Energy-Efficient Opportunistic Topology Control in Wireless Sensor Networks

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Abstract

Topology control has been proposed as a promising technique to achieve energy-efficiency in wireless sensor networks (WSNs). However, existing topology control algorithms assume that wireless links are static, either connected or disconnected. Taking advantage of the time-varying characteristic of wireless links, we define the energy-efficient opportunistic topology control problem, which exploits opportunistic communication to maximize energy-efficiency as well as to satisfy given network performance requirement. After proving this problem to be NP-hard, we propose a greedy solution and show its effectiveness through simulation. To the best of our knowledge, this is the first paper to apply opportunistic communication to topology control in WSNs. We demonstrate that opportunistic topology control can significantly improve energy-efficiency without sacrificing network performance.

Categories and Subject Descriptors

C.2.1 [**COMPUTER-COMMUNICATION NETWORKS]:** Network Architecture and Design – Network topology, Wireless communication

General Terms

Algorithms, Design, Performance

Keywords

Topology Control, Opportunistic Communication; Energy-Efficiency; Wireless Sensor Networks.

1. Introduction

Self-organizing a large number of tiny sensor nodes and aggregating a large amount of sensory data, wireless sensor networks (WSNs) greatly extend our ability to instrument with the physical world [1]. As sensor nodes are always battery-powered, energy-efficiency becomes one of the key challenging problems for WSNs.

Topology control has been proposed as a promising technique to achieve energy-efficiency in WSNs [2-4]. For a given WSN, topology control technique wisely chooses a group of nodes to form a connected infrastructure, so that the other nodes can directly connect to the infrastructure. In other words, they are 1-hop away from the infrastructure. The nodes belong to the infrastructure are called *coordinator nodes*, and the other nodes are called *non-coordinator nodes*. As a non-coordinator node only turns on its radio when it needs to connect the infrastructure, its energy can be significantly saved. An energy-efficient topology control algorithm aims at minimizing the number of coordinator nodes. An example is shown in Figure 1(a) where two nodes are connected by a solid line if they are directly connected. Node A, B, C, and sink O are selected as coordinators. Sink O will be a coordinator by default because of its unlimited energy. Under this topology, non-coordinator F transmits all its sensed data to its neighboring coordinator C, which then forwards the data back to sink through the infrastructure.

Existing topology control algorithms assume underlying wireless links are static, either connected or disconnected. However, in real deployments, wireless links are time-varying so that wireless transmission only succeeds at a probability. Opportunistic communication [5-7] exploits the time-varying characteristic of wireless links to improve network performance. Since every coordinator always turns on its radio, we can opportunistically leverage time diversity of channel conditions among multiple coordinators rather than relying on single coordinator. As shown in Figure 1(b), when node F transmits a packet to its neighboring coordinator C, there is a small probability that coordinator A or B can overhear the packet even link qualities of link FA and FB are bad. Since link AO has higher quality than link CO, the packet has a higher probability to reach O if node A successfully receives and forwards the packet. Furthermore, if link FA and FB can congregate to provide the same probability for a packet from node F to reach sink O as the topology in Figure 1(a) does, we can save more energy by switching node C to a non-coordinator without sacrificing the end-to-end network performance from node F to sink O.

Since the sensed data reported back from all sensor nodes to the sink always dominates network traffic, various WSN applications have different requirements on the end-to-end network performance from all sensor nodes to the sink. Generalizing the above example, we can define the *energy-efficient opportunistic topology control* problem, which employs opportunistic communication to minimize the number of coordinators as well as to satisfy given end-to-end network performance requirements from all the sensor nodes to the single sink. After proving the energy-efficient opportunistic topology control problem to be NP-hard, we propose a greedy solution with a deep analysis of end-to-end performance requirements over opportunistic topology

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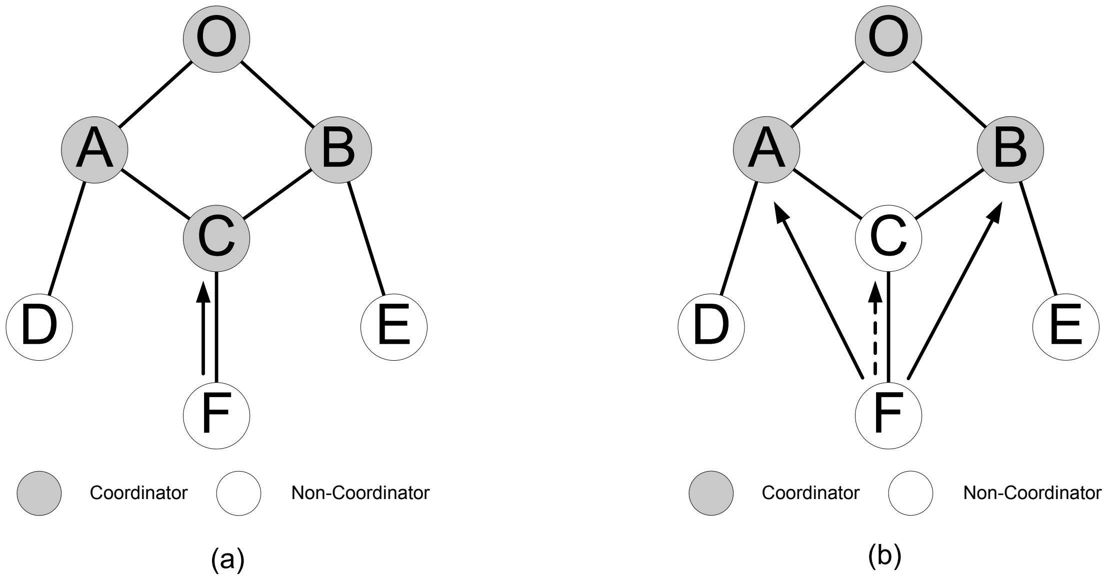

Figure 1. The difference between traditional and opportunistic topology control.

control. The energy-efficiency of our solution is shown through simulations.

To the best of our knowledge, it is the first paper to apply opportunistic communication to topology control in WSNs. Besides defining the energy-efficient opportunistic topology control problem, we demonstrate that opportunistic topology control can significantly improve energy-efficiency without sacrificing network performance.

The rest of the paper is organized as follows. We discuss related topology control and opportunistic communication papers in Section 2. Section 3 formulizes the energy-efficient opportunistic topology control problem, which is proved an NP-hard problem. We analyze the end-to-end network performance over opportunistic topology control in Section 4. We propose a greedy solution for energy-efficient opportunistic topology control in Section 5. Section 6 evaluates our solution and presents the advantage of being opportunistic through simulations. Finally, we give our conclusion and list future work in Section 7.

2. Related Work

Traditional topology control technique has been intensively studied in mobile ad hoc networks and wireless sensor networks. When network topology is modeled as a *connectivity graph* in which each wireless link is either connected or disconnected, the energy-efficient topology control problem can be formulized as the *minimal connected dominating set* (MCDS) problem. Guha and Khuller [8] proved that MCDS problem is an NP-hard problem and proposed a centralized approximation algorithm. Dai and Wu [3] proposed a distributed heuristic-based algorithm called rule *k*, which requires 2-hop neighborhood information on every node. Ma et al. [4] further extended rule *k* to a series of distributed algorithms, which provide different tradeoffs between energy-efficiency and algorithm complexity. Relying on the assumption of static wireless links, traditional topology control algorithms cannot exploit the opportunity existed in time-varying wireless links in real deployments.

Several experimental papers have studied the characteristics of wireless channels. Zhao and Govindan [9] collected experimental link quality data in three different environments and found out that a large percentage of radio links reside in the transitional region between connected and disconnected region. Couto et al. [10] presented that the *expected transmission count* (ETX) metric, which computes the expected number of transmission for a packet over time-varying wireless links from a probability perspective, can more accurately model the end-to-end network performance than the hop distance metric, which simply treats each hop as a connected link.

Recently, opportunistic communication receives growing interest due to time-varying wireless channels. Biswas and Morris [5] proposed the ExOR opportunistic routing protocol, which determines each hop of a packet after the packet's transmission on that hop. The node closest to the destination among all the candidate forwarders that receive the packet is chosen in each hop. Thus, ExOR can achieve better ETX than traditional routing protocols. Besides routing protocols, opportunistic communication can also improve the performance of MAC protocols [6] and scheduling [7] in ad hoc networks. Our work can be a complement of these opportunistic communication protocols.

3. Problem Formulation

Before formulating the energy-efficient opportunistic topology control problem, we give some basic notations first. A WSN can be modeled by a weighted directed graph $G = (V, E, w)$, where V is the set of sensor nodes and E represents the radio links among the nodes. Thus, weight $w(u, v)$ is the packet success rate of the radio link from node u to v. We support asymmetric links so that $w(u, v)$ may not equal to $w(v, u)$. The unique sink node is labeled as node s. If v cannot receive any packet from u, we can either set $(u, v) \notin E$, or set $(u, v) \in E$ and $w(u, v)=0$. We call this kind of graph a *link quality graph* (LQG).

When topology control is concerned, a topology scheme can be represented by a function c: V-$\{s\}\rightarrow\{0,1\}$ such that $c(v)=1$ *iff* node v is a coordinator. Sink s is ignored because it always acts as a coordinator. When topology scheme c is applied, we denote the LQG of the resulted topology as $G(c)$. Since only the coordinators participant in packet forwarding, we can derive $G(c)$ from G by omitting all the incoming edges of non-coordinators. Thus, we can define $G(c) = (V, E, w_c)$ where

$$w_c(u,v) = c(v)w(u,v) \tag{1}$$

We choose ETX to model the end-to-end network performance from all the sensor nodes to the sink. The ETX from v to sink s is denoted as $ETX(v)$.

For energy-efficient opportunistic topology control problem, we employ opportunistic communication to optimize energy-efficiency as well as to satisfy given network performance requirements. Mathematically, given a requirement Q: V-$\{s\}\rightarrow R^+$, we can formulate this problem as a optimization problem to find the topology scheme c such that

minimize $\sum_{v} c(v)$

subject to $ETX(v) \leq Q(v)$ in $G(c)$ for every $v \in V$.

We have the following theorem for the complexity of the energy-efficient opportunistic topology control problem.

Theorem 1. The energy-efficient opportunistic topology control problem is NP-hard.

Proof. For any unit disk graph $G = (V, E)$, we can regard G as a LQG with every edge in E having weight of 1. Given the requirement Q such that $Q(v) = |V|$ for each node v except the sink, a coordinate set C can satisfy this requirement Q *iff* set C is a connected dominating set in unit disk graph G. Thus, we can reduce the energy-efficient opportunistic topology control problem to the MCDS problem. Since the MCDS problem is a well-know NP-hard problem, the energy-efficient opportunistic topology control problem is also a NP-hard problem. □

4. ETX Analysis

In order to satisfy the end-to-end network requirement, we need to analyze $ETX(v)$ in opportunistic topology control. Here we assume that the packet loss among receivers is independent. Experimental result has shown that the majority of packet loss among receivers is uncorrelated [5]. Based on this assumption, we first derive an ETX formula in opportunistic topology control and then take insight into the optimal ETX with respect to the derived formula.

4.1 ETX Formula

Now we consider the scenario in which node v sends a packet to sink s in a LQG G. In traditional single-path routing, $ETX(v)$ in LQG G can be calculated as

$$ETX(v) = \min_{p\in P}\{\sum_{(u,v)\in p} \frac{1}{w(u,v)}\} \tag{2}$$

where set P contains all the paths from v to s in LQG G. Here we regard the inverse of 0 as $+\infty$ from the perspective of limit. We can take advantage of opportunistic communication to improve ETX.

As far as opportunistic communication is concerned, we denote $F(v)$ as the candidate forwarder set of node v. Since the transmission of a packet from v to $F(v)$ is successful if any of nodes in $F(v)$ receives the packet, we can define $w(v, F(v))$ as the aggregate link quality from v to the candidate forwarder set $F(v)$. We have

$$w(v,F(v)) = 1 - \prod_{u\in F(v)} (1 - w(v,u)) \tag{3}$$

We sort $F(v)$ as $\{u_1, u_2, \ldots, u_m\}$ with the ascending order of ETX. Without losing generality, we assume u_1 and u_2 both receive the packet. If both of nodes forward the packet to sink s, the packet from u_1 will first arrive sink s with a high probability since $ETX(u_1) \leq ETX(u_2)$. Thus, the packet from u_2 could be a waste. Generally, we always choose the node with smallest ETX among all the candidate forwarders that receive the packet as the only forwarder. If two nodes have the same ETX, we use node ID to break the tie so that the node with lower node ID is selected. This happens to be very similar to the forwarding strategy used in ExOR.

Now we analyze the ETX formula under this forwarding strategy. First, let us consider a simple example, in which u_k is selected as the forwarder after v transmits the packet. Thus, u_k receives the packet while $u_1, \ldots, u_{k-1}$ all miss the packet. We can calculate the probability of this event p_k as follows.

$$p_k = w(v,u_k)\prod_{i=1}^{k-1}(1 - w(v,u_i)) \tag{4}$$

However, it is possible that every node misses the transmission and v has to retransmit it. Thus, the sum of p_k for k from 1 to m is the probability that at least one candidate forwarder receives the packet, which is the aggregate link quality from v to $F(v)$.

$$\sum_{k=1}^{m} p_k = w(v,F(v)) \tag{5}$$

Generally, we define event $e(k, j)$ as the event that u_k is the selected forwarder after v transmits the packet j times. We can calculate the probability of event $e(k, j)$ as follows.

$$\Pr(e(k,j)) = p_k(1 - w(v,F(v)))^{j-1} \tag{6}$$

Then, the ETX of node v is

$$ETX(v) = \sum_{j=1}^{\infty}\sum_{k=1}^{m} p_k(1 - w(v,F(v)))^{j-1}(ETX(u_k) + j) \tag{7}$$

Based on Equation (5), we can derive the following equation.

$$ETX(v) = \frac{1}{w(v,F(v))}\sum_{k=1}^{m} p_k ETX(u_k) + \frac{1}{w(v,F(v))} \tag{8}$$

We can explain the physical meaning of Equation (8) as follows. The first item in the right hand side is the ETX from the selected forwarder to sink s. This item is a weighted average of the ETXs of all the candidate forwarders, and the weight for any candidate forwarder is the probability that it will be selected. The second item in the right hand side is the ETX from v to the selected

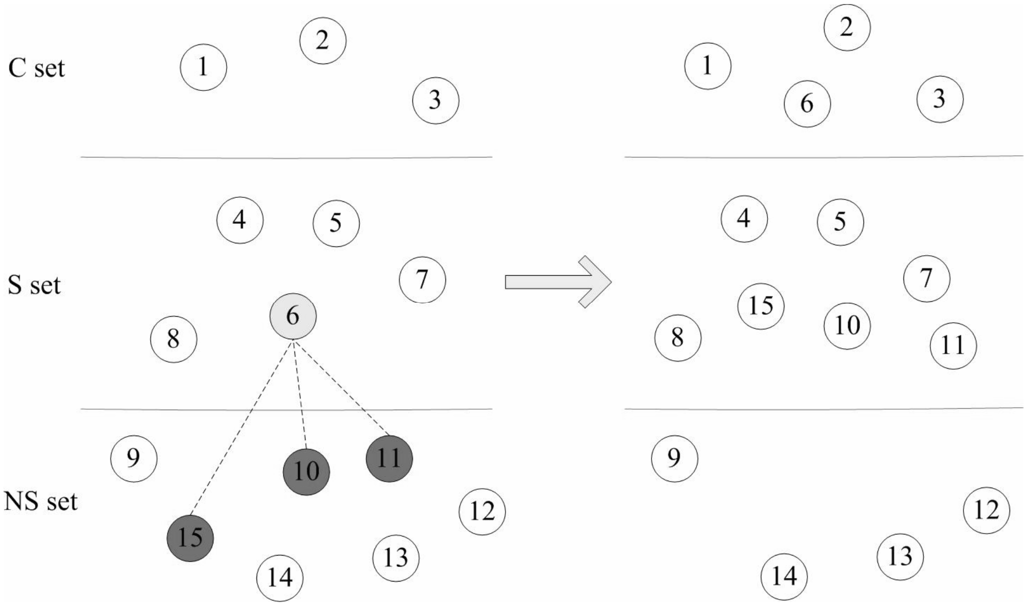

Figure 2. An example step of our algorithm.

forwarder. Since the packet only needs to reach just one candidate forwarder, the corresponding packet success rate is $w(v, F(v))$.

4.2 ETX Optimization

In previous analysis, we assume that $F(v)$ is given. Then a natural question is how to select $F(v)$ to minimize the ETX of v. In other words, we want to optimize ETX under a given topology for each node.

For a non-coordinator v, $F(v)$ can be any set of coordinators. We assume the topology scheme is c, which generates coordinator set $C = \{u_1, u_2, \ldots, u_z\}$ with the ascending order of ETX. From Equation (4), removing u_k from $F(v)$ is equivalent to setting $w(v, u_k)$ to 0. Thus, we can use a function f: $C \rightarrow \{0,1\}$ to represent $F(v)$ so that $f(u_k)=1$ *iff* $u_k \in F(v)$. If we replace $w(v, u_k)$ with $f(u_k)w(v, u_k)$ in Equation (8), the problem of calculating the smallest ETX for v becomes a 0-1 integer programming problem, which chooses the best f to minimize ETX.

If we assume ETX^* is the best ETX for v under topology scheme c, and coordinator subset F^* is the smallest $F(v)$ which can generate ETX^*, we can claim that all the ETXs of nodes belong to F^* are smaller than the ETX of v. Otherwise we denote u^* as the coordinator with maximal ETX in F^*. According to Equation (8), we have

$$\frac{\partial ETX(v)}{\partial f(u^*)} = \frac{[ETX(u^*) - ETX(v)]\prod_{u \neq u^*}(1 - w(v,u))}{w(v,F^*)} \leq 0 \qquad (9)$$

Based on Equation (9), we can set $f(u^*)$ to 0 rather than 1 to get a new ETX that is smaller than or equal to the old ETX. In other words, we can get a smaller set $F(v) = F^* - \{u^*\}$. This is a contradiction. Thus, the ETX of every node in F^* is smaller than the ETX of v. From the perspective of forwarding, it means that v should always choose a forwarder that is closer to the sink. Since ETX makes progress in each hop, this forwarding strategy is loop-free.

As 0-1 integer programming problem is always an NP-hard problem, we propose a simple approach to compute ETX based on the property that a node only chooses the candidate forwarders with smaller ETX. Node v sequentially adds u_1, u_2, …, u_k into $F(v)$ such that $ETX(u_k)<ETX(v)$ and $ETX(u_{k+1}) \geq ETX(v)$ or $F(v)=C$. Through this approach, $F(v)$ consists of all the coordinators with smaller ETX than the ETX of v.

For a coordinator v, we can compute its ETX in the same way. The only difference is that node v itself should be excluded from C when $F(v)$ is constructed.

5. Topology Control Algorithm

After analyzing ETX in opportunistic topology control, we take insight into topology control algorithm. First, we introduce some notations. Set C denotes the coordinator set. Set S denotes the candidate coordinator set, which contains all the non-coordinators that have satisfied their ETX requirements. Set NS denotes the set of non-coordinators that have not satisfied their ETX requirements yet. Thus, we always have $NS=V-C-S$. When a subset of set C can satisfy the ETX requirement of v, we call that C satisfies v.

Since the energy-efficient opportunistic topology control problem is NP-hard, we propose a heuristic algorithm to reduce the size of NS greedily. Initially, we have $C=\{s\}$. Every node computes its ETX by just using sink s as its only forwarder. Those nodes that can satisfy their ETX requirements are added candidate coordinator set S. Then, in each step, we find out the best candidate forwarder, which can satisfy the ETX requirements for the maximum number of nodes belong to NS with the help of existing coordinators. After setting this candidate forwarder as the next coordinator, we can move the nodes in NS that become satisfied from NS to S. An example step is shown in Figure 2 , in which we find that if node 6 is added to C, the set {1, 2, 3, 6} can satisfy the maximum number of nodes in set NS (node 10, 11, and 15). Then we set node 6 as the next coordinator and move it from S to C. We also move node 10, 11, and 15 from NS to S. If there

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$C$ = GreedyOTC()
1. $C = \{s\}$
2. $S = \{v \mid ETX(v) \le R(v)$ if $F(v) = C\}$
3. $NS = V - C - S$
4. do
5.     $u = \{v \in S \mid C \bigcup \{v\}$ satisfies maximum nodes $\}$
6.     $U = \{v \in NS \mid C \bigcup \{u\}$ satisfies $v\}$
7.     $C = C \bigcup \{u\}$
8.     $S = S \bigcup U$
9.     $NS = NS - U$
10.    update the ETX value
11. while ($S \ne \varnothing$ and $NS \ne \varnothing$)
12. if ($S \ne \varnothing$) output "unsatisfiable"
13. return $C$
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Figure 3. The opportunistic topology control algorithm.

are multiple candidate forwarders all satisfy the maximum number of *NS* nodes, we choose the one with the smallest ETX value as the next coordinator.

Finally, the algorithm will continue until *NS* becomes empty, which means every node can satisfy its ETX requirement. This algorithm will also stop if S is empty, which means some nodes cannot satisfy the ETX requirement. In this case, the algorithm reports the message "unsatisfiable". This greedy optimization algorithm is formally described in Figure 3.

After proposing our algorithm, we give an analysis of its time complexity. We denote the total number of node as *n*. In line 5, it costs at most $O(n)$ time for each $v \in S$ to compute the number of nodes which $C \bigcup \{v\}$ can satisfy, because we know the ETX value under the original *C* and always keep the values of parameters in Equation (6) and (8). Therefore, in order to choose the best candidate coordinator from *S*, line 5 totally needs $O(n^2)$ time. Line 6-9 will cost no more than $O(n)$, and line 10 also costs at most $O(n^2)$. Thus, in each iteration of adding coordinator, the running time is $O(n^2)$. Since there are at most *n* iterations, the total running time of the whole algorithm is $O(n^3)$.

6. Evaluation

Besides formal analysis, we employ simulations to compare the performance between traditional and opportunistic topology control. We focus on the energy-efficiency metric. For traditional topology control, we use the same greedy algorithm as opportunistic topology control with the restriction that $F(v)$ can only contain one node. When end-to-end network performance requirement is concerned, we adopt a typical type of requirement, which requires the ETX of each node to be lower than or equal to a threshold *q*. The threshold *q* is changed gradually to represent different requirements. When a requirement cannot be satisfied, we simply set all the nodes to be coordinators.

In terms of simulation settings, sensor nodes are distributed in a square terrain in accordance with predefined side lengths where sink *s* is placed in the center. Two popular node placements are investigated, namely uniform and random. In uniform placement, the terrain is partitioned into unit grids. All the nodes are evenly divided amongst these grids (random distribution inside each grid). In random placement, all nodes are randomly distributed throughout the terrain. The terrain is 20*20 square meters and the number of deployed nodes is 100. We use the wireless link quality generator [11] to generate 20 different LQGs for uniform and random topologies, respectively. The node radio and propagation model follow the default settings of the generator, which are listed in Table 1.

Table 1. Simulation Settings

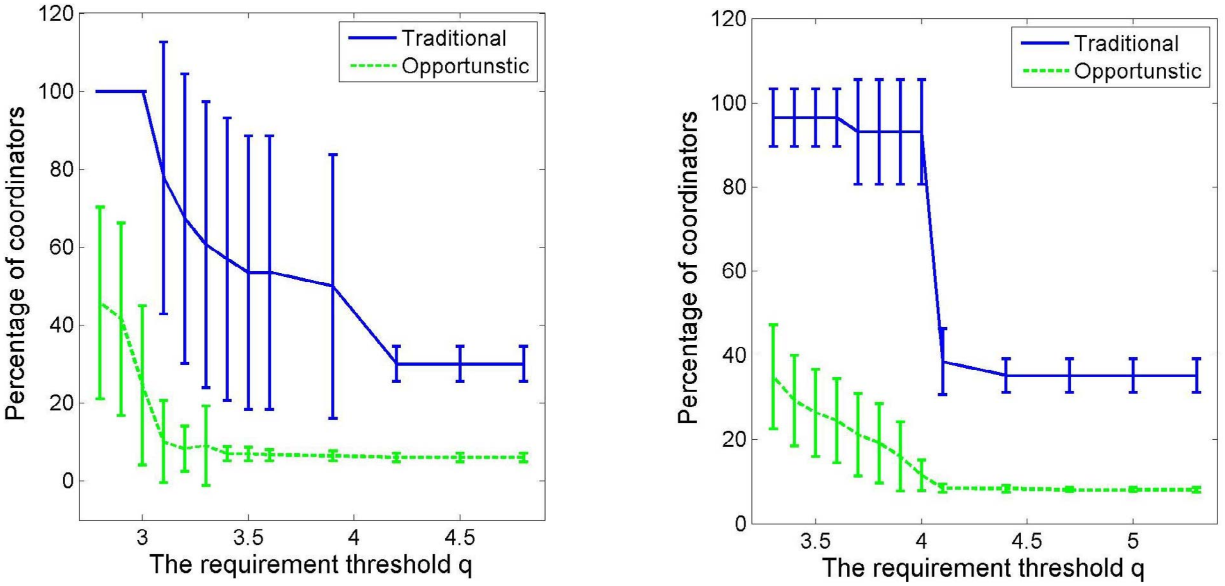
Parameter	Value
Path loss exponent	4.7
Shadowing standard deviation	3.2 dB
Close-in reference path loss	55 dB
Close-in distance	1 m
Modulation	DPSK
Encoding	MANCHESTER
Output power	-7.0 dBm
Noise floor	-105.0 dBm
Preamble length	2 bytes
Frame length	50 bytes

The comparison of energy-efficiency between traditional and opportunistic topology control under random and uniform topologies is shown in Figure 4. For each requirement threshold *q*, we calculate the percentage of coordinators among all the nodes from the 20 topologies and present the average and standard deviation of computed results. For random topology, the threshold *q* ranges from 2.8 to 4.8. For uniform topology, the threshold *q* ranges from 3.3 to 5.3. Under the threshold range we select, the percentage of coordinators in the traditional algorithm changes from 100% to nearly 40%. Compared with uniform topology, random topology can satisfy stricter ETX requirements (smaller *q*) due to larger variation among generated topologies, which leads to larger standard deviations. In both types of topologies, opportunistic topology control can significantly improve energy-efficiency over traditional topology control.

7. Conclusions and Future Work

This paper defines the energy-efficient opportunistic topology control problem, which exploits opportunistic communication to minimize the number of coordinators as well as to satisfy given requirements on end-to-end network performance. We prove the problem to be NP-hard and propose a greedy solution. We demonstrate that opportunistic topology control can significantly improve energy-efficiency without sacrificing network performance.

Potential areas of future work include extending our problem to handle multi-sink scenario, transforming our algorithm from centralized to distributed, and rotating the coordinator duty among all the nodes.



(a) Random

(b) Uniform

Figure 4. The comparison between traditional and opportunistic topology control.

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