M. S. Thesis

A Study on Energy-efficient Self-healing in Wireless Sensor Networks

무선 센서 네트워크에서 에너지 효율적인 자가 치료 연구

by

Dong-Kwan Kim

August 2015

School of Electrical Engineering and Computer Science
College of Engineering
Seoul National University

Abstract

One of key issues in the construction of wireless sensor network (WSN) is how efficiently sensor nodes re-subscribe to the network after networking failure. ZigBee has been considered as an attractive solution for the construction of cluster-tree structured WSNs due to its low-power and low-complexity features. However, it may be able to re-subscribes to the network through network rejoining which may require for large signaling overhead and time delay.

In this thesis, we consider the design of a cluster-wise self-healing (CS) in a beacon-enabled cluster-tree structured WSN. When a router experience networking failure from its parent node, the proposed CS makes it maintain synchronization with its child nodes, preventing from orphan propagation to its child nodes. Meanwhile, it makes only the orphaned router initiate the re-subscription to the network on behalf of its child nodes. Thus, the proposed CS allows the network re-subscription through one re-subscription process of the orphaned cluster head, significantly reducing the recovery time and energy consumption for the recovery as well. We also design a backup link-aided self-healing (BL) where nodes select a parent node for the network subscription and also a back-up parent node for network re-subscription. The proposed BL can reduce the recovery time since it can minimizes the process for the selection of a new parent node and associated message exchanges for network re-subscription. Computer simulation and experimental results show that the proposed schemes can significantly reduce the energy consumption, recovery time and signaling overhead for network re-subscription.

Keywords: Wireless sensor network, self-healing, cluster-wise, backup link

Student number: 2013-20753

Contents

List of Figures

List of Tables

1. Introduction

Rapid development of wireless communication technologies strongly affects human habits and behaviors. Recently, the phrase “The Internet of Things” (IoT), which means connecting everything everywhere in real-time, has appeared as one of key interests in future society [1]. Wireless sensor networks (WSNs), which can make physical connection of things, are one of major elements for IoT services [2]-[5]. However, they may not provide desired connectivity because of channel impairments and limited battery operation [6]-[12]. It is of great concern how fast and efficiently orphaned senor nodes re-subscribe to the network without large processing complexity and power consumption as well.

IEEE 802.15.4 is a standardized physical (PHY) layer and Medium Access Control (MAC) layer protocol applicable to low-power WSNs [13]. IEEE 802.15.4 can provide energy-saving network operation with the use of a beacon-enable mode, where two types of nodes, referred to router and end device, make network communications. The router periodically broadcasts a beacon frame, enabling networked nodes to make communications in a synchronized mode and also new sensor nodes to subscribe to the network. ZigBee based on IEEE 802.15.4 supports the construction of a cluster-tree structured WSN with multi-hop routing [14]. It adds one more node type; router which can subscribe to the coordinator and expand the network. A distributed address allocation mechanism enables network in a distributed manner.

ZigBee can make orphaned nodes re-subscribe to the network by means of self-healing. However, it may not provide desirable performance mainly due to the two main problems; orphan propagation and neighbor scan. When a router node experiences networking failure, its child nodes also experience networking failure, referred to orphan propagation. Thus, all the child nodes of an orphaned router should also initiate network re-subscription, which may require for large processing complexity and power consumption as well. To this end, they need to search for a new parent node by means of neighbor scan, which may also require for large energy consumption and delay as well.

A number of self-healing schemes have been proposed for cluster-tree structured WSNs to alleviate these problems [6]-[12]. A self-healing algorithm, referred to efficient self-healing process (ESP), makes an orphaned router re-subscribe to the network with its child nodes [6]. However, it makes the child nodes wait until their router re-subscribe to the network, keeping them being disconnected from the network for a while. Besides, it may require for large message exchanges for address allocation to the child nodes after the subscription. An improved ESP (IESP) can alleviate the first problem of ESP, by letting the orphaned router makes its child nodes re-subscribe to the network by searching for a new parent node in lieu of the orphaned router when the orphaned router fails to re-subscribe to the network [7]. Once a child node successfully re-subscribes to the network, it changes the parent/child role with the orphaned router. However, it does not consider the orphan propagation, the address allocation and energy consumption for the neighbor scan. An enhanced self-configuration (EC) can prevent the orphan propagation by broadcasting a freeze messages to inform that the orphaned router is performing the network re-subscription [8]. However, it also does not consider address allocation and neighbor scan as well.

In this thesis, we design a cluster-wise self-healing (CS) in a beacon-enabled cluster-tree structured WSN. When a router is disconnected from the network, the proposed CS can prevent the orphan propagation by making the orphaned router maintain synchronization with its child nodes. It makes only the orphaned router search for a new parent node and re-subscribe to the network on behalf of its child nodes. It can significantly reduce message exchanges, waste of energy in addition to time delay. The orphaned node stops the neighbor scan when it finds a new parent node, reducing the recovery time and the energy consumption of the neighbor scan. We also design a self-healing scheme, referred to backup link aided self-healing (BL), where nodes select a parent node for the network subscription and also a back-up parent node for network re-subscription. The proposed BL can reduce the recovery time since it can minimizes the time for the selection of a new parent node and associated message exchanges for network re-subscription.

The rest of this thesis is organized as follows. Section II describes the WSN model in consideration. Section III and IV describe previous works and proposed schemes for self-healing, respectively. Section V evaluates the performance of the proposed schemes by computer simulation and experiments. Finally, conclusions are given in Section VI.

2. System model

As illustrated in Fig. 1, we consider a ZigBee/IEEE 802.15.4 beacon-enabled cluster-tree structured network comprising a network coordinator, routers and end devices [13]-[14]. The network coordinator and routers as parent nodes can have routers and end devices as child nodes. A parent node is a cluster head of the clusters comprising it and its child nodes. The clusters are connected as a tree structure, referred to cluster-tree structure.

We assume that each cluster operates using its own periodic super-frame structure as illustrated in Fig. 1. The cluster head (i.e., parent node) synchronizes with its child nodes by periodically broadcasting beacon frames. Receiving a beacon frame, the child nodes can make communications with the cluster head by means of slotted CSMA/CA during the super-frame duration and enter a power-saving idle mode during the inactive period. The beacon interval and the super-frame duration are determined as, respectively,

$$t_{BI} = \left(aBaseSuperframeDuration \cdot 2^{BO} \right) t_{\mathrm{s}}, \quad \text{for } 0 \le BO \le 14 \tag{1}$$

$$t_{SD} = \left(aBaseSuperframeDuration \cdot 2^{SO} \right) t_{\mathrm{s}}, \quad \text{for } 0 \le SO \le BO \tag{2}$$

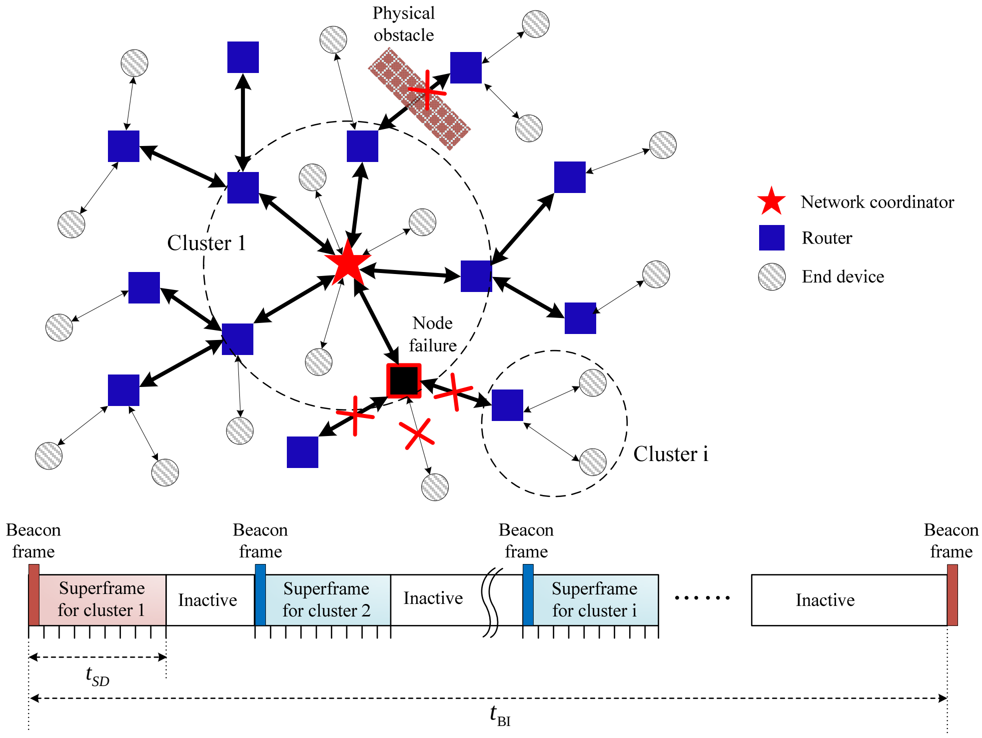

Figure 1. An example of ZigBee/IEEE 802.15.4 cluster-tree structured network.

where BO is the beacon order, SO is the super-frame order and t_s is the symbol time. The network can utilize one of 16 non-overlapped channels in the 2.4 GHz unlicensed spectrum band, whose center frequency is determined by $f_k = 2405 + 5(k-11)$, where k denotes the channel index represented as $k = 11,\ 12, \ldots,\ 26$.

As illustrates in Fig. 2, we consider the distributed address allocation mechanism (DAAM) to construct a hierarchical addressing tree structure based on three addressing parameters [14]; the maximum number of child nodes, Cm, the maximum number of child routers, Rm, and the maximum network depth, Lm, which are predetermined and shared by all the nodes. It allows each router with a network depth of smaller than Lm (including the network coordinator) to uniquely have its own Cm addresses for the address allocation of its child nodes (i.e., Rm addresses for child routers and ($Cm - Rm$) address for child end devices). A router with network depth D and address A_{parent} determines the address of its l_R-th child router ($1 \le l_R \le Rm$) and its l_{ED}-th child end device ($1 \le l_{ED} \le Cm - Rm$) in an ascending order as, respectively,

$$A_{n_R} = A_{parent} + (l_R - 1)Cskip(D) + 1 \tag{3}$$

$$A_{n_{ED}} = A_{parent} + RmCskip(D) + l_{ED} \tag{4}$$

where

$$Cskip(D) = \begin{cases} \max\left\{0,\ 1 + Cm \times \left(Lm - D - 1\right)\right\}, & \text{for } Rm = 1 \\ \max\left\{0,\ \dfrac{Cm \times Rm^{Lm-D-1} + Rm - Cm - 1}{Rm - 1}\right\}, & \text{otherwise.} \end{cases} \tag{5}$$

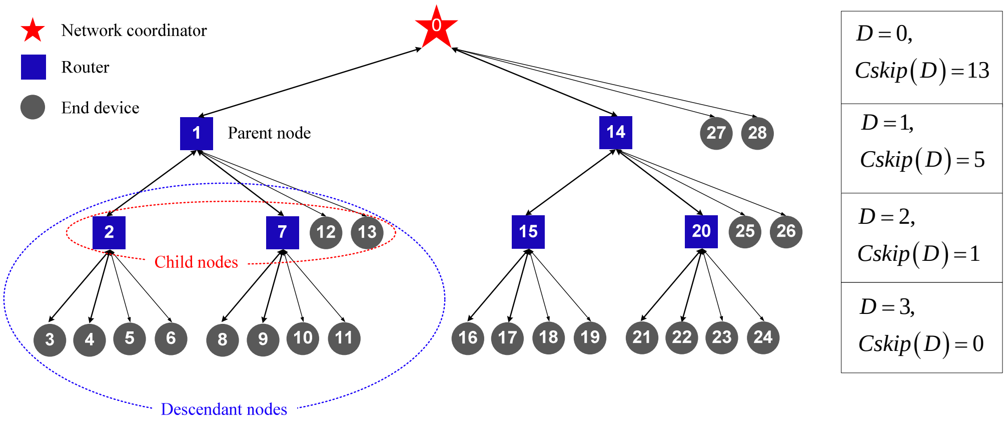

Figure 2. An example of DAAM addressing tree with Cm=4, Rm=2 and Lm=3.

DAAM enables the network to use a hierarchical tree routing which provides a routing path based on address information [14]. When a router receives a packet, it can identify whether the packet destination node belongs to its sub-tree or not. If the destination node belongs to its descendant nodes, the router relays the packet to its child node whose sub-tree includes the destination node. Otherwise, it sends the packet to its parent node. The hierarchical tree routing algorithm can be summarized as

$$A_{next} = \begin{cases} \max\{A_{child} \mid A_{child} \le A_{dest}\}; \text{ if } A_{child} \le A_{dest} < A_{current} + Cskip(D-1) \\ A_{parent} \qquad ; \text{ otherwise} \end{cases} \tag{6}$$

where $A_{current}$ is the address of the router holding the packet, A_{dest} is the destination node address of the packet and A_{child} is the address of the child node.

3. Previous works

3.1. Self-healing in ZigBee

All child nodes have to synchronize with their parent node by receiving a beacon frame. If a child node fails to receive a beacon frame transmitted from its parent node for $aMaxLostBeacons$ consecutive times, it becomes an orphaned node and needs to initiate the network re-subscription. Re-subscription to the network can be achieved through neighbor scan, parent selection and associated message exchanges for address reallocation.

As illustrated in Fig. 3, orphaned node n scans the channel S_{ch} to receive a beacon frame from a neighboring router R_n and makes a potential parent set $\mathbf{P}_n$ comprising potential parent nodes which can allocate a new address to orphaned node n . S_{ch} corresponds to element k_i ($i = 1, 2, \cdots, |\mathbf{K}|$) in the available channel set $\mathbf{K}$ specified by network administrator and the scan time T_{scan} is larger than t_{BI} . Searching for a new parent node through neighbor scan may require for large time delay and energy consumption proportional to the number of available channels [15].

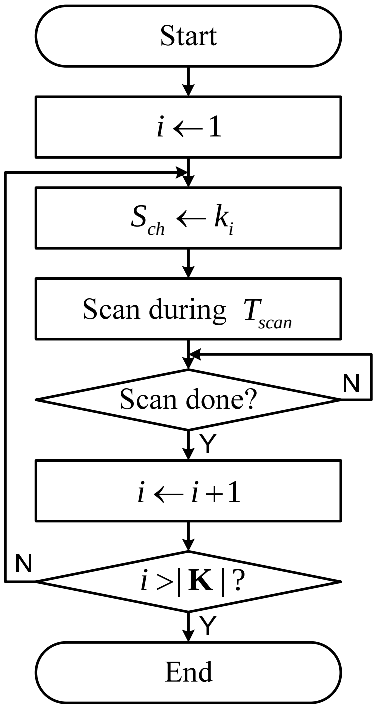

Figure 3. Flow chart of ZigBee neighbor scan.

If orphaned node n collects $\mathbf{P}_n$ by performing the neighbor scan, it selects a potential parent node P_n in $\mathbf{P}_n$ with the minimum network depth. It sends an association request message to P_n for address allocation. If P_n can allocate an address to orphaned node n, it sends an association response message including a new address. If not, it sends an association denial message. Orphaned node n repeats this process until $\mathbf{P}_n = \phi$.

An orphaned router with child nodes does not broadcast a beacon frame during the network re-subscription, making it impossible to and maintain super-frame operation with its child nodes. As a consequence, the child nodes of an orphaned router are also disconnected from the network as illustrated in Fig. 4. They have to initiate the re-subscription to the network, which may require for significant signaling overhead and energy consumption in addition to time delay [8]-[9].

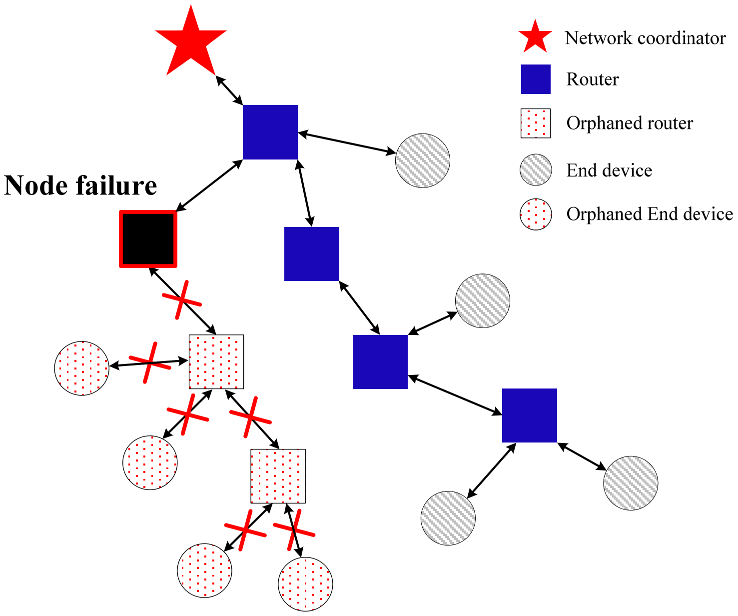

Figure 4. An example of orphan propagation.

3.2. Efficient self-healing process (ESP)

Although ESP does neither consider a beacon-enabled mode nor prevent the orphan propagation, it provides network re-subscription based on DAAM [6]. ESP makes an orphaned router re-subscribe to the network with its descendant nodes. When a router experiences networking failure, it initiates the same neighbor scan as ZigBee, causing the large time delay and energy consumption for searching a new parent node. After performing the neighbor scan, it selects a potential parent node P_n in a potential parent set $\mathbf{P}_n$ with the minimum depth in order to reallocate new addresses to its descendant nodes after the network re-subscription. However, when the orphaned router selects P_n with the depth larger than the previous parent node, it disassociates the descendant nodes whose depth is the maximum network depth Lm by sending disassociation message to them as illustrated in Fig. 5, causing the disassociated descendant nodes to individually initiate the network re-subscription. ESP also does not consider the case of $\mathbf{P}_n = \phi$, leading the orphaned router to re-perform neighbor scan continuously and its descendant nodes to keep them being disconnected from the network. In this way, it may also require for large time delay and energy consumption for the network re-subscription. If the orphaned router successfully re-subscribe to the network with its descendant nodes, it sends an address reallocation message to each of them, also causing significant signaling overhead proportional to the number of descendant nodes.

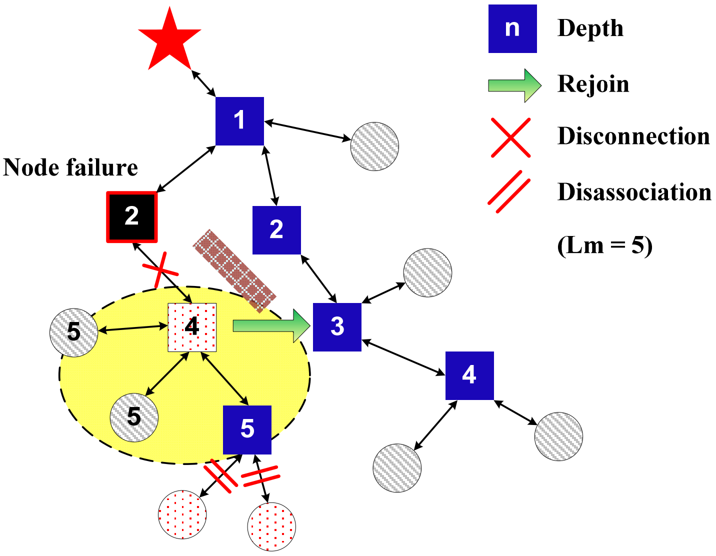

Figure 5. An example of self-healing by ESP.

4. Proposed self-healing

4.1. Energy-efficient neighbor scan

As illustrated in Fig. 6, if an orphaned node n, which performs the proposed energy-efficient neighbor scan, receives a beacon frame transmitted from a neighboring router R_n, it immediately selects a potential parent node P_n. If an orphaned node n is a router which has child nodes, it chooses P_n which can allocate its address and its descendant nodes considering the network depth of the previous parent node. Otherwise, node n chooses P_n which can allocate only its address. If it selects R_n as P_n, it stops to receive a beacon frame immediately. If not, it pauses to receive a beacon frame during T_{pause} equal to the super-frame duration of R_n. In this way, the orphaned node can efficiently reduce the energy consumption and time loss for neighbor scan as well.

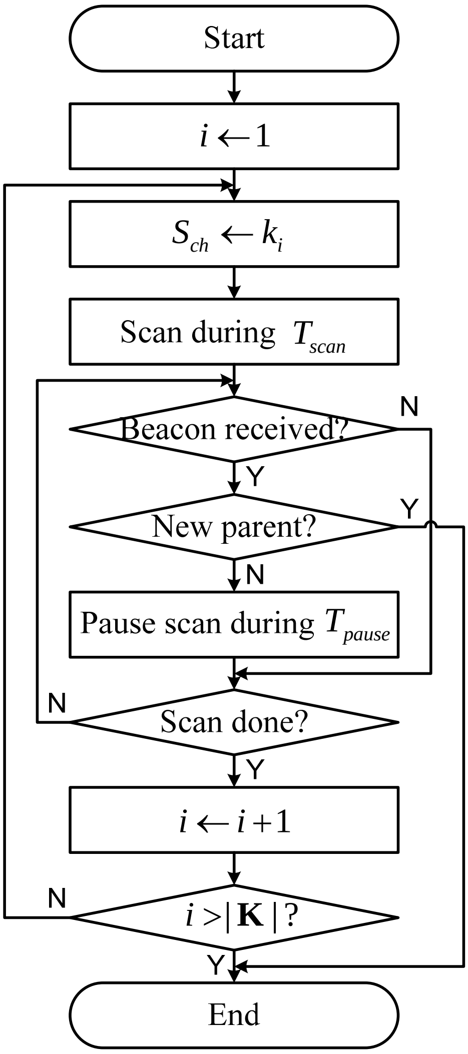

Figure 6. Flow chart of the proposed energy-efficient neighbor scan.

4.2. Cluster-wise self-healing (CS)

When a router n with child nodes is disconnected from a network, the proposed CS prevents orphan propagation by making the orphaned router broadcast a beacon frame periodically and maintain its super-frame operation during re-subscription to the network. If router n finds a potential parent node P_n whose network depth is not larger than that of the previous parent node through neighbor scan, it sends an association request message to P_n on behalf of its all descendant nodes as illustrated in Fig. 7. If not, it disassociates its child routers by transmitting a disassociation message or a beacon frame indicating the increment of the network depth, because it cannot hold descendant nodes whose network depth is the maximum network depth Lm considering address reallocation. If the child routers cannot receive a disassociation message from the their parent node because of data transaction fail due to the contention or collision problem, they can be disassociated from their parent node by receiving a beacon frame and recognizing the increment of the network depth of their parent node. The disassociated child routers also perform the neighbor scan and exchange associated messages with P_n in a cluster-wise manner as illustrated in Fig. 8.

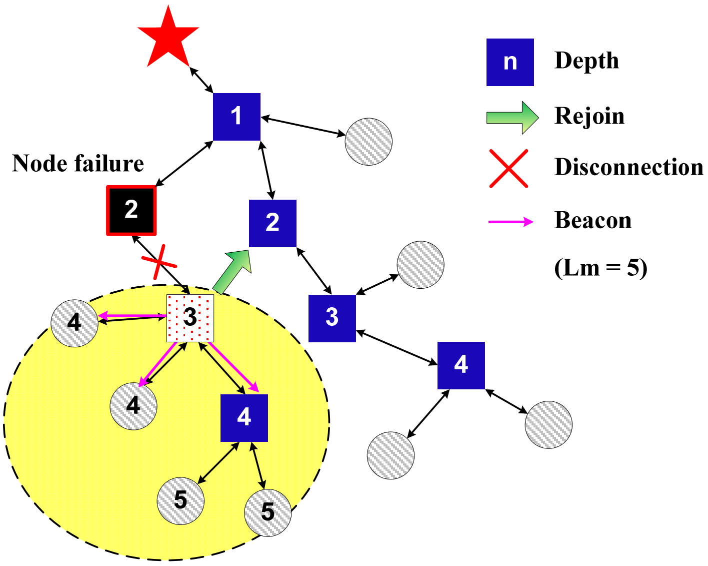

Figure 7. An example of cluster-wise self-healing with descendant nodes.

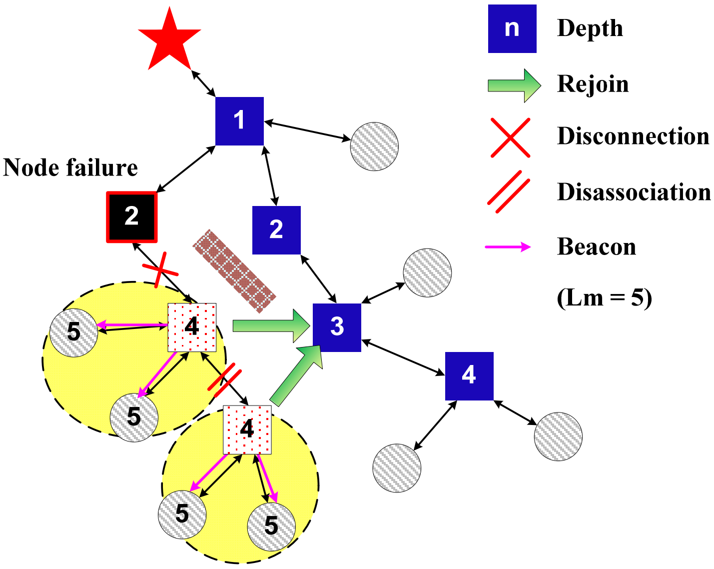

Figure 8. An example of cluster-wise self-healing with child end devices.

If router n successfully re-subscribe to a potential parent node P_n by receiving an association response message including a new address, it updates its address and the network depth. It sends out the previous address and the network depth in the beacon frame to inform its network re-subscription. If the association request is denied, router n re-selects a parent candidate node in $\mathbf{P}_n$ with the minimum network depth and repeats the network depth comparison between the previous parent node and the parent candidate node. If $\mathbf{P}_n = \phi$, router n seeks for P_n through the neighbor scan without its child nodes by stopping its synchronization for its child nodes.

If a child node recognizes the network re-subscription of its parent node by receiving a beacon frame, it updates its address in order to maintain a cluster-tree structure with DAAM. It can autonomously update its address using the network depth and address information in the beacon frame without the exchange of additional messages, as illustrated in Fig. 9. If the network depth is lower than the maximum network depth Lm and the updated network depth of parent node $D_p{}'$ is unchanged (i.e., $D_p{}'$ is the same as the previous network depth of parent node D_p), the child node updates its address A as

$$A \leftarrow A + |\Delta_p| \tag{7}$$

where Δ_p is the address difference between the updated address of parent node $A_p{}'$

and the previous address of parent node A_p. Otherwise, if it is a router, it calculates its address allocation index l_R as

$$l_R \leftarrow (A - A_p) / Cskip(D_p) + 1 \tag{8}$$

and updates its address A as

$$A \leftarrow A_p{}' + (l_R - 1) \times Cskip(D_p{}') + 1 \quad . \tag{9}$$

If it is an end device, it calculates its address allocation index l_{ED} as

$$l_{ED} \leftarrow (A - A_p) - Rm \times Cskip(D_p) \tag{10}$$

and updates its address A as

$$A \leftarrow A_p{}' + Rm \times Cskip(D_p{}') + l_{ED} \, . \tag{11}$$

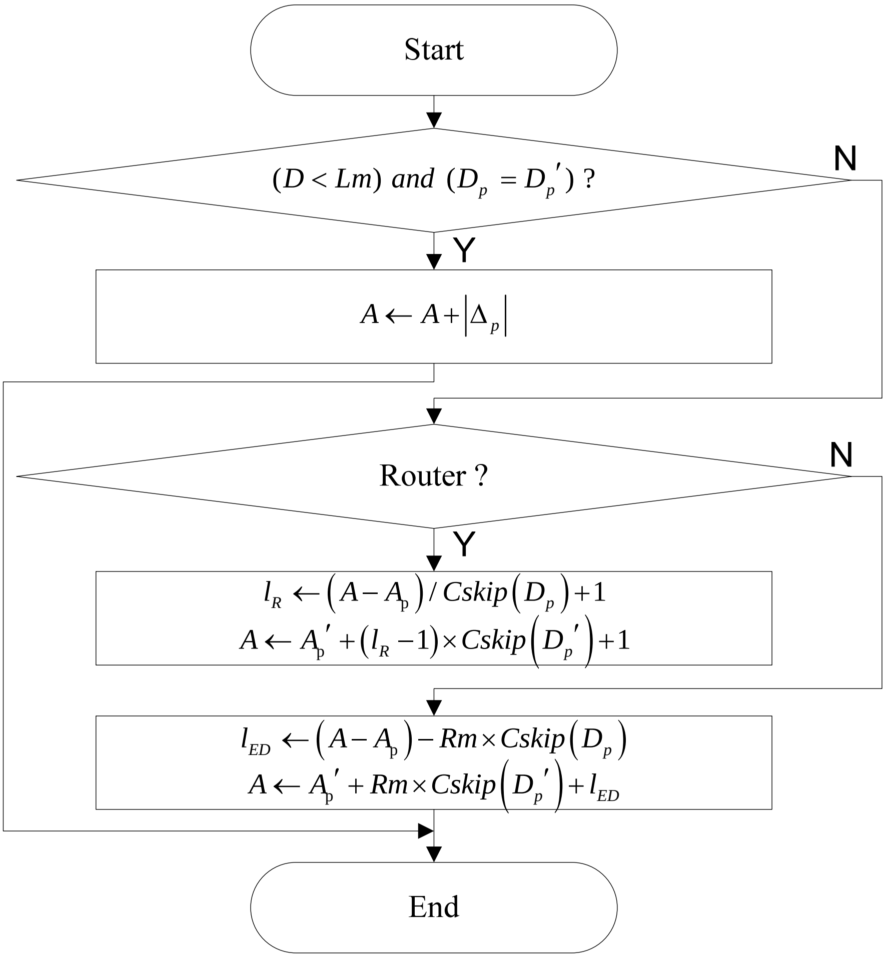

Figure 9. Address update of child nodes.

4.3. Backup link aided self-healing (BL)

A child node can subscribe to a back-up parent node for the network re-subscription. If the original link is disconnected, the child node replaces the new parent node with the back-up parent node, as illustrated in Fig. 10.

If an orphaned node has a back-up link, it can search for a beacon frame broadcasted from its back-up parent node. Searching for the back-up parent node is faster than the neighbor scan, because the orphaned node already knows the operation channel of its back-up parent node, whereas it needs to sequentially search for all available channels through the neighbor scan. If the orphaned node finds the back-up parent node, it transmits an association request message that inform its back-up parent node as the new parent node. If not, it conducts the neighbor scan to start the proposed CS.

A child node does not make synchronization with its back-up parent node in normal condition to save energy waste. However, it can make synchronization with its back-up parent node at a very long period for ease of search after a network failure. If it does not receive a beacon frame from its back-up parent node for *aMaxLostBeacons* consecutive times, it tries to re-subscribe to a new back-up parent node.

In the same manner as the proposed CS, if an orphaned node is router, it also makes a decision for maintaining either its descendant nodes or its child nodes according to the comparison of network depth between the previous parent node and the back-up parent node. The child nodes of an orphaned router also update their address through the algorithm illustrated in Fig.9 using the network depth and address information in a beacon frame broadcasted from the parent node without the exchange of additional messages.

After successfully replacing the new parent node with the back-up parent node, the orphaned node makes a new back-up parent node for future network re-subscription.

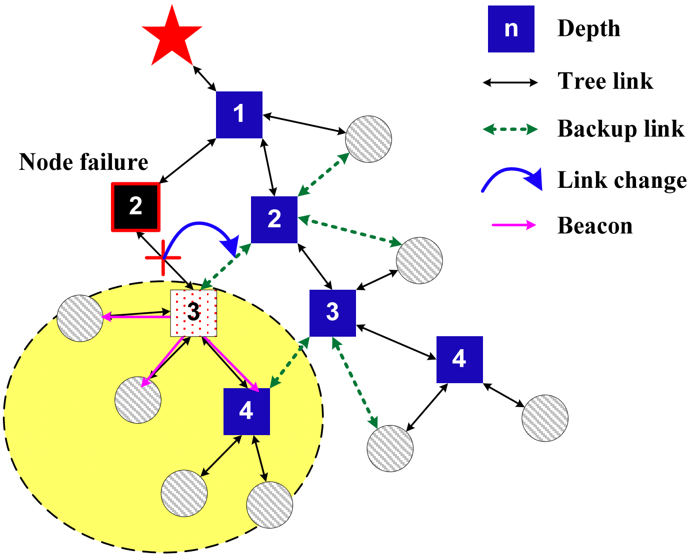

Figure 10. An example of backup link aided self-healing.

4.4. Messages for the proposed self-healing

The messages used for the proposed self-healing are summarized in Table 1. The proposed CS additionally uses a network address of 16-bit. After re-subscribing to the network with its child nodes, an orphaned router informs its child nodes that it performed the network re-subscription and changed its address by indicating the previous 16-bit address in the beacon payload. The proposed BL additionally uses a 1-bit in payload of association request message to inform its back-up parent node as the new parent node.

Table 1. Messages for the proposed self-healing

Message	Type	Additional information	Increment bit size
Beacon	IEEE 802.15.4 MAC frame [13]	Unchanged address before performing the network re-subscription	16 bits (temporarily added)
Association request	IEEE 802.15.4 MAC command [13]	Indication for link transition	1 bit
Association reponse	IEEE 802.15.4 MAC command [13]	-	-
Disassociation notification	IEEE 802.15.4 MAC command [13]	-	-

5. Performance evaluation

The performance of the proposed schemes is evaluated by computer simulation and experiment. For the computer simulation, we construct a cluster-tree structured network, where nodes are randomly distributed in a squared area of $\left(100\times100\right)m^2$. The simulation parameters are summarized in Table 2, which considers the operation of ZigBee with a cluster-tree structured network using the DAAM. The channel is modeled using an indoor path loss model in [13]. It is also assumed that the transmit power is -5dBm and the carrier sensing threshold for CSMA/CA is -85dBm. Hidden node collision may occur when the channel sensing fails to detect ongoing packet transmission. It is also assumed that the network coordinator randomly selects an operating channel among 16 available channels, each nodes can discovers a neighboring router by scanning all the channels, the beacon order is 8 (i.e., the beacon interval is 3.93sec) and the maximum network depth is 3. Spatially non-overlapped super-frame is allocated to the coordinator and many routers in the network by using multiple channels. We perform the computer simulation according to the total number of nodes to examine the results related with network size. The network coordinator is deployed in the center, and in order to reduce the influence of a fixed topology, the routers are newly selected in each iteration of computer simulation for connecting all nodes randomly deployed in the network. End devices are connected to a vicinity router or the coordinator. We assume that ESP uses beacon-enabled mode operation and makes an orphaned router periodically broadcast a beacon frame to prevent orphan propagation during the network re-subscription for the comparison of performance evaluation.

Table 2. Simulation parameters

Parameters	Values
Beacon order (BO)	8
Super-frame order (SO)	2
Number of available channels	16
Maximum number of child nodes (Cm)	64
Maximum number of child routers (Rm)	24
Maximum number of network depth (Lm)	3
Transmit power	-5 dBm
Data rate	250 kbps (IEEE 802.15.4 PHY)
Number of nodes	100 ~ 1000
Deployment area	100 m * 100 m

- Orphaned scenario

Considering the contribution of the proposed schemes is related with an orphaned router, it is assumed that a link between a router and its parent node is disconnected at the 10-th beacon interval after the network configuration.

- Evaluation parameters

The signaling overhead is defined by the number of exchanged messages for re-subscription to the network. The energy consumption is defined by the total amount of energy used by descendant nodes of the initial orphaned router during re-subscription to the network. The recovery time is defined by the time between the beginning of disconnection from the network and the end of re-subscription to the network.

Fig. 11 depicts the signaling overhead for the network re-subscription according to the number of nodes. It can be seen that the signaling of ZigBee increases rapidly as network size increases. It is mainly because child nodes of the orphaned router generate the messages for the network re-subscription.

However, the proposed CS requires for the low signaling, which is slightly increased as the network size increases, compared with ZigBee. It is mainly because the proposed CS makes only the orphaned router try to exchange associated messages as the representative of its child nodes.

It can also be seen that the signaling of ESP increases steadily as network size. Although, ESP tries to make only the orphaned router re-subscribe to the network, the number of messages for address reallocation to each descendant nodes is increases as network size increases. Besides, the disassociated descendant nodes with the maximum depth also increase as network size.

It can also be seen that the signaling of the proposed BL, which includes the signaling for making a new back-up parent node after network re-subscription, is slightly increased as much as it compared with the proposed CS.

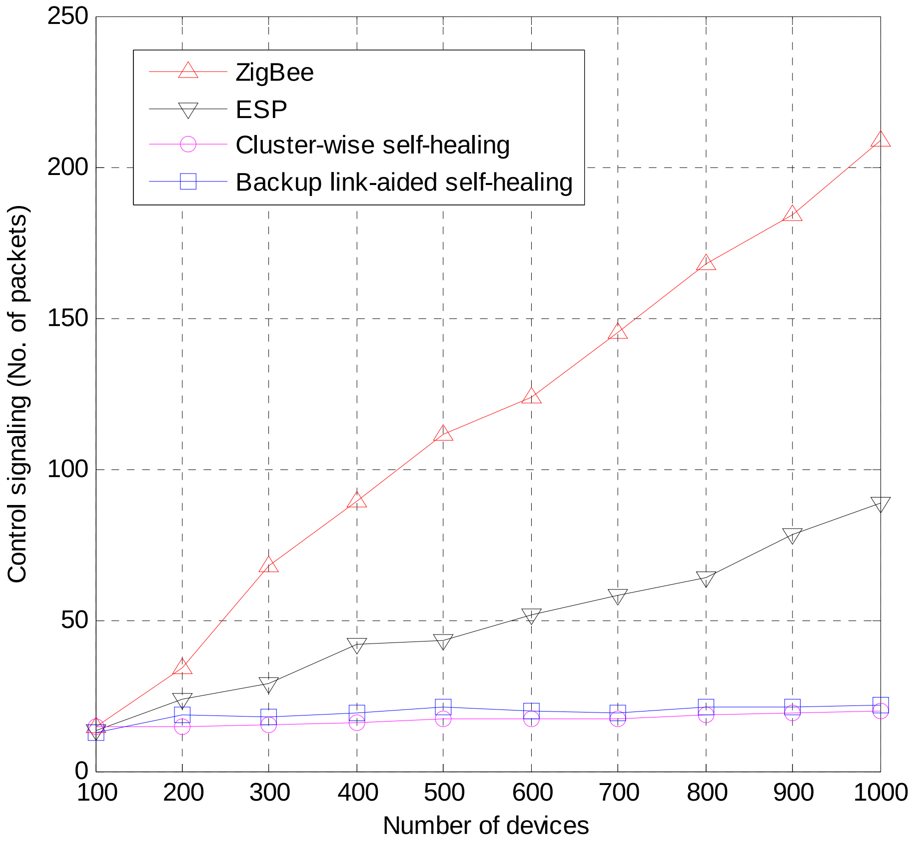

Figure 11. Signaling overhead for the network re-subscription.

Fig. 12 depicts the energy consumption for the network re-subscription according to the number of nodes. It can be seen that the proposed CS remarkably reduces the energy consumption as the network size increases, compared with ZigBee. Similarly as the evaluation of signaling, it is mainly because the proposed CS makes only the orphaned routers need to re-subscribe to a new parent node in a cluster-wise manner while all descendant nodes of it need to initiate the network re-subscription in the case of ZigBee. Besides, the proposed neighbor scan used with the proposed CS can reduce the waste of energy as well.

It can also be seen that the energy consumption of ESP is higher than the proposed CS and BL because of the inefficient neighbor scan and the disassociated descendant nodes with the maximum depth.

It can also be seen that the energy consumption of the proposed BL is larger than the proposed CS due to the energy for making a new back-up parent node after the network re-subscription.

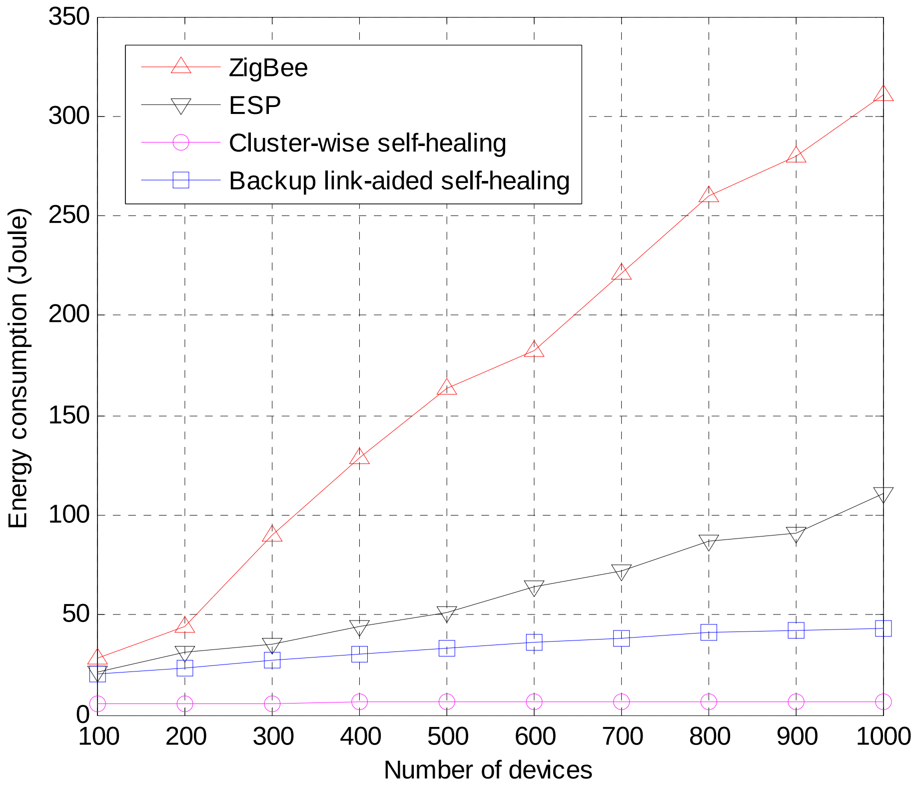

Figure 12. Energy consumption for the network re-subscription.

Fig. 13 depicts the time for the network re-subscription according to the number of nodes. It can be seen that the network re-subscribing time of ZigBee increases steadily as network size increases. It is mainly because all descendant nodes of the orphaned router need to initiate the network re-subscription, causing the re-subscribing competition of the signaling. The neighbor scan of ZigBee also delays the time for the network re-subscription.

However, it can also be seen that the proposed CS needs the low network re-subscribing time almost indifferently from the network size. It is mainly because of conducting the proposed neighbor scan, making the orphan stop listening when it finds a potential parent node to re-subscribe. Besides, the proposed CS reduces the number of orphaned router which is trying to re-subscribe to the network.

It can also be seen that the re-subscribing time of ESP is a little smaller than ZigBee because of only the orphaned router trying to re-subscribe to the network on behalf of its child nodes. However, ESP performs inefficient neighbor scan same as ZigBee, causing always certain amount of time delay proportional to the number of available channels.

It can also be seen that the proposed BL reduces the re-subscribing time more than the proposed CS by replacing the new parent node with the back-up parent node. However, it can also be seen that the re-subscribing time of the proposed BL is similar to the proposed CS as the network size increases. It is mainly because it may be harder for all nodes to have back-up parent node as the network size increases due to the limited addressing space, causing the proposed BL to conduct the same network re-subscription of the proposed CS.

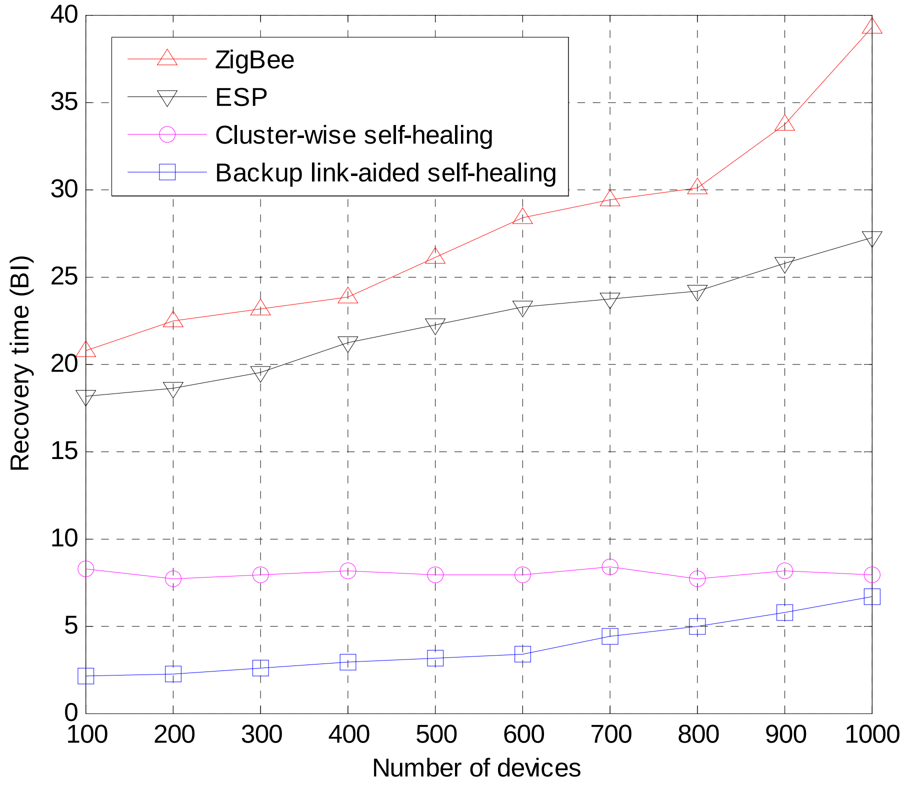

Figure 13. Time for the network re-subscription.

For the experimental evaluation, we implement ZigBee and CS with the proposed neighbor scan onto TelosB mote sensor nodes [16] running on TinyOS 2.1.1 operating system [17]. The TelosB Mote sensor employs a Chipcon CC2420 radio transceiver that can support a transmission rate of up to 250 Kbps over the 2.4 GHz ISM band, while being compliant to the IEEE 802.15.4 PHY-layer [18]. We use TKN 15.4, an IEEE 802.15.4 MAC protocol for TinyOS 2.x with open source code, for the modification of the MAC protocol implemented in the TinyOS software [19]. The experimental environment is summarized in Table 3, which considers the operation of ZigBee with a cluster-tree structured network using the DAAM. As illustrated in Fig. 14, we construct a 3-hop cluster-tree topology in the office by using 11 TelosB sensor motes. The network coordinator randomly selects an operating channel among 16 available channels and non-overlapped super-frame is allocated to the coordinator and routers in the network. We use packet sniffer [20] which employs a Chipcon CC2420 radio transceiver to monitor ZigBee packet transmitted from the sensor motes and get experimental results for the network re-subscription. Memory size for the implementation of ZigBee and CS with the proposed neighbor scan is represented in Table 4.

- Orphaned scenario

Considering the contribution of the proposed schemes is related with an orphaned router, we remove the battery of no. 1 router in experiment (a), making its child nodes (i.e., no. 2 and no. 3 router) disconnect from the network and evaluate time and signaling overhead for the network re-subscription. We also remove the battery of no. 8 router in experiment (b) in order to compare experimental results according to the number of child nodes of the orphaned router.

Table 3. Experimental parameters

Parameters	Values
Beacon order (BO)	7
Super-frame order (SO)	3
Number of available channels	16
Maximum number of child nodes (Cm)	64
Maximum number of child routers (Rm)	4
Maximum number of network depth (Lm)	3
Transmit power	-15 dBm
Data rate	250 kbps (IEEE 802.15.4 PHY)
Number of nodes	1 (coordinator), 10 (router and end devices)
Deployment area	6 m * 5 m

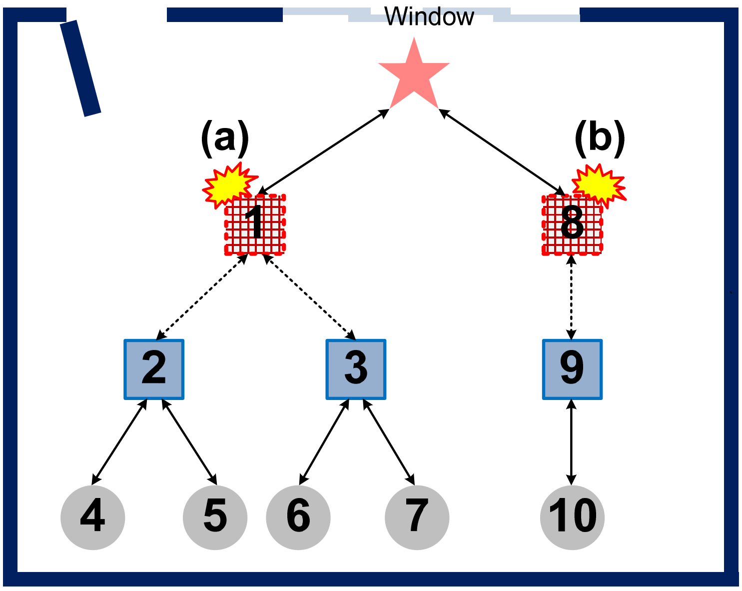

Figure 14. Network topologies for performance evaluations.

Table 4. Memory overhead on ROM and RAM

	ROM (program)	RAM (data)
ZigBee	45654 bytes	2529 bytes
Proposed	+2752 bytes (6.02%)	+18 bytes (0.07%)

Table 5 summarizes the time and the signaling overhead for the network re-subscription. It can be seen that the proposed scheme decreases the network re-subscribing time compared with ZigBee by conducting the proposed neighbor scan, making the orphan stop listening when it finds a potential parent node to re-subscribe the network. It can also be seen that signaling of the proposed scheme is lower than ZigBee, because the proposed CS which makes only the orphaned router re-subscribe to the network with its child nodes in a cluster-wise manner. However, in the experiment (b), the alleviation of time and signaling for the network re-subscription is decreases, because the number of child nodes of orphaned router is lower than the experiment (a).

Table 5. Energy consumption and signaling for the network re-subscription

	Time (BI)		Signaling overhead (No. of packets)	
	(a)	(b)	(a)	(b)
ZigBee	25.2	6.7	13.5	7.2
Proposed	7.1	3.3	7.3	5.0

6. Conclusions

In this thesis, we design a cluster-wise self-healing (CS) in a beacon-enabled cluster-tree structured WSN. When a router experiences networking failure from its parent node, the proposed CS can prevent the orphan propagation by making the orphaned router maintain synchronization with its child nodes. It makes only the orphaned router search for a new parent node and re-subscribe to the network on behalf of its child nodes. Thus, the proposed CS allows the re-subscription of network through one re-subscription process of the orphaned cluster head. The orphaned node stops the neighbor scan when it finds a new parent node, reducing the recovery time and the energy consumption of the neighbor scan. We also design a self-healing scheme, referred to backup link aided self-healing (BL), where nodes select a parent node for the network subscription and also a back-up parent node for network re-subscription. The proposed BL can reduce the recovery time since it can minimizes the time for the selection of a new parent node and associated message exchanges for network re-subscription. Computer simulation and experimental results show that the proposed schemes can significantly reduce the energy consumption, recovery time and signaling overhead for network re-subscription.

References

[1] A. Zanella *et al*., "Internet of Things for Smart Cities," *IEEE Internet of Things Journal,* vol. 1, no. 1, pp. 22-32, Feb. 2014.

[2] J. Stankovic, "Research Directions for the Internet of Things," *IEEE Internet of Things Journal*, vol.1, no.1, pp.3-9, Feb. 2014.

[3] S. Chen, et al., "A Vision of IoT: Applications, Challenges, and Opportunities with China Perspective," *IEEE Internet of Things Journal*, vol.1, no.4, pp. 349-359, Aug. 2014.

[4] M. Gigli and S. Koo, "Internet of Things: Services and Applications Categorization," *Advances in Internet of Things Journal*, vol. 1, no. 2, pp. 27-31, Jul. 2011.

[5] I. Khan *et al*., "Wireless Sensor Network Virtualization: A Survey," *IEEE Communications Surveys & Tutorials*, vol. PP, no. 99, Mar. 2015.

[6] W. Qiu, P. Hao, and R. J. Evans, "An efficient self-healing process for ZigBee sensor networks," *Proc. IEEE ISCIT*, Oct. 2007.

[7] S. Hur, J. Kim, J. Choi, and Y. Park, "An efficient addressing scheme and its routing algorithm for a large-scale wireless sensor network," *Proc. EURASIP J. Wireless Communication and Networking*, Dec. 2008.

[8] K. I. Hwang, “Designing robust ZigBee networks with enhanced self-configuration,” *Proc. IEEE ICCE*, Jan. 2009.

[9] K. I. Hwang, “Fault-tolerant ZigBee-based Automatic Meter Reading Infrastructure,” *Journal of Information Processing Systems*, vol. 5, no. 4, Dec. 2009.

[10] T. Song and C. Yang, “A Connectivity Improving Mechanism for ZigBee Wireless Sensor Networks,” *Proc. IEEE EUC*, Dec. 2008.

[11] M. Pan and Y. Tseng, “A Lightweight Network Repair Scheme for Data Collection Application in ZigBee WSNs,” *IEEE Communication Letters*, vol. 13, no. 9, pp. 649-651, Sep. 2009.

[12] C. Wu *et al*., “An innovative scheme for increasing connectivity and life of ZigBee networks,” *Journal of Supercomputing*, vol. 65, no. 1, pp. 136-153, Sep. 2011.

[13] IEEE Std. 802.15.4-2006, Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specification for Low Rate Wireless Personal Area Networks (LR-WPANs), *IEEE*, Sept. 2006.

[14] ZigBee Alliance, “ZigBee specification,” www.zigbee.org, Jan. 2008.

[15] N. Karowski *et al*., “Optimized Asynchronous Multi-channel Neighbor Discovery,” *Proc. IEEE INFOCOM*, Apr. 2011.

[16] TelosB mote Website [Online].

Available: http://www.willow.co.uk/Te losB_Datasheet.pdf

[17] TinyOS Website [Online]. Available: http://www.tinyos.net

[18] Chipcon CC2420 Website [Online].

Available: http://focus.ti.com/docs/prod/folders/print/cc2420.html

[19] J.-H. Hauer, “TKN15.4: An IEEE 802.15.4 MAC implementation for TinyOS 2,” Telecommunication Networks Group, Technical Univ. Berlin, Berlin, Germany, Tech. Rep. TKN-08-003, Mar. 2009.

[20] Texas Instruments [Online].

Available: http://www.ti.com/lit/ug/swru208b/swru208b.pdf

1. 초 록

네트워킹 실패(networking failure)가 발생했을 때, 효과적으로 네트워크에 재연결시키는 것은 무선 센서 네트워크를 구축하는 중요한 이슈 중 하나다. 지그비(ZigBee)는 저전력 및 저복잡도의 특징 때문에 무선 센서 네트워크에서 클러스터 트리 네트워크를 구축함에 있어서 적합한 솔루션으로 고려된다. 그러나 지그비가 제공하는 단순한 네트워크 재가입 절차는 연결을 복구 함에 있어서 많은 에너지, 시간, 메시지 트래픽을 발생시킨다.

본 학위 논문은 비컨 모드를 지원하는 클러스터 트리 무선 센서 네트워크에서 클러스터 단위의 자가 치료를 제안한다. 제안하는 클러스터 단위 자가 치료는 라우터가 네트워킹 실패를 겪을 경우, 자가 치료 중에 자녀 기기와 동기를 유지하여 자녀 기기들에게 고아가 전파되는 현상을 방지하고, 오직 고아 라우터만이 자녀 기기들을 대표하여 새로운 부모 기기를 찾아 네트워크에 재가입함으로써 네트워크 재연결에 필요한 에너지, 시간, 메시지 트래픽을 효과적으로 줄인다. 또한 우리는 자녀 기기들이 기존 부모 기기 외, 또 다른 백업 부모 기기를 가지는 백업 링크 기반의 자가 치료를 제안한다. 상기 백업 링크 기반의 자가 치료는 새로운 부모 기기를 찾는 과정과 네트워크 재가입을 위한 메시지 교환 절차를 최소화하여 네트워크 재연결 시간을 더욱 줄일 수 있다. 컴퓨터 시뮬레이션과 실장 실험을 통해

제안 기법이 연결 복구에 필요한 에너지, 시간, 메시지 트래픽에 대해서 기존 자가 치료보다 뛰어난 성능을 나타내는 것을 확인하였다.

主要語 : 무선 센서 네트워크, 자가 치료, 클러스터 방식, 백업 링크

Student number: 2013-20753