ZigBee-Based Long-Thin Wireless Sensor Networks: Address Assignment and Routing Schemes

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Abstract: Although *wireless sensor networks (WSNs)* have been extensively researched, its deployment is still a big concern. This paper makes two contributions to this issue. First, we promote a new concept of *long-thin (LT) topology* for WSNs, where a network may have a number of *linear paths* of nodes as backbones connecting to each other. These backbones are to extend the network to the intended coverage areas. At the first glance, a LT WSN only seems to be a special case of numerous WSN topologies. However, we observe, from real deployment experiences, that such a topology is quite general in many applications and deployments. The second contribution is that we show that the *address assignment* and thus the *tree routing scheme* defined in the original ZigBee specification may work poorly, if not fail, in a LT topology. We then propose simple, yet efficient, address assignment and routing schemes for a LT WSN. Simulation results are reported.

Keywords: address assignment; pervasive computing; routing; wireless sensor network; ZigBee.

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1 Introduction

The rapid progress of wireless communication and embedded micro-sensing MEMS technologies has made wireless sensor networks (WSN) possible. A WSN usually needs to configure itself automatically and support ad hoc routing. A lot of research works have been dedicated to WSNs, including power management (Ye et al., 2002), routing and transportation (Braginsky and Estrin, 2002; Eghbali et al., 2011), sensor deployment and coverage issues (Huang et al., 2004; Sung and Yang, 2010), and localization (Ahmed et al., 2005). In the application side, health care is discussed in (Huo et al., 2011) and navigation is studied in (Tseng et al., 2006).

In this paper, we discuss the *long-thin (LT)* network topology, which seems to have a very specific architecture, but may be commonly seen in many WSN deployments in many applications, such as gas leakage detection of fuel pipes, carbon dioxide concentration monitoring in tunnels, stage measurements in sewers, street lights monitoring in highway systems, flood protection of rivers, and vibration detection of bridges. In such a network, nodes may form several long backbones and these backbones are to extend the network to the intended coverage areas. A backbone is a linear path which may contain hundreds of sensor nodes and may go beyond thousands of meters. So the network area can be scaled up easily with limited hardware cost.

Recently, several WSN platforms have been developed. For interoperability among different systems, standards such as ZigBee (ZigBee, 2006) have been developed. In the ZigBee protocol stack, physical and MAC layer protocols are adopted from the IEEE 802.15.4 standard (IEEE 802.15.4, 2003). ZigBee solves interoperability issues from the physical layer to the application layer. ZigBee supports three kinds of network topologies, namely star, tree, and mesh networks. A *ZigBee coordinator* is responsible for initializing, maintaining, and controlling the network. A star network has a coordinator with devices directly connecting to the coordinator. For tree and mesh networks, devices can communicate with each other in a multihop fashion. The network is formed by one ZigBee coordinator and multiple *ZigBee routers*. A device can join a network as an *end device* by associating with the coordinator or a router. In ZigBee, a device is said to join a network successfully if it can obtain a 16-bit network address from the coordinator or a router. ZigBee specifies a distributed address assignment scheme, which allows a parent device to locally compute addresses for child devices. While the assignment scheme has low complexity, it also prohibits the network from scaling up and thus cannot be used in LT networks.

In this paper, we propose address assignment and routing schemes for ZigBee-based LT WSNs. To assign addresses to nodes, we design rules to divide nodes into clusters. Each node belongs to one cluster and each cluster has a unique *cluster ID*. All nodes in a cluster have the same cluster ID, but different *node IDs*. The structure of a ZigBee network address is divided into two parts: one is *cluster ID* and the other is *node ID*. Following the same ZigBee design philosophy, the proposed scheme is simple and has low complexity. Moreover, similar to the ZigBee tree routing protocol, the proposed routing protocol can also utilize nodes' network addresses to facilitate routing. In addition, routing can take advantage of shortcuts for better efficiency, so our scheme does not restrict nodes to relay packets only to their parent or child nodes as ZigBee does.

Existing works (Ali and Uzmi, 2004; Ould-Ahmed-Vall et al., 2005; Schurgers et al., 2002) have discussed address assignment for WSNs. Ali and Uzmi (Ali and Uzmi, 2004) propose a hierarchical address assignment scheme, where sensors are divided into clusters, and clusters are logically divided into layers. A cluster is a small group, and sensors in a cluster contend to different node addresses. The real address of a sensor will be the concatenation of node address, cluster address, and layer address. The basic concept of (Ould-Ahmed-Vall et al., 2005) is similar to the ZigBe address assignment. Before assigning address, the sink constructs a tree to calculate the subtree size of each intermediate node. Each intermediate node locally reserves enough address spaces for its descendants and carefully assign addresses to its children. In (Schurgers et al., 2002), the authors propose a distributed address assignment scheme, which aims to reduce message overhead when solving address conflict. After choosing an unused address, a node first encodes its address and then broadcasts it. Nodes use the received code word to detect if there are address conflicts. The above three works (Ali and Uzmi, 2004; Ould-Ahmed-Vall et al., 2005; Schurgers et al., 2002) are designed for general WSNs and cannot be used in LT or ZigBee networks. There are two works (Pan et al., 2009) and (Yen and Tsai, 2010) discuss the network formation protocols for ZigBee networks. The proposed schemes in (Pan et al., 2009) and (Yen and Tsai, 2010) are aimed to improve the address utilization in ZigBee networks but cannot be directly applied in LT WSNs. Reference (Li et al., 2008) and (Qiu et al., 2009) design enhancements for ZigBee routing protocols. In (Li et al., 2008), the authors propose to modify ZigBee AODV routing scheme to utilize ZigBee tree information. A relay node finds the destination is located in its subtree can switch to use ZigBee tree routing to relay packets. But most routing paths in LT WSNs are along linear paths, the AODV routing scheme is not suitable. Reference (Qiu et al., 2009) presents a similar idea to (Li et al., 2008). In this work, we adopt the idea of ZigBee tree routing to design our routing protocol, and nodes can find some shortcuts on the linear paths to quickly relay packets.

This paper extends the preliminary work (Pan et al., 2008) in the following ways: 1) introducing a systematic network planning flows for network managers; 2) proposing a node ranking procedure to guarantee the address assignment result as be as planned; 3) modifying address assignment scheme to utilize node ranking results; 4) discussing link maintenance; 5) expanding the performance evaluations.

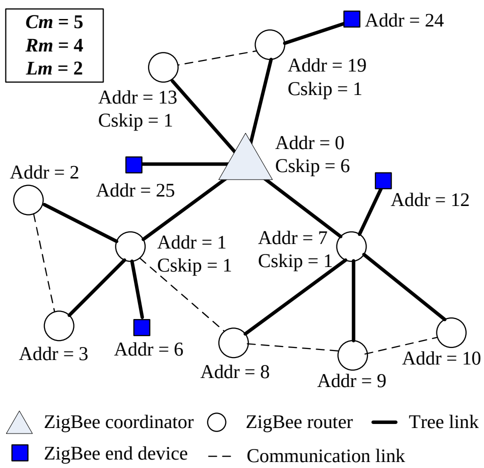
The rest of this paper is organized as follows. Preliminaries are given in Section 2. Section 3 presents our algorithms. Performance evaluations are given in Section 4. Finally, Section 5 concludes this paper.

2 Preliminaries

2.1 ZigBee Address Assignment

In ZigBee, network addresses are assigned to devices by a distributed address assignment scheme. Before forming a network, the coordinator determines the maximum number of children of a router (Cm), the maximum number of child routers of a router (Rm), and the depth of the network (Lm). Note that children of a router can be routers or end devices, so $Cm \geq Rm$. The coordinator and routers can each have at most Rm child routers and at least $Cm - Rm$ child end devices. Devices' addresses are assigned in a top-down manner. For the coordinator, the whole address space is logically partitioned into $Rm + 1$ blocks. The first Rm blocks are to be assigned to the coordinator's child routers and the last block is reserved for the coordinator's own child end devices. From Cm, Rm, and Lm, each router computes a parameter called $Cskip$ to derive the starting addresses of

Figure 1 A ZigBee address assignment example.



its children's address pools. The $Cskip$ for the coordinator or a router in depth d is defined as:

$$Cskip(d) = \begin{cases} 1 + Cm \times (Lm - d - 1), & \text{if } Rm = 1. \\ \dfrac{1 + Cm - Rm - CmRm^{Lm-d-1}}{1 - Rm}, & \text{otherwise.} \end{cases} \quad (1)$$

The coordinator is said to be at depth $d = 0$, and d is increased by one after each level. Address assignment begins from the ZigBee coordinator by assigning address 0 to itself. If a parent node at depth d has an address A_{parent}, the n-th child router is assigned to address $A_{parent} + (n - 1) \times Cskip(d) + 1$ and n-th child end device is assigned to address $A_{parent} + Rm \times Cskip(d) + n$. An example of the address assignment is shown in Fig. 1. The $Cskip$ of the coordinator is obtained from Eq. (1) by setting $d = 0$, $Cm = 5$, $Rm = 4$, and $Lm = 2$. Then the child routers of the coordinator will be assigned to addresses $0 + (1 - 1) \times 6 + 1 = 1$, $0 + (2 - 1) \times 6 + 1 = 7$, $0 + (3 - 1) \times 6 + 1 = 13$, etc. The address of the only child end device of the coordinator is $0 + 4 \times 6 + 1 = 25$. Note that the length of a network address is 16 bits; thus, the maximum address capacity is $2^{16} = 65536$. Obviously, the above assignment is much suitable for regular networks, but not for LT WSNs (where the monitored area may contain hundreds of sensor nodes in a linear path). For example, when setting $Cm = 4$ and $Rm = 2$, the depth of the network can only be 14. Also, when there are some LT backbones, the address space will not be well utilized.

2.2 *ZigBee Tree Routing Protocol*

In a ZigBee network, the coordinator and routers can directly transmit packets along the tree without using any route discovery. When a router receives a packet, it first checks if it is the destination or one of its child end devices is the destination. If so, this router will accept the packet or forward this packet to the designated child end device. Otherwise, it will relay packet along the tree. Assume that the depth of this router is d and its address is A. This packet is for one of its descendant devices if the destination address A_{dest} satisfies $A < A_{dest} < A + Cskip(d - 1)$, and this packet will be relayed to the child router with address

$$A_r = A + 1 + \left\lfloor \frac{A_{dest} - (A + 1)}{Cskip(d)} \right\rfloor \times Cskip(d).$$

If the destination is not a descendant of this device, this packet will be forwarded to its parent. In ZigBee tree routing, each node can only choose its parent or child as the next node. Since no shortcut can be taken, this strategy may cause longer delay in LT networks.

3 LT WSN: Formation, Addressing, and Routing

Our goal is to automatically form a LT WSN, give addresses to nodes, and conduct routing. Fig. 2(a) shows an example of a LT WSN. For simplicity, we assume that all nodes are router-capable devices. To form the network, nodes are divided into multiple *clusters*, each as a line segment. For each cluster, we define two special nodes, named *cluster head* and *bridge*. The cluster head (resp., the bridge) is the first (resp., last) in the line segment. As a special case, the coordinator, is also considered as a cluster head. The other nodes are *network nodes* (refer to Fig. 2(b)). A cluster C is a *child* cluster of a cluster C' if the cluster head of C is connected to the bridge of C'. Reversely, C' is the *parent* cluster of C. Note that a cluster must have a linear path as its subgraph. But it may have other extra links beside the linear path. For example, in Fig. 2(b), there are two extra radio links (A, $A2$) and ($A1$, $A3$) in A's cluster. To be compliant with ZigBee, we divide the ZigBee 16-bit network address into two parts, an m-bit *cluster ID* and a $(16 - m)$-bit *node ID*. The value of m will be discussed later on. The network address of a node v is thus expressed as (C_v, N_v), where C_v and N_v are v's cluster ID and node ID, respectively.

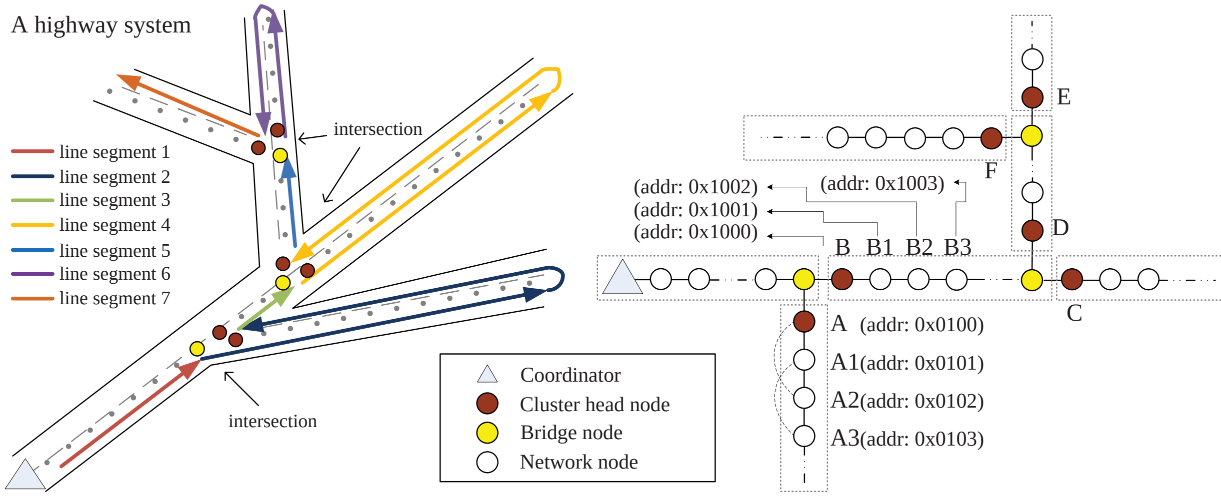
3.1 *Node Placement*

Before deploying a network, the network manager needs to carefully plan the network by the following three steps. First, the network manager has to mutually identifies clusters according to maps or charts of the target area by the following two principles. 1) The network manager traverses linear paths of the target area from the coordinator in a depth-first manner. 2) When there is a intersection, the network manager identifies the traversed path as a cluster and consider the following paths as new clusters. Fig. 2(a) shows an example, where there are three intersections and the network can be divided into seven line segments (clusters). Second, after identifying clusters, the network manager needs to carefully plan the placement of cluster heads, bridges, and network nodes by the following rules:

1. For each cluster, the first and the last nodes are pre-assigned (manually) as cluster head and bridge, respectively.

2. A cluster head that is not the coordinator should have a link to the bridge of its parent cluster.

Figure 2 (a) A LT WSN. (b) Role assignment.



(a) (b)

3. Conversely, the bridge of a cluster which has child clusters should have a link to the cluster head of each child cluster.

4. Place sufficient network nodes in each cluster to ensure the network connectivity.

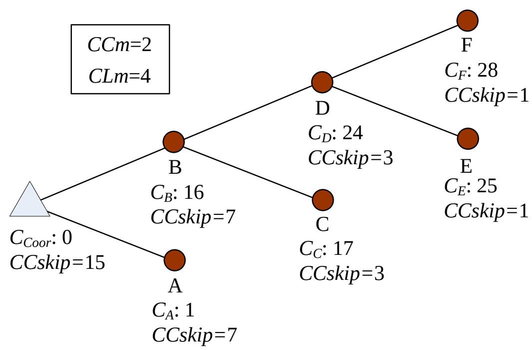
Third, after planning the placement of nodes, the network manager can construct a *logical network* G_L to decide some network parameters. In G_L, each cluster is converted into a single node and the parent-child relationships of clusters are converted into edges. For example, Fig. 3 is the logical network of Fig. 2(b). From G_L, we can determine the maximum number of children CCm of a node in G_L and the depth CLm of G_L. By CCm and CLm, we can know that this network will have at least $CN = \frac{1-CCm^{CLm+1}}{1-CCm}$ clusters. Then the network manager can decide the value of m (which determines how many clusters in this network) such that $2^{m-1} < CN \leq 2^m$ is satisfied. Nodes are mutually placed based on the above network plan.

After deploying network nodes, the network can be initialized automatically by each node periodically broadcasting HELLO packets including its IEEE 64-bit MAC address, 16-bit network address (initially set to *NULL*), and role. In this work, we consider only symmetric links. A communication link (u, v) is established only if u receives v's HELLO including u as its neighbor and the HELLO's signal quality is above a threshold. Note that the signal quality should be the average of several packets. Then each node can maintain a neighbor table containing its neighbors' addresses, roles, and ranks. After such HELLO exchanges, the coordinator will start a *node ranking algorithm* to differentiate nodes' distances to it (Section 3.2). Then, a *distributed address assignment procedure* will be conducted to assign network addresses to nodes (Section 3.3).

3.2 Node Ranking

We extend the concept of one-dimensional ranking algorithm in (Lotker et al., 2004) to assign a *rank* to each node. Nodes' rank values reflect their distances following the line segments to the coordinator. For example, in Fig. 2(b), we can see that the distance from $A1$ to the coordinator is shorter than the one from $A2$ to the coordinator. After the ranking procedure, the rank result will be $A1 < A2$. In this work, nodes decides their ranks in a distributed manner, and all nodes except the coordinator will perform the same procedure. Initially, the rank of the coordinator is 0 and all other nodes have a rank of K, where K is a positive constant. At the end of the algorithm, each node will have a stable rank. The rank value facilitates our address assignments which will be described in Section 3.3.

Figure 3 The logical network of Fig. 2(b).



Except the coordinator, all other nodes will continuously change their ranks. The coordinator will periodically broadcast a *Heartbeat* packet with its rank. On receiving a *Heartbeat*, a node will rebroadcast it by including its current rank. After receiving all its neighbors' *Heartbeat* packets, a node will calculate its new rank by averaging its neighbors' ranks. Since the coordinator's rank is fixed, after receiving several *Heartbeat* packets, nodes that locate closer to the coordinator will have lower ranks.

Now we give the details of the ranking algorithm. The format of *Heartbeat* is *Heartbeat*(*sender's 64-bit address*, *seq*, *rank*). In the beginning, the coordinator broadcasts a *Heartbeat*(*coordinator*, 0, 0). Then it periodically broadcasts

Heartbeat packets, each time with an incremented *seq*, until *seq* $> h$, where h is the maximum hop count distance from the coordinator to any node, which can be easily obtained when planning the network. The operations taken by a non-coordinator node v are defined as follows.

1. On receiving a *Heartbeat*(u, u's *seq*, u*'s rank*), v checks if it has broadcast a *Heartbeat* with this sequence number *seq*. If not, v updates its sequence number to this received *seq* and broadcasts a *Heartbeat*(v, v's *seq*, v*'s rank*). Then v keeps a record of the pair (u's *seq*, u*'s rank*). If v has received all its neighbors' *Heartbeat* packets with the same *seq* as its own, it updates its rank to the average of its neighbors' ranks (not including its own rank). Otherwise, it sets a timer *WaitHeartbeat*.

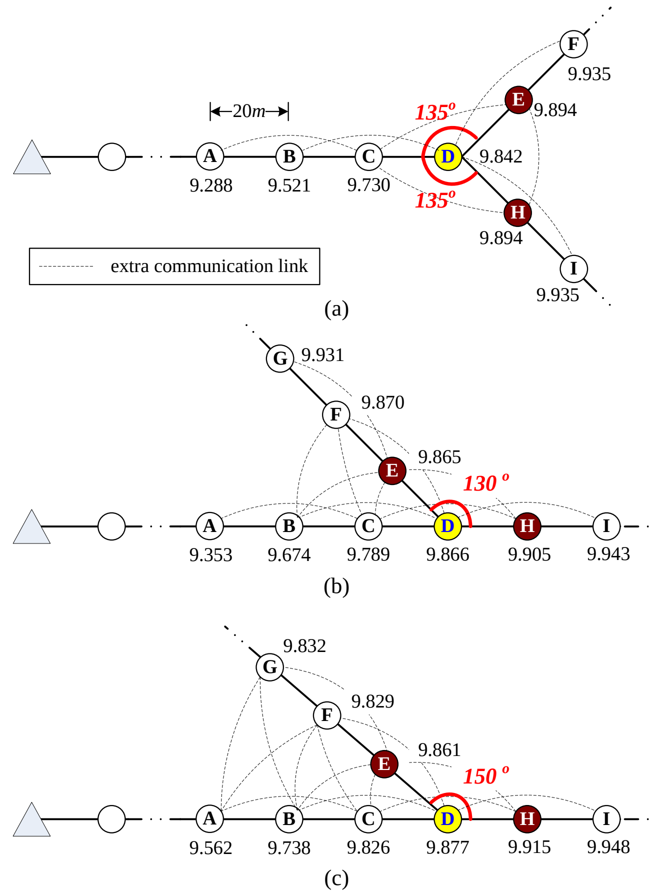
2. When timer *WaitHeartbeat* times out, v broadcasts a *NACK*(L), where L is the list of neighbors whose *Heartbeat*s are still missing. Then it sets another *WaitHeartbeat* timer, until the maximum number of retries is reached.

3. When v receives a *NACK*(L) such that $v \in L$, it broadcasts a *Heartbeat*(v, v's *seq*, v*'s rank*).

The above step 1 enforces a node to broadcast its rank whenever a new *seq* is received. New *seq*s are issued by the coordinator. A node can update its rank after receiving ranks of all its neighbors with the same *seq* as its own. Steps 2 and 3 are to guarantee reliability due to the fact the broadcast is unreliable in wireless networks. Note that when the coordinator broadcasts the first *Heartbeat*, only those one hop neighbors of the coordinator can change their ranks. When the coordinator broadcasts the next *Heartbeat*, those one hop and two hop neighbors can modify their ranks. So, in this scheme, the coordinator needs to broadcast at least $h+1$ *Heartbeat* packets to guarantee that every node can modify its initial rank. During the ranking procedure, the coordinator's zero rank value gradually diffuses to the rest of the nodes and thus decreases their ranks. At the end of the algorithm, each node can record its neighbors' final ranks in its neighbor table. We say that a ranking result is *in-order* if for each cluster, (i) the cluster head (resp., bridge) has the smallest (resp., largest) rank value, (ii) the ranks of cluster members correspond to their distances to the cluster head, and (iii) the bridge node's rank value is smaller than the ranks of the cluster's child cluster members.

In a linear path topology, the above ranking method can effectively achieve in-order ranking since the coordinator keeps its rank value as zero and continuously pull down the ranks for nodes that locate close to it. As a result, the nodes' rank values increment from the coordinator to the last node of the linear path. However, a LT WSN may have some branches, and thus the ranking result may not always be in-order. Fig. 4 shows some results, where the inter-node distance is $20\ m$ and the transmission range is $45\ m$. The ranking result in Fig. 4(a) is in-order. In Fig. 4(b), the ideal ranking result should satisfy $B < C < D < E < F$. Unfortunately, the result satisfies $B < C < E < D < F$.

Figure 4 Some ranking examples.



The ranks of some members of E's cluster are smaller than the ones of some members of H's cluster because some E's members are affected by some members of its parent cluster. We see that D and E have the same number of neighbors but D's rank is affected by some H's cluster members. This makes D's rank higher than E's, causing the final ranking result not in-order. In Fig. 4(c), F and G have smaller ranks than E because they are affected by A's and B's ranks. To summarize, we observe that if some members of a cluster have links to the cluster's parent cluster members, the ranking result may not be in-order.

Here we make two remarks. First, compare to ZigBee network formation protocol, the ranking procedure requires nodes to broadcast extra *Heartbeat* packets. Let n be the total number of *Heartbeat* packets from the coordinator. The additional message complexity as opposed to ZigBee for each node is $O(n)$. Second, if a ranking result is in-order, it will facilitate our address assignment and thus network formation. Even if a ranking result is not in-order, we can still assign addresses. After assigning address, a node can refine its address if it overhears a neighbor's beacons having better signal quality than those from its parent. Details will be elaborated further later on.

3.3 Distributed Address Assignment

The basic idea of our address assignment is as follows. The assignment of cluster IDs depends on the maximum number of branches in the logical network G_L. If $CCm = 1$, then the network is a linear path and the address assignment is a trivial job. If $CCm \geq 2$, then we follow the style of ZigBee to assign addresses in a recursive and distributed manner. The coordinator has an ID of 0. For each node at depth d in G_L, if its cluster ID is C, then its i-th child cluster is assigned a cluster ID of $C + (i-1) \times CCskip(d) + 1$, where

$$CCskip(d) = \frac{1 - CCm^{CLm-d}}{1 - CCm}.$$

Fig. 3 shows the assignment result for the network in Fig. 2(b). Since each cluster is a linear path, node IDs of the cluster members can be assigned sequentially. Starting from the cluster head with an address of 0, the rest of the nodes can gradually increment their node IDs following the former ranking results, until the bridge node is reached. In Fig. 2(b), we have shown some assignment results, where each address is expressed in Hex and the first two symbols represent the cluster ID and the last two represent the node ID.

Now we present the detail algorithm. It is started by the coordinator by broadcasting beacons with the predefined CCm and CLm. When a node u "without" a network address receives a beacon, it will send an *Association_Request* to the beacon sender. If it receives multiple beacons, the node with the strongest signal strength will be selected. When the beacon sender, say, v at a logical depth d, receives the association request(s), it will do the following:

1. If v is *not* a bridge node, it sets a parameter $N = N_v + 1$ (note that when entering this procedure, v already obtains its address (C_v, N_v)). Then it sorts these request senders according to their ranks in an ascending order into a list L. Then v sequentially examines each node $v' \in L$. There are two cases:
   (a) If v' is a cluster head node, v skips v' and continues to examine the next node in L.
   (b) Otherwise, v assigns address (C_v, N) to v' and increments N by 1. Then v replies an *Association_Response* to v' with this address. In case that v' is a bridge node, v stops examining L; otherwise v loops back and continues to examine the next node in L.
2. If v is a bridge node, it only accepts requests from cluster heads. At most CCm requests will be accepted, and v will reply to the i-th least ranked cluster head, $i \leq CCm$, an *Association_Response* with an address $(C_v + (i-1) \times CCskip(d) + 1, 0)$. Note that, these cluster heads need to set their logical depths to $d + 1$.

When the node u obtains an address, it will use the MLME-START primitive defined in IEEE 802.15.4 to start its beacons. There is a special design in this algorithm to refine the address assignment when the ranking result is not in-order. After getting an address, a node u may reconnect to a new parent by the following procedure. Assume a node u, which is not a cluster or a bridge, receives a beacon from a neighbor node u'. Node u checks if u' is located in the same cluster as it. If not, u will track if u' beacon for a period of time to see if the signal quality of u' is better than its current parent v. If u identifies u' is better than v, u sends *Disassociation_Request* to its children and to v and then re-associates to u'. We will give an example to show the effectiveness of the above reconnect procedure later. Since the address assignment works in a distributed manner, this algorithm eventually stops when all nodes obtain their network addresses.

We say that an address assignment result is *as planned* if (i) each pair of cluster head and bridge are assigned to the same cluster ID and (ii) each bridge is correctly connected to its child cluster heads. Below, we make two observations about the address assignment results. First, if the ranking result is in-order and the nodes near-by each cluster head can receive stronger signal from its own cluster head than from others, the address assignment will be as planned. For example, in Fig. 4(a), the network will be formed as planned. Second, there are some cases that the formed network is as planned even if the ranking result is not in-order. For example, in Fig. 4(b), assuming B as the beacon sender, B will accept nodes C and D with D as the bridge. Although F may send an *Association_Request* to B, B will not accept F according to step 1.b of the algorithm. More specifically, when B examines its list, B stops assigning address when the bridge D is encountered. There is another example in Fig. 4(c). Assuming A as the beacon sender, A may accept B, C, F, and G. After the cluster head E connects to bridge D, E can start to broadcasts its beacons. Note that at this time F and G is located in the parent cluster of E. When F and G receive E's beacon, they know that E's cluster ID is not as theirs. Then F realizes that E is a better choice than its original parent A. So do G may reconnect to E or F. After F and G choose their new parents, the address assignment can be as planned.

3.4 Routing Rules

Routing in our LT WSN can be purely based on the above address assignment results. Through HELLO packets, a node can collect its neighbors' network addresses. Suppose that a node v at logical depth d receives a packet with a destination address (C_{dest}, N_{dest}). If v is the destination, it simply accepts this packet. Otherwise, v performs the following procedures.

1. If the destination is a neighbor of v, v sends this packet to the destination directly.
2. If $C_{dest} = C_v$, the destination is within the same cluster. Node v can find an ancestor or a descendant in its neighbor table, say, u such that $C_u = C_{dest}$ and the value of $|N_u - N_{dest}|$ is minimized, and forward this packet to u.
3. If C_{dest} is a descendant cluster of C_v, i.e., $C_v < C_{dest} \leq C_v + CCm \times CCskip(d) + 1$, then v checks if it has a neighbor u which satisfies $C_u \leq C_{dest} \leq C_u + CCm \times CCskip(d+1) + 1$. If such a u exists, then v forwards the packet to u. In case that there are multiple candidates, the one with the

smallest $|N_u - N_{dest}|$ is selected. Otherwise, v finds a neighbor u which is located in the same cluster and has the maximum N_u, where $N_u > N_v$, and forwards the packet to u. If no such u exists, v simply drops this packet.

4. For all other cases, C_{dest} must be an ancestor cluster of C_v or not within the same logical subtree. Then v checks if it has a neighbor u which satisfies $C_u < C_v \leq C_u + CCm \times CCskip(d-1) + 1$. If such a u exists, v forwards the packet to u. Note that the above condition confines that C_u is the parent cluster of C_v. Otherwise, v finds a neighbor u which is located in the same cluster and has the minimum N_u, where $N_u < N_v$, and forwards the packet to u. If no such u exists, v simply drops this packet.

Note that the above design tries to strike a balance between efficiency and simplicity. It basically follows the ZigBee tree-like routing. However, making shortcut along the linear paths of the LT WSN is possible due to the existence of neighbor tables and our design of hierarchical network addresses. Therefore, unlike the original ZigBee tree routing, nodes are not restricted to relay packets only to their parents or children. Also note that each node identifies its neighbors are alive based on periodical HELLO exchanges. Nodes compute routing paths based neighbor information and do not remember routing paths after relaying packets. In step 3 and step 4, a node drops a packet if it can not find a suitable neighbor to route the received packet. At this moment, the network is partitioned due to broken of neighbor nodes, signal temporarily unstable at last HELLO exchange, or other reasons. If a node does not receive HELLOs from a neighbor for a period of time, it removes that neighbor from its neighboring list and informs the coordinator.

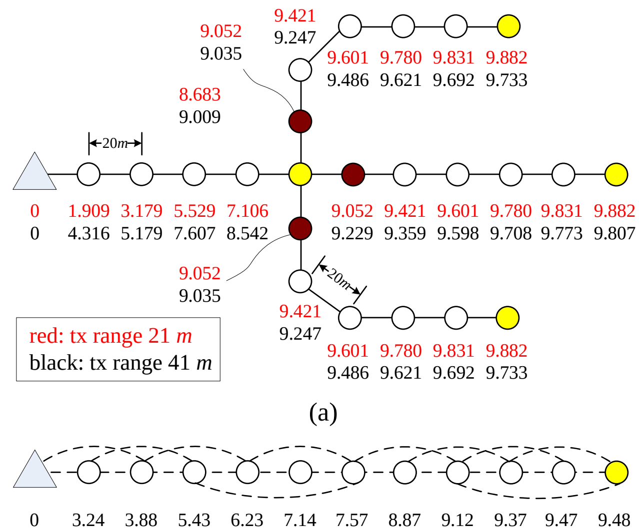
4 Performance Evaluations

We first simulate the node ranking algorithm in two LT networks as shown in Fig. 5, where adjacent nodes are evenly separated by a distance of $20\ m$. After 20 *Heartbeat* packets from the coordinator, we see that both networks will have in-order ranking. In particular, note that the linear path in Fig. 5(b) has irregular links between nodes.

Next, we simulate some LT-WSNs that are generated by a systematical method as follows. An $n_1 \times n_2$ rectangle region is simulated, on which k nodes are generated randomly to serve as bridge nodes. From these bridges, we conduct Delaunay triangulation. Using the bridge nearest to the upper-left corner of the rectangle as the root, we build a shortest path tree from the edges of the Delaunay triangulation to connect to the other $k-1$ bridges. The root is then connected to the coordinator at the left-top corner. Then we traverse the tree from the coordinator and generate nodes at every distance of d on each edge of the shortest path tree. Fig. 6(a) shows an example of a random generated Delaunay triangulation. A LT topology based on Fig. 6(a) is illustrated in Fig. 6(b).

Based on the above model, we generate networks in a $4.8\ km \times 3.2\ km$ field with adjacent nodes evenly separating

Figure 5 Some ranking results.



(a)

(b)

by a distance of $20\ m$. We set the maximum transmission ranges of nodes to be $81\ m$, i.e., the receiver can detect the sender's signal if the distance between sender and receiver is not longer than $81\ m$. The signal strength detected by a receiver degrades according to the square of distance between sender and receiver. As mentioned in Section 3.2, the ranking result may not be in-ordered. For example, in Fig. 6(b) the nodes marked in black small circles are not in-ordered ranked. Fig. 6(c) shows the network topology for region A (the dotted lines are the order of address assignment). We can see that the descendant of B_1 is not as planned since B_2 connects to B_1's parent cluster. After B_1 gets its address and broadcasts its beacon, B_2 will reconnect to B_1. Again, Fig. 6(d) shows the ranking result and the network topology of region B. In this case, nodes B_2, B_3 ,..., B_6, which are planned to be the descendants of B_1, are connected by B_1's parent cluster members. B_1 can not find a neighbor to form its cluster, resulting in the descendants of B_6 being disconnected from the network. B_6 can join this network after its ancestors B_2 to B_5 in the linear path joining to the cluster formed by B_1. Here, we call these temporarily disconnected nodes as *orphans*. Fig. 7 shows that before nodes' reconnecting procedure, nodes can still be assigned to the desired address with high probability ($\geq 94\%$) even when there are not-in-order ranked nodes. In average, less than 3% of the nodes will become orphans in our simulations. This result indicates that the network formation can connect all nodes with high probability before some nodes having to reconnect to new parents. Fig. 8 shows the percentages of 100% in-order ranking and no orphan before some nodes reconnecting to new parents. We can see that only few cases can achieve 100% in-ordered ranking. But, in most cases, all nodes can be connected to the network. Based on the above simulations, we can observe that to avoid the overhead of changing parents, the network manager should decrease node density near bridges to reduce the numbers of links in such areas. Fig. 8 also shows the averaged number of needed Heartbeats when ranking. There are about 1100 to 1700 nodes

Figure 6 (a) A random generated Delaunay triangulation. (b) A LT-WSN generated from the Delaunay triangulation. (c) The ranking result of the region A. (d) The ranking result of the region B.

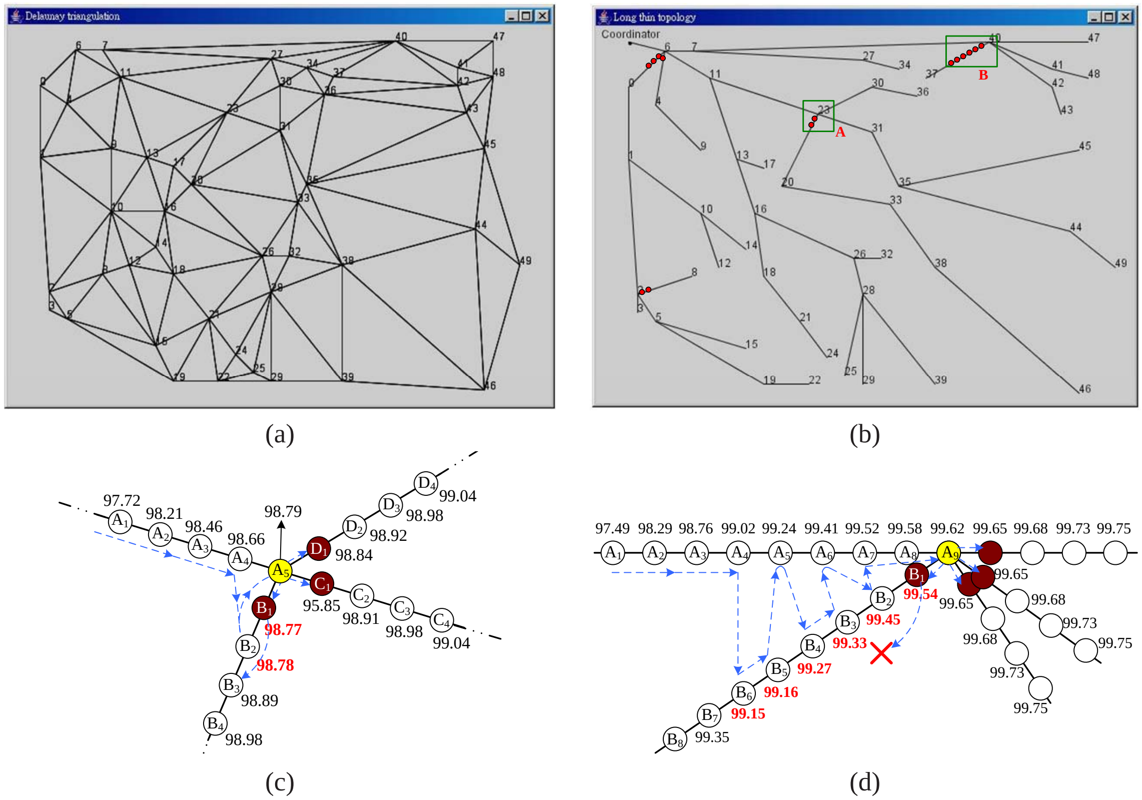


Figure 7 Simulation results of the numbers of not-in-order ranked and not-as-planned nodes without some nodes reconnecting to new parents.

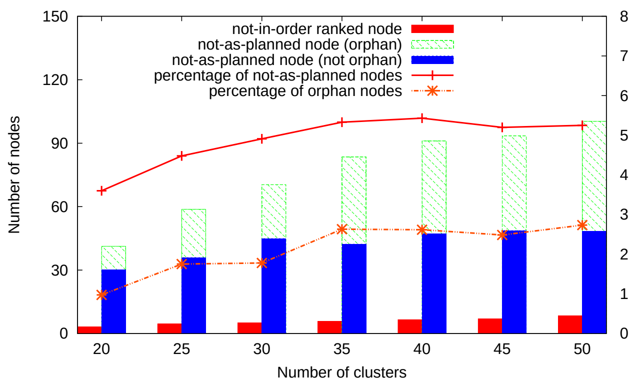
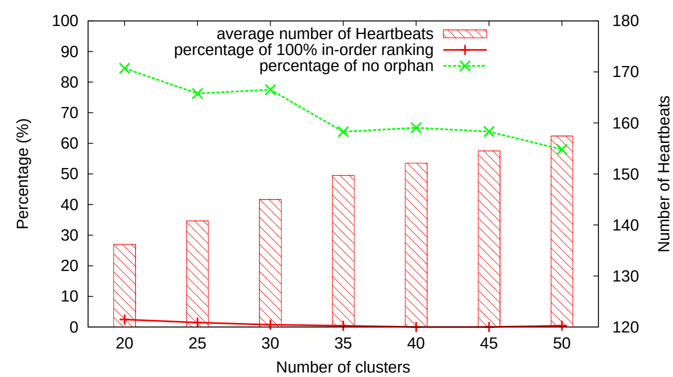


Figure 8 (1) The percentages of 100% in-order ranking and no-orphan cases without some nodes reconnecting to new parents and (2) averaged number of Heartbeats when ranking.



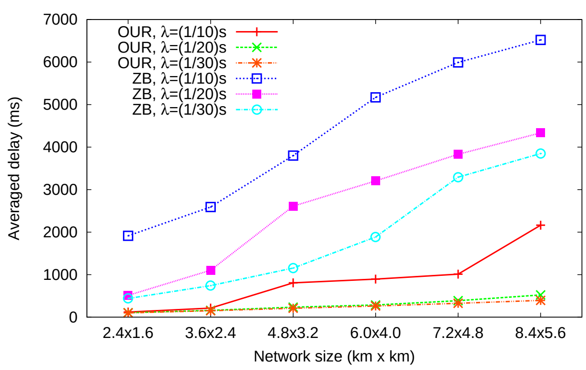
in our simulations. The coordinator has to broadcast about 140 to 160 heartbeats to finish ranking procedure. We can observe that when the network becomes larger, the overhead of broadcasting heartbeats does not increase much.

Next, we evaluate the proposed routing protocol. The results are from networks with 50 adjacent nodes evenly separating by a distance of $20\ m$. IEEE 802.15.4 unslotted CSMA/CA mechanism is implemented. Packets are generated from each node to random destinations with a poisson process at a rate λ. The buffer size of each node is 6.4 KB. When a node's buffer overflows, no further packets will

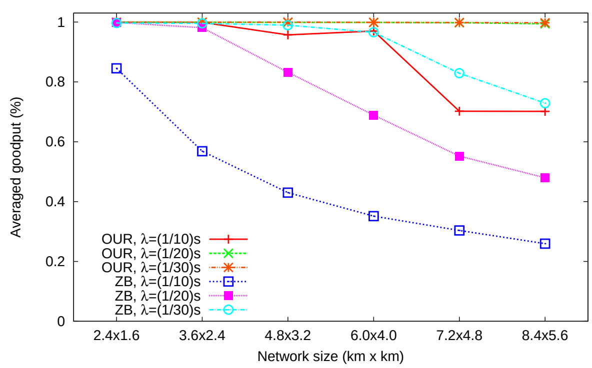
Table 1 Simulation parameters.

Parameter	Value
length of a frame's header and tail	18 Bytes
length of data payload	46 Bytes
bit rate	250k bps
symbol rate	62.5k symbols/s
aUnitBackoffPeriod	20 symbols
aCCATime	8 symbols
macMinBE	3
aMaxBE	5
macMaxCSMABackoffs	4
maximum number of retransmissions	3

Figure 9 Comparison on (a) delay and (b) goodput at various data rates.



(a)

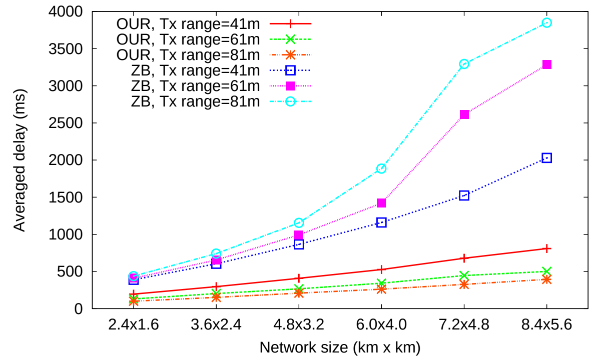


(b)

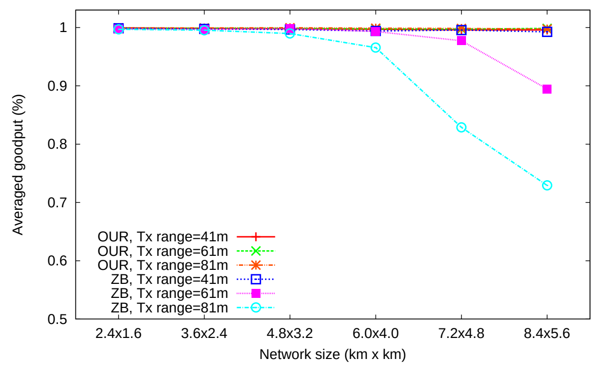
be accepted. We measure the *goodput* of the network, which is defined as the ratio of packets successfully received by the specified destinations. We compare the proposed routing scheme (denoted as OUR) with the ZigBee scheme (denoted as ZB). When using ZB, the node v that receives a packet will do the following procedures. If v is a normal node, it simply judges to relay the incoming packet to (C_v, N_v+1) or (C_v, N_v-1). For the case that if v is a cluster head (resp., bridge node), it relays the packet to the bridge node (resp., cluster head) of its parent (resp., the corresponding child) cluster. Some other parameters are list in Table 1.

We first set the transmission ranges of nodes to $81\ m$ and vary λ. Fig. 9 shows the result. Note that packets may be delayed or dropped due to buffer constraint. Our scheme outperforms ZB in averaged delay in all cases. In terms of the goodput, our scheme can almost reach 100% packet delivery when $\lambda = (1/20)\ s$ or $(1/30)\ s$, where ZB suffers from lower goodputs as the traffic load increases or the number of clusters increases. Fig. 10 shows another result when we vary the transmission ranges of nodes when $\lambda = (1/30)\ s$. It shows that when the transmission range increases, our scheme induces less delay. But this is not the case for ZB because it restricts packets to be transmitted hop-by-hop while ours allows taking shortcuts. The trend is similar when we look at the goodputs.

Figure 10 Comparison on (a) delay and (b) goodput at various transmission ranges.



(a)



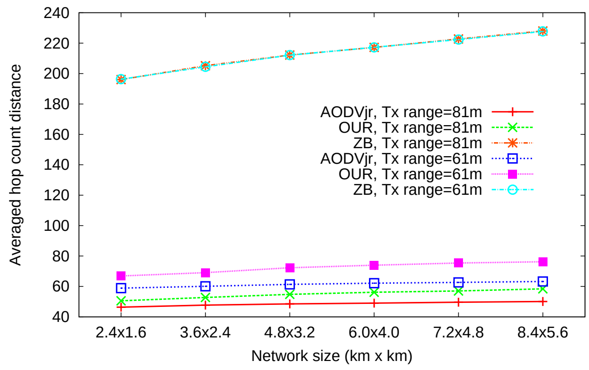
(b)

Next, we simulate the averaged hop count distances when routing packets. We further implement the mesh routing scheme in (ZigBee, 2006) (denoted as AODVjr). As shown in Fig. 11, compare to AODVjr, the proposed scheme only slightly increases the hop count distance. The AODVjr scheme can have the best performance since it establishes routing paths before transmissions. The proposed scheme uses only local information to route packets.

5 Conclusions

We have proposed hierarchical address assignment and routing schemes for ZigBee-based LT WSNs. The proposed address assignment scheme divides nodes into several clusters and then assigns each node a cluster ID and a node ID as its network address. With such a hierarchical structure, routing can be easily done based on addresses of nodes and the spaces required for the network addresses can be significantly reduced. We also show how to allow nodes to

Figure 11 Comparison on averaged hop count distance at various transmission ranges.



utilize shortcuts. With our design, not only network addresses can be efficiently utilized, but also the network scale can be enlarged to cover wider areas without suffering from address shortage. We verify our schemes by simulation programs. It deserves to further discuss address assignment and routing schemes for more complicated topologies such as meshes that are connected by “long-thin” links.

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