ISSN (Online) 2278-1021
ISSN(Print) 2319 5940

International Journal of Advanced Research in Computer and Communication Engineering
Vol. 4, Issue 7, July 2015

Broadcasting in ZigBee Network

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Abstract: This paper studies broadcast in ZigBee Network efficiently and simple way. In ZigBee Network, ZigBee Alliance specifies ZigBee specification and used with IEEE 802.15.4 Standard. ZigBee specification is used for network and application layers and IEEE 802.15.4 Standard is used for physical layer and MAC (Medium Access Control) layer.Since in general ad hoc networks,find minimum number ofthe rebroadcast nodes is NP-hard, which employs current broadcast protocols either employ extra knowledge such as information of 2-hop neighbor or position. However, the ZigBee network is mainly characterized as low cost, low data rate and low power consumption. ZigBee network cannot give information of 2-hop neighbor or position, but it needs an efficient broadcast algorithmto reduce the rebroadcast nodes with limited storage space and computation complexity. In this paper, Self-Pruning and Forward Node Selection algorithm is studied and usedfor exploiting the space of hierarchical address in ZigBee networks. Inthese algorithms, only information of 1-hop neighbor is required and without exchanges any messages between neighboring nodes, 2-hopneighbors's partial list is derived. The ZigBee Forward Node Selection algorithm is also studied in this paper. This algorithm is used for finding the minimum rebroadcast nodes with memory space and polynomial computation time.

Keywords: WPAN (Wireless Personal Area Network), PHY (Physical Layer), MAC (Medium Access Control), FFD (Full Function Devices), RFD (Reduced Function Devices), CSMA/CA (Carrier Sense Multiple Access/Collision Avoidance).

I. INTRODUCTION

Wireless Personal Area Network (WPAN) and Wireless Local Area Network (WLAN) technologies are increasing fast with the new rising standards being developed. Before some time, Bluetooth was most widely used for short range communications. Now, ZigBee is appropriate as an alternative to Bluetooth for devices with low power consumption and for low data rate applications. ZigBee standard is developed by ZigBee Alliance, which has hundreds of member companies, from the semi-conductor industry and software developers to original equipment manufacturers and installers. The ZigBee alliance was produced in 2002 as a nonprofit organization open to everyone who wants to connect. The Physical Layer (PHY) and Medium Access Control (MAC) protocols of the IEEE 802.15.4 are adopted by ZigBee standard. Therefore, a ZigBee compliant device is compliant with the IEEE 802.15.4 standard as well.

ZigBee is the only standards-based wireless 802.15.4 technology designed to address the unique needs of low-cost, low-power wireless sensor and control networks. The ZigBee standard employs 64 bit extended address and 16bit short addresses. The 16 bit short address supports over 65535 nodes per network. ZigBee is a multiple access network with CSMA/CA access method where the preferred topologies are the star and mesh. Mesh topology provides redundancy in the available routes and enables flexible network configuration. The star topology is needed for RF (Reduced Function) devices, as they are not capable of routing [3],[4].

ZigBee is designed for those applications that need to transmit small amounts of information or data while being battery powered so the architecture of the protocols and the hardware is optimized for low power consumptions of the end device. It provides long battery life. The ZigBee security architecture includes security mechanisms to protect transmitting data. There are number of publications devoted to the study of ZigBee technology and their implementation in real applications. ZigBee found usage in many applications like building automation, remote control, health care, home automation and many others [5].

ZigBee takes its name from the zigzag flying of bees that forms a mesh network among flowers. It is an individually simple organism that works together to tackle complex tasks.

ZigBee technology was developed for a wireless Personal Area Networks (PAN), aimed at control and military applications with low data rate and low power consumption. ZigBee is a low-cost, low-power, wireless mesh networking standard.

First, the low cost allows the technology to be widely deployed in wireless monitoring and controlapplications. Second, the low power-usage allows longer life with smaller batteries. Third, the mesh networking provides high reliability and more extensive range. The work presented here is to show how we can implement In the paper, we will use the ZigBee network to represent a wireless network that involves both IEEE 802.15.4 for Physical and MAC layers and ZigBee Protocols for Network and Higher layers.

This paper is organized as follows: Section 2 introduces IEEE 802.15.4 and ZigBee and summarizes related work on broadcasting in general ad hoc networks. Assumptions and notations are given in Section 3. The ZigBee On-tree Self pruning and On-tree Forward node Selection broadcast algorithms are presented in Section 4 and Section 5, respectively. Their performance is evaluated in Section 6. Section 7 concludes the paper.

II. BACK GROUND AND RELATED WORK

A ZigBee device should be of small size and low cost, so it cannot obtain accurate position information using extra hardware like GPS (Global Positioning System). ZigBee Networks are targeting low data rate and low power applications, so they cannot provide large communication bandwidth and power for exchanging position or neighbor information among neighbors. Even if such information can be obtained by a ZigBee device, it may not even have enough memory space to store it when the network size is large. Given the above limitations, we are motivated to find a localized and light-weight broadcast algorithm for ZigBee networks. In a typical ZigBee network, the network addresses are organized in a hierarchical manner so that one node can easily identify addresses of its tree neighbors, including its parent and children. In this work, we exploit the hierarchical address assignment in ZigBee networks and propose two localized broadcast algorithms: the Self-pruning algorithm and the Forward node Selection algorithm. Both algorithms select a subset of network nodes to rebroadcast, while every node in the network is still able to receive the packet. In the first algorithm, a node decides by itself whether it should rebroadcast or not; it need not rebroadcast if a certain subset of its 1-hop neighbors have already received the packet. In the latter algorithm, a node selects a subset of its 1-hop neighbors, called forward nodes, for forwarding, so as to cover all its 2-hop tree neighbors. It is proven that the proposed algorithm is of polynomial computation complexity and memory complexity, and it provides an optimal solution of selecting the minimum number of forward nodes. In contrast, for general ad hoc networks, this optimum problem is NP-hard so that it cannot be solved by any known algorithms of polynomial complexity [9].

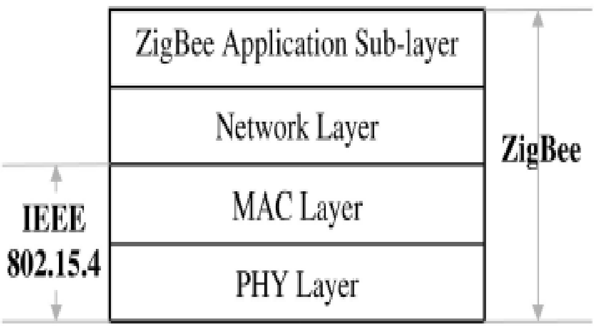


Fig. 1.ZigBee Architecture

The IEEE 802.15.4 standard is for low-rate WPANs that require low power, low cost, and low complexity. An IEEE 802.15.4 device can be deployed in sensor networks, home automation, and industrial automation and monitoring, etc. At the physical layer, IEEE 802.15.4 defines 27 channels of data rates 250 kb/s, 40 kb/s, and 20 kb/s. At the MAC layer, IEEE 802.15.4 controls access to the radio channel using the Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA) mechanism. IEEE 802.15.4 defines two types of devices: 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 device. An RFD is a simple device that associates and communicates only with an FFD. Based on IEEE 802.15.4, the ZigBee Alliance specifies the standards for network and application sub layer, as shown in Fig. 1. The responsibilities of network layer [3] include joining/leaving a network, routing, security, discovering 1-hop neighbors and storing neighbor information. The ZigBee network layer assigns addresses and builds a hierarchical tree topology. A coordinator is responsible for starting a new ZigBee WPAN and setting network parameters such as the maximum allowable number of children nm of each device and the maximum level dm of the logical tree. The coordinator is the root of the tree with address 0.

When a new device is willing to join a network, its MAC layer scans the available WPANs and notifies the network layer. After the upper layer selects a suitable WPAN, the network and MAC layer perform the association process with an existing device in the selected WPAN. If the existing device has enough address space, it will assign a free network address to the new device and make it one of its children. In case a child loses the association with its parent, it can initiate a rejoining process, called orphaning, and its parent will respond to resume the association.

The ZigBee Routing Algorithm is a hybrid of tree forwarding and ad-hoc on-demand routing. Any node can route frames to its parent or direct children on the tree.The RFDs are leaf nodes and canonly forward the data packet to their own parents. If an FFD has enough computation capacity and storage space, it can be a router-capable FFD (RFFD) and store routes to devicesother than its tree neighbors. An RFFD discovers a route bybroadcasting a route request and waiting for replies from thedestination or intermediate nodes, similar to the Ad-hoc on demand Distance Vector (AODV) routing protocol for general multi-hop ad hoc networks [8].

Most research on ad hoc networks models, the network topology as a unit disk graph in which each node has a unit transmission range. Ni et al. [6] introduced the broadcast storm problem when every node rebroadcasts a packet once. To reduce the broadcast redundancy and avoid collisions during rebroadcasting, they introduced some simple 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 [9], the authors improved the above algorithms by adaptively choosing the threshold as a function of the number of neighbors. Both simulation comparison [10] and theoretical analysis [11] have been conducted. These approaches are simple to implement, but they cannot guarantee coverage of the whole network [10]. More complicated algorithms assume the knowledge of network topology in order to guarantee network coverage and reduce broadcast redundancy. When the global network information is available, the problem of selecting the minimum number of forward nodes is essentially the well studied set cover problem, which is NP-hard [12]. But, its solution can be approximated by a greedy algorithm [13] with an approximation factor of

ISSN (Online) 2278-1021
ISSN(Print) 2319 5940

International Journal of Advanced Research in Computer and Communication Engineering
Vol. 4, Issue 7, July 2015

log(n), where n is the maximum number of neighbors.Since global network topology is not practically available, localized algorithms which only need the information of 1-hop and 2-hop neighbors are preferred [9].
To facilitate the description, some notations are listed in Table 1, where A and B represent a set of nodes or a single node [9].

Table 1. Notations

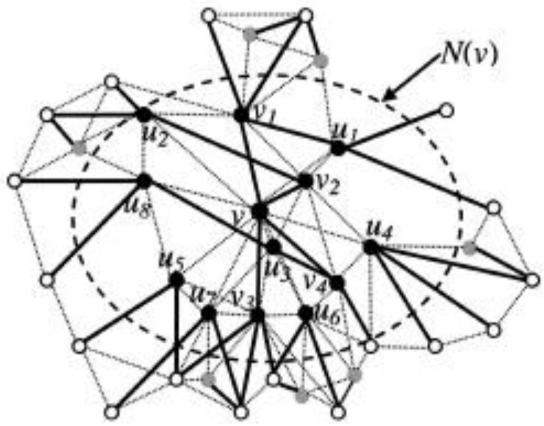
$N_0(A)$ or $TN_0(A)$	A
$N_1(A)$ or $N(A)$	1-hop neighbors of A, including A
$N_k(A)$ $(k \geq 2)$	$N(N_{k-1}(A))$, k-hop neighbors of A
A *covers* B	$B \subseteq N(A)$
$TN_1(A)$ or $TN(A)$	1-hop tree neighbors of A, including A
$TN_k(A)$ $(k \geq 2)$	$TN(TN_{k-1}(A))$
A *on-tree covers* B	$B \subseteq TN(A)$
$A - B$	$A \cap \overline{B}$
$S(A)$	Candidate forward nodes of A
$C(A)$	To-be-covered nodes of A
$F(A)$	Forward nodes of A

Due to the resource constraints in IEEE 802.15.4 and ZigBee networks, following assumptions are used in this paper:

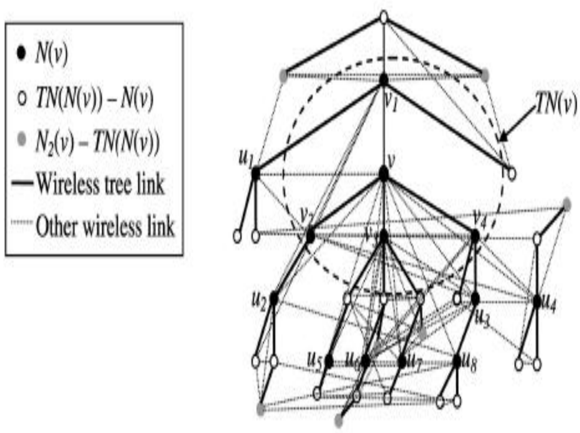
- The distance between nodes and the position of nodes are not available.
- The transmission power of nodes is fixed and the same.
- The network topology is not necessarily modeled as a unit disk graph. But, the symmetry of neighborhood is assumed. That is, if A is a neighbor of B, then B is also a neighbor of A.
- Addresses are hierarchically assigned. Hence, given the network address of a device, the addresses of its parent and children can be derived without information exchange.
- Every device maintains a table of only 1-hop neighbors. Each neighbor table entry consists of a neighbor's network address and the number of its children [9].

III. ZIGBEE ON-TREE SELF-PRUNING ALGORITHMS

An on-tree self-pruning broadcast algorithm for ZigBee networks is presented in this section. Upon reception of a broadcast packet, a node decides whether to rebroadcast or not. Basically, after a source broadcasts a packet, all of its 1-hop neighbors receive it. If they all rebroadcast the packet at the same time, catastrophic packet collisions may happen and delay the whole process of broadcast. To avoid collisions, every forward node waits for a random period of time before rebroadcasting. During this waiting period, a node v may receive the duplicated broadcast packet from another node u. So, node v only needs to cover N(v) -N(u), provided v knows 1-hop neighbors N(u) of node u. If node v learns that all of its 1-hop neighbors have already been covered before time out, it does not need to rebroadcast. For a general ad hoc network, one issue with the above self-pruning algorithm is that the 2-hop neighbor information is assumed to be available to node v. When this assumption does not hold, node v can only know that the source node u of a duplicate packet has been covered so that v still needs to cover N(v) - u. Node v can be self-pruned only if it has received the broadcast packet from all its 1-hop neighbors in N(v), which does not happen with a high probability during a short waiting period, especially when N(v) is very large. As a result, the self-pruning broadcast algorithm would perform poorly when applied to ZigBee networks where the 2-hop neighbor information is not available. On the other hand, by exploiting the tree structure of ZigBee address space, a node can find addresses of a partial list of 2-hop neighbors without introducing any communication or storage overhead. In other words, given the address of a 1-hop neighbor in N(v) and its number of children, one can determine the addresses of all its tree neighbors in TN(N(v)) [9].



(a)
Fig. 2.ZigBee Network Topology
(a) Physical Topology



(b)

Fig. 3.ZigBee Network Topology
(b) Logical ZigBee Tree Topology

ISSN (Online) 2278-1021
ISSN(Print) 2319 5940

International Journal of Advanced Research in Computer and Communication Engineering
Vol. 4, Issue 7, July 2015

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On-tree Self-pruning Rebroadcast (OSR)
Input: receiving node v and broadcasting node u
Output: none
if it is the first time to receive a broadcast packet,
    Set an on-tree to-be-covered set: TS = TN(v) – TN(u)
    if TS = Ø,
        Drop the packet.
    else
        Buffer the packet and record its broadcast ID.
        Start a timer with random timeout.
    end if
else
    if the early copy of this packet is waiting,
        Update TS = TS – TN(u)
        if TS = Ø,
            Drop the packet and stop the timer.
        end if
    else
        Drop the duplicated broadcast packet.
    end if
end if

if the timer expires
    broadcast the packet.
end if
```

Fig. 4.ZigBee On-tree Self-pruning Rebroadcast algorithm.

IV. OPTIMAL ON-TREE SELECTION ALGORITHM

Given a node v, which can be the source of a broadcast packet or a selected forward node receiving packet from node u, the localized algorithm OOSis given in Fig. 4 selects the minimum size forward node set F(v) from N(v) to on tree cover TN(N(v)) [9].

```
Optimal On-tree Selection (OOS)
Input: N(v) and broadcasting node u with F(u)
Output: F(v)
1. if v is the source of broadcast
                S(v) = N(v) – v,                              (1)
                C(v) = TN(N(v)) – N(v).                       (2)
   else /* v must receive the broadcast packet from another node u. */
                S(v) = N(v) – v – TN(u) – F(u),               (3)
                C(v) = TN(N(v)) – N(v) – TN2(u) – TN(F(u)).   (4)
   end if
   Initialize F(v) = Ø.
2. Construct a forest composed of all nodes in S(v) ⋃ C(v), which is part of the
logical ZigBee tree of the whole network.
3. for every tree in the forest,
      for every level in the tree, starting from the bottom,
        for every node w ∈ C(v), from left to right,
          if x = Parent(w) ∈ S(v),
              F(v) = F(v) ⋃ {x}, S(v) = S(v) – {x}, C(v) = C(v) – TN(x).
          else there must exist y ∈ S(v) such that w = Parent(y)
              F(v) = F(v) ⋃ {y}, S(v) = S(v) – {y}, C(v) = C(v) – {w}.
          end if
        end for
      end for
   end for
```

Fig. 5. Optimal On-tree Forward node Selection algorithm

The first step in the OOS reduces the size of the candidate forward node set S and the to-be-covered set C. If node v is the source or a forward node, it will definitely rebroadcast and cover all its 1-hop neighbors, so it does not need to be selected as a forward node again, and all its neighbors do not need to be covered again, as shown in (1) and (2). If node v receives the broadcast packet from another forward node u, it can remove set TN (u) and TN_2 (u) from S and C, respectively.

V. ZIGBEE ON-TREE SELECTION ALGORITHM

The OOS Algorithm assumes that the construction and traversing of a tree does not introduce any extra cost. When implementing the algorithm in the real system, however, this assumption is not practical because a ZigBee device usually has very limited memory and computation capacity. Since a large part of the memory has already been used by the routing table and neighbor table, it may not even have enough space to store the whole forest or even a tree of O (nn_m) nodes. It needs considerable computation capacity to generate, merge, and delete nodes on the tree. Even if a tree is constructed, it requires extra effort to sort and traverse it level by level. ZigBee On-tree Selection (ZOS) algorithm is given in Fig. 6. It only needs O(n) of memory space while keeping the same computational complexity as the OOS. The ZOS has the same result as the OOS, but it is implemented in a more memory-efficient [9].

```
ZigBee On-tree Selection (ZOS)
Input: N(v) and broadcasting node u with F(u)
Output: F(v)
1. Same as step 1 in OOS algorithm.
2. Given N(v) stored in a neighbor table, sort N(v) by level and network address at each level.
   Initialize a piece of memory M of size nl equal to the maximum size of all levels.
   for every node x in N(v)
      if x ∈ S
         Status(x) = "Initial"
      else
         Status(x) = "alreadyForward"
      end if
   end for
   currentLevel = the depth of bottom level.
3. for (each node x in currentLevel) and (Status(x) = "Initial"),
      if (x does not have any children) or (x's every child is in (currentLevel + 1) or M)
        Status(x) = "nonForward"
      else
        Status(x) = "Forward"
      end if
   end for
   Empty M.
4. for (every node y in (currentLevel + 1)) and (Status(y) ≠ "alreadyForward"),
      if w = Parent(y) is not in currentLevel
         Add w to M
         if (Status(y) = "nonForward") and (x = Parent(w) belongs to (currentLevel – 1)),
            Status(x) = "Forward",
         else
            Status(y) = "Forward",
         end if
      end if
   end for
5. currentLevel = currentLevel – 1,
   if currentLevel = 0,
      Go through the whole neighbor table and collect all nodes with status "Forward",
      exit
   else
      go to 3.
   end if
```

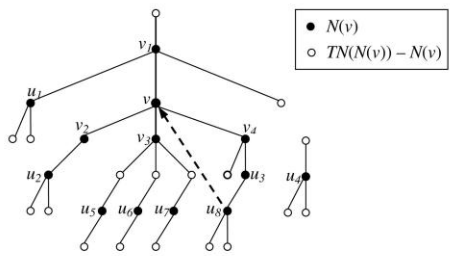

Fig. 7. An example of using the OOS algorithm

ISSN (Online) 2278-1021
ISSN(Print) 2319 5940

International Journal of Advanced Research in Computer and Communication Engineering
Vol. 4, Issue 7, July 2015

VI. PERFORMANCE EVALUATION

MATLAB Tool is used to broadcast physical and logical ZigBee Network Topology. Assume an ideal case when there is no packet loss in the MAC and physical layer. The reliability issue was recently studied in [25]. The network topology is generated within a 100 m x 100 m square area. The location of each node is randomly generated.

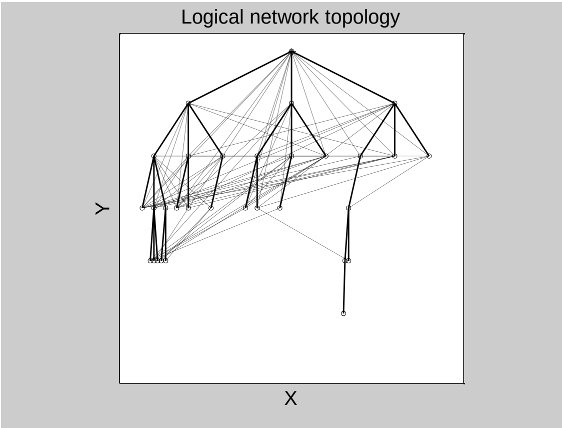

Fig. 8. Logical Network Topology

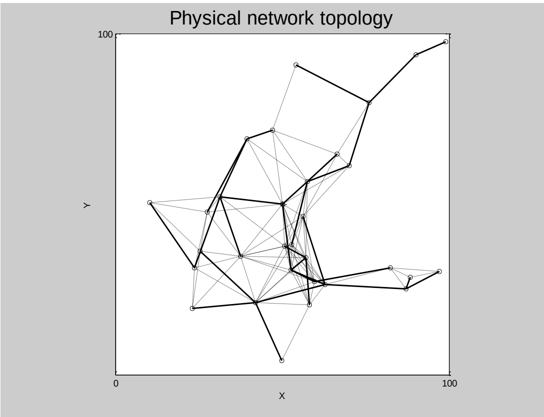

Fig. 9. Physical Network Topology

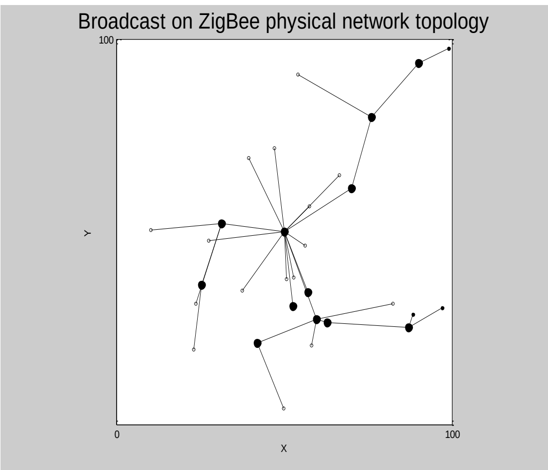

Fig. 10. Broadcast on ZigBee Physical Network Topology

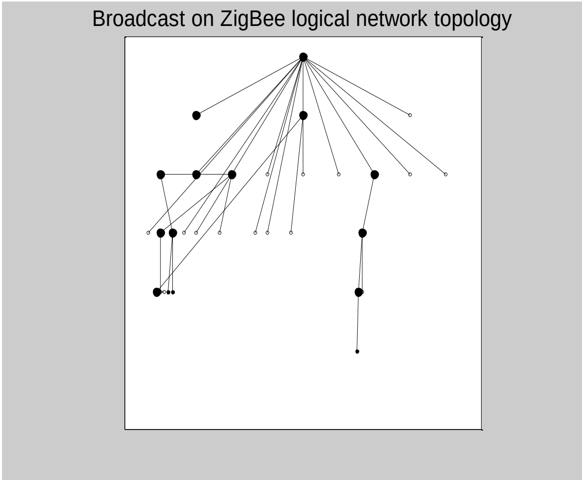

Fig. 11. Broadcast on ZigBee Logical Network Topology

VII. RESULTS AND CONCLUSION

Only physical 1-hop neighbors and logical tree neighbors are known in ZigBee networks. in this paper, two broadcast algorithms for IEEE 802.15.4 and ZigBee networks: the on-tree self-pruning rebroadcast algorithm OSR and the ZigBee on-tree selection algorithm ZOS are studied and used.

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