ENERGY EFFICIENT AND FAULT-TOLERANT BROADCAST PROTOCOL IN WIRELESS AD-HOC NETWORKS

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Abstract

To achieve efficient broadcasting with low interference and low energy consumption, each node optimizes its transmission power. In a tree-based topology, the message of node *u* can be overheard by nodes which are in the region of transmission radius of node *u* but not in a logical neighborhood of *u*. Therefore, some protocols have been proposed to reduce energy consumption by using overhearing. Since using the minimum energy to reach its neighboring nodes weakens the network connectivity, fault-tolerant topologies have been proposed. However, there is no broadcast protocol which takes into account of the reliability of transmissions. We propose a fault-tolerant broadcast protocol which uses overhearing to reduce energy consumption, while maintaining reliability of its transmissions.

Keywords: Ad-hoc networks; broadcast; energy efficiency; fault-tolerance

1 Introduction

Recent advances in wireless technologies have fostered the development of ad-hoc networks, including sensor networks. Since nodes operate with limited battery power, reducing energy consumption to prolong lifetime of the network has always been an important issue. Broadcast transmissions in ad-hoc networks are used for sending control packets, distributing cryptographic keys, and so forth. Broadcast by flooding usually consumes much energy. Therefore, it is not readily applicable in ad-hoc networks due to resource constraints of mobile nodes.

One of the approaches to reduce energy consumption is that, each node transmits packets by using relatively lower power while preserving network connectivity. This approach is referred to as *topology control*. Topology control algorithms are generally localized, i.e., each node uses only the information that is one-hop away. Especially, tree-based algorithms, such as Local Minimum Spanning Tree (LMST) [1], provide considerable performance. Based on the topology derived by a topology control algorithm, several protocols which achieve additional reduction of energy consumption have been proposed.

On the other hand, transmitting by using minimum power results in a topology, without redundancy to tolerate external factors. Fault-tolerant topology control algorithms, such as Local Tree-based Reliable Topology [2], have been proposed to enhance network reliability. However, there is no broadcast protocol which aims to reduce energy consumption, while preserving transmission reliability.

In this paper, we propose a broadcast protocol based on a fault-tolerant topology. We extend the existing broadcast protocol to preserve the reliability of topology, and propose some optimizations which achieve further improvement on energy consumption.

The remainder of this paper is organized as follows. Section 2 reviews some related works. We discuss a proposed fault-tolerant broadcast protocol in Section 3. In Section 4, we introduce some optimization schemes. Performance evaluations based on extensive simulation are illustrated in Section 5. Finally, Section 6 concludes the paper and presents the future work.

2 Related Works

Topology control has been widely studied to save energy [3]. Cone-Based distributed Topology Control (CBTC(α)) [4] is among the first algorithms that adjusts the transmission power to save energy consumption. Relative Neighborhood Graph (RNG) (first appeared in [5]) is also used to reduce the number of links between a node and its neighbors [6]. An edge belongs to the RNG only if it is not the longest leg of any triangle. Li *et al.* [1] proposed a Minimum Spanning Tree based

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algorithm for topology control. In LMST, each node uses the information of any neighbor that is one hop away to build a minimum spanning tree.

Although the above topology control algorithms achieve good energy efficiency, they do not take fault-tolerance into account. Therefore, fault-tolerant topology control algorithms have been proposed to mitigate this shortcoming. To achieve reliability, the k-connectivity approach is adopted. In k-connected topology, there are k disjoint paths for any pair of two nodes. Bahramgiri *et al.* [7] proved that CBTC(α) preserves k-connectivity if $\alpha < 2\pi / 3k$. Fault-tolerant Local Spanning Subgraph ($FLSS_k$) [8] and LTRT [2] also guarantee k-connectivity if the network has k-connectivity. As compared to CBTC(α), $FLSS_k$ and LTRT show much better performance. Although $FLSS_k$ outperforms LTRT, the computational cost of $FLSS_k$ is much higher than that of LTRT. Therefore, LTRT is more suitable for highly dense networks or mobile networks than FLSS.

Several algorithms focus on the broadcast protocol based on the derived topology by a topology control algorithm. The protocol uses overhearing message to reduce energy consumption as shown in the Figure 1. There are some nodes that are not logical neighbors but can receive messages such as node C and D in Figure 1.

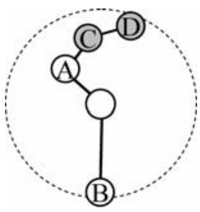

Figure 1. Nodes C and D will receive the message from u although they are not neighbors of u.

RNG based Broadcast Oriented Protocol (RBOP) [9] is one example of protocols that make use of overhearing message. In RBOP, when node u receives the message from the node that is not a neighbor of u, u makes the list of RNG-neighbors that have not received this message. After the given timeout, the node u retransmits the message with a range which can reach the furthest neighbor left in the associated list. The idea is that when node u receives a message from a given neighbor, v, node u does not need to transmit with a radius that can reach node v or nodes already covered by node v. The authors [9] have also proposed RBOP with full timeout (RBOP-T) and LMST Broadcast Oriented Protocol with full timeout (LBOP-T). In both protocols, all nodes apply timeout before possible retransmission. Among these three algorithms, RBOP, RBOP-T, and LBOP-T, the latter shows the best performance.

TR-LBOP and TRDS [10] are proposed for a highly dense network. The authors claimed that it is not always optimal to transmit at minimum power in highly dense networks. Broadcast on LMST (BLMST) [11] is a flooding algorithm applied to the network topology derived by LMST with the optimization such that if a node has received a broadcast message from all its neighbors, it will not relay the message.

However, no broadcast protocol, which can reduce energy consumption and be applied for k-connected topology, has been proposed. If the algorithm like RBOP is applied to k-connected network, each node might receive the message from only one neighbor, regardless of the original connectivity of the topology. In this case, one link failure might affect the network connectivity even though the original topology guarantees k-disjoint paths between every pair of two nodes.

In the next section, we propose a fault-tolerant broadcast protocol which guarantees k times reception of all the nodes, according to k-connectivity of given topology

3 Fault-tolerant broadcast protocol

In this section, we propose a fault-tolerant broadcast protocol to reduce the energy consumption of broadcasts, while preserving network reliability. Cartigny et al. [9] showed that LBOP-T is the best algorithm to reduce the energy consumption. Therefore, we adopt their idea and modify the algorithm to guarantee k times reception according to k-connectivity of given topology.

3.1 Network model

We assume that each node can control the power of its transmissions to reduce energy consumption. Each node u can transmit packets within its transmission radius, r_u, $0 \le r_u \le r_{\max}$. Let $d(v_1, v_2)$ be the Euclidean distance between two vertices v_1, v_2. Neighbor set of node u is represented as $N(u)$.

A graph $G(V, E)$ is k-connected if the removal of any $(k - 1)$ vertices or links does not partition the network. In other words, there are k-vertex-disjoint paths for any $v_1, v_2 \in V$, or there are k-edge-disjoint path for any $v_1, v_2 \in V$.

3.2 Algorithm

In LBOP-T, each node assumes that a neighbor has received a message if the node is in the transmission range of other nodes which have already transmitted the message.

In our proposed algorithm, neighbors that have received a message from k nodes are assumed to have surely received the message, as long as the derived topology is k-connected. The protocol for k-connected topology is described as follows:

1) Source node s broadcasts a message at a radius

$$r_s = \max\{d(s,v) \mid v \in N(s)\}\,, \qquad (1)$$

i.e., node s transmits with the radius that can reach the furthest neighbor of node u.

2) When node v receives a new broadcast message from node u, node v generates, for this broadcast, the table of neighbors in the derived topology, initialized by 0, and sets the value of node u in the table to k. This scheme is expressed as follows:

$$\forall t \in N(u) \quad T_v(t) \leftarrow 0\,, \qquad (2)$$

$$T_v(u) \leftarrow k\,, \qquad (3)$$

Besides, node v sets a given timeout.

3) When node v receives a previously received message from node u:
   a) The node ignores this message if it has already forwarded it.
   b) In the table of node v, the value of node u is set to k, and the values of neighbors which are in the transmission range of node u, are incremented by one, i.e.,

$$\forall t \in N(v) \;\; T_v(t) \leftarrow T_v(t) + 1 \;\; \text{if } d(x,u) < r_u, \qquad (4)$$

$$T_v(u) \leftarrow k\,. \qquad (5)$$

4) When the timeout of v for a broadcast has passed:
   a) If all the values of the neighbor table are k or more, i.e., $\forall t \in N(v) : T_v(t) \geq k$, the node sends no message.
   b) The node transmits a message with the radius that can reach all the neighbors where the value of the table is less than k, i.e., transmission radius is

$$r_v = \max\{d(v,t) \mid t \in N(v) \cap T_v(t) < k\} \qquad (6)$$

In this way, k-times transmission per node is guaranteed, thus reducing redundant retransmission. However, as the connectivity k increases, the number of transmissions becomes larger and the protocol becomes not-so-efficient. Therefore, we introduce an optimization scheme in the next section.

4 Protocol optimization

Since k-times of overhearing are needed for a node to reduce the transmissions in a broadcast, this may lead to high energy consumption when connectivity k is large. Yet, energy efficiency is the most important in energy-constraint ad-hoc networks. Therefore, we propose two types of optimization to improve the efficiency of the protocol.

4.1 Timeout based on connectivity and neighbor nodes

In LBOP-T, how to determine the timeout is not mentioned, and especially in the simulation, the timeout used in the neighbor elimination scheme is fixed to three times the duration of a message transmission.

However, it is important to use the timeout effectively in the protocol. We claim that the timeout should have the following two features:

1) The connectivity becomes larger, as well as the timeout, because each node needs to receive more transmissions to reduce its own transmission.
2) Nodes, which have more neighbors relay messages earlier, because such nodes exert a larger effect than the other nodes..

4.2 Transmission of the table value

When node u and node v have the same neighbor t, some transmissions can be received by u, but cannot be received by v. Therefore, by having node u sent the table information with the broadcast message, node v can know that node t has already received the message and will not need to send the message to node t.

Therefore, in our proposal, each node u transmits its own table T_u with a broadcast message. When node v receives the packet, it updates the table by using node u's table information. For each node x in the table T_u, node v updates the table as $T_v(x) \leftarrow T_u(x)$ if $T_v(x) < T_u(x)$.

In the next section, we evaluate the effectiveness of these optimizations via simulations.

5 Performance evaluation

In order to demonstrate the effectiveness of optimization, we evaluate the performance via extensive simulations.

5.1 Simulation setting

Simulations have been performed with our own C++ simulator. Nodes are randomly placed in a square region. The length of the square region is 1000[m]. Each node has a maximum transmission radius of r_{max} = 250[m]. After nodes are placed, we apply one of the fault-tolerant topology controls, LTRT. Based on the derived topology, every node makes a broadcast message. We compare the performance of our proposed protocol, with or without optimization.

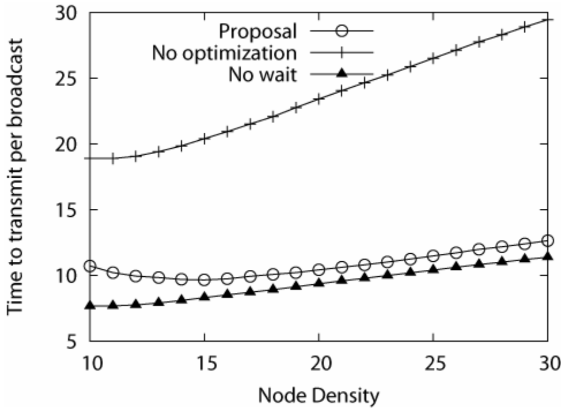

Figure 2. EER (k = 5)

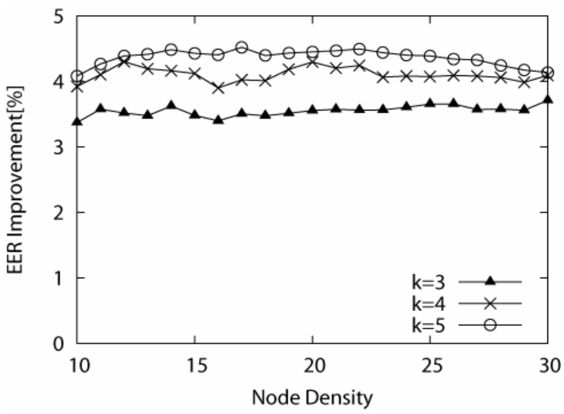

Figure 3. EER improvement for each connectivity

The MAC layer is assumed to be ideal, i.e., there are no collisions and no link failures. The timeout which satisfies the assumption in Section 4.1 is set to

$$t = t_{\max} - \frac{|N|}{k}, \quad t_{\max} = 1 + \log_2 k , \tag{7}$$

where the duration of a message transmission is regarded as 1. If $t < 1$, t is set to 1. The timeout of the protocol without optimization is fixed to 3.

We vary the node density from 10 to 30, and connectivity of LTRT from k = 3 to 5, where the node density is the average number of neighbors per node. We generated a network with nodes randomly placed in a square region. Simulations are executed 100 times for each density. Resulting values are obtained by averaging over 100 runs of simulations.

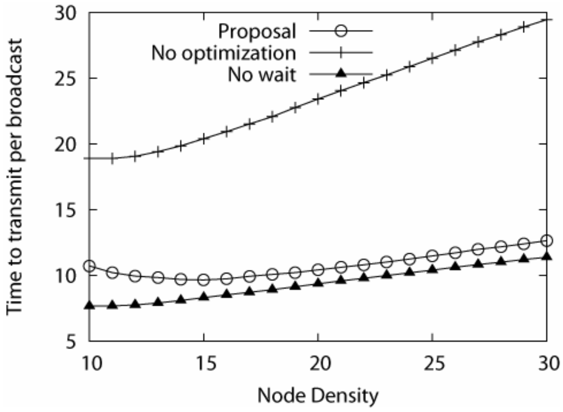

Figure 4. Delay (k = 5)

For comparison, we computed the average energy expended ratio (EER), average delay, and number of nodes which do not relay messages. EER is defined by

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$$EER = \frac{E_{total}}{E_{flooding}} \times 100 , \tag{8}$$

where $E_{flooding}$ is the energy consumption needed for flooding with maximal transmission range. Delay is the duration from the time when the source node starts broadcasting to the end of all the transmissions.

5.2 Results

Figure 2 illustrates EER obtained by the proposed protocol with optimization and without optimization when the connectivity k is 5. Figure 2 shows that the value of EER is improved with our optimization scheme. Figure 3 shows the percentage of improvement in EER for each connectivity. As the connectivity increases, the improvement becomes more pronounced. This result demonstrates that optimization scheme is suitable for fault-tolerant topologies.

Figure 4 shows the average delay of each broadcast. If the timeout value is fixed, the transmission duration is high. The delay can be reduced by applying an appropriate timeout value. Figure 5 illustrates the percentage of the nodes which do not relay the message. Since nodes which have many neighbors transmit messages by priority, the values improve as density increases.

6 Conclusions and future work

We have considered the broadcast transmission in energy-constraint ad-hoc networks. In this paper, we have proposed an energy efficient and reliable broadcast protocol.

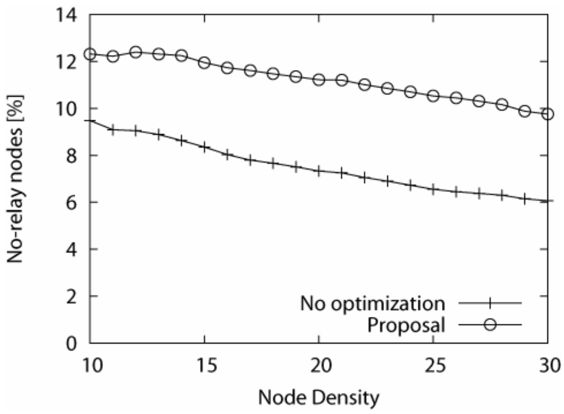

Figure 5. Nodes which do not relayed the message ($k = 5$)

This protocol guarantees the reception of messages from k neighbors for each node, based on a fault-tolerant topology. To reduce energy consumption in highly connected networks, we have proposed an appropriate timeout and table sharing scheme. We have demonstrated the performance of optimizations via simulations. The results show that two optimization schemes operate effectively in energy-constraint ad-hoc networks.

Our future work will further improve the broadcast protocol and evaluate our scheme against optimal fault-tolerant broadcasts. Moreover, we aim to implement our protocol under NS2 [12] to consider mobility or a realistic MAC layer.

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References

[1] N. Li, J. Hou, C. Sha, and L. Sha, "Design and analysis of an MST-based topology control algorithm," IEEE Trans. on Wireless Communications, vol. 4, no. 3, pp. 1195–1206, May 2005.

[2] K. Miyao, H. Nakayama, N. Ansari, Y. Nemoto, and N. Kato, "A reliable topology for efficient key distribution in ad-hoc networks," in Proc. of IEEE Workshop on SPAWN 2008, June 2008.

[3] S. Guo and O. W. W. Yang, "Energy-aware multicasting in wireless ad hoc networks: A survey and discussion," Comput. Commun., vol. 30, no. 9, pp. 2129–2148, June 2007.

[4] L. Li, J. Y. Halpern, P. Bahl, Y. Wang, and R. Wattenhofer, "Analysis of a cone-based distributed topology control algorithm for wireless multi-hop networks," in Proc. ACM Symposium on Principles of Distributed Computing, Aug. 2001, pp. 264–273.

[5] G. T. Toussaint, "The relative neighborhood graph of a finite planar set," Pattern Recognition, vol. 12, pp. 261–268, 1980.

[6] J. Cartigny, D. Simplot, and I. Stojmenovic, "Localized minimum-energy broadcasting in ad-hoc networks," in Proc. of IEEE INFOCOM 2003, vol. 3, Apr. 2003, pp. 2210–2217.

[7] M. Bahramgiri, M. Hajiaghayi, and V. Mirrokni,"Fault-tolerant and 3-dimensional distributed topology control algorithms in wireless multi-hop networks," in Proc. of the IEEE Int'l. Conf. on Computer Communications and Networks, Oct. 2002, pp. 392–397.

[8] N. Li and J. C. Hou, "Localized fault-tolerant topology control in wireless ad hoc networks," IEEE Trans. on Parallel and Distributed Systems, vol. 17, no. 4, pp. 307–320, Apr. 2006.

[9] J. Cartigny, F. Ingelrest, D. Simplot-Ryl, and I. Stojmenovic, "Localized LMST and RNG based minimum-energy broadcast protocols in ad hoc networks," Ad Hoc Networks, vol. 3, no. 1, pp. 1–16, Jan. 2005.

[10] F. Ingelrest, D. Simplot-Ryl, and I. Stojmenovic, "Optimal transmission radius for energy efficient broadcasting protocols in ad hoc and sensor networks," IEEE Trans. on Parallel and Distributed Systems, vol. 17, no. 6, pp. 536–547, June 2006.

[11] N. Li and J. Hou, "BLMST: a scalable, power-efficient broadcast algorithm for wireless networks," in Proc. of IEEE QSHINE 2004, Oct. 2004, pp. 44–51.

[12] "The Network Simulator NS-2," http://www.isi.edu/nsnam/ns/.