unavoidable factor. However, the result is quite similar with the theoretical gain of dipole antenna.

Based on the antenna gain, we applied our algorithm. We used MST algorithm to adapt our algorithm. Figure 15 shows the result. In the figure, solid red line represents connected link between two nodes. Left figure shows the MST algorithm when ideal isotropic antenna is used. Because MST

is performed only using distance information, the topology is shown as follows:

$$\begin{aligned}
 G_{\text{MST ISO}} &= (E_{\text{MST ISO}}, V_{\text{MST ISO}}) \quad (9) \\
 E_{\text{MST ISO}} &= \{(1, 2), (2, 3)\}, \quad V_{\text{MST ISO}} = \{1, 2, 3\}.
 \end{aligned}$$

However, actual algorithm should increase transmission power of nodes 2 and 3 to communicate with each other when dipole antenna is used. Then, there exists unexpected link between nodes 1 and 3. Then the topology is shown as follows:

$$\begin{aligned}
 G_{\text{MST DIPOLE}} &= (E_{\text{MST DIPOLE}}, V_{\text{MST DIPOLE}}), \\
 E_{\text{MST DIPOLE}} &= \{(1, 2), (2, 3), (1, 3)\}, \quad (10) \\
 V_{\text{MST DIPOLE}} &= \{1, 2, 3\}.
 \end{aligned}$$

Our proposed remapping algorithm remaps the node distance between each node. Because antenna gain between nodes 1 and 2 is very low, the virtual distance is increased by our algorithm. As a result, MST algorithm is performed using the virtual distance and finds another topology as follows:

$$\begin{aligned}
 G_{\text{REMAP}} &= (E_{\text{REMAP}}, V_{\text{REMAP}}), \quad (11) \\
 E_{\text{REMAP}} &= \{(1, 3), (2, 3)\}, \quad V_{\text{REMAP}} = \{1, 2, 3\}.
 \end{aligned}$$

When dipole antenna is applied, the transmission power of each node is -5 dBm (node 1), -5 dBm (node 2), and -25 dBm (node 3). When our remapping algorithm is applied the transmission power of each node is -25 dBm (node 1), -25 dBm (node 2), and -25 dBm (node 3). As a result, our algorithm eliminates unnecessary link and reduces transmission power.

8. Conclusion

This paper proposed three-dimensional topology control algorithm considering antenna radiation pattern which is not considered in other topology control algorithms. In wireless sensor network, energy efficiency is the most important issue. However, because of the radiation pattern, existing topology control algorithms do not operate efficiently and as a result energy efficiency is degraded. Our simple local remapping algorithm reduces topology size caused by dipole antenna and as a result energy efficiency is increased. Simulation results show that our algorithm operates with MST and RNG efficiently. Our algorithm can be adapted to the most existing algorithms which use distance information to find topology with distributed manner.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

This work was supported by the IT R&D program of MKE/KEIT. [10041262, Open IoT Software Platform Development for Internet of Things Services and Global Ecosystem]. This research was funded by the MSIP (Ministry of Science, ICT & Future Planning), Korea in the ICT R&D Program 2014.

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