CERIAS Tech Report 2005-147

Reliable Broadcast in ZigBee Networks

by G Ding, Z Sahinoglu, P Orlik, J Zhang, B Bhargava
Center for Education and Research
Information Assurance and Security
Purdue University, West Lafayette, IN 47907-2086

MITSUBISHI ELECTRIC RESEARCH LABORATORIES
http://www.merl.com

Reliable Broadcasting in ZigBee Networks

Zafer Sahinoglu, Philip Orlik, Jinyun Zhang and Bharat Bhargava, Gang Ding

TR2005-029   December 2005

Abstract

Due to scarce resources, such as transmission power, storage space and communication bandwidth, current broadcast approaches for general ad hoc networks can not be applied to IEEE 802.15.4 based ad hoc networks (e.g., ZigBee networks). This paper proposes a forward node selection algorithm that significantly reduces broadcast redundancy. The algorithm exploits the hierarchical address space in ZigBee networks. Only one-hop neighbor information is needed: a partial list of two-hop neighbors is derived at a node without exchanging messages between neighboring nodes. The complexity of the proposed algorithm is polynomial in terms of both computation time and memory space. The localized algorithm provides an optimal and feasible solution of selecting the minimum number of rebroadcast nodes in ZigBee networks, which is an NP-hard problem for general ad hoc networks. The proposed algorithm is extended to deal with packet loss during data transmission. A ZigBee rebroadcast algorithm is also proposed to further reduce the number of rebroadcast nodes and cover the whole network faster by assigning a non-random rebroadcast timer determined by the number of neighbors to be covered, distance and link quality. Simulations are conducted to evaluate the broadcast redundancy, coverage time, and coverage ratio.

IEEE SECON

Reliable Broadcast in ZigBee Networks

Gang Ding
Electrical and Computer Engineering
Purdue University
West Lafayette, IN 47907, USA
dingg@ecn.purdue.edu

Zafer Sahinoglu
Technology Laboratory
Mitsubishi Electric Research Laboratories
Cambridge, MA 02139, USA
zafer@merl.com

Bharat Bhargava
Computer Sciences
Purdue University
West Lafayette, IN 47907, USA
bb@cs.purdue.edu

Philip Orlik, Jinyun Zhang
Technology Laboratory
Mitsubishi Electric Research Laboratories
Cambridge, MA 02139, USA
{porlik, jzhang}@merl.com

Abstract— **ZigBee is a new industrial standard for ad hoc networks based on IEEE 802.15.4. It is used for low data rate wireless networks and sensor networks. The data broadcast algorithms for ZigBee networks have been recently studied in [21], where the major task is to reduce the number of rebroadcast nodes. A broadcast algorithm should be robust, which can be achievable by introducing redundant transmissions to some extent. This issue will be studied by this paper. Results presented here extend the forward node selection algorithm in [21] for ZigBee networks. The tree neighbor information is exploited to make sure that every node is covered by at least one of its tree neighbors. A non-random rebroadcast timer is set according to the number of neighbors to be covered, distance and link quality to trigger rebroadcast times. The complexity of the proposed algorithm is polynomial in terms of both computation time and memory space. Simulations are conducted to evaluate the broadcast redundancy, coverage time, and coverage ratio, when the number of nodes varies and there is packet loss.**

Keywords—ZigBee; broadcast; reliability; ad hoc network

I. INTRODUCTION

A rapidly growing industrial consortium, called the *ZigBee Alliance* [1], has more than 150 companies working together to enable reliable, cost-effective, low-power, wirelessly networked products. The alliance selects IEEE 802.15.4 [2] as MAC and PHY layer standard, and ratified the ZigBee specifications for network and higher layers in December 2004. Expected Applications for ZigBee include wireless sensor networks for remote monitoring, home control, and industrial automation. Some prototypes and products compatible with ZigBee standards have already appeared. In contrast to the intensive industrial activities on ZigBee, academic research is in the early stage ([3, 4]). We here introduce ZigBee to the academic community which contribute to evaluate and improve the performance of current standards. The ZigBee specification was only available for members of the ZigBee Alliance. It was made publicly available for non-commercial use in June 2005 ([1]). This paper addresses the reliability aspect of broadcast algorithms for ZigBee networks.

There have been many results that reduce the broadcast redundancy for general ad hoc networks. But all the current approaches assume that the position and/or k-hop ($k \geq 2$) neighbor knowledge is easily available. But this is not feasible in ZigBee networks. The footprint for the full protocol stack is required to occupy less than 32 Kbytes of memory due to cost constraints. Other scarce resources include computation capability, battery power, and communication cost. Therefore, a ZigBee device can not afford to conduct complex algorithms based on data structures that take a large size of memory; neither can it obtain accurate position or 2-hop neighbor information by extra equipments and communications. The only information available is the 1-hop neighbors.

We have recently studied the broadcast efficiency in ZigBee networks ([21]), where a self-pruning algorithm and a ZigBee Forward node selection Algorithm (ZiFA) are presented in order to reduce the number of rebroadcast nodes. In addition to the efficiency, a good broadcast algorithm should be 1) *reliable*: make sure the packet is received by the intended receiver even when packet loss happens or the neighbor information is not up-to-date, 2) *fast*: cover the whole network in a timely fashion, 3) *simple*: low complexity in terms of both computation time and storage space. In ZiFA, each broadcasting node selects a subset of its 1-hop neighbors to cover part of its 2-hop neighbors that are known without exchanging information among neighbors. This is due to the hierarchical address space supported by ZigBee network layer ([6]). It is proven that the ZiFA algorithm finds the minimum number of rebroadcast nodes with polynomial computation time and memory space, which is an NP-hard problem for general ad hoc networks. But as stated in the conclusion of [21], the realistic broadcast algorithm should allow some kind of redundancy in order to cover the whole network even if the 1-hop neighbor information is not up-to-date or the nodes are moving. The trade-off between broadcast efficiency and

This work is supported in part by NSF grants ANI 0219110 and CCR 0001788, and Mitsubishi Electric Research Laboratories.

reliability is the focus of this paper. The previous forward node selection algorithm is extended so that every non-forward node can be covered by at least one of its tree neighbors other than the source. Since the tree neighbor relationship is well maintained by ZigBee networks, this guarantees that every node will be covered, at the cost of broadcast redundancy. To avoid collisions due to simultaneous rebroadcasts, each selected forward node waits for a short duration before rebroadcasting. The neighbor information and the link quality measured at the physical layer are used to decide the waiting interval. Since nodes with more uncovered neighbors rebroadcast earlier, the whole network tends to be covered in a shorter period of time.

This paper is organized as follows. Section II briefly introduces ZigBee and IEEE 802.15.4. Related work is reviewed in Section III. The reliable broadcast algorithm for ZigBee networks is detailed in Section IV. The rebroadcast algorithm for faster coverage is presented in Section V. Simulation results are given in Section VI. Section VII concludes the paper.

II. ZIGBEE AND IEEE 802.15.4

The protocol stack of ZigBee networks is given in Fig. 1. At PHY layer, IEEE 802.15.4 defines 27 channels: 16 channels of data rate 250 kb/s in the license free industrial scientific medical (ISM) 2.4 – 2.4835 GHz band that is globally available, 10 channels with data rate 40 kb/s in the ISM 902 – 928 MHz band available in North America, and one channel with data rate 20 kb/s in the 868.0 – 868.6 MHz band available in Europe. Two types of devices are defined: full function device (FFD) and reduced function device (RFD). An FFD can serve as a coordinator or a regular device. It can communicate with any other devices within its transmission range. An RFD is a simple device that associates and communicates only with an FFD. The IEEE 802.15.4 PHY layer provides a parameter, Link Quality Indication (*LQI*), to characterize the quality of received signal. It can be the received power, the estimated signal-to-noise-ratio (SNR), or a combination of both. *LQI* is passed to MAC layer and finally available to the network and upper layers. Other features of PHY layer include the activation and deactivation of the radio transceiver, channel selection, clear channel assessment, and transmitting/receiving packets across physical medium.

At MAC layer, IEEE 802.15.4 controls access to the radio channel using the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism. The optional use of a superframe structure is allowed by IEEE 802.15.4. A superframe is bounded by network beacons sent by the coordinator, and is divided into 16 equally sized slots. Beacons are used to synchronize the attached devices, to identify the PAN, and to describe the structure of the superframes. Any device wishing to communicate during a superframe shall compete with other devices using slotted CSMA/CA. For low-latency applications, the WPAN coordinator may dedicate portions of the superframe to that application. These portions are called guaranteed time slots (GTSs). The GTSs form the contention-free period at the end of the superframe. Other features of the MAC sublayer include

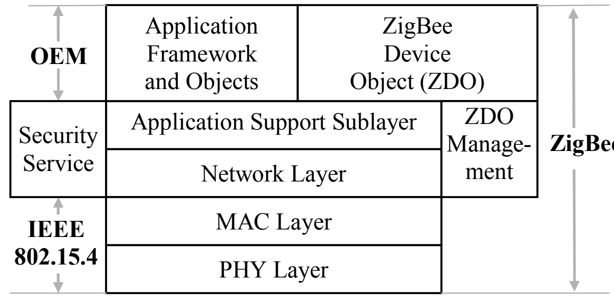


Figure 1. ZigBee network protocol stack

synchronization, frame validation, acknowledged frame delivery, association and disassociation.

Based on IEEE 802.15.4, the ZigBee Alliance specifies the standards for the network layer and the application layer, including the application support sublayer, the ZigBee device object (ZDO) and the manufacturer defined application objects. The responsibilities of the ZigBee network layer include joining/leaving a network, security, routing, discovering 1-hop neighbors and storing neighbor information. The ZigBee network layer [6] builds a logical network topology above IEEE 802.15.4. The network topology can be multi-hop so that any pair of devices can communicate with each other through the help of intermediate nodes. A ZigBee coordinator is responsible for starting a new network and assigning addresses to newly associated devices. A ZigBee WPAN allows up to 4096 (=2^{12}) devices. The network address is assigned based on a hierarchical tree structure. The coordinator is the root. There are at most d_m levels. At every level, the network address is evenly assigned from left to right. Each node has a limited number, n_m, of associated children. If one traverses the tree by the depth-first search, the network address will be in ascending order. Any node can route packets to its *tree neighbors*, including its parent and direct children. An RFD can only be a leaf of the tree. An FFD can be a router-capable FFD (RFFD) that stores routes to devices other than its tree neighbors. An RFFD discovers a route by broadcasting a route request and waiting for replies from the destination or intermediate nodes, similar to the Ad hoc On-demand Distance Vector (AODV) routing protocol for general multi-hop ad hoc networks ([7]).

The ZigBee application support sublayer maintains tables for binding two devices based on their services and needs, and forwards messages between bound devices. The ZDO defines the role of the device, initiates and responds to binding requests and establishes a secure relationship between devices.

III. RELATED WORK

Ni *et al.* [8] first introduce the *broadcast storm problem* when every node rebroadcasts the packet. To reduce broadcast redundancy and avoid collision during rebroadcast, they introduce heuristic algorithms. For example, the counter based algorithm rebroadcasts a packet only if the number of duplicated broadcast packets received during a waiting period is less than a threshold; the location based approach only rebroadcasts when the additional coverage by the rebroadcast is larger than a threshold. In [9], the authors improve the above schemes by adaptively choosing the threshold as a function of the number of neighbors. These approaches are simple to implement, but they cannot guarantee that every node will receive the packet ([10]). In this paper, we also propose a heuristic approach to determine the waiting time before rebroadcasting, which takes advantage of the *LQI* measurement from IEEE 802.15.4 physical layer. But it is only used to make the broadcast faster; the coverage of the whole network is guaranteed by a proposed reliable ZigBee forward node selection algorithm.

More complicated algorithms assume the knowledge of network topology in order to guarantee the network coverage and reduce the broadcast redundancy. When the global network information is available, the problem of selecting the minimum number of rebroadcast nodes, also called *forward nodes*, is essentially the well-studied Set Cover problem, which is NP-hard. Since global network topology is not practically available, localized algorithms, which only need the information of 1-hop and 2-hop neighbors, are preferred. Lim and Kim [11] proposed two localized algorithms. The *self-pruning* algorithm checks if a receiving node's 1-hop neighbors are all included in the sending node's 1-hop neighbors. If so, the receiving node need not rebroadcast the packet. The *dominant pruning* algorithm selects a list of forward nodes from a node's 1-hop neighbors to cover all its 2-hop neighbors. The size of the candidate forward node set can be reduced by neighbor designation approaches in [12]. However, selecting a minimum number of forward nodes to cover all 2-hop neighbors is still a Set Cover problem. The optimum solution can be approximated by a greedy algorithm ([13]) with an approximation factor of $\log(n)$, where n is the maximum number of neighbors. A scalable broadcast algorithm (SBA) is proposed by Peng and Lu [14], which extends the above self-pruning algorithm by checking and reducing a node's uncovered 1-hop neighbors based on multiple previous transmissions. If all its 1-hop neighbors have been covered in a waiting period, it will resign from rebroadcasting. A forward node selection algorithm similar to the above dominant pruning, called *multipoint relaying*, is proposed in [15]. A detailed overview of broadcast in ad hoc networks can be found in [16]. We recently studied how to reduce broadcast redundancy in ZigBee networks in [21], where a self-pruning algorithm OSR and a forward node selection algorithm ZiFA are proposed. For the ZiFA algorithm, a partial list of 2-hop neighbors is covered without knowing the 2-hop neighbor information. The problem is not NP-hard in this case. The proposed algorithm can actually find the minimum number of forward nodes in polynomial computation time with polynomial memory space.

Pagani and Rossi [17] first study the reliable broadcast in mobile ad hoc networks. They assume a multiple-cluster network in which cluster-heads help to deliver the broadcast packets and acknowledgements. Gopalsamy *et al*. [18] propose a reliable multicast algorithm which utilizes the concept of link lifetime instead of hop-count to determine the route. The reliability is guaranteed by explicitly sending acknowledgements. More reliable broadcast and multicast algorithms are overviewed by [19]. In a recent study on reliability of broadcast algorithms, Lou and Wu [20] take the rebroadcast of each selected forward node as an acknowledgement of receiving the packet, while each non-forward node is covered by at least two forward nodes, at the cost of a higher broadcast redundancy. Based on the logical network topology in ZigBee networks, this paper proposes a reliable broadcast algorithm so that every non-forward node is a tree neighbor of at least one forward node. This guarantees the coverage of this non-forward node as far as the ZigBee tree neighbor association is correctly maintained.

IV. Reliable Forward Node Selection and Retransmission

Due to the resource constraints in ZigBee networks, we have following assumptions.

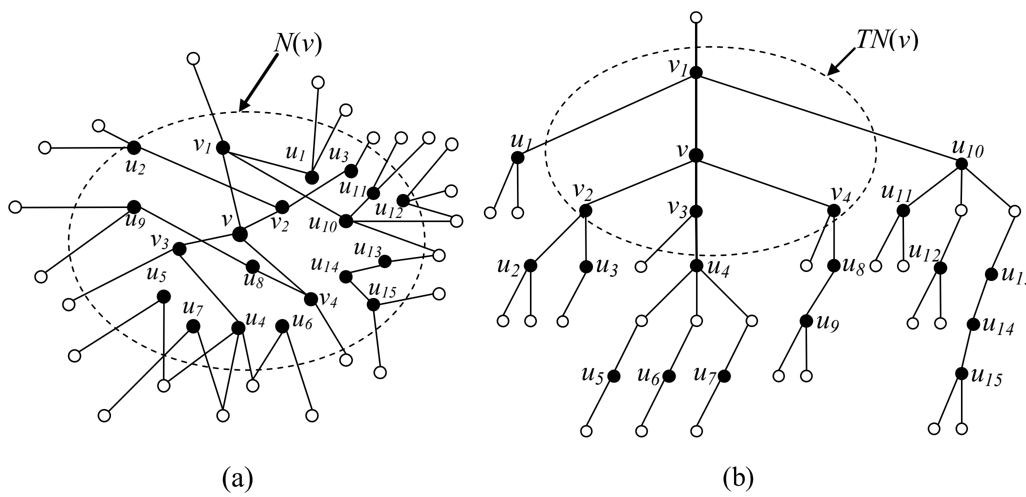


Figure 2. An example of ZigBee network topology. Black dots represent 1-hop neighbors of node v, white dots represent tree neighbors of 1-hop neighbors of v. Every line connects a pair of tree neighbors. (a) Physical network topology, where 1-hop neighbors of v are in the dashed circle. (b) ZigBee logical network topology, where tree neighbors of v are in the dashed circle.

A.1. The distance among nodes and the position of nodes are not available;

A.2. Transmission power is fixed;

A.3. Node addresses are hierarchically assigned by ZigBee network layer. So given the network address of a device, the addresses of all its tree neighbors can be derived without information exchange;

A.4. The association of every pair of tree neighbors is correctly maintained by ZigBee network layer;

A.5. Every device maintains a table of all its 1-hop neighbors. Each entry in the neighbor table includes a neighbor's network address and the number of its children.

After a source initiates a broadcast process, it selects a subset of its 1-hop neighbors as forward nodes. Each forward node further selects its own forward nodes and rebroadcasts the packet after a short waiting time. This section elaborates on the *Reliable ZigBee forward node selection algorithm* (ZiFA-R). The *ZigBee rebroadcast algorithm* (ZiRA) will be introduced in the Section V.

For the sake of description, we use $N(A)$, $N_k(A)$, $TN(A)$, and $TN_k(A)$ ($k \geq 2$) to represent the 1-hop neighbors, k-hop neighbors, tree neighbors, and k-hop tree neighbors of a set A of nodes, respectively. Knowing the addresses of 1-hop neighbors $N(v)$ of a ZigBee node v, the addresses of all its tree neighbors in $TN(N(v))$, which is a subset of all 2-hop neighbors $N_2(v)$, can be identified. As an example, Fig. 2.a and Fig. 2.b show node v's 1-hop neighbors and their tree neighbors when $n_m = 3$, in a physical topology and a ZigBee logical topology, respectively. Node v has four tree neighbors in $TN(v)$: a parent v_1 and three children v_2, v_3, and v_4. In addition to $TN(v)$, v has fifteen other 1-hop neighbors in $N(v)$: u_1 to u_{15}, which could be located anywhere on the ZigBee logical tree. Given the network addresses of v_1 to v_4 and u_1 to u_{15}, v can identify their parent and children. All these nodes form $TN(N(v))$.

One possible broadcast algorithm is to request every tree neighbors to rebroadcast, which is adopted by the current ZigBee network specification. But according to Fig. 2, one broadcast from node v can actually cover not only its tree neighbors, but all the other physical 1-hop neighbors in $N(v) - TN(v)$. As a result, it is possible that all the tree neighbors of a node w in $TN(v)$ are also in $N(v) - TN(v)$, so that w does not need to rebroadcast. This motivates us to find a more efficient broadcast algorithm to reduce the broadcast redundancy, which is based on forward node selection. Given the partial list of 2-hop neighbors, $TN(N(v))$, the forward node selection problem in ZigBee networks reduces to finding a minimum size forward node set $F(v)$ from $N(v)$ to cover $TN(N(v))$. In this special case, the problem can actually be solved in polynomial time.

However, during the real rebroadcast, the packet may not be correctly received by every 1-hop neighbor due to radio propagation fading or mobility. The current ZigBee broadcast protocol employs a simple retransmission technique to make the broadcast more reliable. Basically, since every neighbor of the source node v is required to rebroadcast as specified in [6], node v should receive the rebroadcast packets from all its neighbors. If any of them has not been received for a certain period of time, node v should transmit again. Node v will stop retransmission if all its neighbors have rebroadcast or it has retransmitted for certain times without success. By using forward node selection algorithm, the forward nodes of v form only a subset of its 1-hop neighbors. The rebroadcast packets from these forward nodes can serve as the acknowledgement of successful reception. But there will be no rebroadcast from non-forward nodes. To make it more reliable, node v should find a way to make sure that all its non-forward nodes receive the packet.

Reliable ZigBee forward node selection algorithm (ZiFA-R)

1. Given the neighbor table $N(v)$, find the minimum size forward node set $F(v)$ by ZiFA algorithm ([21]). So at the end of this step, every node in $F(v)$ has status "*Forward*" and every node in $N(v) - F(v)$ has status "*nonForward*".

```
2. for (each node x in neighbor table with
        Status(x) = "nonForward")
      if (S_1 = TN(x) ∩ N(v) is empty) or
         (Every node in S_1 is "nonForward")
          Status(x) = "Forward"
          for each node y in TN(x) – N(v)
              y must be covered by a forward node z
              if (S_2 = TN(z) – {y} is not empty) and
                 (at least one node in S_2 ∩ N(v) is
                  "Forward") and
                 (Every node in S_2 – N(v) is covered by
                  a forward node)
                  Status(z) = "nonForward"
              end if
          end for
      end if
   end for
   Go through the whole neighbor table and collect all
   nodes with status "Forward",
   exit.
```

Figure 3. Reliable ZigBee Forward node selection algorithm

In a ZigBee network, the information of all the 1-hop neighbors may not be up-to-date, but according to assumption A.4, the tree neighbors are always correctly associated by ZigBee network layer, which implies that a broadcast packet sent by one node has high probability of being successfully received by its tree neighbors. So if every non-forward node is a tree neighbor of at least one forward node, it will receive the rebroadcast packet from the forward node with high probability, provided the forward node does rebroadcast. This gives a reliable broadcast condition:

At lease one tree neighbor of a non-forward node should be a forward node.

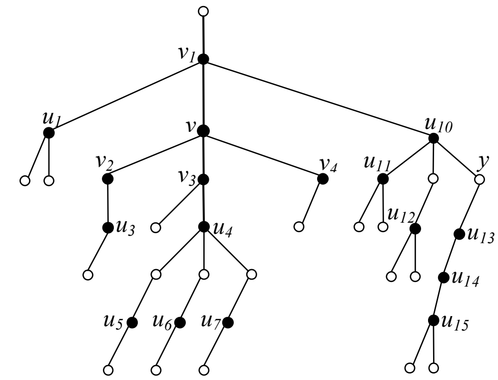
The minimum size forward node set may not satisfy the above condition, so we need to update the forward node set according to this reliable condition. Given a node v which can be the source of a broadcast packet or a forward node selected by another node, the reliable ZigBee forward node selection algorithm in Fig. 3 selects the forward node set in polynomial time. It only needs a memory space of size n_l, which is the maximum size of all levels in the ZigBee tree topology. The algorithm is explained as follows.

The first step of ZiFA-R is actually ZiFA which selects the minimum number of forward nodes $F(v)$. The ZiFA algorithm is briefly introduced as follows. 1) Neighbor table $N(v)$ is sorted level by level based on the network address; 2) A small piece of memory M is used to temporarily store nodes at one level; 3) Starting from the bottom level and from left to right at each level, it checks if any 1-hop neighbor x at current level needs to be selected to cover its children in the immediate lower level; 4) It makes sure that the parent x of any node y below the current level is covered by either x's parent or y. The details of ZiFA and the proof of its correctness and optimality can be found in [21].

Step 1 in ZiFA-R is used for selecting the minimum number of forward nodes, under the assumption that every 1-hop neighbor can successfully receive the packet from v and the neighbor information is up-to-date. In step 2 of the ZiFA-R algorithm, we need to check every non-forward node x in order to make sure that the above reliable condition is satisfied. It is noted that x must have at least one tree neighbor, i.e. its parent, except that x is the root of a ZigBee network. If none of x's tree neighbors is in the neighbor table of node v, node x itself must be selected as a forward node because none of its tree neighbors can be selected by v as a forward node. Similarly, if some of x's tree neighbors are in the neighbor table of node v but they are all non-forward nodes, node x still has to be a forward node. After changing the status of node x from "*nonForward*" to "*Forward*", its tree neighbors need not be covered by other forward nodes. So we may unselect some previously selected forward node z that was only used for covering x's tree neighbor y. To this end, we must make sure that z itself and its tree neighbors are already covered by other forward nodes.

It is evident that, at any instance, the temporary memory M only needs to save parents of at most one level of nodes in the neighbor table. So its size is at most $n_l = O(n)$. For the complexity of computation time, the complexity of step 1 is $O(n\log(n_l))$ as proven in [21]. Step 2 checks tree neighbors for four times, so the complexity is $O(nn_m^4)$. The total computational complexity is the maximum of $O(nn_m\log(n))$ and $O(nn_m^4)$, which is polynomial.

As an illustrative example based on Fig. 2, we assume node v receives a broadcast packet from node u_8, and u_8's selected forward node set $F(u_8) = \{v, u_2\}$, v can find the reduced candidate forward node set and their tree neighbors, as shown in Fig. 4. For the tree rooted at node u_4, nodes u_5, u_6, and u_7 are selected in order to cover their children, respectively. So node u_4 need not be selected because all its tree neighbors have already been covered. In contrast, if a greedy algorithm was applied and the node with the highest degree is selected first, u_4 would be selected, so would u_5, u_6 and u_7, which is not optimal. At the end of step 1 in the ZiFA-R algorithm, the minimum size forward node set selected by



(c)

Figure 4. Reduced ZigBee network topology when ZiFA-R is applied. We assume node v receives a broadcast packet from node u_8, where u_8's forward node set is assumed to be $F(u_8) = \{v, u_2\}$.

node v is $F(v) = \{v_1, v_3, v_4, u_1, u_3, u_5, u_6, u_7, u_{10}, u_{11}, u_{12}$, and $u_{15}\}$. In step 2, node u_{13} is a non-forward node whose only tree neighbor in neighbor table, node u_{14}, is also a non-forward node, so u_{13} should be selected as a forward node for reliability reason. For node u_{13}'s tree neighbor node y, it is covered by a previously selected forward node u_{10}. Since node u_{10}'s all the other tree neighbors are either forward nodes or already be covered by a forward node, node u_{10} need not be a forward node anymore. So the final selected forward nodes are $F(v) = \{v_1, v_3, v_4, u_1, u_3, u_5, u_6, u_7, u_{11}, u_{12}, u_{13}$, and $u_{15}\}$.

The above reliable forward node selection algorithm is based on the assumption that every forward node can successfully receive the broadcast packet from node v. In a real system, node v keeps a record of duplicated broadcast packets sent by its forward nodes during a certain period of time. If v receives the broadcast packet from all its forward nodes before time out, this implies that all its forward nodes have received and rebroadcast the packet so that all its non-forward nodes have also received the packet from one of the forward nodes. If the rebroadcast packet from a forward node f is not received until the time out, node v assumes that node f does not receive the packet, so it retransmits the broadcast packet.

V. REBROADCAST

The ZiFA algorithm is locally executed by the broadcast source and every forward node. It can be formally proven, as in [21], that for an arbitrary broadcast source, every node in the network is guaranteed to receive the packet, provided the physical network topology is connected. But in addition to the coverage of whole network, we expect it to be covered as fast as possible. This section introduces a heuristic rebroadcast algorithm that tries to cover more nodes in a shorter time and further reduces the number of forward nodes.

So far we have assumed that after a node broadcasts a packet, all its forward nodes will rebroadcast the packet at the same time. For a unicast data transmission, IEEE 802.15.4 based networks employ CSMA/CA mechanism to control channel access and avoid packet collision. Request to Send/Clear to Send (RTS/CTS) dialogue can be further employed to overcome hidden terminal problem. But for broadcast, these techniques will introduce too much time delay and is costly. However, if all forward nodes just blindly rebroadcast the packet simultaneously, significant amount of packet collisions may occur and delay the coverage of the whole network. One way to avoid collisions is to have every forward node wait for a different period of time before rebroadcasting. The waiting time is usually determined randomly, without considering the current condition of the transmission channel or the network.

In ZigBee networks, information about the current link quality, *LQI*, is measured at IEEE 802.15.4 PHY layer, and can be employed to make a better decision on when to rebroadcast a packet. Due to radio propagation, the *LQI* measured at the receiver is inversely proportional to d^α, where d is the link distance between the sender and the receiver, and α is the path loss exponent typically between 2 and 5. We consider the instance when node u broadcasts the packet and all its selected forward nodes have received the packet. When a smaller *LQI* is measured by a forward node v because the distance d from node u to node v is longer than others, this usually implies that more new nodes can be covered by rebroadcasting from node v. So node v should be given a higher priority, or equivalently shorter waiting time T, to rebroadcast.

Another factor that helps to determine the waiting time is the number of new nodes to be covered by the rebroadcast from node v, called the *degree*, which can be calculated by

$$degree = |N(v)| - |TN(u) \cap N(v)|$$

where $|\cdot|$ represents the number of entries in a set. A larger *degree* of a forward node v implies that more nodes can be covered by v's rebroadcasting. If node v broadcasts earlier than others, it may even cover the neighbors of another forward node who can finally withdraw from rebroadcasting. It should be noted that most previous broadcast algorithms based on determining the waiting time are usually used on their own; they aim at covering more node by a simple mechanism, but the full coverage of the network still cannot be guaranteed. For example, [9] suggests to rebroadcast earlier when the *degree* is smaller. But in this paper, the reliable forward node selection algorithm has already guaranteed to cover the whole network. So increasing the probability of coverage is not a problem for the rebroadcast algorithm in this section; a node with larger *degree* should rebroadcast earlier in order to cover a larger amount of nodes earlier.

According to the above discussion, the waiting time T should be a function of both *LQI* and *degree*:

$$T = f(LQI, degree),$$

which satisfies

$$\frac{\partial f}{\partial degree} < 0, \quad \frac{\partial f}{\partial LQI} > 0 .$$

One possible choice is

$$T = k \cdot LQI / Degree,$$

where the parameter k is used to scale T to the appropriate range.

ZigBee rebroadcast algorithm (ZiRA)

1. **If** it is the first time to receive the broadcast packet
  - Buffer the packet.
  - Get *LQI* from MAC layer.
  - $C = N(v) - \{v\} - \{u\}$.
  - $degree = |N(v)| - 1 - |TN(u) \cap N(v)|$.
  - **if** C is empty **or** $degree = 0$
    - Drop the packet and **exit**.
  - **end if**
  - Start a timer with $T = f(LQI, degree)$

else if the early copy of this packet has been waiting for t
  - Get current *LQI* from MAC layer.
  - $C = C - \{u\}$.
  - $degree = degree - |TN(u) \cap N(v)|$.
  - **if** C is empty **or** $degree = 0$
    - Clear the timer, drop the packet and **exit**.
  - **end if**
  - Update the timer $T = \max(0, f(LQI, degree) - t)$.

else /* node v has already rebroadcast */
  - Drop the duplicated broadcast packet.

end if

2. **When it is time out for a waiting packet**
  - Find forward node set $F(v)$ by running ZiFA or ZiFA-R
  - Broadcast the packet.

Figure 5. ZigBee rebroadcast algorithm

Given waiting time T, the ZigBee rebroadcast algorithm (ZiRA) for a forward node v receiving a broadcast packet from node u is shown in Fig. 5. Node v starts a timer when it first receives a broadcast packet. C is the set of candidate forward nodes. Every time when node v receives a duplicated packet from another node, set C and the *degree* are reduced. The waiting time is also updated based on the latest *degree* and *LQI*. Node v will not rebroadcast if there is no node to cover. When the waiting time is expired, node v runs ZiFA or ZiFA-R algorithm to select its forward node set $F(v)$ and broadcast the packet. It is noted that if a forward node rebroadcasts later than other forward nodes, it will have smaller candidate set C and *degree*, and have a higher possibility of withdrawing itself from rebroadcasting.

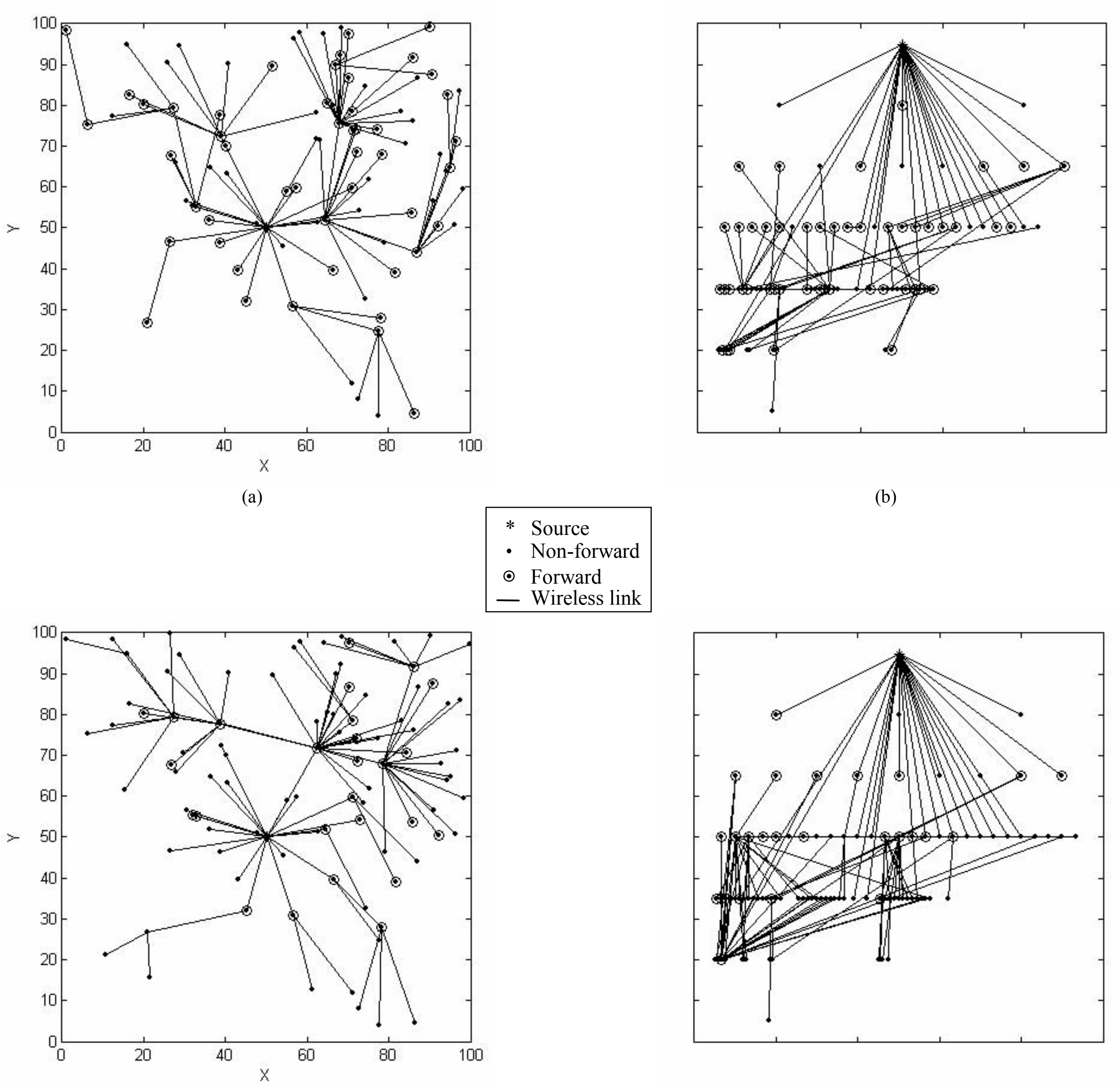


Figure 6. Rebroadcast nodes using ZigBee2 and ZiFA-R algorithms. (a) and (b) are the physical topology and logical ZigBee tree topology for ZigBee2, respectively. 49 nodes rebroadcast, shown as circles. (c) and (d) are the physical topology and logical ZigBee tree topology for ZiFA-R when there is no packet loss. 29 nodes are selected as forward nodes and rebroadcast. Only wireless links that connect a rebroadcast node and its 1-hop neighbors are displayed.

VI. Simulation Results

We have proposed the reliable ZigBee forward node selection algorithm *ZiFA-R* and the ZigBee rebroadcast algorithm *ZiRA*. We developed an event-driven simulator to evaluate the performance of these algorithms for ZigBee networks. The network topology is generated in a 100 m × 100 m square area. When a new device is joining a ZigBee network, it goes through the association process in order to find a parent which is already located within the circular transmission range of the new device and has less than n_m children. The location of each node is randomly generated, but they need not be uniformly distributed in the area. We assume an idealized MAC layer for data broadcast, in which two packets collide and are lost only when they are transmitted by two neighboring nodes at the same time.

The proposed algorithms are compared with two existing algorithms for ZigBee networks: 1) *ZigBee1* algorithm, in which only tree neighbors rebroadcast as forward nodes; 2) *ZigBee2* algorithm in which all 1-hop neighbors rebroadcast like flooding. To avoid the high redundancy due to flooding, a rebroadcast algorithm similar to ZiRA is integrated into

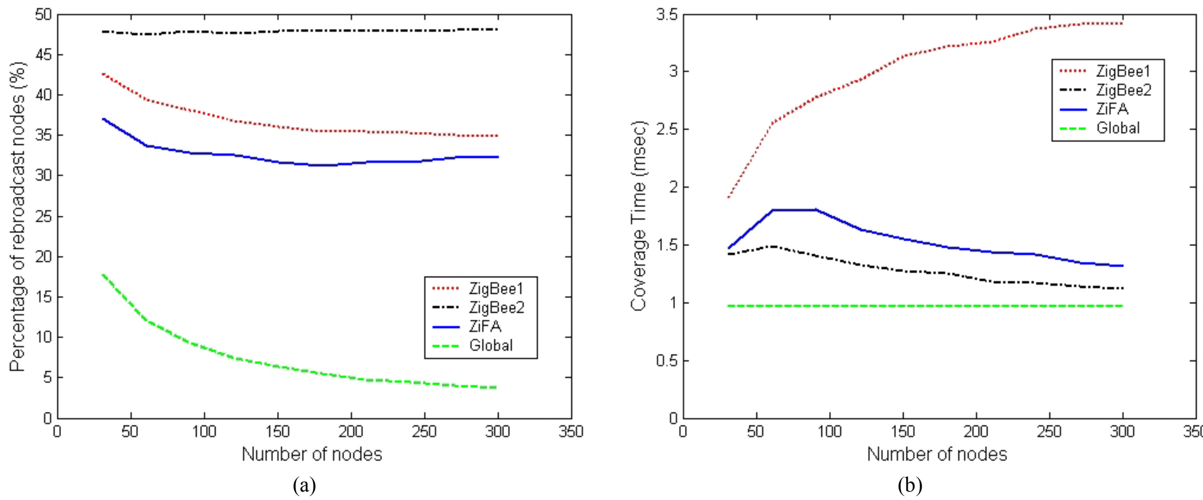


Figure 7. Simulation results for ZiFA algorithm when there is no packet loss. (a) Percentage of rebroadcast nodes, (b) Coverage time.

ZigBee1 and ZigBee2, which is used to prune a node's rebroadcast if all its tree neighbors have been found covered during its waiting time, while the waiting time is randomly generated within one millisecond. Due to the fact that most broadcast algorithms for general ad hoc networks need 2-hop neighbor information for forward node selection, they cannot be tested for a ZigBee network. We simulated a greedy algorithm that assumes the global network topology information. It serves as an approximation of the lower bound of the number of forward nodes. In this *Global* algorithm, every node counts the number of its neighbors not yet covered. The node with the maximum number of uncovered neighbors is selected first.

A. Performance Evaluation of ZiFA-R

Fig. 6 displays the rebroadcast nodes resulted from ZigBee2 and ZiFA-R. The randomly generated ZigBee network consists of 100 nodes. Both the physical topology and the logical ZigBee topology are displayed. We assume that the ZigBee network coordinator is the broadcast source and is located at the center of the area. But choosing any other node as the broadcast source gives similar results. It is obvious that the forward node selection algorithm needs less rebroadcast nodes to cover the whole network.

We first show some simulation results when there is no packet loss so that the minimum number of forward nodes are selected by ZiFA. Fig. 7 shows the percentage of rebroadcast nodes and the coverage time when the transmission range is 25m. Each data point is the average of 100 simulation runs on different randomly generated network topologies. The network sizes ranges from 31 to 301. The maximum number of children n_m and the ZigBee tree depth d_m are 3 and 6, respectively. It is observed that the percentage of rebroadcast nodes is almost a constant for any network size, except for the Global algorithm. The flooding based ZigBee2 algorithms needs the most number of rebroadcast nodes near 50% of the total number of nodes. The ZiFA algorithm selects much less number of forward nodes. The ZigBee1 algorithms only covers the tree neighbors and the other 1-hop neighbors just ignore the packet, while the ZigBee2 algorithm always waits for the coverage of all its tree neighbors to prune itself. The global algorithm gives much better results where total number of rebroadcast nodes is nearly a constant with respect to the network size. This is mainly due to the availability of global network information.

The coverage time of ZigBee1 is much larger than others because it only covers tree neighbors even if every broadcast can be received by other 1-hop neighbors, which significantly delays the time when all nodes receive the packet. ZigBee2 needs less time than ZiFA to cover the network at the cost of higher broadcast redundancy due to flooding. It is observed that the coverage time of both ZigBee2 and ZiFA converges to that of the Global algorithm when the network size is increasing.

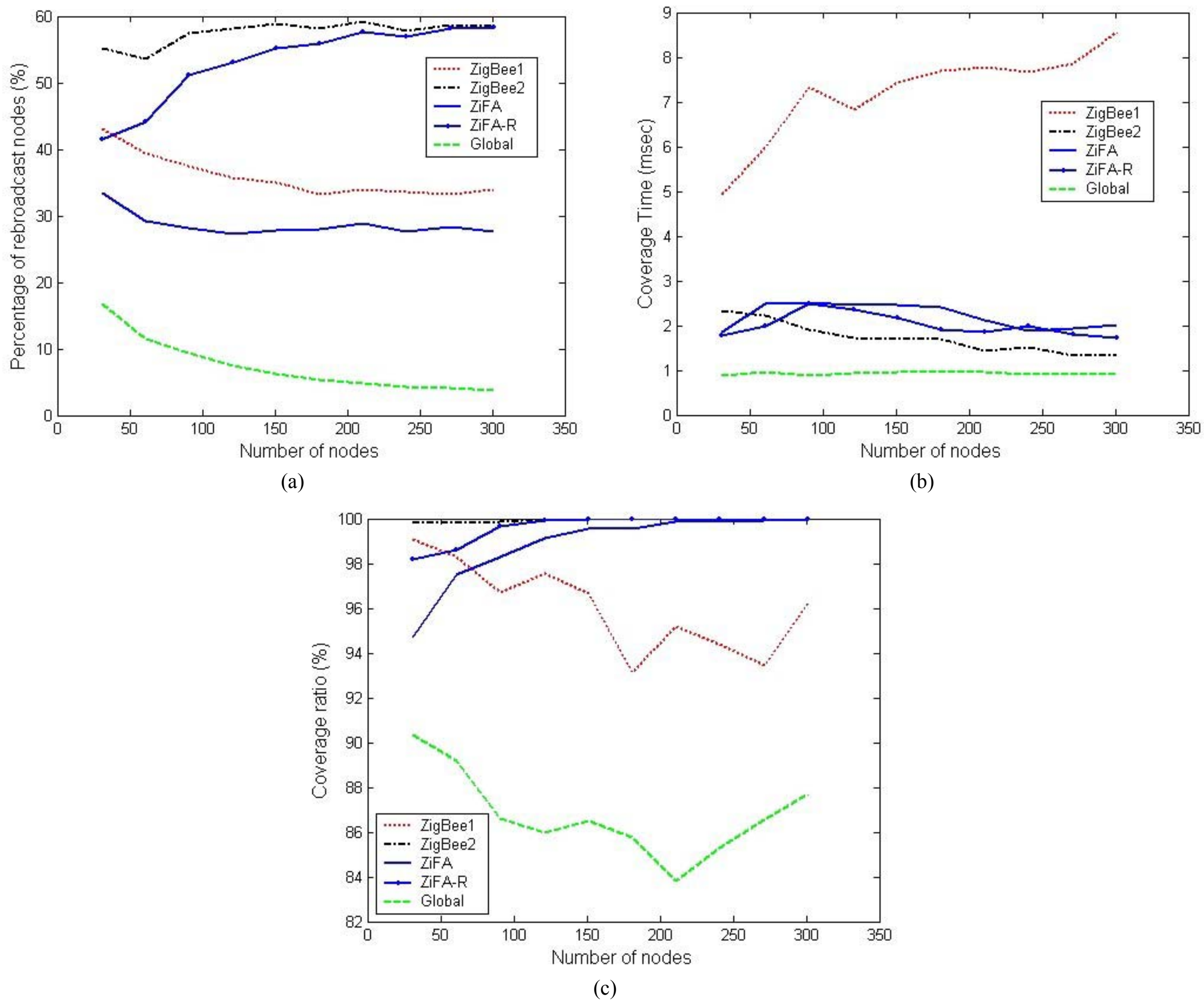


Figure 8. Simulation results for ZiFA-R when there is packet loss. (a) Percentage of rebroadcast, (b) coverage time, (c) coverage ratio.

In the above scenario, we only tested ZigBee networks of up to 301 nodes. A ZigBee network can actually support more nodes. The maximum size of a ZigBee network is determined by the parameters n_m and d_m. More simulation results can be found in [21].

To evaluate the reliability, packet loss during data transmission is introduced. We assume there is a common loss rate for each packet transmitted. For every simulated algorithm, a retransmission mechanism is added to retransmit a packet if a packet loss is detected. Fig. 8 shows the percentage of rebroadcast nodes, the coverage time, and the coverage ratio when the packet loss rate is 30% and every broadcast node retransmits at most three times. Comparing ZiFA-R with ZiFA, it is noticed that more broadcast redundancy is introduced by ZiFA-R, which helps to increase the coverage ratio. The flooding-based ZigBee2 algorithm gives the highest coverage ratio due to its highest broadcast redundancy. In contrast, the Global algorithm shows poor reliability because many nodes are only covered by one forward node; when the transmission from the forward node fails, these nodes cannot be covered by any other forward nodes.

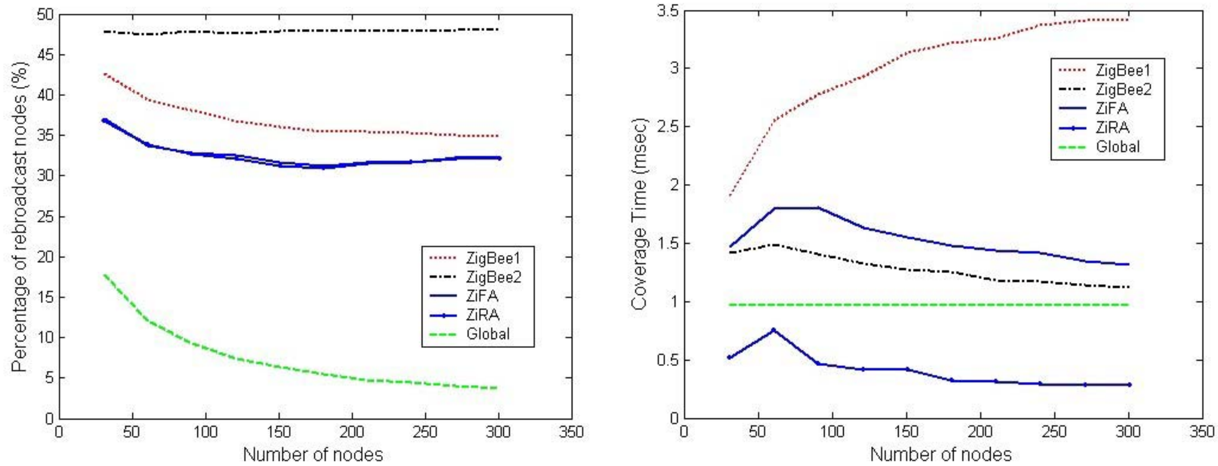
B. *Performance Evaluation of ZiRA*

When there is no packet loss, Fig. 9 shows the performance of ZiRA algorithm. It is observed that, by using non-random waiting time in ZiRA, the number of forward nodes is slightly decreased and the coverage time is significantly reduced. This is because that the waiting time for a forward node with more uncovered neighbors is shorter than others, so that more nodes tend to be covered earlier. In addition, a forward node may find that all its neighbors have already been covered by others before its time out, so it need not rebroadcast, which reduces the number of forward nodes.

When packet loss is considered, the simulation results are given in Fig. 10. According to Fig. 10c, the ZiRA gives a higher coverage ratio than ZiFA that uses random waiting time. Combining ZiRA with ZiFA-R further increases the coverage ratio.

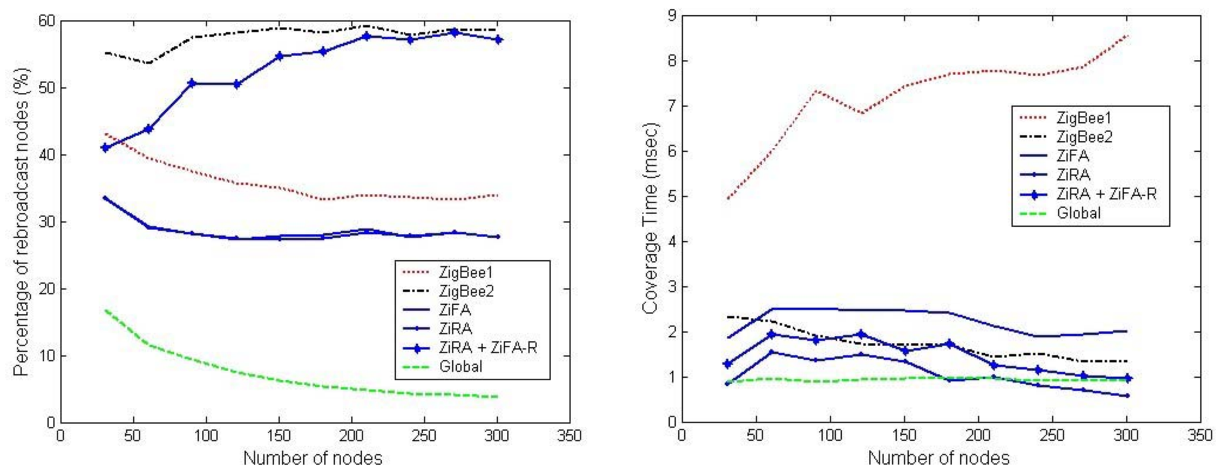
VII. CONCLUSION

In a real ZigBee network, in addition to reducing the number of rebroadcast nodes, we need to consider the reliability of the broadcast algorithm. There is always a trade-

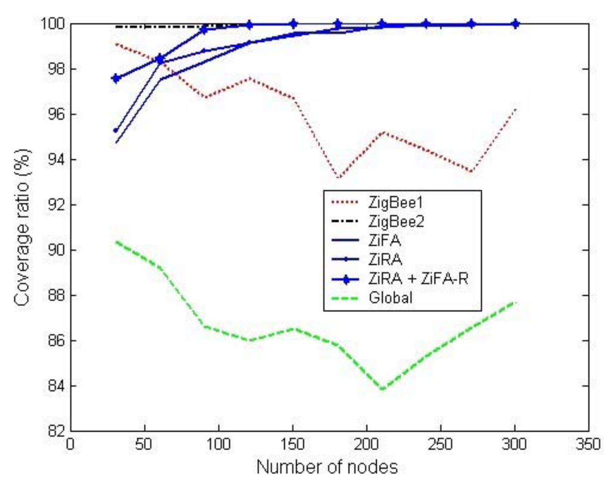


(a) (b)

Figure 9. Simulation results for ZiRA algorithm when there is no packet loss. (a) Percentage of rebroadcast nodes, (b) Coverage time.



(a) (b)



(c)

Figure 10. Simulation results for ZiRA algorithm when there is packet loss. (a) Percentage of rebroadcast nodes, (b) Coverage time, (c) Coverage ratio.

off between the reliability and efficiency; a higher level of reliability can be achieved at the cost of (or with the help of) broadcast redundancy. How to increase the redundancy for the sake of reliability is addressed is this paper. A reliable ZigBee forward node selection algorithm is proposed so that every non-forward node is covered by at least one of its tree neighbors. In order to cover the whole network faster, the link quality measured by IEEE 802.15.4 physical layer can be employed to make a better decision on when to rebroadcast. This also helps to avoid packet collisions and further reduce the broadcast redundancy.

The relationship between the broadcast performance and the ZigBee network parameters will be studied in our future work. Some other challenging research topics on ZigBee networks include the mobility, location-aware routing and applications, and dynamic network address assignment, and so on.

REFERENCES

[1] http://www.zigbee.org

[2] IEEE Standard 802, part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low Rate Wireless Personal Area Networks (WPANs), 2003.

[3] G. Lu, B. Krishnamachari, and C. Raghavendra, "Performance Evaluation of the IEEE 802.15.4 MAC for Low-Rate Low-Power Wireless Networks," in Proc. of the Workshop on Energy-Efficient Wireless Communications and Networks, 2004.

[4] J. Zheng and M. Lee, "Will IEEE 802.15.4 Make Ubiquitous Networking a Reality?: A Discussion on a Potential Low Power, Low Bit Rate Standard," IEEE Communications Magazine, vol. 42, no. 6, pp. 140-146, 2004.

[5] http://www.renesas.com

[6] ZigBee Alliance, Network Layer Specification 1.0, Dec. 2004. http://www.zigbee.org

[7] C. E. Perkins and E. M. Royer, "Ad hoc On-Demand Distance Vector Routing," in Proc. of the 2nd IEEE Workshop on Mobile Computing Systems and Applications, pp. 90-100, 1999.

[8] S. Ni, Y. Tsing, Y. Chen, and J. Sheu, "The Broadcast Storm Problem in a Mobile Ad Hoc Network," in Proc. of ACM MobiCom, 1999.

[9] Y. Tseng, S. Ni, and E. Shih, "Adaptive Approaches to Relieving Broadcast Storms in a Wireless Multihop Mobile Ad Hoc Network," IEEE Transactions on Computers, vol. 52, no. 5, pp. 545-557, 2003.

[10] B. Williams and T. Camp, "Comparison of Broadcasting Techniques for Mobile Ad Hoc Networks," in Proc. of ACM MobiHoc, pp. 194–205, 2002.

[11] H. Lim and C. Kim, "Flooding in Wireless Ad Hoc Networks," Computer Communication Journal, vol. 24, no. 3-4, pp. 353-363, 2001.

[12] W. Lou and J. Wu, "Localized Broadcasting in Mobile Ad Hoc Networks Using Neighbor Designation," in Handbook of Mobile Computing, CRC Press, 2005.

[13] V. Chvatal, "A Greedy Heuristic for the Set-covering Problem," Mathematics of Operation Research, vol. 4, no. 3, pp. 233-235, 1979.

[14] W. Peng and X. C. Lu, "On the Reduction of Broadcast Redundancy in Mobile Ad Hoc Networks," in Proc. of ACM MobiHoc, pp. 129-130, 2000.

[15] A. Qayyum, L. Viennot, and A. Laouiti, "Multipoint Relaying for Flooding Broadcast Message in Mobile Wireless Networks," in Proc. of Hawaii Int'l Conf. System Sciences, 2002.

[16] I. Stojmenovic and J. Wu, "Broadcasting and Activity-Scheduling in Ad Hoc Networks," in Ad Hoc Networking, S. Basagni, M. Conti, S. Giordano and I. Stojmenovic, Eds., IEEE Press, pp. 205-229, 2004.

[17] E. Pagani and G. P. Rossi, "Reliable Broadcast in Mobile Multihop Packet Networks," in Proc. of ACM MobiCom, 1997.

[18] T. Gopalsamy, M. Singhal, D.Panda, and P. Sadayappan, "A Reliable Multicast Algorithm for Mobile Ad Hoc Networks," in Proc. of IEEE ICDCS, 2002.

[19] E. Vollset and P. Ezhilchelvan, "A Survey of Reliable Broadcast Protocols for Mobile Ad-hoc Networks," Technical report CS-TR-792, School of Computing Science, University of Newcastle upon Tyne.

[20] W. Lou and J. Wu, "Double-Covered Broadcast (DCS): A Simple Reliable Broadcast Algorithm in MANETs," in Proc. of IEEE INFOCOM, 2004.

[21] G. Ding, Z. Sahinoglu, P. Orlik, J. Zhang, and B. Bhargava, "Tree-Based Data Broadcast in IEEE 802.15.4 and ZigBee Networks," Technical report, Mitsubishi Electric Research Laboratories, submitted to IEEE Transactions on Mobile Computing, 2004.