

Opportunistic Transmission Based QoS Topology Control in Wireless Sensor Networks

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Abstract

In wireless sensor networks (WSNs), QoS topology control achieves energy-efficiency by turning off redundant nodes and links, while still satisfying the given QoS requirement. However, existing topology control algorithms assume that links are either connected or disconnected. Recent experiments have shown that, besides the connected and disconnected region, a large percentage of links reside in the transitional region with fluctuating link qualities. In this paper, we propose both centralized and distributed solutions for QoS topology control, where we employ the opportunistic transmission to catch the best transmission opportunities on transitional links. Our simulations demonstrate that opportunistic transmission based approach can significantly improve energy-efficiency in QoS topology control with low communication overhead. A unique contribution of this paper is to consider link quality and apply opportunistic communication in topology control for WSNs.

Keywords- Topology Control; Opportunistic Transmission; QoS; 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 the ability to interact with the physical world [1]. As sensor nodes are typically battery-powered, energy-efficiency becomes one of the key challenges for WSNs.

Topology control has been proposed as a promising technique to achieve energy-efficiency in wireless networks [2, 3, 4]. For a given WSN, topology control technique selects a group of nodes to form a connected infrastructure, so that the other nodes can directly connect to the infrastructure [3]. The nodes belonging to the infrastructure are called *coordinator nodes*, and others 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 signifi-

cantly saved. An energy-efficient topology control algorithm aims at achieving an optimal number of coordinator nodes with minimal energy cost.

In some WSN applications such as wildfire detection [1] and sniper localization [5], besides energy-efficiency, they also have some application-dependent QoS requirements such as delay, throughput, and packet reliability. Generally, we can define the *QoS topology control* problem as the problem that not only minimizes the energy cost, but also satisfies the given QoS requirement.

In this paper, we focus on a particular QoS metric called *expected transmission count* (ETX), which is the expected number of packet transmissions required to successfully deliver a packet to its destination. ETX metric is a good indicator for end-to-end delay and throughput [6] and is widely used in routing protocols for WSNs [7]. We assume that there only exists one sink so that an ETX requirement specifies the end-to-end ETXs from all the nodes to the sink.

Most of the existing topology control algorithms, no matter they concern QoS or not, assume that links are either fully connected or completely disconnected [13]. In other words, these algorithms are connectivity-based. However, recent studies [8] [9] [10] have pointed out that, besides the connected and disconnected regions, many links reside in the *transitional region*, where the link qualities fluctuate. We call those links *transitional links*.

Opportunistic routing, which was first presented by Biswas and Morris in their protocol ExOR [11], is a promising mechanism for obtaining high throughput even when links are not perfectly reliable. We can employ the similar opportunistic transmission concept to catch the best transmission opportunities on transitional links for WSNs.

Here we would like to give a general comparison between the opportunistic transmission based topology control problem with the traditional topology control. The algorithm for the traditional topology control problem is to find a spanning tree with the minimum

number of non-leaf nodes for the whole topology, which form the connected dominate set like a backbone. The key observation we have for opportunistic transmission based topology control is that, although some nodes may not be connected to the backbone with fully reliable links, by employing several transitional links together they can still satisfy the QoS requirement. Therefore, this approach can significantly reduce the number of backbone nodes (coordinators) to save energy.

In this paper, we prove the NP-hardness of the QoS topology control problem, and propose both centralized and distributed solutions, which employ opportunistic transmission to achieve better energy-efficiency.

The rest of this paper is organized as follows. Section 2 formulates the QoS topology control problem and provides a deep analysis of opportunistic transmission based ETX. In Section 3, we propose both centralized and distributed solutions, which employ opportunistic transmission for QoS topology control. Section 4 evaluates our solutions and presents the advantage of opportunistic transmission through simulations. Finally, we give our conclusion and future work in Section 5.

2. Problem formulation

In this section we first provide an example to show the idea about opportunistic transmission based topology control and its advantages. Then we give a formal definition of QoS topology control problem.

2.1 Illustrative example

Here we provide an illustrative example as shown in Figure 1. We assume all the connected links have link qualities of 1 in both directions. Since a link's ETX is the inverse of the link's quality in the forward direction, the ETX of each connected link is 1. Further, as each node's ETX is the sum of the link ETXs along the lowest-ETX path to the sink O, the ETX of node F is 3. Given the ETX requirement that demands every node to have an ETX less than or equal to 3, the connectivity-based topology control selects nodes A, B, C, and sink O as coordinators as shown in Figure 1(a). Under this topology, non-coordinator F transmits its sensed data to its neighboring coordinator C, which then forwards them back to sink through the infrastructure.

As shown in Figure 1(b), however, links FA and FB are transitional links with qualities of $1/3$ and $1/4$, respectively. Under opportunistic transmission, when node F transmits a packet to its neighboring coordinator C, coordinators A and B have a small chance to

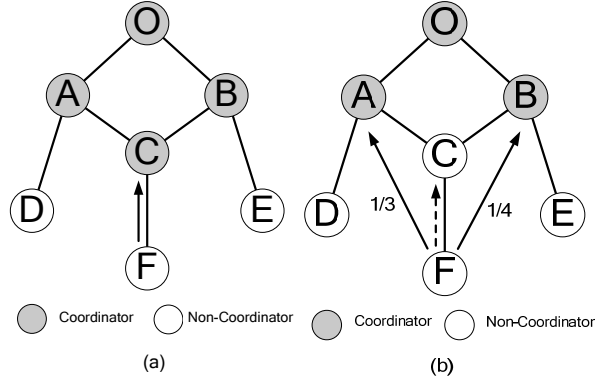


Figure 1. The difference between connectivity-based and opportunistic transmission based QoS topology control.

overhear the packet since they always turn on their radios. If the packet happens to reach coordinator A, opportunistic transmission takes this opportunity and chooses coordinator A to forward the packet because A has a better ETX than C. Since the chance for coordinator A or B to receive a packet from node F is $1 - (1 - 1/3)(1 - 1/4) = 1/2$, the ETX of F to reach coordinator A or B is 2 and the ETX of F is 3. Thus, the opportunistic transmission based ETX is better than the original ETX. Further, when the same ETX requirement that demands every node has an ETX less than or equal to 3 is considered, we can save more energy by switching node C to a non-coordinator.

From the above example, it can be seen that by leveraging transitional links and by using opportunistic transmission based QoS topology control, the number of coordinator nodes can be significantly reduced.

2.2 Problem formulation

In this work, we make the following assumptions: 1) we do not take mobility into consideration, i.e., every sensor stands still; 2) we only consider one QoS metric, i.e., ETX. Other metrics can also be considered using the similar analysis in the future; and 3) the optimization target on which we focus is the number of coordinators.

Here we give some basic notations. 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. Weight $w(u, v)$ is the quality 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 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 of concern, a topology scheme can be represented by a function $c: V \rightarrow \{0, 1\}$.

$\{s\} \rightarrow \{0,1\}$ 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

$$w_c(u, v) = c(v)w(u, v) \quad (1)$$

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 a resultant topology $G(c)$, we can employ opportunistic transmission to get better ETX.

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

$$\begin{aligned} & \text{minimize } \sum c(v) \\ & \text{subject to } ETX(v) \leq Q(v) \text{ in } G(c) \text{ for every } v \in V. \end{aligned}$$

We call a node *satisfied* if its ETX requirement is satisfied. Otherwise, the node is *unsatisfied*. Thus, the QoS topology control problem tries to make every node satisfied with the minimum number of coordinators. The QoS topology control problem can be proved as NP-hard.

In order to satisfy the given ETX requirement, we need to analyze opportunistic transmission based ETX in QoS topology control. Here we assume that the packet loss among different receivers is independent. Experimental results have shown that the majority of packet loss among receivers is uncorrelated [12]. We first derive a formula for opportunistic transmission based ETX in QoS topology control and then take insight into the optimal ETX with respect to the derived formula.

Now we consider the scenario in which node v sends a packet to sink s in LQG G . Without opportunistic transmission, $ETX(v)$ in LQG G can be calculated as

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

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 transmission to improve ETX.

Rather than relying on a fixed single forwarder, opportunistic transmission exploits the opportunities on the links to a set of candidate forwarders, which is denoted as set $F(v)$ for node v . The opportunistic trans-

mission 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 can derive the following equation [14]

$$ETX(v) = \frac{1}{w(v, F(v))} \sum_{k=1}^m p_k ETX(u_k) + \frac{1}{w(v, F(v))} \quad (3)$$

where,

$$p_k = w(v, u_k) \prod_{i=1}^{k-1} (1 - w(v, u_i)) \quad (3)$$

We can explain the physical meaning of Equation (3) as follows. The first term in the right hand side is the ETX from the selected forwarder to sink s . This term 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 term in the right hand side is the ETX from v to the selected forwarder. Since the packet only needs to reach just one candidate forwarder, the corresponding packet success rate is $w(v, F(v))$.

3. Topology control algorithms

After obtaining the opportunistic transmission based ETX formula, we propose several algorithms for the QoS topology control problem. Since the problem is NP-hard, we first design a centralized algorithm, which greedily increases the number of satisfied nodes. To simulate the centralized algorithm, we design a distributed algorithm that only relies on 2-hop neighborhood information. Finally, we take insight into the issue of reliable broadcast in our distributed algorithm and replace high-overhead reliable broadcast with low-overhead opportunistic broadcast.

Before jumping into the detail of the proposed algorithms, we introduce some notations here. Set C denotes the coordinator set, and set NC denotes the non-coordinator set. Set S denotes the set of satisfied non-coordinators, and set NS equals to $NC - S$. When coordinator set C can satisfy the ETX requirement of node v , we call that set C can satisfy node v . We denote a non-negative function $U(v)$ as the utility function of node v , which represents the contribution of node v for satisfying ETX requirement Q if it becomes a coordinator. Obviously, the utility value of a coordinator is 0 as it is already a coordinator. As we only turn a satisfied non-coordinator to a coordinator, the utility value of an unsatisfied non-coordinator is 0. For any satisfied non-coordinator v , its utility value depends on the current network topology.

$C = \text{CentralizedQoSSTC}()$

1. $C = \emptyset$
2. $S = \{s\}$
3. $NS = V - C - S$
4. **do**
5. choose $c \in S$ and $U(c) = \max_{v \in S} \{U(v)\}$
6. $C = C \cup \{u\}$
7. every node in NS update ETX values
8. $S' = \{v \in NS / C \text{ satisfies } v\}$
9. $S = S \cup S'$
10. $NS = NS - S'$
11. **while** ($S \neq \emptyset$ and $NS \neq \emptyset$)
12. **if** ($S \neq \emptyset$) output “unsatisfiable”
13. **return** C

Figure 2. The centralized topology control algorithm

3.1 Centralized algorithm

Since the QoS topology control problem is NP-hard, we propose a heuristic algorithm to reduce $|NS|$ greedily. In the MCDS algorithms [x], $U(v)$ is defined as the degree of the vertex v . By employing opportunistic communication, we define $U(v)$ as the number of nodes that v can satisfy, i.e., the decrement of $|NS|$ if v becomes a coordinator.

The idea of our algorithm is the following. We grow a connect component from the root (sink). Nodes in set S always form a connected component. Unlike traditional topology control algorithms, some nodes in the connected component may not be connected with fully reliable links, but by several transitional links with the benefit of opportunistic communication. At each step, we grow connect component by picking the node that can satisfy the most number of nodes outside the connect component. Turning the picked node into coordinator, those nodes which are satisfied and are outside the connect component can be added into it. At the end, all nodes are involved into the connect component and we are done.

Initially, we have $C = \emptyset$ and $S = \{s\}$. All the other nodes belong to set NS . In every step, we add the node to S with the maximum utility value into set C . Then, every node update its opportunistic transmission based ETX according to the new set C , and the nodes in NS that become satisfied are moved to S . The algorithm will continue until NS becomes empty. It will also stop if S becomes empty, which means some nodes cannot be satisfied. In this case, the algorithm reports the message “unsatisfiable”.

This greedy centralized algorithm is formally described in Figure 2. When its time complexity is concerned, we can denote the total number of nodes as n . In line 5, it costs at most $O(n)$ time for each $v \in S$ to compute the number of nodes which $C \cup \{v\}$ can satisfy, because we know the ETX value under the origin-

$C = \text{DistributedQoSSTC}()$

1. **if** (state = **COORDINATOR**)
2. **return**;
3. **else**
4. (ID, util) = (self.ID, self.util)
5. **if** (state = **SATISFIED**)
6. broadcast its ticket
7. receive tickets
8. **else**
9. receive tickets
10. broadcast its ticket
11. **if** (ID = self.ID)
12. state = **COORDINATOR**
13. announce itself as a coordinator
14. **else**
15. receive coordinator announcements
16. update ETX
17. **if** (ETX requirement becomes satisfied)
18. state = **SATISFIED**

Figure 3. The distributed topology control algorithm

nal C and always keep the values of parameters in Equation (3). Therefore, in order to choose the best candidate coordinator from S , line 5 totally needs $O(n^2)$ time. Lines 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 a coordinator, the running time is $O(n^2)$. Since there are at most n iterations, the total running time of the whole algorithm is $O(n^3)$.

3.2 Distributed algorithm

As centralized algorithms introduce significant communication overhead for large-scale WSNs, we propose a distributed algorithm, which simulates our centralized algorithm but only relies on localized information. When only localized information is available, we simulate the centralized algorithm by choosing the satisfied non-coordinators with locally maximum utility to be the new coordinators.

Note that without centralized coordination, there could be collisions when nodes make their local role decisions. Suppose nodes 1 and 2 will become coordinators as they have the maximum utility value in their neighborhood. If both nodes contribute to lower the ETX of a non-coordinator, their utility values may depend on the role decision of each other. Thus, they cannot make their role decisions simultaneously.

In order to resolve the collision, we choose the nodes with maximum utility values within its 2-hop neighborhood rather than 1-hop neighborhood to become coordinators. We use node ID to break a tie on utility values so that a node with a lower ID has a higher priority to become a coordinator.

To implement our collision avoidance mechanism, each non-coordinator maintains a *ticket* (ID, util), which aims to store the node ID with the maximum

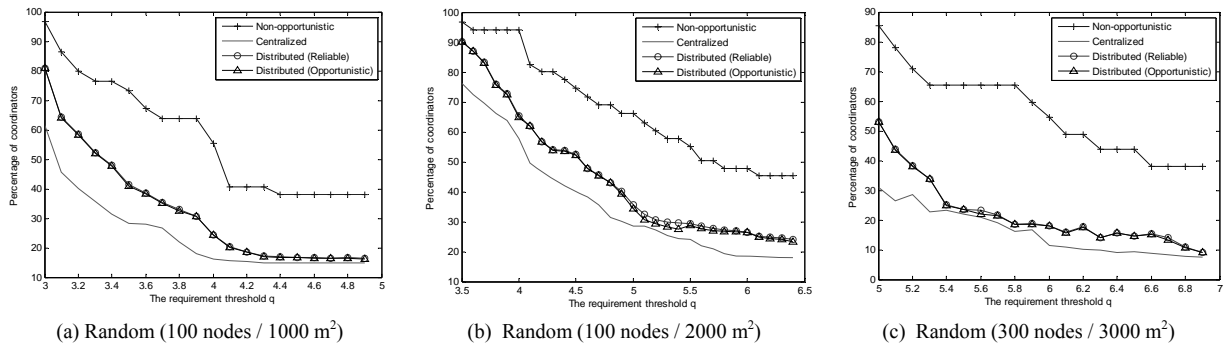


Figure 4. The comparison of energy-efficiency between non-opportunistic and opportunistic transmission based topology control algorithms.

utility value in its 2-hop neighborhood. A node will keep updating its ticket after receiving tickets from its neighbors. In each round, every non-coordinator first initializes its ticket with its own ID and utility value. Then, all the satisfied non-coordinators broadcast their tickets. Next, all the unsatisfied non-coordinators broadcast their tickets after receiving tickets from all of their neighboring satisfied non-coordinators. Finally, a satisfied non-coordinator will announce itself as a coordinator if the ID of its ticket is the same as its own ID. All the nodes will update their opportunistic transmission based ETXs according to new coordinator announcements, and some unsatisfied non-coordinators could become satisfied. A round of the distributed opportunistic topology control algorithm is formally described in Figure 3. The algorithm will stop when a node becomes a coordinator or cannot find any unsatisfied non-coordinator in its neighborhood.

We can further reduce the communication overhead by replacing reliable broadcast with *opportunistic broadcast*, in which a node just broadcasts a packet several times and whether a neighbor can receive the packet depends on the opportunity on its link.

4. Performance evaluation

Besides formal analysis, we employ simulations to evaluate the performance of our opportunistic transmission based topology control algorithms. When ETX 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.

We use the wireless link quality generator [15] to generate LQGs and implement the topology control algorithms in our own C++ simulator. The node radio

and signal propagation parameters follow the default setting in the link quality generator.

4.1 Energy-efficiency

When energy-efficiency is considered, we compare four topology control algorithms, the non-opportunistic algorithm (the SP algorithm from [3]) and three opportunistic transmission based algorithms, namely the centralized algorithm, the distributed algorithm with reliable broadcast, and the distributed algorithm with opportunistic broadcast. For non-opportunistic algorithm, we use the same greedy algorithm but compute ETX according to Equation (2). For opportunistic broadcast, we test different settings for the broadcast ratio for ticket packets and choose 0.7 as the ratio, which provides a good tradeoff between energy-efficiency and communication overhead.

We adjust the threshold q in the range where the centralized algorithm will choose 20% to nearly 100% nodes as coordinators. For each requirement threshold q , we calculate the percentage of coordinators among all the nodes from 20 different topologies and present the average results.

We first deploy 100 nodes in the terrain of 1000 square meters. The results of random topologies are shown in Figure 4(a). The centralized algorithm is the best and the non-opportunistic algorithm is the worst. There is little difference between the two distributed algorithms. Then, we lower the density by keeping the same number of nodes while doubling the size of terrain to 2000 square meters. The results of the low-density networks for random topologies are shown in Figure 4(b). When the density becomes lower, ETXs of nodes are increased, but the resulted curves are similar to that for higher-density. We also increase the number of nodes while keeping the same density. The results for 300 nodes in 3000 square meters terrain are shown Figures 4(c), where the threshold q is adjusted

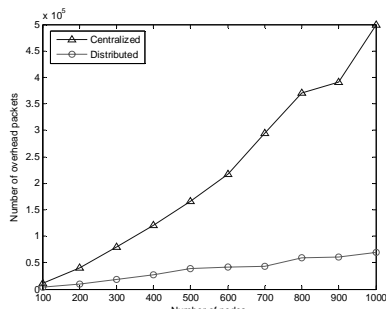


Figure 5. Comparison of communication overhead.

so that the coordinator percentage in non-opportunistic algorithm ranges from 40% to nearly 100%.

In both types of topologies, opportunistic transmission can significantly reduce the number of coordinators so that to improve energy-efficiency in QoS topology control. Further, compared with reliable broadcast, opportunistic broadcast rarely affects energy-efficiency.

4.2 Communication overhead

Since opportunistic broadcast provides nearly the same energy-efficiency as reliable broadcast, we only compare the communication overhead between the centralized algorithm and the distributed algorithm with opportunistic broadcast.

We increase the node number from 100 to 1000 with the step being 100 while keeping the same node density. To normalize the ETX requirement according to network size, we set the threshold q of each LQG G as the maximum ETX of all the nodes in single-path routing based on Equation (2). The comparison of total number of overhead packets is shown in Figure 5. The distributed algorithm has much lower communication overhead than the centralized algorithm, especially when the number of nodes is large.

5. Conclusion and future work

In this paper, we observe that transitional links can make an important impact on the design of QoS topology control algorithms. We consider transitional links and introduce opportunistic communication in topology control for WSNs. Catching the transmission opportunities provided by the transitional links, opportunistic transmission can significantly improve energy-efficiency in QoS topology control with low communication overhead.

Our work opens a new direction for topology control and many issues are worth to be investigated. These issues include extending our problem to handle multi-sink scenario, considering other QoS requirements except ETX, such as time delay and throughput

[16], and rotating the coordinator duty among all the nodes to achieve energy balance, etc. We are also interested in other influences by opportunistic transmission, including data transmission performance and MAC layer designs. We believe our protocol can also be extended to other fields, e.g., mobile ad-hoc networks and wireless mesh networks.

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