February 2017
Master's Degree Thesis

Proactive Neighbour Aware Fast Association Scheme over IEEE 802.15.4

Graduate School of Chosun University

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IEEE 802.15.4 에서의 능동적 이웃 인지 고속 결합 기법

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A thesis submitted in partial fulfillment of the
requirements for a Master’s degree

October 2016

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November 2016

Graduate School of Chosun University

ABSTRACT

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IEEE 802.15.4 is the de facto standard for wireless sensor network (WSNs) which define the physical and the MAC layers. IEEE 802.15.4 has been extensively employed in various sensor network applications and its application domain is expanding day by day. Furthermore, efficiency and improvement in mobility handling are expected to facilitate numerous more applications. The awareness and concern of healthy life and explosion of various smart wearable for continuous health monitoring have demanded a need for wireless technology with robust mobility handling and IEEE 802.15.4 is no doubt a suitable candidate. However, the poor efficacy of mobility handling in IEEE 802.15.4 is one salient reason preventing it from being a dominant choice. We observed that the amount of time required for the association process is the key reason why IEEE 802.15.4 is unable to handle the mobility. Nevertheless, there are various improvements possible in order to enhance the association process, which is the main topic of this thesis.

In this thesis, a new fast association technique is proposed that prevents nodes from scanning multiple channels. In the proposed scheme we propose to

maintain a list with details of all the neighbors in the vicinity such that the mobile node has a clear picture of the surrounding. Whenever the node needs to perform a handover, it scans only those channel in the list, which drastically decrease the number of channels the node has to scan. Our scheme is simple but yet effective for the fast association of devices. Based on the theoretical and the simulation based analysis, we verify the benefits of the proposed mechanism in terms of most relevant performance metrics.

We have developed both the mathematical model and the simulation model for the analysis. The detailed performance analysis is provided to demonstrate the performance gain achieved by the proposed scheme.

The schemes that we have presented in this dissertation is simple and can be easily implemented in IEEE 802.15.4. We expect that our proposed method will be beneficial in various sensor network applications.

요 약

IEEE 802.15.4 에서의 능동적 이웃 인지 고속 결합 기법

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IEEE 802.15.4 프로토콜은 무선 센서 네트워크 (WSN)의 표준이며 물리계층과 MAC 계층이 정의되어 있다. 이 표준은 다양한 센서 네트워크 어플리케이션에 광범위하게 적용되고 있다. 더불어, 이동성 관리에 따른 효율 개선 등을 통해 더 다양한 어플리케이션 분야에서 활용될 것으로 예측된다. 헬스 라이프에 대한 인식과 관심, 연속적인 헬스 모니터링이 가능한 다양한 스마트 웨어러블의 폭발적인 증가는 안정적인 이동성 관리와 무선 기술의 필연성을 요구하고 있다. 그러나, IEEE 802.15.4 표준의 이동성 관리가 효율적이지 못하다는 단점은 이 표준이 무선환경에서의 모니터링 시스템 등에서 주도적으로 활용되지 못하는 이유로 작용한다. 본 연구에서는 IEEE 802.15.4의 이동성 관리가 효율적이지 못한 주된 이유가 결합 과정 (association process)에 요구되는 시간이 길다는 것임을 확인하였다. 이러한 지연특성의 단점을 해결하고자하는 다양한 시도가 진행되었으며 본 연구에서도 이를 해결하고자 한다.

본 논문에서는 노드가 다수의 채널을 스캐닝하는 것을 방지할 수 있는 새로운 고속 결합 기법을 제안하였다. 제안 기법에서 이동 노드는 자신의 주변에 대한 정확한 정보를 기반으로 이웃 노드의 리스트를 관리한다. 노드가 핸드오버를 수행할 경우, 자신이 관리하는 이웃노드의 리스트를 기반으로 스캐닝을 수행함으로써, 핸드오버시 필요한 스캐닝 시간을 줄이고자 하는 것이 핵심이다. 제안된 기법은 단순하지만 단말들의 고속 결합에 효과적임을 입증하였다. 이론적 분석과 시뮬레이션 방법을 확용하여 제안 기법이 다양한 성능 척도 관점에서 이점이 있음을 확인하였다. 제안된 기법은 기존의

IEEE 802.15.4 표준 상에 쉽게 구현될 수 있으며 이를 통해 다양한 센서 네트워크 응용 분야에 활용될 수 있을 것으로 판단한다.

Acronyms

AP	Access Point
BI	Beacon Interval
BO	Beacon Order
CAP	Contention Access Period
CCA	Clear Channel Assessment
CFP	Contention Free Period
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CW	Contention Window
FFD	Full Functional Device
GTS	Guaranteed Time Slots
HWSN	Healthcare Wireless Sensor Networks
ISM	Industrial, Scientific and Medical
LR-WPAN	Low Rate WPAN
LQI	Link Quality Indication
MAC	Medium Access Control
NAV	Network Allocation Vector
PAN	Personal Area Network
PDR	Packet Delivery Ratio
PHY	Physical Layer
RF	Radio Frequency
RFD	Reduced Functional Device
RSSI	Received Signal Strength Indicator
SD	Super-frame Duration
SO	Super-frame Order
UDP	User Datagram Protocol
UWB	Ultra-Wideband
WBAN	Wireless Body Area Networks
WDS	Wireless Distribution System
WLAN	Wireless Local Area Network
WPAN	Wireless Personal Area Networks
WSN	Wireless Sensor Networks

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Chapter 1

Introduction

Wireless Sensor Network (WSNs) is a combination of spatially distributed, less cost tiny devices called sensors. The main function of this sensors is to perform communication, computation and sensing activities [1]. WSNs are considerably used in applications like smart homes, weather monitoring as well as in defense and hospital applications. With all these attributes, WSN are likely to dominate the world of data communication.

Wireless communication forms a base for the interconnection of sensor devices. Wireless communication is considerably better than the conventional wired communication technology in terms of system cost, flexibility and deployment complexity. Over the past few decades, wireless communication has become a paramount solution for the connection of devices. With the popularity of wireless communication and modern embedded technologies, new possibilities for wireless communication are emerging.

Nowadays, sensors are embedded in everything from small items such as gadgets, toys, mobile phones, home appliances, bridges, roads, buildings, and even animals and people. This ubiquitous of computing has improved our quality of life. Enabling connectivity among diverse types of services and various devices such as computers, sensors, RFID tags, appliances, vehicles etc., is a challenging issue. For enabling communications with devices via existing network infrastructures, various technologies have been developed. Smart buildings, smart cities, smart grids, e-Health, or automotive applications are some among many other examples [2]. WSN communications are characterized by low power, low cost , and low human intervention[3]. In a typical WSN network, the efficient sharing of radio resources and maintaining enough quality-of-service for reliable communications are challenging requirements [4, 5]. Similarly, maintaining low power consumption with acceptable latency is one of the major issues of WSN[6]. Moreover, there are applications like the vehicular network, robotic networks, and health-care that need support for mobility [7].

Energy efficiency, reliability, scalability, routing, mobility, latency, security, and time synchronization are some of the challenges of wireless networks. A broad range of latest applications like smart city, smart home, consumer electronics, industrial automation, environmental control and personal health care are some of the examples enabled by

WSN. There are different types of wireless technologies in use. The coverage range of wireless personal area networks (WPAN) is short (few meters) whereas WLAN belongs to the middle range (a couple of hundred meters). Wireless technologies used in WSN are summarized as follows:

- IEEE 802.11 [10]: IEEE 802.11 or WLAN is one of the most popular wireless technology. The most popular WLAN is the IEEE 802.11g, which offers data rates up to 54 Mbps and the latest one is the IEEE 802.11n, using multiple antenna interface technology, which achieves data rates up to 600 Mbps.

- Ultra-Wideband (UWB) [11]: UWB is a WPAN technology suitable for very high data rate applications. The UWB technology which eventually dominated and currently exists is the multi-band orthogonal frequency division multiplexing [11]. Similarly, direct-Sequence UWB (DS-UWB) is supported by UWB Forum [12].

- IEEE 802.15.4 [9]: IEEE 802.15.4, also popularly known as WPAN, is suitable for sensor networks. It is widely used for monitoring and home automation applications [13]. A UWB version is also available which offers higher data rates [12].

- Bluetooth [8]: IEEE 802.15.1 is a popular WPAN standard for connection of devices such as smart phones and various accessories associated with them (i.e. headset), PC accessories (i.e. mouse and keyboard). Nevertheless, it has high power consumption, thus, is not used where power saving is crucial. However, this issue seems to be resolved with the latest low energy Bluetooth version (v4.0).

1.1 Wireless Technology Studied

In this thesis, IEEE 802.15.4 standard, one of the major wireless technologies used in WSN communications was studied. Especially, the association process of IEEE 802.15.4 has been rigorously scrutinized.

1.2 Research Objectives

In IEEE 802.15.4, a device has to associate with coordinator before starting data communication. Association is the process of becoming the member of a network. Therefore,

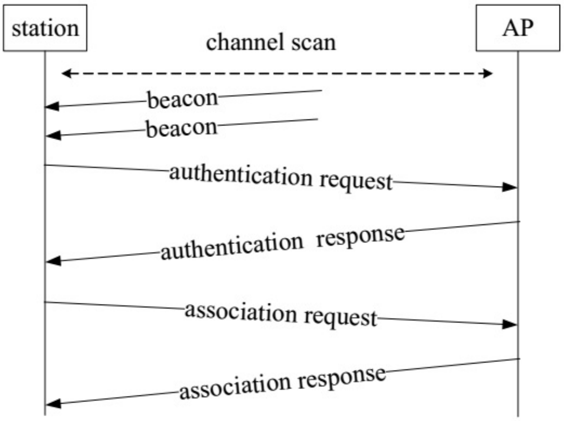


Figure 1.1: Association in IEEE 802.15.4.

whenever a device is initialized, the device scans the standard defined radio channels and lists all coordinators which it can detect along with their corresponding signal strength. It then chooses to associate itself with the coordinator of its choice. Only after the association is completed, the device can start data communication within the network. Figure 1.1 shows the general association procedure in a IEEE 802.15.4. First, the station is authenticated and then is associated. The amount of time spent by a device in the association process plays the key role in communication. Delay in association means a delay in the communication. Thus, the association should be done as soon as possible.

In this thesis, the association procedure of IEEE 802.15.4 was extensively examined. The major goal of this research is to analyze the association procedures in IEEE 802.15.4 and to suggest an algorithm which can improve the association delay.

1.3 Research Contribution

This thesis contributes to improvise the association time in IEEE 802.15.4. We observed that the amount of time spent for the association process in IEEE 802.15.4 can be significantly reduced. We present a fast association technique for IEEE 802.15.4. In the proposed scheme, by scanning just a few channels, a node can learn about all the coordinators working in different channels. The proposed method is capable of decreasing the association delay of IEEE 802.15.4 standard (2.4 GHz) by multiple folds as compared with the original protocol. Experimental results have verified that our scheme works well also in the mobile sensor network environment. By virtue of rigorous performance analysis carried using computer simulations in NS-2 and through numerical analysis, we show that our association scheme considerably outweighs the original method by reducing the association time.

1.4 Research Organization

The remaining part of the thesis is as follows. In Chapter 2, the overview of IEEE 802.15.4 standard is presented. Channel scanning and association procedure of IEEE 802.15.4 network are comprehensively discussed. Chapter 3 presents proposed association method for IEEE 802.15.4 along with numerical and simulation results. Finally, Chapter 4 presents the conclusion of the thesis.

Chapter 2

IEEE 802.15.4

2.1 Background

The requirement for Low Rate Wireless Personal Area Networks (LR-WPANs) is driven by the plethora of trending applications such as industry automation, smart home, healthcare monitoring, and environmental monitoring [15]. IEEE 802.15.4 has been well approved as the de facto standard for WSN, which focuses on short-range wireless communications. The goal of the IEEE 802.15.4 is to support low data rate connection between sensor nodes with low complexity, cost and energy consumption [9, 14].

2.2 Overview of the Standard

IEEE 802.15.4 standard specifies the media access control (MAC) sub layer and the physical layer (PHY) for LR-WPANs as depicted in Figure 2.1 [9, 31, 32]. IEEE 802.15.4 is mainly intended for low data rate, low power, and low cost networks which fulfills the requirements of short range WSN applications. IEEE 802.15.4 is developed to support the range of applications at the lower end of spectrum of data rates, energy consumption, and device cost. IEEE 802.15.4 has short coverage area. Coordinator only covers a limited region, also called its personal area network (PAN). Mainly there are 2 kinds of devices in IEEE 802.15.4: (i) reduced function device (RFD) and (ii) full function device (FFD). FFD supports all the network functions and can act as a PAN coordinator or as an end device whereas RFD can be used only as the end device. The IEEE 802.15.4 supports 3 types of topology: peer-to-peer, star, and cluster tree topologies, which can operate on the beacon and the non-beacon-enabled modes.

2.3 Physical Layer

There are mainly 2 services in the physical layer: (i) data service and (ii) the management of data service. The management part acts as the interface to the higher layers. Similarly, the data service part helps in the transmission and reception of physical protocol data

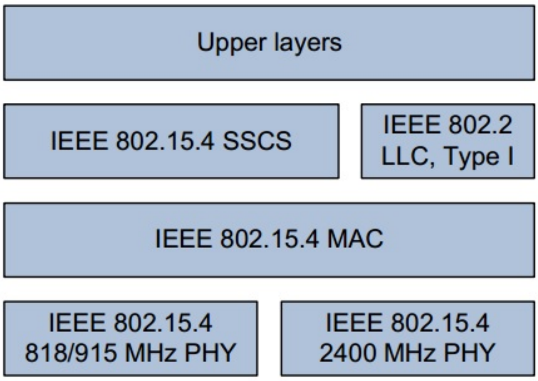


Figure 2.1: Architecture of IEEE 802.15.4 standard.

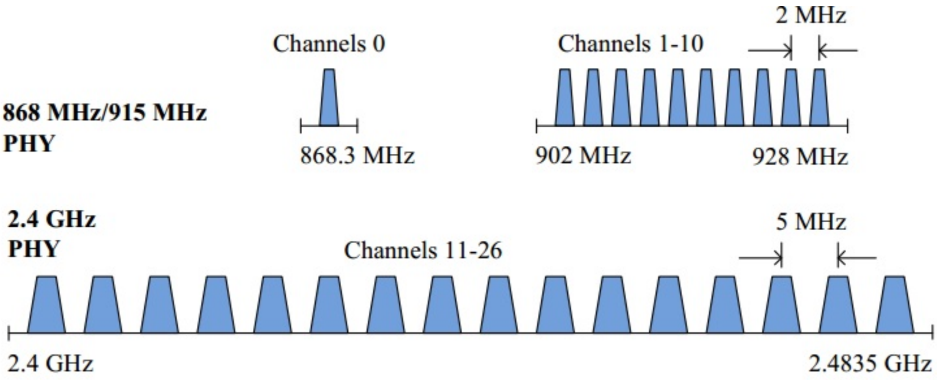


Figure 2.2: Overview of IEEE 802.15.4 physical layer.

units (PPDU) over the radio channel. There are two kinds of modulation techniques used in the standard: offset-quadrature shift keying (O-QPSK) and binary phase shift keying (BPSK). Both modulation techniques use direct sequence spread spectrum a 2 MHz wide channel. IEEE 802.15.4 operates in the ISM bands, and the range is typically 10m to 70 m. The IEEE 802.15.4 standard operates in three bands of frequency : 2.4 GHz, 915 MHz, and 868 MHz. The data rates are of 20 Kbps in the 868 MHz frequency band, similarly, 40 Kbps in the 915 MHz frequency band, and finally 250 kbps in the 2.4 GHz. BPSK is used in the first two cases whereas O-QPSK modulation is used in the latter case. The three operational frequency bands are shown in Figure 2.2.

- 868-868.6 MHz: is the European standard and allows only one channel for communication.

- 902-928 MHz: is the North American standard and allows communication up to 10 channels .

- 2400-2483.5 MHz: used worldwide and has 16 channels for communication.

IEEE 802.15.4 also allows dynamic selection of a channel , a channel scan function, receiver energy detection function, link quality indication mechanism, and switching of the channel . The physical layer of IEEE 802.15.4 can perform following functions:

- **Switch On/Off transceiver:** The radio transceiver can operate in the following four states: idle, transmitting, receiving and sleeping state. The transceiver is switched ON or OFF upon request from the MAC sub-layer. The turnaround time from the transmission to the reception and vice versa shall not be more than 12 symbol periods, as per the standard (each symbol corresponds to 4 bits).

- **Energy Detection (ED):** ED is the approximation of the received signal strength. However, the received signal is not decoded. The measurement is particularly employed as a part of the channel selection algorithm or for clear channel assessment (CCA).

- **Link Quality Indication (LQI):** Link quality indication is the measurement of the quality/strength of a received frame. This measurement can be employed either using receiver ED or a signal to noise ratio or a mixture of both techniques.

- **Clear Channel Assessment (CCA):** Clear channel assessment is the estimation of the channel state: idle or busy. The CCA is performed in three operational modes: (i) Energy Detection mode: the CCA reports the medium as busy if the energy detection is greater than the energy detection threshold. (ii) Carrier Sense mode: the CCA reports the channel as busy only if it detects a signal with the spreading characteristics and modulation of IEEE 802.15.4 standard that could be greater or less than the ED threshold. (iii) Carrier Sense with Energy Detection mode: it is a combination of the aforementioned both techniques.

- **Channel Frequency Selection:** The IEEE 802.15.4 has defined 27 different wireless channels. The individual network can support only part of the channel set. Therefore, upon the request from the higher layer, the physical layer should be able to switch its transceiver into the specific channel.

2.4 Medium Access Control Layer

The MAC protocol can operate in two operational modes: beacon enabled mode and non-beacon enabled modes.

- **The non Beacon-enabled Mode:** There is neither beacon nor superframe when the network is operated in the non-beacon enabled mode. Medium access is done through an unslotted CSMA/CA protocol.

- **The Beacon-enabled Mode:** In the beacon-enabled mode, there is periodic beacons and communication is synchronized and controlled by the PAN coordinator. A beacon frame is transmitted at the beginning of a superframe and the superframe has active and inactive parts. During the active part of the superframe, the message is exchanged between nodes. Medium access is basically done by slotted CSMA/CA. Nevertheless, the beacon-enabled mode also employs guaranteed time slots (GTSs), the contention free time slots for nodes requiring guaranteed bandwidth.

2.5 Superframe

The superframe of IEEE 802.15.4 is depicted in Figure 2.3. Superframe order (SO) and beacon order (BO) are the parameters that determines the structure of the superframe. SO is used to configure the length of superframe duration, whereas BO determine the beacon interval. In the beacon-enabled mode, individual coordinator defines a superframe structure which is defined based on:

- **The Beacon Interval (BI):** BI is the time duration between two consecutive beacon frames.

- **The Superframe Duration (SD):** SD defines the active part in the BI and can be divided into 16 equal time slots, during which frame transmissions are allowed. An inactive period is optional and is employed if BI $>$ SD. If there is an inactive period,the device may go into sleep mode for energy conservation. BI and SD are determined as follows:

$$\left.\begin{aligned} BI &= aBaseSuperframeDuration \times 2^{BO} \\ SD &= aBaseSuperframeDuration \times 2^{SO} \end{aligned}\right\} \textit{for } 0 \leq SO \leq BO \leq 14$$

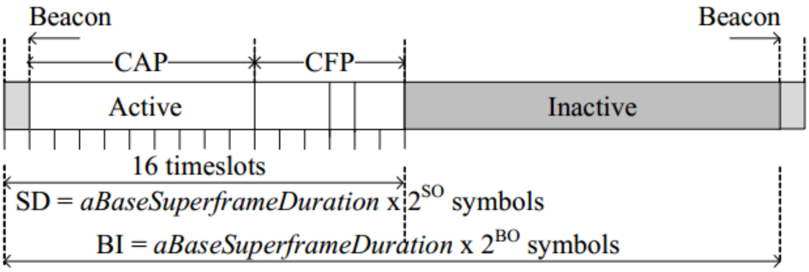


Figure 2.3: Superframe of IEEE 802.15.4.

aBaseSuperframeDuration = 15.36ms (we assumed 250 kbps at 2.4 GHz) denotes the minimum superframe duration corresponding to SO = 0.

The superframe shown in Figure 2.3 consists of active period and inactive period. Active portion of the superframe is composed of 3 different parts: beacon, contention access period (CAP), and contention free period (CFP).

- **Beacon:** The beacon frame is transmitted at the beacon period, which is the first period of the superframe. Beacon frames contain the information about superframe specification, the addressing fields, the GTS slots, the pending address fields, and other network related information.
- **Contention Access Period (CAP):** The CAP period immediately follows the beacon period and ends before the start of the CFP, if it exists. Otherwise, the CAP also ends with the end of active part of the superframe. The minimum length of the CAP is equal to aMinCAPLength (440 symbols). All transmissions during the CAP are employed using the slotted CSMA/CA protocol. However, the ACKs and any data frames that immediately follows the ACK of a data request command are transmitted contention free. The transmission must be deferred until the following superframe if the transmission cannot be completed until the end of the CAP.
- **Contention Free Period (CFP):** The CFP begins right after the end of the CAP and should complete before the end of the superframe. Transmissions are contention-free because they use GTS, which must be previously allocated by the PAN coordinator. All the GTSs that may be allocated by a PAN coordinator are located in the CFP and must be allocated continuous slots. The CFP can shrink or grow depending on the total length of all the GTSs.

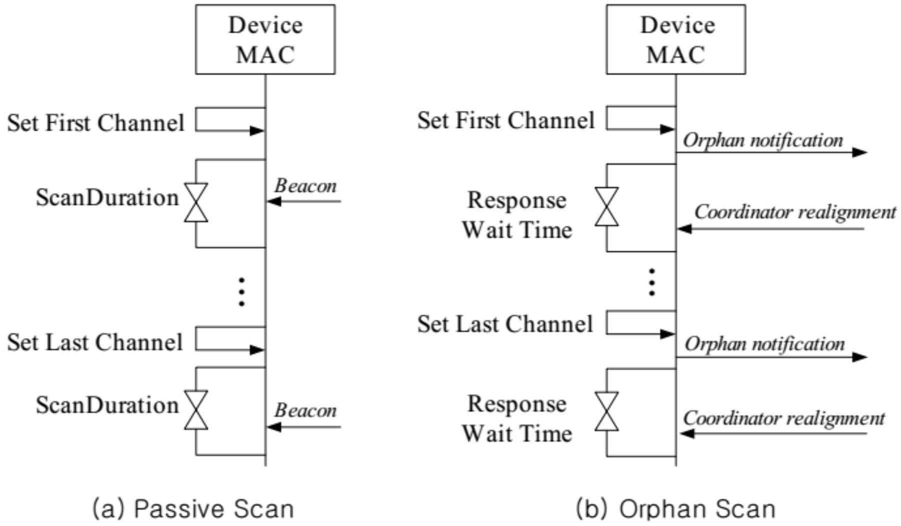


Figure 2.4: Channel scanning in IEEE 802.15.4.

2.6 Association

Any FFD can be a PAN coordinator. FFD should firstly perform the ED scan in order for the detection of the peak energy of a channel and then an appropriate channel is chosen for communication. Then, FFD performs an active scan to search any coordinator transmitting beacon frames around its personal operating space (POS). Depending on the availability of a coordinator in the vicinity, the FFD can join the existing network or starts its own PAN. After a PAN has been initialized, it transmits a periodic beacon. The other nodes in the coverage range of the PAN may communicate with the coordinator and shall associate with it. In order to start the association process, an end node needs to discover coordinators in the vicinity. In the beacon-enabled IEEE 802.15.4, there are 2 kinds of channel scanning operations performed by the end devices. During the channel scans, nodes are deprived of data communication and must discard all data frames received. The association procedure begins when a device intends to associate with an AP(Access Point). This mechanism can be classified into three different phases: (a) channel scan procedure; (b) selection of a possible coordinator; (c) association with the coordinator. IEEE 802.15.4 employs 4 types of channel scan procedures:

- **Energy Detection Scan:** Energy Detection Scan is performed to obtain a measurement of the peak energy in each channel. The energy detection scan is used to determine which channels are the quietest. In every channel, ED scan is done for the time duration of t_{scan} symbols.

- **Active Scan:** Active Scan is performed to search all coordinators in the surrounding. The active scan begins by first transmitting a beacon request command on each channel. During the active scanning, FFD initially sends out a beacon request frame and awaits for the duration of t_{scan} symbols. If a beacon could not be detected during t_{scan}, the FFD can construct its own PAN by broadcasting its beacon frame periodically. During an active scan,the MAC discards all frames received which are not beacon frames.

- **Passive Scan:** Passive Scan is performed for the discovery of coordinators. As illustrated in Figure 2.4(a), during a passive scan, in each and every channel a device searches for the beacon for the time duration of t_{scan} symbols and saves the beacon frames received in each channel. After the scanning is completed, the device may select any coordinator from the available pool for the association. If a beacon is not detected, the node begins another passive scan after a period of certain time. During the passive scan, the MAC sub-layer discards all the received frames that are not beacon frames.

- **Orphan Scan:** Orphan Scan allows a device to relocate its coordinator, immediately following a loss of synchronization (missing of beacon more than *aMaxLostBeacons* times). The device at first send the orphan notification command frame, and then waits for the coordinator realignment frame for *macResponseWaitTime* symbols as illustrated in Figure 2.4(b). This procedure is repeated until either if it receives the coordinator realignment frame or if all the available channels are scanned. If the orphan scan is not successful, the device searches for a new parent coordinator by performing the passive scan again. During an orphan scan, the MAC layer discards all the frames received over the PHY data service which is not coordinator realignment MAC command frames.

In order to begin the association process, a device needs to figure out the PAN's physical channel, coordinator's ID, PAN ID and addressing mode. However, as the channel on which a coordinator operates are not known, nodes have to scan each and every channel

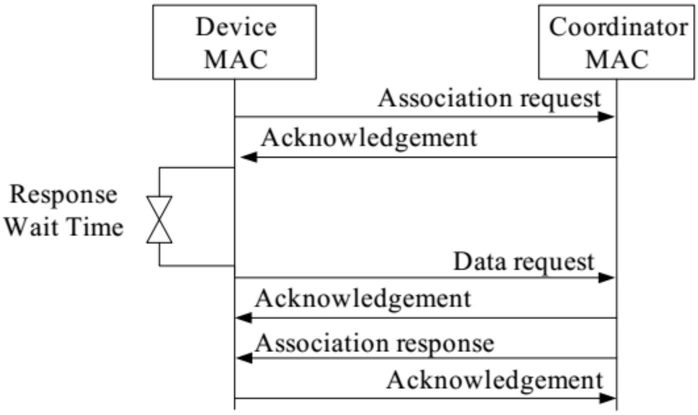


Figure 2.5: Association frames used in IEEE 802.15.4.

[23, 38, 24, 25, 26, 37]. Therefore, the passive scan is performed for the discovery of a coordinator. In IEEE 802.15.4, each node maintains a list known as PANDescriptor in which all the beacons received during the passive scan are recorded. Based on the information collected during the scanning, the device shall choose the most suitable parent that allows associations.IEEE 802.15.4 standard does not specify in detail on how coordinator is selected. However, LQI is one of the most relevant attributes to be considered. [15, 16]. Once the node finds the suitable coordinator, it begins the association procedure by sending an association request as illustrated in Figure 2.5. Next, if the coordinator accepts the device, it adds the device to its neighbor table as its child. In the case of a successful association, an association response command frame is sent to the device that contains its short address. Otherwise, if there is an unsuccessful association, the association response replies with the problem status information. The coordinator acknowledges to the association command frame with ACK embedding the pending data control flag active, which means it has data ready for transmitting to the device. The association procedure is over when the device transmits a data request command to the coordinator, requesting for the pending data. After a successful association, the device saves all the information of the new PAN by saving its MAC PAN information base (MAC PIB) and then can start transmissions. Thus, a node association requires channel scanning followed by the exchange of association message which is a time consuming procedure [23, 42, 16, 36]. For a mobile node,the association procedure is even worse,it is because the mobile node has to pass through first the orphan scan, followed by the passive scan and finally can start the association message exchange [23, 42, 16, 27]. The term re-association is explicitly used to denote the association procedure employed by a mobile node. We have observed from our detail study that if somehow the whole association duration is reduced to some acceptable level, IEEE 802.15.4 can be used in a mobile sensor network.

The process of disassociation from a coordinator is done by the disassociation request command. The disassociation process can be initiated either by the device or by the coordinator. After the disassociation process, the device loses its short address and is unable to communicate. The coordinator shall update the list of associated devices, but it may still keep the device related information for a possible future re-association.

2.7 Guaranteed Time Slot (GTS)

The GTS mechanism allows nodes to access the medium without a contention in the CFP. On request from the device, GTSs are allocated by the PAN coordinator and are used only for the communication between a PAN coordinator and a device. Each GTS allocation may contain one or more time slots. The coordinator may allocate up to 7 GTSs in a superframe. Each GTS is only one direction: from the node to the AP or from the AP to the node. The GTS can be released at any time on the initiation by the coordinator or by the node that originally requested for the GTS allocation. The PAN coordinator is responsible for performing the GTS management.

2.8 Concluding Remarks

In this chapter, a brief overview of IEEE 802.15.4 standard and its main features were presented. The IEEE 802.15.4 is designed for static network and is an attractive choice for various short range WSN applications. However, its inability of mobility support makes it undesirable for mobile sensor network applications. We observed that the amount of time spent for the association is the main reason that IEEE 802.15.4 is unable to handle mobility. In the next chapter, we will highlight long association delay problem of IEEE 802.15.4 and present our innovative solutions for the problem.

Chapter 3

Decreasing Association Time in IEEE 802.15.4

In this chapter, we propose an innovative method to reduce the association time in IEEE 802.15.4. Analytical and simulation-based studies are presented to illustrate its superiority over the conventional counterpart.

3.1 Motivation of this Work

A plentitude of WSN applications demands the mobility of sensor nodes. Health-care wireless sensor networks (HWSNs) and wireless body area networks (WBANs) are such areas where node mobility is dominant as sensors are generally attached to human body [17, 21, 30]. The rapid growth in sensor technology, low power integrated circuits, and wireless technology have leverage wireless body area networks in or on our body for continuous monitoring of vital signs such as temperature, heart-rate and blood pressure. [17, 21]. A number of smart sensors can be integrated and embedded into a wearable wireless network, which monitors vital body signs [22]. If any emergency is detected, the doctors will be immediately notified through the communication system by sending necessary messages or alarms. Furthermore, WBAN can also be installed in the home environment which monitors not only the person's health but also his daily activities to provide high-quality, low-cost health care, and social network services to users [18][19]. WBANs used to monitor patients should offer mobility support to the sensors attached to patients. Nevertheless, enabling mobility support in IEEE 802.15.4 raises lots of new challenges and issues [34, 28, 30]. In IEEE 802.15.4, support of mobility is expected to motivate numerous applications, from home health-care and medical monitoring to target detection [34, 23, 28, 29].

IEEE 802.15.4 has small coverage area. Therefore, a myriad number of access points need to be deployed for extended coverage. An access point covers a limited area, which is called its PAN. Hereafter, we will use the term PAN coordinator or coordinator to refer to an AP. The mobility of devices causes frequent connectivity loss. To maintain the network connectivity, nodes should frequently switch their AP by performing a mechanism known as handover. However, providing complex handover mechanism to IEEE 802.15.4 is not feasible because of its low memory footprint [20]. Thus, in this work, we propose light-weighted handover scheme that can be easily handled by IEEE 802.15.4. A mobile node loses its connection with the parent coordinator once it moves out of the transmission range of its parent. The mobile node should first detect the loss of connectivity with its parent and then find a new parent for the new connection in order to perform handover.

- **Detection of Loss of Connectivity**
  A node without a parent is called an orphan node. A node considers itself as an orphan node if it is unable to receive beacon frames from its parent coordinator for *aMaxLostBeacons* number of times. The orphan scan allows a device to relocate its parent following a loss of connectivity. If the orphan scan is not successful, the node searches for a new parent by initiating the passive scan. In a mobile environment, a nodes' connection with their parent coordinator could frequently break and the reassociation procedure is also time consuming as the mobile nodes have to go through the orphan scan firstly followed by the passive scan and then the exchange of association messages. We explicitly used the term reassociation to denote the association procedure used by a mobile node. It is observed from our study that the IEEE 802.15.4 protocol can be used in a mobile sensor network if the whole reassociation length is shortened to some tolerable level.

- **Neighbor Discovery**
  In order to start the association, a sensor node must find a coordinator at first. The passive scan is done for the coordinator discovery. During the passive scan, a device looks for beacon frame in each channel and records the beacon frames received. From the list of coordinator, the node selects the suitable coordinator and starts association procedure by sending an association request. Once the request is accepted by the coordinator, the node becomes a member of the network and then can start data exchange.

The association is a time consuming procedure, where the required duration is proportional to the total number of channels scanned. Furthermore, the connection is lost if the mobile node moves away from the coverage range of the coordinator. To support the node mobility, the association procedure should be updated such that the node's connectivity lost shall be quickly realized followed by the prompt discovery of the neighboring coordinators.

This work focuses on the beacon-enabled network in 2.4 GHz bands, where all coordinators have fixed positions, but the sensor nodes could be mobile. These type of topology are mainly suitable for health care and smart home applications, where sensor nodes are attached to the human. It is shown that a fast and energy efficient coordinator discovery cannot be achieved in this mobile WBAN without proper methods. Thus, the contribution of this work is as follows. We proposed a proactive algorithm which maintains a list of all the neighboring coordinators such that the search area can be confined to a limited number of coordinators. We present a novel association scheme that prevents a node from scanning multiple channels. The proposed association scheme provides support for mobility without the involvement of any higher layers. Our scheme provides support for mobility while keeping intact the original features such as flexibility, scalability, adaptability, and low power consumption of typical IEEE 802.15.4.

3.2 Related Works

Various studies have shown that node mobility deteriorates the performance of IEEE 802.15.4 network [16, 33, 34]. Also, mobility highly depends on network topology; network performance deteriorates with the number of nodes or when mobile nodes are moving fast. At higher node speeds, nodes continuously lose their connectivity with its parents and fail to associate with a new coordinators [33]. There are several efforts done to reduce the association duration in IEEE 802.15.4 standard. In IEEE 802.15.4e [35], optional fast association (FastA) is introduced that allows a node to associate fast. However, most of the works are limited to mobility management, decreasing the time duration of association message exchange [36], increasing connectivity [34] or fast coordinator discovery [16, 37, 37], whereas the channel scanning section has been left untouched. The authors in [38] have presented an interesting solution called greedy channel scan (GCS) scheme to decrease the channel scanning duration. In the GCS scheme, nodes are expected to use only 4 clear channels and those channels are scanned first. However, in GCS, if a node is unable to find the coordinator in all the 4 channels, then it has to scan all remaining channels. Similarly, there are many works on multi-channel solutions but are confined to throughput enhancement or beacon collision avoidance [39, 40, 41].

In [36], Zhang et al. proposed an improved association method called simple association process (SAP) that removes the redundant primitives, thus decreases the packet collisions and the association delay.

A fast association mechanism [42] has been proposed for real time WPAN applications. The time delay caused by scanning multiple channels is decreased because the channel scanning process is immediately stopped as soon as a beacon is received. Even though this scheme prevents nodes from scanning all the available channels; however, nodes still need to scan several channels before it can find a coordinator. Furthermore, the first beacon frame received may not be the suitable new coordinator.

Similarly, there are several other works whose primary focus is on the neighbor discovery process for the quick association. In [37], several algorithms have been proposed for the fast discovery of IEEE 802.15.4 static and the mobile networks which are operating in multiple frequency bands and with variable beacon intervals. In [34], a method to increase coordinator connectivity time with a mobile node is presented for beacon-enabled networks. Nodes use time-stamp of the received beacons during the scan, along with LQI to determine the suitable coordinator for the association. Other mobility management schemes for cluster-tree based WPAN is proposed by Chaabane et al. [37] and Bashir et al. [16]. These approaches utilize the LQI based speculative algorithm to determine the node mobility. Based on LQI value, a mobile node anticipates cell change before the actual loss of connection and tries to associate with a new coordinator. However, nodes still have to scan several channels to find coordinators in all the cases.

3.3 Network Model

One dominant choice for IEEE 802.15.4 to cover the large areas is by using cluster tree topology. But, a cluster tree topology presents 2 major problems. First, the collision probability is very high because all nodes transmit on the same channel. Second, IEEE 802.15.4 does not specify about the synchronization of a cluster tree network [37]. Thus, we select the star topology to balance the network load. But, the communication between the PAN coordinators is not possible because they operates on different channels. In this work, we consider that different wired connected PAN(s) can form a unique heterogeneous network. All PANs are considered to be connected with a base station through the wired connection. Messages exchange between nodes that are not in the same PAN can

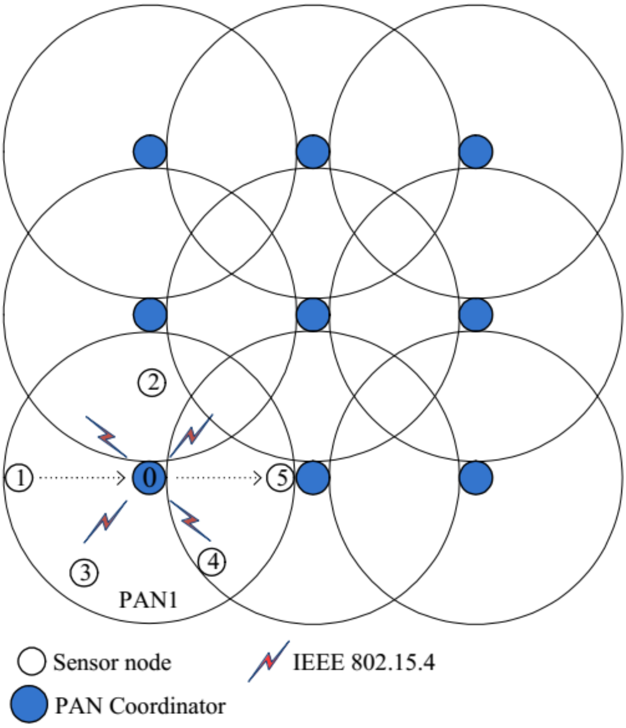


Figure 3.1: Network model.

be routed through the base station.

The basic network design is shown in Figure 3.1, which models a typical HWSN. The construction of an HWSN comprises three main elements, namely, a) a base station (AP) or gateway that performs as a bridge between the HWSN and Internet, b) PAN coordinator that enables communication to/from the sensor nodes, and c) the sensor devices themselves that accumulate body parameters and transmit them wireless over the network. Due to the small coverage area of individual PAN in indoor environments, several PAN coordinator are deployed for the coverage of the monitored zone as demonstrated in the figure. Furthermore, to prevent interference, each PAN operates on a different transmission channel. The mobile node changes its AP as it passes from one AP to another in the network. The coordinators are assumed to be separated by the distance of transmission range for the optimum coverage of the area. However, adjacent PAN does not interfere each other as they operate in different channels.

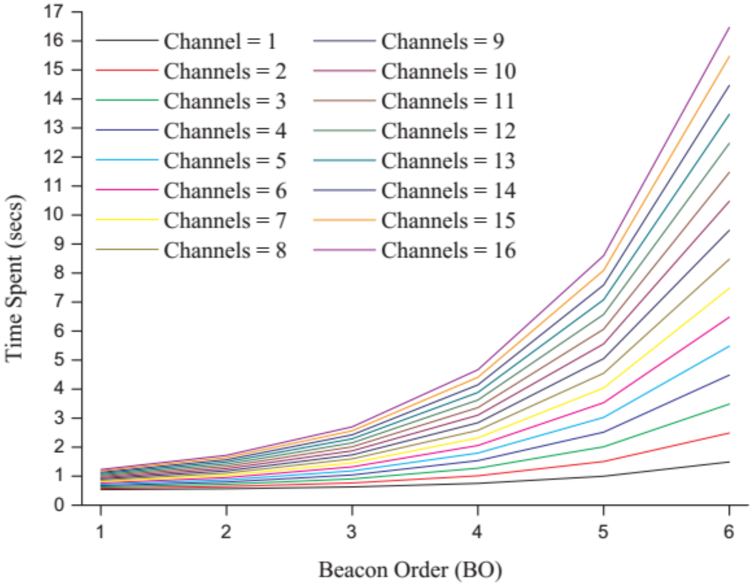
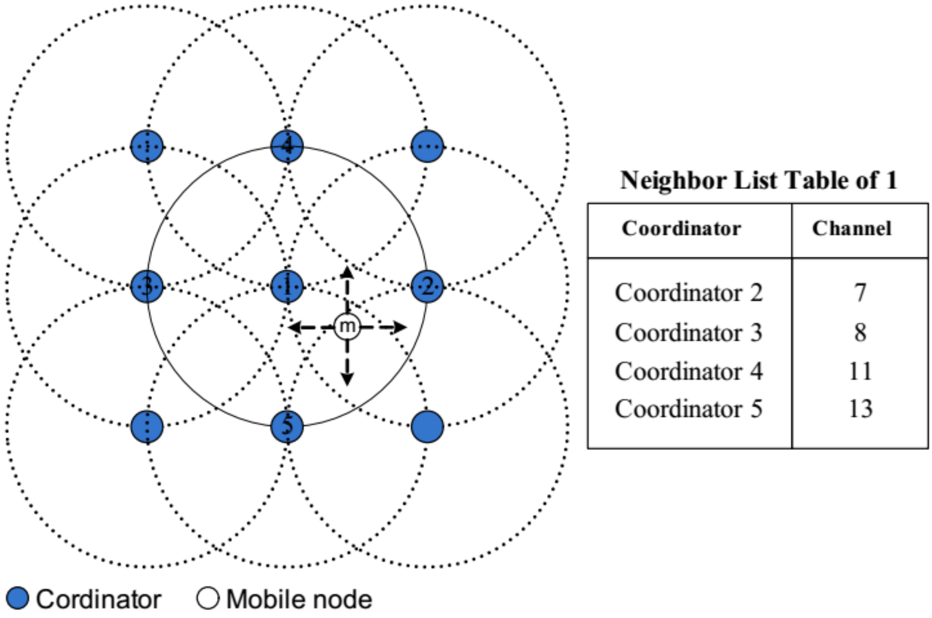


Figure 3.2: Time spent on association as the number of channels and BO varies.

3.4 Proposed Method

Channel scanning is the most time consuming part of the association procedure. The time spent on the association for various values of BO are shown in Figure 3.2. For every values of BO, the time spent on the association as the number of channels varies from 1 to 16 is shown in the figure. The figure illustrates that the association time increases as the number of channel increases. From the rigorous study of IEEE 802.15.4 standard, it is observed that prompt neighbor discovery could enable IEEE 802.15.4 in efficient mobility handling. The channel scanning for the coordinator discovery is the most time consuming process. If somehow the mobile nodes are deprived from scanning multiple channels, the node mobility can be efficiently handled. Similarly, the early detection of loss of connectivity can further decrease the association time. The detection of loss of connectivity by counting the number of lost beacons for *aMaxLostBeacons* times is time consuming. A speculative proactive scheme can considerably reduce the link breakage detection time.

The main idea of the proposed scheme is to maintain the list of all the neighboring coordinators and their operating channels so that whenever a connection is lost with the current coordinator, a new coordinator can be found immediately. Our proactive scheme



Neighbor List Table of 1

Coordinator	Channel
Coordinator 2	7
Coordinator 3	8
Coordinator 4	11
Coordinator 5	13

Figure 3.3: The network scenario.

of being aware of the neighbors limits the channel scanning to only those channels used by neighboring coordinators, saving both energy and time.

For the network model, a typical IEEE 802.15.4 network has been considered, which consists of coordinators and mobile nodes, as shown in Figure 3.3. Since each AP or coordinator covers only a limited area, a number of such coordinators need to be deployed to cover a larger area. The mobility of device causes frequent loss of connection with an APs. To maintain the sensor connectivity, sensor node frequently changes their AP by performing a mechanism known as a handover. In this work, we propose a simple but fast handover mechanism for IEEE 802.15.4 network.

In the proposed scheme, each coordinator maintains a list of all the neighboring coordinator and their operating channels. During the initialization of a coordinator, the coordinator performs ED and active scan as mentioned above. In our scheme, during the initialization stage, as a coordinator scans each channel, it saves the neighbor's id and working channel in a table called neighbor list table. At the end of initialization phase, each coordinator will have its neighbor list table, which contains information of all the neighbors. Once initialized, each coordinator broadcasts its neighbor list table in the beacon frame. However, we note that we do not propose to modify the beacon frame of IEEE

802.15.4. The Beacon Payload Field of the beacon can be used to transmit user data (up to 52 bytes). Thus, the neighbor list table can be transmitted in beacon payload field, without changing the standard format of the beacon frame. Mobile nodes use beacon from the parent coordinator for synchronization. Now, from the beacon, a mobile node can learn about all the neighboring coordinators even though the node cannot directly hear the coordinators. In our scheme, the mobile node also maintains the neighbor list table. In another word, both the coordinator and the mobile node share the same neighbor list table. As soon as the mobile node loses connection with the coordinator, the mobile node scans only those channels which are present in the list. Once it finds a new coordinator, it updates its neighbor list table same as with the new coordinator. Furthermore, in order to further decrease the association time, we propose to remove the orphan scan and directly perform the passive scan once a node lost its connectivity with the coordinator.

3.4.1 Initialization of a PAN Coordinator

In the proposed scheme, when an FFD is initialized, it performs the ED scan and the active scan in all the channels for finding out if there is any other FFD in the vicinity. If beacons are received, FFD saves the ID and the channel number in its neighbor list. Once all the channels are scanned, FFD can build its own PAN by broadcasting periodic beacons in a free channel (the channel where there is no other FFD). Once the FFD selects its suitable channel, it informs all its neighbor about its presence by sending beacon in their corresponding channels.

3.4.2 Coordinator Selection

A device that wants to perform association with a PAN can be a new (just on) or an orphan device. Unlike in IEEE 802.15.4, an unassociated node only performs the passive scan in the channels listed in the neighbor list table and scans each channel for the duration of t_{scan} symbols. Let's see a coordinator selection process with an example. Figure 3.3 shows our scheme in operation. Node 1, 2, 3, 4, and 5 are coordinators and *m* is a mobile node moving at the speed at 1 m/s. Initially, *m* is connected with the Coordinator 1, and the Coordinators 2, 3, 4, and 5 are the neighbors of 1. The right side of the figure shows the neighbor list table maintained by 1. As can be seen in the figure, the neighbor list table contains all the neighbors with their corresponding operating channels. The mobile node *m* also maintains the same neighbor list table of Coordinator 1 (current AP). The mobile node *m* can take any direction from its current position. Therefore, whenever, a node loses the connection with the current parent coordinator, only those channels listed in the neighbor list table are scanned for searching a new coordinator. It is patently clear that whichever direction *m* chooses to take, the new coordinator will always be the one among from the neighbor list table. In this way, the proposed scheme assists in prompt coordinator discovery without having to scan all the available channels.

Algorithm 1 The Proposed Scheme.

```
1. All coordinators maintain the neighbor list table
2. Coordinators share the table with member nodes
3. An orphan node only scans the channel listed in neighbor list table to find a new
   coordinator
```

3.5 Numerical Analysis

Let *n* be the number of available channels and *nc* be the average number of neighboring coordinators. Similarly, let *aBaseSuperFrameDuration* be the number of symbols that forms a superframe when SO=0 and t_{scan} symbols be the total time spent on a channel scan. In IEEE 802.15.4 standard, it takes equal duration to perform active, ED, and passive scan on a channel and is given by,

$$t_{scan} = aBaseSuperFrameDuration \times (2^{BO} + 1). \tag{3.1}$$

3.5.1 Association

The total time spent for the association process is the sum of the time utilized in the channel scanning and the time spent in the exchange of association messages ($Asso_{msg}$). A device desiring to get associated with a PAN can be a new device or orphan device. IEEE 802.15.4 has different procedures for the association of a new device and orphan devices. The total time spent for association by a newly joining device for both the protocols are given by,

$$t_{802.15.4\_asso} = n \times t_{scan} + Asso_{msg}. \tag{3.2}$$

$$t_{pro\_asso} = nc \times t_{scan} + Asso_{msg}. \tag{3.3}$$

3.5.2 Reassociation

In beacon-enabled IEEE 802.15.4, once a node knows that it has lost the connectivity with the PAN, an orphan scan is performed. An orphan node first performs the orphan scan on every channel for duration of *macResponseWaitTime (32×aBaseSuperFrameDuration)* symbols until its parent coordinator is found or all the *n* channels are scanned. Upon the failure of an orphan scan, a new parent is found through the passive scan as mentioned before. Therefore, the total time required for re-association process is given by,

$$t_{802.15.4\_reasso} = n \times macResponseWaitTime + t_{802.15.4\_asso}. \tag{3.4}$$

In the proposed scheme, (3.3) also gives the reassociation duration since there is no orphan scan. Thus, from the comparison of (3.3) with (3.4), it is obvious that the proposed scheme can decrease the re-association time of a node by many folds.

3.6 Numerical Example

Assuming network parameters of Table 3.2, we get *aBaseSuperFrameDuration* = 15.36 ms and *macResponseWaitTime* and $Asso_{msg}$ of 0.49s [9]. Assuming the node deployment scheme of Figure 3.1, each node has a maximum of 4 neighbors. Therefore, using the above values and equations, the association time for both original IEEE 802.15.4 and the proposed scheme are shown in Table 3.1. From the values shown in the table, we can claim that our scheme decreases the total association time of IEEE 802.15.4 by a significant amount. Similarly, the comparison of association and reassociation duration between IEEE 802.15.4 and the proposed protocol for all values of BO is shown in Figure 3.4.

Table 3.1: Total time spent on association.

	Association		**Re-Association**	
Channels	**802.15.4**	**Proposed**	**802.15.4**	**Proposed**
1	1.22 s	0.67 s	9.06 s	0.67 s
2	1.71 s	0.79 s	9.55 s	0.79 s
3	2.70 s	1.04 s	10.54 s	1.04 s
4	4.66 s	1.53 s	12.5 s	1.53 s
5	8.6 s	2.51 s	16.44 s	2.51 s
6	16.46 s	4.48 s	24.3 s	4.48 s

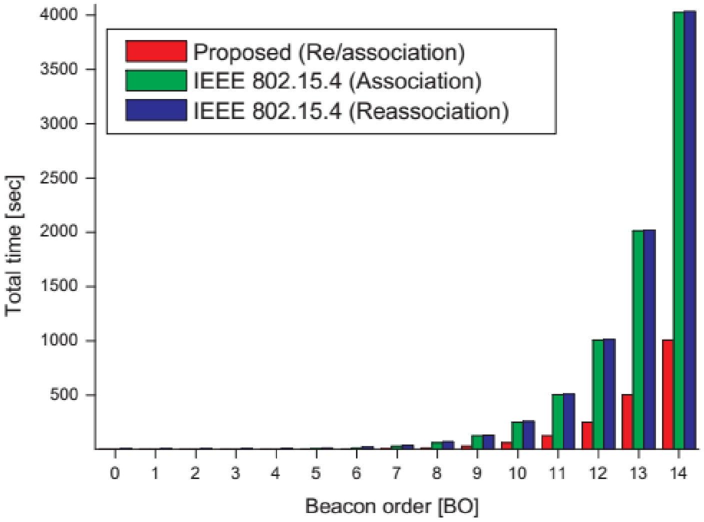


Figure 3.4: Comparison of association durations in 2.4 GHz for various values of BO.

3.7 Performance Evaluation

For the simulation, nodes are deployed in a 50×50 m field with the PAN coordinator located at the center as shown in Figure 3.5, where arrow heads demonstrate the movement of the mobile device. Nodes are distanced by 10 m and there is only one mobile node (node 9) and all others are coordinators. All coordinators broadcast beacon. In the simulation time of 100 s, the mobile node starts data transmission and starts to move at 110 s. The mobile node moves continuously while transmitting data to PAN coordinator. The simulation ends when the mobile node is back to its original start position. In all the simulations, SO is same as BO. The parameters of Table 3.2 are taken from CC2420 datasheet [43].

Table 3.2: Network parameters and values.

Parameter	**Value**	**Parameter**	**Value**
Assumed power supply	3 V	Number of Channels	16
Transition time	192 μs	Transmission range	10 m
Frequency band	2.4 GHz	Radio data rate	250 kbps
Routing	AODV	Traffic	CBR
Data rate	2 kbps	Buffer size	10 packets
Packet size	50 B		

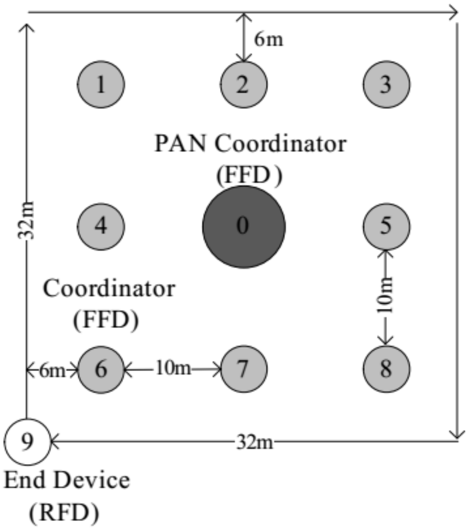


Figure 3.5: Topology in the simulation.

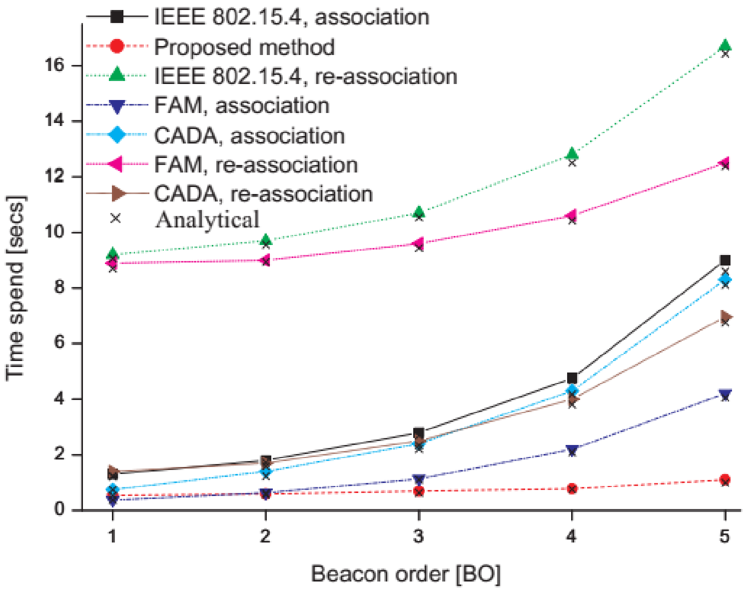


Figure 3.6: Total amount of time spent for association at different BIs

3.7.1 Association Time

Figure 3.6 shows the time spent for the re/association in terms of various BOs obtained from numerical analysis and NS-2 simulations. The proposed work has been compared with original IEEE 802.15.4 and two other related works: FAM [42] and CAPD [16]. In FAM, channel scanning stops as soon as a node finds a coordinator. However, it does not mention about the re-association process in detail. Therefore, we assume it uses default behavior of IEEE 802.15.4 to find parent coordinator (performs orphan scan) before it scans for a new coordinator. Similarly, In CAPD, it does not discuss channel scanning, therefore, we assume it uses default behavior of original IEEE 802.15.4 to perform channel scanning.

In order to calculate re/association time, (3.5) is used to calculate t_{scan} first. Then, (3.2) and (3.4) are used to calculate association and reassociation times respectively for IEEE 802.15.4. Since, the proposed method does not have separate orphan scan, (3.3) is used to calculate both association and reassociation times.

$$t_{scan} = aBaseSuperFrameDuration \times (2^{BO+1} + 1). \tag{3.5}$$

In all cases, the analytical results match well with the simulation results. As shown in the figure, the time required by the proposed method for re/association is much lower because

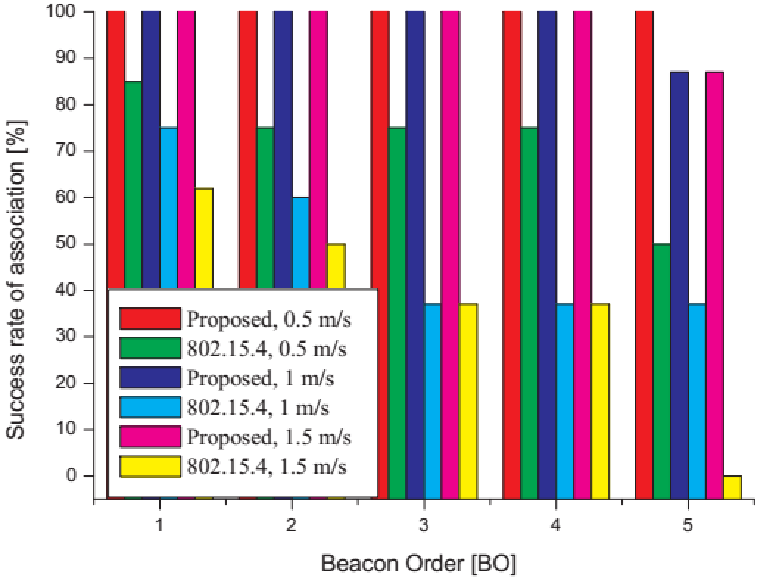


Figure 3.7: Association success rate at different beacon interval in the proposed method and IEEE 802.15.4 at 0.5 m/s, 1 m/s, and 1.5 m/s.

only a few channels are scanned for the association procedure. But, in the case of IEEE 802.15.4, FAM and CADA, they scan all available 16 channels spending a significant amount of time and energy. At BO = 3, the proposed method is able to decrease the node association time by 6 times and the re-association time by 16 times as compared with original IEEE 802.15.4.

3.7.2 Association Success Rate and Packet Delivery Ratio

The successful rate of association is evaluated as the ratio of a total number of successful associations to total number of associations possible. In our simulation, there are total eight associations possible before the mobile node comes to rest. BO was used same for all nodes. The proposed method increases the success rate of association of a mobile node by enabling quick passive discovery of a coordinator. The percentage of successful associations at different BOs and node speeds are shown in Figure 3.7. It was observed that even a slight mobility of node has a significant detrimental impact on the association process in the case of IEEE 802.15.4. At the human walking speed at 1.5 m/s, original IEEE 802.15.4 had a poor success rate of association even at the low values of BO and

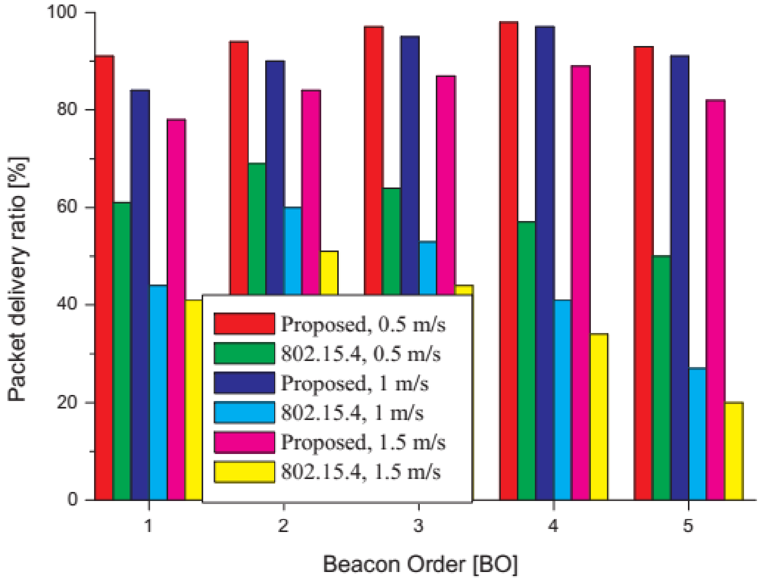


Figure 3.8: PDR at different beacon intervals in the proposed method and IEEE 802.15.4 at 0.5 m/s, 1 m/s, and 1.5 m/s.

nodes were completely unable to associate at BO = 5. It is observed that the poor association ratio of IEEE 802.15.4 is due to the long duration required for reassociation. The time spent by the mobile node within the coverage range of a coordinator might not be sufficient to complete the association, which accounts for poor association rate. However, in the case of proposed method, association rate was 100% until BO of 4 and even at BO of 5, proposed method could successfully perform 7 associations out of 8. However, at mobile node speed at 1.5 m/s, proposed method was completely unable to associate at BO$\geq$9. Figure 3.8 shows the throughput observed at the PAN coordinator in the packet delivery ratio (PDR). Due to IEEE 802.15.4 lengthy association time, most of the generated packets were dropped. As it can be seen from the graph, PDR was just 60% even at BO=1 and node speed at 0.5 m/s. However, the prompt re/association capability of the proposed method enabled a mobile node to transmit most of the generated data frame to the coordinator which increases the overall throughput of the network. We can see in Figure 3.8 that PDR of proposed method is significantly better than that of IEEE 802.15.4 for various node speeds, which leads to the better throughput. At node speed at 1.5 m/s and BO of 5, the PDR of original IEEE 802.15.4 was just 20% due to the fact that the mobile node 9 got some opportunity for data transmission through node 6 before

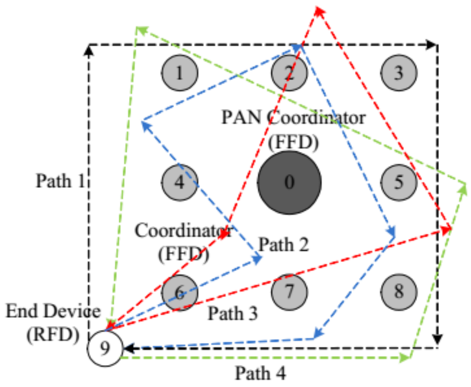


Figure 3.9: Four random paths taken by the mobile node.

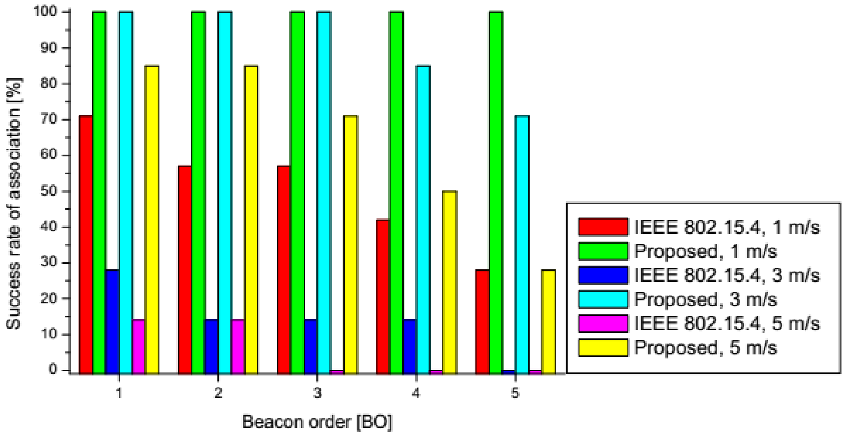


Figure 3.10: Successful association rate for random motion.

the mobile node starts to move and could not associate then after. However, the PDR of proposed scheme was of 82% for the same situation.

3.7.3 Association rate for the random motion

To simulate a random motion of a person, the mobile node is moved in the paths illustrated in Figure 3.9. The mobile node is allowed to choose a random path during a simulation and follows that path during the entire duration of the simulation. The BO is varied and the speed of the mobile node is varied from 1m/s to 5m/s and the obtained association success rate is plotted in Figure 3.10. The results show that under a normal walking condition, for node speed up to 3m/s, the proposed model can perform 100%

association (for BO=3). However, once the node speed increases beyond 3m/s, the association success rate gradually decreases. Also, for the node speed at 5m/s, the success rate of association is around 28%, and the node is completely unable to perform once the speed is beyond 9m/s.

3.8 Concluding Remarks

In this chapter, a new association scheme for IEEE 802.15.4 is presented that can decrease the association time by several folds. The proposed method uses the proactive scheme of maintaining the list of all the neighbors and their operating channels, which prevents nodes from scanning multiple channels; consequently, decreasing the association time. Our simulation and analytical results illustrated that our proposed scheme is highly efficient and saves the considerable amount of time. The implementation of proposed scheme gives IEEE 802.15.4 the new direction to handle mobility.

Chapter 4

Conclusions

In this thesis, we presented a new approach to improve the association delay in IEEE 802.15.4 network. The remarkable attributes of the proposed improvised approaches are simple and easy to implement. Such attributes make the proposed approaches attractive for practical implementation in the real-world mobile sensor network applications. In the following paragraphs, we summarize this thesis in the order they have appeared.

In Chapter 1, a brief introduction to the current trends in wireless networks was presented along with the research objective of this thesis.

Similarly, in Chapter 2, the main attributes of IEEE 802.15.4 is presented and the association procedure is explained in detail.

In Chapter 3, the fast association technique is presented. We showed through numerical analysis and simulation that channel scanning is the key reason for long association delay in IEEE 802.15.4. The proposed method prevents nodes from scanning multiple channels, thus, decreasing the association delay. Our approach results in significant improvement by reducing the number of channels a node has to scan. Experimental results have demonstrated that our schemes work well.

Our fast association methods are simple and can be implemented in any infrastructure based network. We expect that our proposed methods will be beneficial in various sensor network applications.

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Acknowledgement

The journey of my two years of Master's degree in Computer Engineering at Chosun University, South Korea is now almost at the end of the completion. It would have not been possible without the profound support of many people around me. First of all, I would like to express my sincere gratitude to my respected parents for having so much faith on me, for believing me and for constantly supporting me in each and every step of my life. Hence, I would like to dedicate my degree to my beloved dad Mr.Suddhi Nepali and my dear mom Mrs. Sumitra Amatya Nepali.

Likewise, I would like to thank my advisor Prof. Shin Seokjoo for all his guidance, advice, and support. Working with Prof. Shin has been a great learning experience, which I believe would be very useful to take my future career assignments in a very confident way.

Furthermore, I would like to thank my thesis committee members Prof. Sangman Moh and Prof. Moonsoo Kang for their valuable comments and expertise feedbacks. Likewise, I would like to thank all anonymous reviewers at different leading international conferences and reputed journals for their time and efforts they spend in giving valuable feedbacks for the manuscripts that I have submitted for possible publication. Their suggestions have certainly raised the quality of those manuscripts, which are the foundation of this thesis.

Finally, I am very grateful and deeply indebted to my dear friend Dr. Pranesh Sthapit for his unconditional support, motivation, and encouragement throughout my stay in Korea.

Samrachana Nepali