M. S. Thesis

Interference-robust Beacon Tracking in ZigBee-based Sensor Networks

무선 센서 네트워크에서 간섭에 강인한 비컨 신호 추적 기법

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Abstract

It is of great concern for commercial deployment of wireless sensor networks (WSNs) to securely construct a network while preventing a network association failure. ZigBee has been considered as an attractive protocol for the construction of cluster-tree structured WSNs due to its low-power and low-complexity features. However, it may not provide desired network connectivity in practical operation environments.

In this thesis, we consider the beacon-tracking for network association in a beacon-enabled cluster-tree structured WSN. For the network association, ZigBee devices need to track a beacon frame transmitted from a candidate parent device (e.g., the coordinator or a router). ZigBee devices can avoid the presence of severe co-channel interference by means of channel hopping. However, a network joining device may not reliably track the beacon frame when ZigBee devices are in a channel hopping process. To alleviate the beacon tracking problem, we consider the beacon tracking using the beacon sequence number (BSN). The network joining device keeps the BSN of the received beacon frame during channel scanning and increases the BSN by one at every beacon interval. Thus, it can estimate which channel is used by the parent candidate device. We verify the proposed scheme by computer simulation. The proposed scheme can significantly reduce the beacon tracking failure, improving the self-networking performance.

Keywords: Wireless sensor network, self-construction, network connectivity

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1. Introduction

Recently, the Internet of Things (IoT) has appeared as one of key technologies for future industry [1]. With various IoT services, “everything” around us will be on a network in one form or another, where wireless sensor network (WSN) plays a key role by providing physical connection of things [2]-[5].

IEEE 802.15.4 is a popular global standardized protocol that defines the physical (PHY) and Medium Access Control (MAC) layer for low-power WSNs [6]. It can construct a WSN comprising three types of nodes, referred to a coordinator, routers and end devices. ZigBee with IEEE 802.15.4 beacon-enabled mode can be applied to the construction of a cluster-tree structured WSN with multi-hop routing [7]. It employs a distributed address allocation mechanism (DAAM), enabling to construct a network in a distributed manner. However, it may not support desired network connectivity in practical operation environments. It may suffer from frequent failure of network joining in the presence of co-channel interference generated by coexisting radio systems such as IEEE 802.11 wireless local area networks (WLANs) [9]. A single channel-handoff mechanism was proposed for improved network association in interference environments [7]. When a parent device (e.g., the coordinator or a router) detects the presence of interference by measuring packet errors, it selects a channel for the channel-handoff by scanning available channels. Then, it broadcasts a channel-handoff command through the channel being already interfered, making the channel-handoff unreliable. A multi-channel hopping mechanism was proposed for improved channel-handoff [10]. Even when a child device fails to receive a hand-off command, it can make a reliable channel-handoff by utilizing a predetermined multi-channel hopping set.

On the other hand, changing the operating channel by channel hand-off may cause severe impact to network joining. When a network joining device receives a beacon frame during the channel scanning, it records the channel index of the beacon frame and tracks the beacon with the recorded channel information. After successful beacon tracking, it initiates a network association process. However, channel-handoff mechanisms in [9]-[10] may make the network joining device track the beacon frame difficult. In practice, parent devices in a large-scale WSN may need frequent channel hopping in the presence of severe co-channel interference, which makes the beacon tracking much difficult, yielding poor network connectivity.

In this thesis, we consider the beacon-tracking for network association in a beacon-enabled cluster-tree structured WSN. To alleviate the beacon tracking problem, we consider the beacon tracking using the beacon sequence number (BSN). A network joining device keeps the BSN of the received beacon frame during the channel scanning and increase the BSN by one at every beacon interval. Thus, it can estimate which channel is used by the parent candidate device. The proposed scheme can significantly reduce the failure ratio of the network joining.

The remainder of this thesis is organized as follows. Section II describes the WSN model in consideration. Section III describes the proposed scheme. Section IV evaluates the proposed scheme by computer simulation. Finally, Section V concludes this paper.

2. System model

As illustrated in Fig. 1, we consider an IEEE 802.15.4 beacon-enabled cluster-tree structured network [6]-[7]. The network comprises three types of devices; a coordinator, routers and end devices. The coordinator and routers operates as a parent device which can have routers and end devices as its child devices. A parent device can be the cluster head of a cluster comprising itself and its child devices. The clusters are connected as a tree structure, referred to cluster-tree structure, forming a WSN.

We assume that each cluster operates using its periodic super-frame structure which are not over-rapped to each other as illustrated in Fig. 1. The parent device periodically broadcasts a beacon frame to synchronize the operation with its child devices. Receiving a beacon frame, the child devices can make communications with the parent device by means of slotted CSMA/CA during the active period and stay in a power-saving idle mode during the inactive period.

The beacon interval and the super-frame duration are determined as, respectively,

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

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

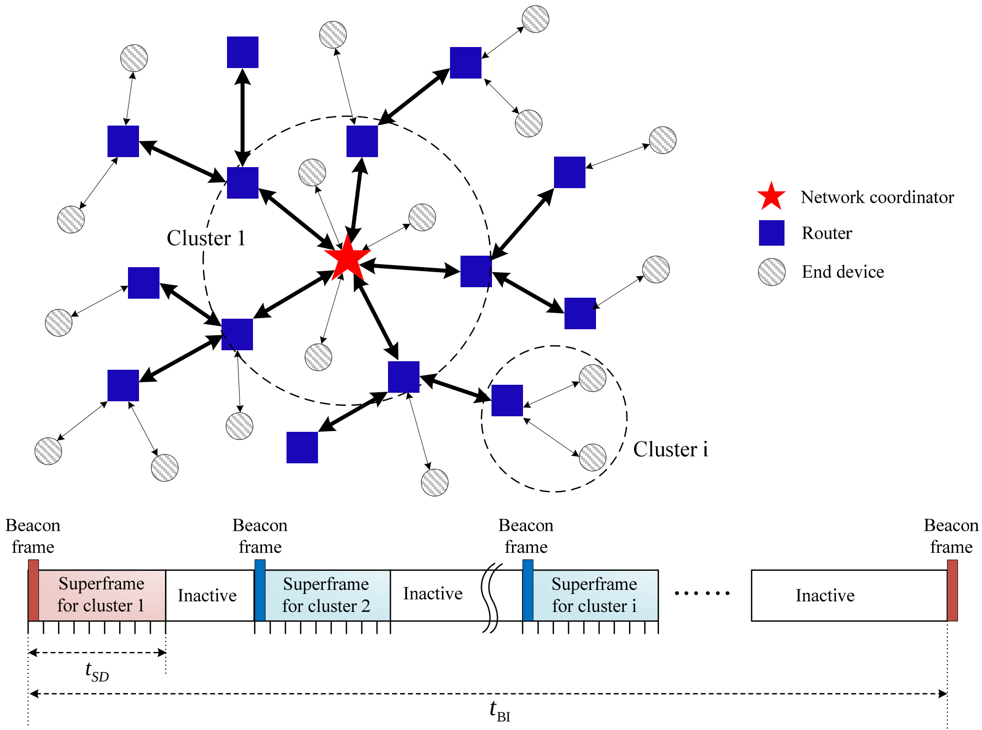

Figure 1. An example of IEEE 802.15.4 cluster-tree structured network.

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 ISM spectrum band, where the center frequency is determined by $f_k = 2405 + 5(k-11)$. Here, k denotes the channel index and $k = 11, 12, \ldots, 26$.

As illustrates in Fig. 2, we consider the use of a distributed address allocation mechanism (DAAM) to construct a hierarchical addressing tree structure based on three addressing parameters [7]; the maximum number of child devices, Cm, the maximum number of child routers, Rm, and the maximum network depth, Lm, which can be predetermined and shared by all the devices. 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 to its child devices (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

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

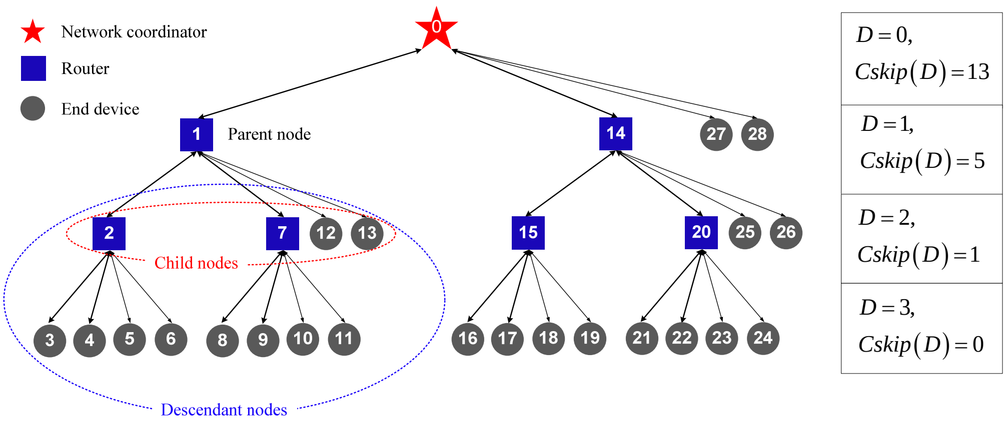

Figure 2. An example of DAAM addressing tree with Cm=4, Rm=2 and Lm=3.

DAAM allows the network to use a hierarchical tree routing that provides a routing path based on address information [7]. When a router receives a packet, it can identify whether the packet is to be delivered to a device in its sub-tree or not. If it is, the router relays the packet to its child device whose sub-tree includes the target device. Otherwise, it sends the packet to its parent device. The hierarchical tree routing algorithm can be summarized as

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

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

3. Proposed beacon tracking

Fig.3 illustrates an example of beacon tracking failure. This failure may occur when a network joining device receives a beacon frame from a parent candidate device that is operating in a channel hopping mode to avoid co-channel interference [10]. The joining device may track the beacon frame using the old beacon information without acknowledging the change of the operation mode, failing to track the beacon frame in the presence of interference. If a router is already in a hopping mode when the joining device performs the channel scanning, the network joining device cannot track the beacon transmitted from the router, not being included in a set of parent candidate devices for the network joining device. These tracking problems can be alleviated by exploiting the BSN.

When the coordinator or a router broadcasts a beacon frame in a channel hopping mode, a network joining device can detect the operating channel based on the BSN. Assuming that n hopping channels are used in the channel hopping mode [10], we can divide the BSN by n and determine the channel for the hopping by the remainder. With this kind of a simple rule, the joining device can easily track the beacon frame even though it has no information on the parent candidate device.

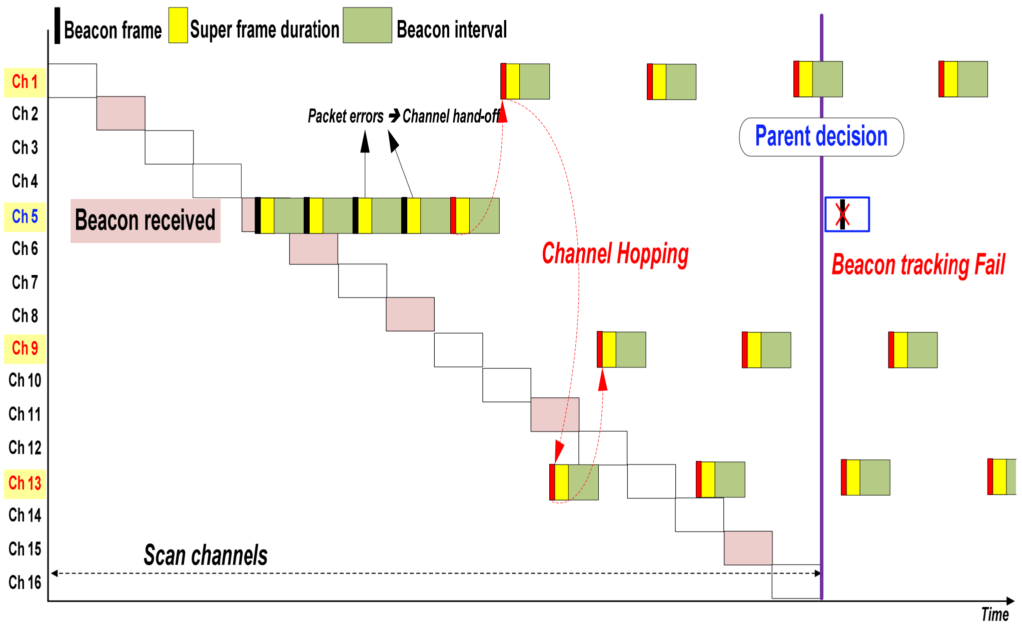

Figure 3. An example of beacon-tracking failure.

Performing the channel scanning, a network joining device records the BSN of a beacon frame transmitted from parent candidate devices and then increases the BSN by one at each beacon interval until it starts the beacon tracking. If it chooses a parent candidate device in a normal operation mode, it can track the beacon in a conventional way. When a parent candidate device is operating in the channel hopping mode, the joining device can track the beacon using the BSN recorded during the channel scanning. An example of the proposed scheme is illustrated in Fig. 4.

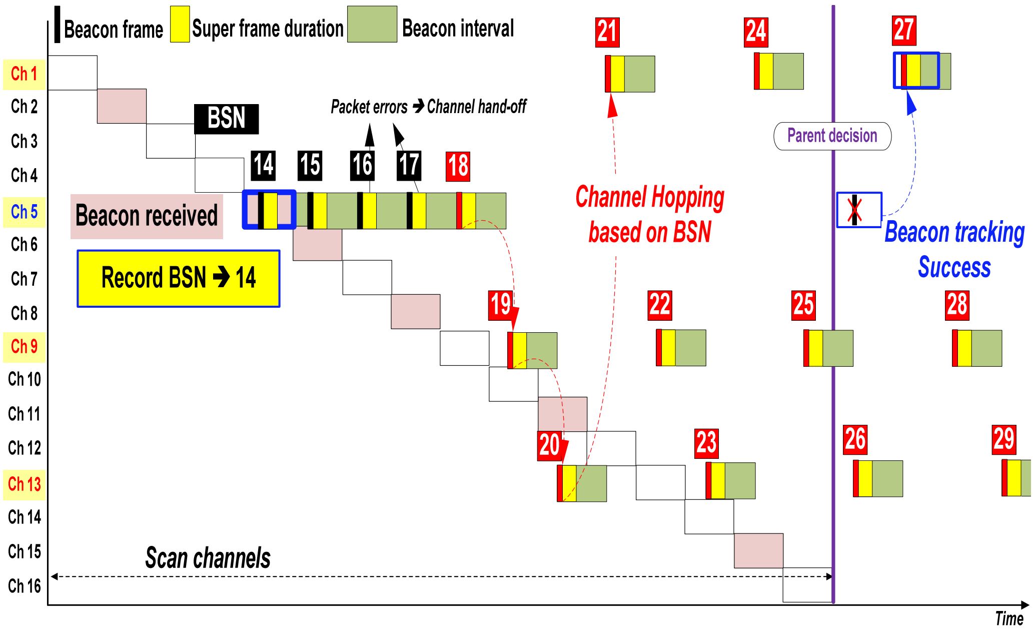

Figure 4. An example of beacon-tracking using the BSN.

4. Performance evaluation

The performance of the proposed schemes is evaluated by computer simulation. For the computer simulation, we construct a cluster-tree structured network, where the network coordinator is deployed in the center and other devices are randomly distributed in a squared area of $(30\times30)m^2$. The simulation parameters are summarized in Table 1, which considers the operation of a cluster-tree structured ZigBee network with the DAAM. The channel is modeled using an indoor path loss model in [6]. We assume that the transmit power is -5dBm, the carrier sensing threshold for CSMA/CA is -85dBm, the beacon order is 8 (i.e., the beacon interval is 3.93sec) and the maximum network depth is 3. We also assume that hidden node collision may occur when the channel sensing fails to detect ongoing packet transmission and that the network coordinator randomly selects one for the operation among 16 available channels, while devices can find a parent candidate device by scanning all the 16 channels. We also assume that the coordinator and routers can use spatially non-overlapped super-frame.

Table 1. Simulation parameters

Parameters	Values
Beacon order (*BO*)	8
Super-frame order (*SO*)	2
Number of available channels	16
Maximum number of child devices (*Cm*)	64
Maximum number of child routers (*Rm*)	16
Maximum number of network depth (*Lm*)	3
Transmit power	-5 dBm
Data rate	250 kbps (IEEE 802.15.4 PHY)
Number of devices	50, 100, 500
Deployment area	30 m * 30 m
WLAN loading factor	Variable (0~0.3)

Fig. 5 depicts the failure rate of network association due to the failure of beacon tracking according to the WLAN loading factor. We also consider a conventional scheme that employs a multi-channel hopping (MH) scheme to manage the interference [10] It can be seen that the conventional scheme cannot alleviate the joining failure problem due to the failure of beacon tracking and that as interference loading factor increases, the network joining failure also increases. It can also be seen that the proposed scheme successfully performs the beacon tracking in the MH mode and thus it significantly reduce the failure ratio of network association.

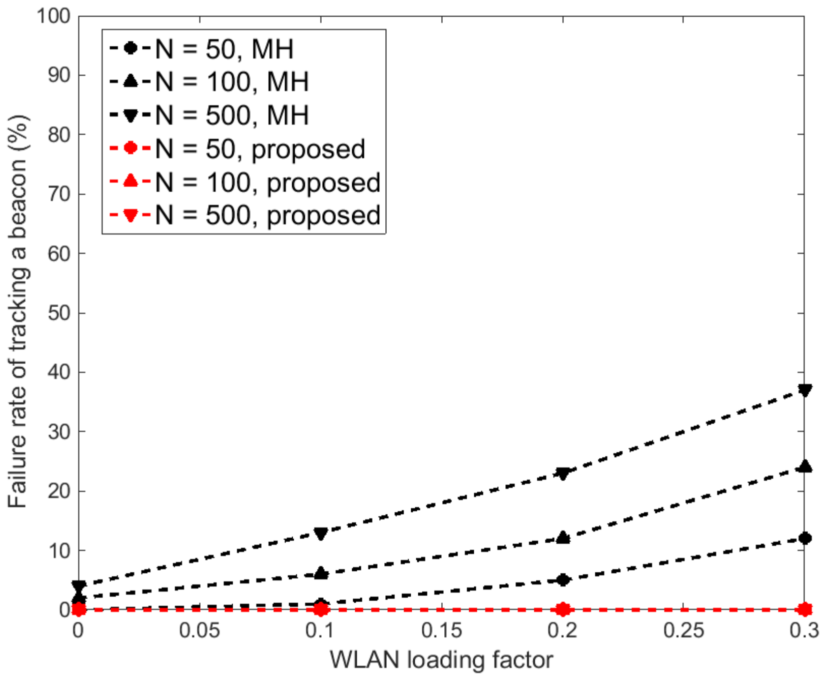

Figure 5. Ratio of network joining failure due to failure of beacon tracking.

Fig. 6~8 depicts the success rate of network association according to the WLAN loading factor. It can be seen that the conventional scheme [10] cannot provide network construction with a probability of 100%. It is mainly because devices that fail to track the beacon frame cannot make network association. It can also be seen that the proposed scheme can provide network construction with a probability of 100%. With the proposed scheme, the network joining device can reliably track beacon frames repeatedly following hopping sequence by using the BSN. So that it makes it possible to make network association successfully even in the presence of severe co-channel interference.

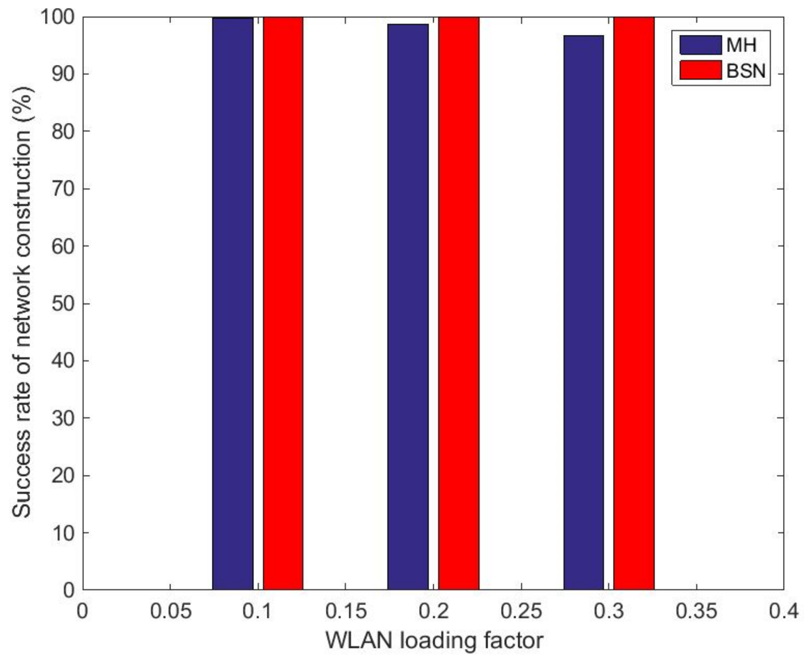

Figure 6. Success rate of network construction (N=50).

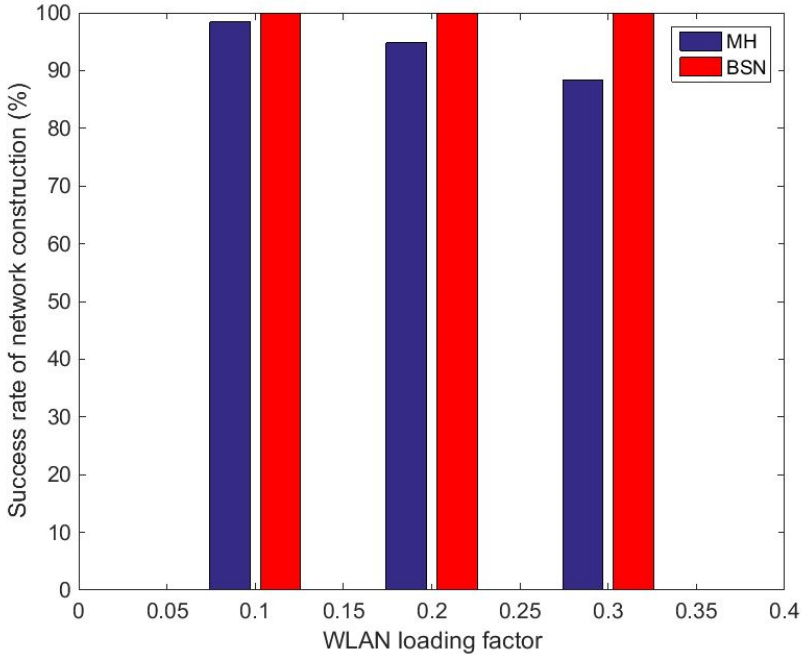

Figure 7. Success rate of network construction (N=100).

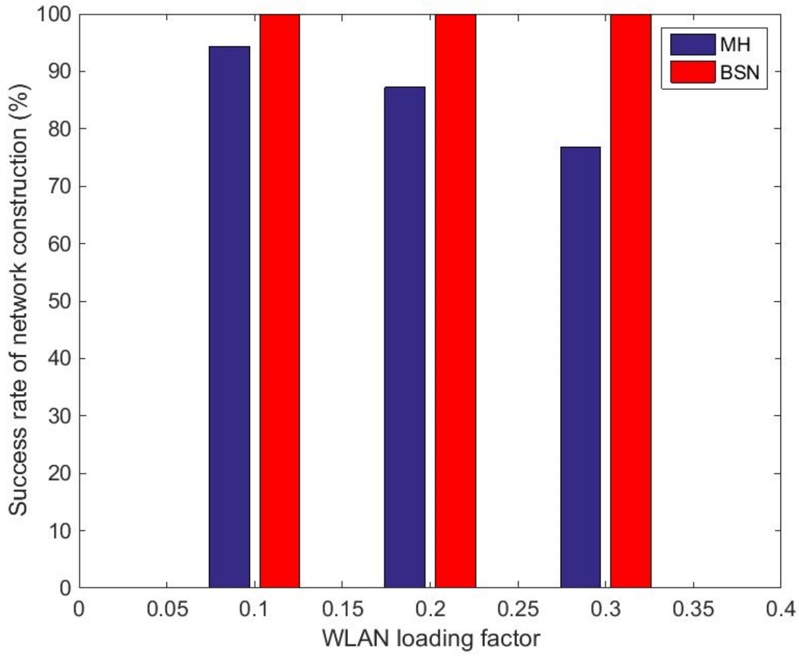

Figure 8. Success rate of network construction (N=500).

5. Conclusions

In this thesis, we have considered the beacon tracking in a beacon-enabled cluster-tree structured WSN, where the cluster head may use channel hand-off to avoid the interference. To track a beacon frame transmitted from a parent candidate device in a channel hopping mode to avoid severe co-channel interference, a network joining device can exploit the beacon sequence number (BSN). It records the BSN obtained during the channel scan and increases the BSN by one at each beacon interval. For a given number of hopping channels, it can detect the hopping channel by the remainder of the BSN divided by the number of hopping channels. The simulation results show that the proposed scheme can significantly reduce the failure ratio of the network association even in the presence of severe interference.

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초 록

네트워크 가입 실패율을 줄여서 네트워크 망 연결성을 보장하는 것은 무선 센서 네트워크를 구축하는 중요한 이슈 중 하나이다. 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 네트워크 망 연결성을 보장하지 못한다.

본 학위 논문은 비컨 모드를 지원하는 클러스터 트리 무선 센서 네트워크에서 개선된 자가 망 구축 기법을 제안한다. 제안기법은 네트워크에 가입을 시도하는 기기가 스캐닝을 통하여 수신된 비컨으로부터 부모 기기를 선정할 때 호핑 중에 있는 라우터도 예비 부모 리스트에 포함시킬 수 있도록 하며, 상기 선정된 부모 후보 기기의 비컨을 추적할 때 비컨 시퀀스 번호를 이용하여 신뢰성 있는 추적이 가능하게 한다. 컴퓨터 시뮬레이션을 통해 제안 기법이 망 연결성 측면에서 기존 기법보다 뛰어난 성능을 나타내는 것을 확인하였다.

主要語 : 무선 센서 네트워크, 자가 망 구축, 네트워크 연결성

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