Establishment and optimization of wireless sensor network for micro-grid demand response system and body area networks

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**Establishment and Optimization
of Wireless Sensor Network
for Micro-grid Demand Response System
and Body Area Networks**

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A dissertation submitted to the Nanyang Technological University
in fulfillment of the requirement for the degree of Doctor of Philosophy

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Summary

Sensor network has attracted worldwide attention over two decades, particularly with the proliferation in Micro-Electro-Mechanical Systems (MEMS) technology which has facilitated the development of smart sensors. Unlike traditional networks, wireless sensor network has its own resource constraints which include a limited amount of energy, short communication range, low bandwidth, and limited processing and storage in each node. This dissertation presents the development of the cross layer optimization to solve the compensation for overload, latency or other mismatch of requirements and resources without considering the hierarchical structure of Open System Interconnection (OSI) model with strict boundaries between layers. To implement the cross layer optimization of link layer and MAC layer, in this thesis, interference mitigation without feedback channel in the wireless body area network (WBAN) and feedback overhead reduction in the smart electric vehicle charging system are investigated as applications.

Firstly, the link layer optimization in the wireless body area network is presented to maximize link capacity between transmitter and receiver by considering interference mitigation. Pseudo orthogonal resource allocation patterns are proposed to mitigate the interference in the wireless body area network. To design pseudo orthogonal resource allocation patterns, it is necessary to analyze the properties of a pseudo orthogonal code (POC). By considering the properties of the distance matrix of a pseudo orthogonal code, the low bound of the length of the pseudo orthogonal code is theoretically calculated. However, to optimize data throughput of the resource allocation, the trade-off relationship between the orthogonal properties of a POC and the quantity of resource allocation of WBAN is considered. To mitigate the collisions, the two dimensional resource allocation patterns are proposed, where random assignment of codewords to time domain and that of

frequency sub-channel offsets are considered. In addition, based on the properties of correlation and cyclic shift on the POC, the transmission efficiency of WBAN is calculated. Based on the low bound of a POC and the transmission efficiency, the optimal quantity of resource allocation of each WBAN is theoretically analyzed, which is exactly the ratio of the length of a POC to the number of WBANs in the system. The simulation results illuminate that the theoretical low bound of the proposed scheme is more close to the real structure of POC compared to the conventional schemes.

The other application of WSN is the electric vehicle (EV) charging system in the MAC layer, which optimizes the scheduling of data transmission. The penetration of EV charging system imposes a heavy burden on the conventional power distribution system, so that the coordination of EV charging demands is required via a bi-directional real time monitoring system. However, it may cause the performance degradation in the whole EV charging system due to the significant control signal overhead. To mitigate the control signal overhead from electric vehicles to a central controller, the threshold based charging scheme in electric vehicle charging system is proposed, which only EVs with low level of battery state of charge below the predetermined charging threshold can transmit their charging request to controller. In the simulation results, the proposed threshold based charging scheme can achieve the reduction of the control signaling overhead and the satisfactory charging performance.

Chapter 1

1. Introduction

1.1 Motivation

A sensor network has attracted worldwide attention over several decades, particularly with the proliferation in Micro-Electro-Mechanical Systems (MEMS) technology which has facilitated the development of smart sensors [1-3]. These MEMS sensors are small, with limited processing and computing resources with an inexpensive price compared to the traditional sensors. Thus, the sensor network has a great potential for many applications in scenarios such as military target tracking and surveillance, natural disaster relief, biomedical health monitoring, and hazardous environment exploration, seismic sensing, wearable devices, and entertainment [4-8].

Sensor nodes are low power devices which are composed of one or more sensors, a processor, memory, a power supply, radio frequency devices, and an actuator [2, 5]. These sensor nodes can sense, measure, and gather information from the environment, and they can transmit the sensed data to the user or controller. A variety of mechanical, thermal, biological, chemical, optical, and magnetic sensors may be attached to the sensor node to measure the properties of the environment. Since the sensor nodes have limited memory and are typically deployed in difficult-to-access locations, data transmissions are implemented for wired or wireless communication to a controller (e.g., a laptop, a personal handheld device, or an access point to a fixed infrastructure). Unlike traditional networks, the sensor network has its own design and resource constraints [3, 5, 6, 9, 10]. Design constraints and applications of the sensor network are dependent on the monitored

environment. Resource constraints include a limited amount of energy, short communication range, low bandwidth, and limited processing and storage in each node. In addition, the environment which set up the sensor network plays a key role in determining the size of the network, the deployment scheme, and the network topology [5, 11, 12].

Due to these limitations of the sensor network, it is necessary to study a cross layer optimization [9, 10, 13-15]. The cross layer optimization can avoid the hierarchical structure of the Open System Interconnection (OSI) model with strict boundaries between layers, which the data of each layer is transacted strictly within a given layer [16-18]. Thus, to solve the compensation for overload, latency or other mismatch of requirements and resources, the cross layer approach permits information exchange and interaction through the layer boundaries dynamically. For example, if the current channel state in the PHY layer is known by MAC layer, a channel allocation scheme or an automatic repeat request (ARQ) strategy at the MAC layer is assisted to achieve throughput maximization. Therefore, in this dissertation, we consider a cross layer optimization approach between link layer and MAC layer to optimize the performance of the sensor network.

To achieve the cross layer optimization between link layer and MAC layer, methodologies to optimize for each layer are considered for the initial step. Afterwards, the integration of both optimization methodologies aims at the cross layer optimization. Therefore, we seek representative systems for link layer and MAC layer respectively, and study to optimize the representative system for each layer.

In the case of link layer, a pseudo orthogonal resource allocation scheme is studied to mitigate interferences without feedback channel in the wireless body area network. Wireless body area network (WBAN) is an emerging research topic in the sensor network

[19, 20]. WBAN is a short-range wireless sensor communication which is within, on, and in the immediate proximity of a human body for the usage of various proposes such as military, entertainment and medical devices as shown in the *Figure 1-1* [2, 3, 21]. WBAN consists of multiple wireless sensor nodes, and provides a reliable link for body signal transmission by considering the internal electrical property of the human body or wireless links near the human body. However, there are some technical challenges in the existing body area network design, including limited battery life, low transmission data rate, poor resilience to environment interference, human mobility and low spectral efficiency. One of the significant problems is the interference mitigation among sensor nodes. These are the reasons why we decide WBAN as representative example for link layer.

Figure 1-1 Wireless body area network applications [2, 3, 21].

In the MAC layer, to reduce control signaling overhead in the electric vehicle (EV) charging system, a threshold-based charging system is considered. When the EV charging system is penetrated to a conventional power distribution system, smart sensor network is considered to mitigate the negative effect of the penetration of electric vehicles (EVs) [22-24]. There are several previous researches on the uncoordinated EV charging system, which the penetration of EVs becomes the burden of the conventional power distribution system when the demand of residential loads is concentrated [24-26]. Thus, a bi-directional real time monitoring is necessary to distribute the demand from residential and EVs. However, the bi-directional real time monitoring scheme requires significant control signaling overhead for coordination purposes, so that the huge burden of the control signal overhead will cause the performance degradation of total power distribution system [27, 28]. Therefore, this is the reason why the EV charging system is selected as MAC layer problem.

1.2 Research objective

To solve technical challenges of WBAN, the pseudo orthogonal resource allocation scheme based on a pseudo orthogonal code (POC) is proposed to mitigate interference among WBANs with asynchronous environment and without a feedback channel. Pseudo orthogonal code (POC) is a collection of binary sequences with good correlation properties, which is widely used for protocol sequence, code division multiple access in the fiber optics, user identification and frame synchronization [29-31]. Most of previous researches focus on calculating the theoretical upper bound of the cardinality of a POC within the prefixed length of code, correlation properties and Hamming weight, because the cardinality represents the capability of services at the same time [32-37]. However,

the calculation of the amount of capable resources is needed when the estimated number of users is predetermined in wireless communication system. For example, code division multiple access system has used the predetermine number of gold codes [38-40]. In addition, in terms of the analysis of pseudo orthogonal resource allocation pattern, it is necessary to study the low bound of length of a POC under the given cardinality, because the quantity of resources and the number of users mean the length of and the cardinality of a POC, relatively. In this thesis, to analyze the properties of a POC, the distance matrix of the POC is introduced. By exploiting the properties of the distance matrix, the new theoretical low bound of the length of a POC is proposed.

Based on these properties of a POC such as correlation and the minimum length of pseudo orthogonal code, the pseudo orthogonal resource allocation without feedback channel in the WBAN system is proposed to mitigate interference among sensor nodes. In terms of the resource allocation, both the orthogonality of resource allocation patterns and the efficiency of data transmission are equally significant. Based on the correlation properties of a POC, the transmission efficiency of WBAN is theoretically calculated. Afterwards, in order to maximize the transmission efficiency of WBAN, the optimal amount of resource allocation is proposed, which is exactly the ratio of the length of a POC to the number of WBANs in the system.

In the EV charging system, the control signal overhead to coordinate the EV charging system and the conventional power distribution system may causes the performance degradation of total power distribution system [27, 28]. To resolve this problem, the threshold based charging scheme is proposed by deriving inspiration from selective multiple user diversity in wireless communication [41-46]. The threshold based charging scheme is that only EVs had low level of battery state of charge below the predetermined

charging threshold can transmit their charging request signal to controller whereas those above the predetermined threshold cannot transmit their signals. To further mitigate the control signal overhead, the hybrid threshold based charging scheme with combining the random access method is considered, which the EVs randomly transmit their BSOC information with the predetermined access rate after the specific charging period.

By aggregating both optimization schemes of link layer and MAC layer, the cross layer optimization for the sensor network is designed in the future work. For instance, in the smart EV charging system, uplink control signal channels are considered by random access channels. Therefore, the additional improvement of the random access channel is possible through the pseudo orthogonal access pattern, which is designed by using the properties of POC to obtain the robustness of the collisions.

1.3 Organization

After the introduction in Chapter 1, Chapter 2 introduces the previous researches on the sensor networks. Chapter 3 describes the properties of the distance matrix on a pseudo orthogonal code is studied to calculate the low bound of the length of a POC with general correlation. In Chapter 4, the application of pseudo orthogonal code is shown as pseudo orthogonal resource allocation patterns to mitigate interference without feedback channel in the wireless body area network. In the case of the resource allocation, transmission efficiency is also important. Thus, the transmission efficiency is theoretically analyzed by using the properties of auto- and cross-correlation and the optimal quantity of resource allocation is proposed in order to maximize the transmission efficiency. Chapter 5 explains that the threshold based charging scheme is proposed to achieve the performance improvement of EV charging system through the smart charging system, which can

reduce a control signal overhead by the concept of multiple user diversity and the distributed system as the example for a MAC layer. Chapter 6 describes that future works can be extended by all of the proposed researches.

Chapter 2

2. Literature review

2.1 Pseudo orthogonal code

In order to accommodate the expected growth in wireless sensor networks, ad-hoc networks and radio-frequency identification (RFID), the simple and efficient multiple-access algorithms for these systems are necessitated. Randomness is widely exploited to design the multiple-access schemes [30, 47, 48]. For example, when collisions occur in ALOHA system [49, 50], transmitters should independently wait for random time before trying to send their data again. To implement the random access schemes in practice, pseudo random sequence is usually used for random parameters [51-53]. However, there are complexity problems to generate high-quality pseudo random numbers, because computing power and battery are limited in wireless sensor networks. To solve this problem, there are several different methods to conduct random multiple-access algorithms and generate randomness.

The deterministic coding sequences which is defined by random access protocol without feedback channel can commence with the seminal research of Massey and Mathys [29]. The protocol sequence is binary sequences which can successfully transmit at least one packet in the predetermined length of time slots. The zero error sum-capacity is characterized by e^{-1} in the collision channel without feedback, which is defined for all non-empty subsets of users, not just for pairs of users. Protocol sequences with high-quality auto- and cross-correlation properties are called shift-invariant sequences [29, 54, 55]. The advantage of the shift-invariant protocol sequences is less fluctuation of system

throughput according to the delay offsets. Nevertheless, as the number of users increases in the system, the period of the shift-invariant protocol sequences exponentially increases [54]. The increment of the period may indicate that individual users undergo low system throughput, because the throughput of the shift-invariant protocol sequences is averaged over a long period. In this reason, the shift invariant protocol sequences have the significant degradation of system throughput.

Afterward, more constructions of protocol sequences are investigated, such as a cyclically permutable constant-weight code, or an optical orthogonal code (OOC) [32, 35, 37, 56-96]. OOC is introduced for a multiuser communication network in the optical fiber. The usage of code-division multiple-access (CDMA) technique is considered especially, which allows many users to share a single optical channel by assigning unique orthogonal or pseudo orthogonal sequences. CDMA had a long history and was widely used in the 2G cellular network. In the cellular network, the modulated signals passed through the wireless channels are composed of positive and negative components, so that the binary phase-shift keying scheme is normally used when the received signals are demodulated. However, the optical systems is incoherent processing where only signal intensity is measured, and the performance of optical system has an important influence of the design of OOC [35].

According to the auto- and cross-correlation and the dimension of code, OOC has a diversity of constructions. 1-D OOC with the same auto- and cross-correlation has been introduced [35, 56-80], and there are several prior works conducted in the case of different auto- and cross-correlation [32, 37, 81-87]. Furthermore, 2-D OOC has been studied to improve the bandwidth utilization compared with 1-D OOC [61, 88, 90, 91, 93, 94]. *Figure 2-1* shows 2-D cross-correlation array of two different OOCs. In the previous

researches [88, 91, 95], OOC with the same auto- and cross-correlation are investigated, whereas T.L. Alderson et al [57] is carried out with different auto- and cross-correlation. However, the limitation of all of these works is that the calculation of the upper bound of the cardinality of an OOC is focused except [94]. Otherwise, the low bound of the OOC length with the fixed cardinality and the auto- and cross-correlation of 1 is adduced in [94]. However, it is necessary to improve the low bound of the length of an OOC in [94] due to the wrong conditions.

In order to achieve the short period length and small variance of Hamming cross-correlation, another class of protocol sequences, called by Chinese remainder theorem (CRT) code, is considered in [30]. CRT code is a result about congruence in number theory and related to the correlation among different codewords. Thus, CRT code is basically similar to OOC in terms of the construction of the protocol sequences. The only difference is that CRT sequences have dense Hamming weight compared with an OOC, so that the properties of auto- or/and cross-correlation may be degraded.

As a result, most of previous researches focus on designing the structure of pseudo orthogonal code (POC), or calculating the upper bound of the cardinality of a POC. However, in wireless communication, the number of users which are serviced at the same time is predetermined by considering resource capacity, the estimated number of users, and spectral efficiency. For example, the code division multiple access system has predetermined the number of the gold codes according to the estimated number of serviced users in each base station [38-40]. Therefore, the consideration of minimum length of a POC with a given cardinality is also necessary to analyze the system efficiency of the resource allocation without feedback channel. There are several previous researches [32, 35, 94] related to the theoretical analysis on the low bound of the length of

a POC, which were inadequately represented by the properties of a POC under the certain conditions. Especially, the low bound of the length of a POC is only directly described in [94], which is calculated according to the properties of the distance matrix between Hamming weights. However, this bound does not approximate to the actual length of a POC. In this thesis, to apply the pseudo orthogonal resource allocation without feedback channel in the wireless sensor network, the calculation of theoretical low bound of length of a POC with given correlations is concentrated and accurately improved.

Figure 2-1 2D cross-correlation array with three squares shifted vertically and one square shifted horizontally from the top-left corner in the expanded plane of x by a 2 x 2 arrangement. The overlapped slot means a hit.

2.2 Wireless body area network

In developed countries over the last 30 years, the age structure of their population has been significantly changed. There are continuously growing trends towards relative increment of the number of elder persons, especially those who are aged 80 and more, over the next decades [97]. In addition, developing countries will become an ageing society according to the economic growth of the developing countries. Therefore, the serious problems of this aging society may happen, which are related to the decrement of industrial productive and the increment in average life expectancy, the necessity of improvement in living conditions and the cost increment of health care. This draws public attraction to the introduction of novel technologies, which small and intelligent (bio-) medical sensors can be worn on or implanted in the human body.

It is necessary for these medical sensors to send their measured data to an external medical server, which the server can store and analyze the measured data. To achieve this purpose, the usage of a wired connection is unamenable due to high costs for deployment and maintenance. Patient mobility is the significantly important issue of the actual discussion about the future development of the health care systems, because the patient is not constrained to stay in a hospital any longer. Thus, the usage of a wireless interface has an advantage of cost efficient and easier installation [98]. Currently, eHealth and mHealth are introduced as a health care platform for enhancing the personal health care and the continuous health status measure system, as well as decreasing the costs of the health care system. For example, numerous diseases would benefit from continuous or prolonged monitoring, such as Alzheimer's disease, asthma, Cardiovascular disease (CVD), diabetes hypertension, renal failure, Parkinson's disease, post-operative monitoring, and stress-monitoring [20, 99]. Thus, it shows not only the necessity of continuous health

monitoring system and usefulness of WBANs, but also the increment of the market size for WBANs. To fully obtain the benefits telemedicine called by eHealth and mHealth, a new protocol of wireless network is necessary: a wireless on-body network or a Wireless Body Area Network (WBAN) [2, 21, 100-104].

Furthermore, WBAN can be easily extended to for various applications such as wearable devices, entertainment, and public safety [3, 20, 97]. For instance, WBAN detects a life threatening emergency such as the high level of poisonous gases, and warns the soldiers or firefighters. Another application of WBAN is wearable devices, neural interface devices and head-mounted displays. And also, WBAN can become one solution to make virtual reality. As a result, all of the application of the WBAN is already showing the huge potential and the main characteristic of WBAN can enhance human's quality of life.

To actually implement the communication between WBAN devices, Wireless Sensor Network (WSN) or ad-hoc network protocols can be widely used as shown as *Table 2-1*. According to the typical properties of WBAN, however conventional protocols which are installed for WSN and ad-hoc network are not suitable for WBAN. WBAN emphasizes the following characteristics compared with WSN:

1. Wireless sensors for body area network have a limitation of energy resource such as battery, because the spatial factor of the sensors is important (less than 1 cm^3 [20]). Although a long lifetime of the wireless sensors is required, it is difficult for most wireless sensors to recharge the batteries. In addition, the computational power and available memory of wireless sensor will be also limited by restricting the spatial factor;

Table 2-1 characteristics of candidate protocols for WBAN [97]

Protocol	Spectrum	Data rate	Operating space	Peak power	Topology
Bluetooth classic	2.4GHz	1-3 Mb/s	1–10 m on-body only	~45mA @3.3V	Scatternet
Bluetooth low energy	2.4GHz	1 Mb/s	1–10 m on-body only	~28mA @3.3V	Piconet, Star
ZigBee	2.4GHz	250 kb/s	1–100 m on-body only	~16.5mA @1.8V	Star, Mesh
ANT	2.4GHz	1 Mb/s	1–30 m on-body only	~22mA @3.3V	Star, Tree or Mesh
Sensium	868MHz 915MHz	50kb/s	1-5 m on-body only	~3mA @1.2V	Star
Zarlink ZL70101	402-405MHz 433-434MHz	200-800kb/s	2 m in-body only	~5mA @3.3V	P2P

2. WBAN is typically considered as a heterogeneous network, but WBAN may have different structures compared with the cellular network, which are different demands and resource requirements in terms of system reliability, security, power consumption and data rate. Most current implementations of WBANs are based on Bluetooth (IEEE 802.15.1) [105], IEEE 802.15.4 [106, 107] or ZigBee [108], and the characteristics of candidate protocols for WBAN are given in *Table 2-1*. It means that WBAN coexists with other types of protocol. However, it is difficult for WBAN to achieve the cooperation with other technologies because of the limitations of WBAN sensors such as a battery and calculation capability;

3. The transmit power of each wireless sensor is minimized to mitigate the interference between wireless sensor nodes and the effect of the wireless sensors on the body [109, 110]. The harmful effect on the body which is caused from electromagnetic radiation of radio frequency should be considered within recommended specific absorption rate (SAR) constraints [111, 112]. In the United States, Federal Communications Commission limits to a SAR level at or below 1.6W/kg in 1g of tissue as the safe exposure. Therefore, the transmission power of WBAN is constrained;

4. The devices are located on the human body that can be changed by human motion. Therefore, WBANs should devise the change of network topology and interference control. Because, the movement and mobility of human can cause the distance variation between the transmitter and the receiver in the inter-cells or intra-cell. Especially, as the human motion can block the line of sight which has the direct path between the transmitter and the receiver antenna without any obstacle, the path loss of channel is significantly increased up to 30 dB [113]. In addition, the decrement of the distance from the other WBANs can give rise to the drastic increment of interference;

5. The channel between the wireless sensor nodes is a lossy medium, because signals are propagated along, in or on the body [111, 114, 115]. The order of magnitude of the path loss from front to behind body is approximate to the power of the multipath components for a medium sized room [116]. In addition, IEEE 802.15 Special Interest Group's first report concluded that WBAN should be operated within the limited range of body (<0.01 to 2 meters) [112]. Therefore, the cell coverage of each WBAN and the number of

interfered WBANs are restricted due to the lossy medium of body and limited transmission power;

Figure 2-2 Radar charts for characteristic comparison analysis among Wireless Body Area Network (WBAN), Wireless Sensor Network (WSN), and Wireless Local Area Network (WLAN) [20].

6. The data mostly consists of medical information. Hence, high reliability and low delay is required.

From these properties of WBAN compared to other networks as *Figure 2-2*, WBAN is more difficult to control inter- and inner-cell interference due to the limited power, limited calculation capability, mobility of patient, and non-cooperation among WBANs [9, 117-119]. In this dissertation, a pseudo orthogonal resource allocation method of the WBAN system is proposed, which is the generation method for resource allocation patterns to minimize the collisions among different resource patterns by using the

properties of a pseudo orthogonal code. And also, by deserting the control signal channel and cooperation among inter-WBANs, the proposed pseudo orthogonal resource allocation can have the advantages of receiver antenna space, battery saving and calculation complexity. Therefore, the proposed pseudo orthogonal resource allocation scheme can achieve both the mitigation of interference among WBANs and the alleviation of WBAN constraints such as limited power and calculation capability.

2.3 Smart charging in electric vehicle system

Due to fossil fuels depletion and threats from global warming, relevant authorities have been pressured to look into green efforts in the current developments. With aims of creating a sustainable future, development of EVs are widely discussed and researched. EVs have advantages in terms of environment, energy efficiency and energy resilience. In the case of environment, EVs typically generate less air and noise pollutions than internal combustion engine vehicles, whether EVs are at rest or in motion [120]. And also, the mechanism of EV is really simple due to the uselessness of gearboxes and torque converters, so that the energy conversion efficiency of 90% can be obtained [121]. Another advantage of EVs is energy resilience. Electricity is a form of energy that remains within the country or region where it was produced and can be multi-sourced. As a result it gives the greatest degree of energy resilience.

There are two types of EVs' charging system; 1) plug-in EVs (PEVs), and 2) battery replacement charging system [122]. PEVs usually charge the electric plug in the conventional power distribution system. PEVs take advantages that the connection infrastructure can be minimized and the additional charge station doesn't need. Usually, a charging process can be completed night time, because the charging process takes time.

Although the charging process is implementing avoid the normal usage, the penetration of EVs system into the conventional power distribution system seems to be not a sustainable solution [24-26]. Since the charging of EVs is uncoordinated in the existing network distribution, the penetration of EVs will eventually become the huge burden for conventional networks on top of the demanding residential loads to support [27, 28, 123]. By imposing smart charging system, which optimizes the charging of EVs with coordination, several studies [22-26, 123, 124] have been performed to analyze the possible impact on power system due to EV charging load. Some studies have proposed to mitigate the impacts by minimizing increases in peak load [23, 24], minimizing costs of charging, minimizing power losses [26, 124] or maximizing profits from discharging, i.e. vehicle-to-grid [22]. In addition, the maximization of the total amount of energy that can be transmitted to all EVs under the network limitations is completed is studied when a charging period [25]. Therefore, most of the research done so far mainly discuss about optimizing charging system by minimizing network/power losses and voltage deviation or by maximizing the total delivery power to EVs. Recently, Clement-Nyns et al. (2010) considered computational time as the part of performance rating among all the studies reviewed [22]. However, most research on smart charging system [22-26, 123-125] requires significantly huge amount of system controlling signal overhead for coordination purposes. As a result, the enormous signal overhead takes a toll on charging system and causes performance degradation. In this thesis, instead of minimizing the power loss of the power distribution system, the feedback overhead reduction scheme in the EV charging system is proposed, which the concept of the proposed reduction scheme is derives from the opportunistic user scheduling techniques in the wireless communication.

2.4 Selective multiple user diversity

In multiple user packet switched wireless networks (i.e., 4 Generation mobile communication), multiuser diversity (MUD) is obtained by opportunistic user scheduling which the transmitter manages the priority of users through the qualities of each channel between the transmitter and each receiver at any given packet [42-44, 126]. Although an average Signal to Noise Ratio (SNR) is a function of the distance between base station and mobile station, the channel is fluctuating over time, called by channel fading, due to the scattering and reflection of transmitted signals [127, 128]. Thus, each receiver must send the channel quality information such as signal to noise ratio (SNR) to the transmitter, in order for the transmitter to achieve multiuser diversity. *Figure 2-3* shows the schematic diagram of multiuser diversity in the base station. All of the mobile stations send their channel information to the base station, the base station allocates the mobile station with the best channel condition to the frame. Due to the wireless channel is fluctuating according to time, the channel condition is improved by the increment of the number of the mobile stations in the system. One drawback of MUD is that enormous feedback overhead is required in proportion to the number of the instantaneous channels from all candidate users to the transmitter or base station.

To solve this problem, selective multiple user diversity (SMUD) scheme is widely used to achieve both feedback overhead reduction and multiple user diversity [41, 46, 129-131]. In the SMUD scheme, users who have a better channel condition than a predetermined threshold transmit their requests for data transmissions with their channel information to base station, and the others remains silent. And then, the base station prioritizes the users to allocate data transmission. As a portion of users who can participate in the request of data transmission to the base station, it is possible to reduce the control signaling

overhead compared with the conventional multiple user diversity schemes. Therefore, SMUD can obtain multiple user diversity and mitigate the control signaling overhead. In this reason, SMUD is widely known to a kind of distributed scheduling algorithms. Based on this concept of SMUD, in this thesis, the reduction algorithm for the control signaling overhead of the EV charging system is proposed, which only EVs with low level of battery state of charge can participate in the battery charging process.

Figure 2-3 Schematic diagram of multiuser diversity in the base station. Solid lines indicate channel condition of each mobile station. Dotted line implies the selected channel condition through user scheduling. The selected channel condition in MUD is the best among the channel condition of mobile stations.

Chapter 3

3. Properties of a Pseudo Orthogonal Code (POC) according to Correlation

In this chapter, the new theoretical low bound of the length of a POC with given cardinality is proposed by exploiting the properties of the distance matrix. According to the correlation and Hamming weight, the distance matrix has different properties such as the number of the same valued elements. By considering these properties, the proposed low bound of a POC is calculated. The simulation results illuminate that the proposed theoretical analysis is more approximate to the computer simulation compared to previous researches of [32, 35, 94].

3.1 Definitions and Notations

3.1.1 Pseudo Orthogonal Code

Pseudo orthogonal code (POC) is a collection of binary sequences with good auto- and cross-correlation. In this chapter, the c -cardinality of a $(L_T, \omega, \lambda_a, \lambda_c)$ -POC is considered, where L_T is the length of pseudo orthogonal code, ω is the Hamming weight, λ_a is the auto-correlation, and λ_c is the cross-correlation. When λ_a and λ_c are smaller, a $(L_T, \omega, \lambda_a, \lambda_c)$ -POC has better pseudo orthogonality, and L_T also increases to achieve the

better pseudo orthogonality with the fixed the cardinality of the POC. $\Phi(L_T, \omega, \lambda_a, \lambda_c)$ denotes the cardinality of a $(L_T, \omega, \lambda_a, \lambda_c)$ -POC, which is equal to c .

3.1.2 Auto- and cross-correlation

The auto- and cross-correlation of a POC are necessary to evaluate the orthogonal properties of the POC. In [5], the auto-correlation of a pseudo orthogonal codeword $s_1[n]$ with a minimum length L_T can be represented by

$$Z_{s_1 s_1}[k] := \sum_{n=0}^{L_T-1} s_1[n] s_1[n-k] \quad (3-1)$$

where n is time offset, and $n-k$ is the difference in modulo- L_T arithmetic. $Z_{s_1 s_1}[k]$ satisfies

$$Z_{s_1 s_1}[k] \begin{cases} = \omega, & \text{if } k = 0 \\ \leq \lambda_a, & \text{otherwise} \end{cases} \quad (3-2)$$

where λ_a denotes the peak out of phase autocorrelation. The cross-correlation ($Z_{s_1 s_2}[k]$) between two periodic pseudo orthogonal codewords $s_1[n]$ and $s_2[n]$ with length L_T is represented as

$$Z_{s_1 s_2}[k] := \sum_{n=0}^{L_T-1} s_1[n] s_2[n-k] \quad (3-3)$$

$Z_{s_1 s_2}[k]$ satisfies

$$Z_{s_1, s_2}[k] \leq \lambda_c, \quad \text{if } 0 \leq k \leq L_T - 1 \quad (3-4)$$

where λ_c denotes the peak out of phase cross-correlation.

3.1.3 Distance matrix of pseudo orthogonal code

To analyze the characteristics of the c -cardinality of a $(L_T, \omega, \lambda_a, \lambda_c)$ -POC, the distance matrix of H is considered, where the dimension of the H matrix is $c \times \omega(\omega-1)$. Each row of the H matrix is a function of different pseudo orthogonal codeword in the POC, which is composed of all of the possible distances between Hamming weights in each pseudo orthogonal codeword. Let $h_{k,l}^{(L_T, \omega, \lambda_a, \lambda_c)}(i)$ be the distance between l -th and k -th Hamming weights of i -th codeword in the c -cardinality of $(L_T, \omega, \lambda_a, \lambda_c)$ -POC as follows:

$$h_{k,l}^{(L_T, \omega, \lambda_a, \lambda_c)}(i) = \begin{cases} l(i) - k(i), & \text{if } l(i) \geq k(i) \\ l(i) - k(i) + L_T, & \text{otherwise} \end{cases} \quad (3-5)$$

where $1 \leq l, k \leq \omega$, $l \neq k$, $1 \leq i \leq c$, $1 \leq l(i), k(i) \leq L_T$, $l(i) \neq k(i)$, $l(i)$ and $k(i)$ are the chip positions of the l -th and k -th pulses in the i -th codeword of a $(L_T, \omega, \lambda_a, \lambda_c)$ -POC, respectively. Construction of H matrix for the c -cardinality of a $(L_T, \omega, \lambda_a, \lambda_c)$ -POC is explained with an example at $c = 3$ and $\omega = 3$ as shown in

$$\begin{aligned}
 \mathbf{H}^{(L_T, \omega, \lambda_a, \lambda_c)} &= \mathbf{H}^{(L_T, 3, \lambda_a, \lambda_c)} \\
 &= \begin{bmatrix} h_{1,2}(1) & h_{2,3}(1) & h_{3,1}(1) & h_{1,3}(1) & h_{2,1}(1) & h_{3,2}(1) \\ h_{1,2}(2) & h_{2,3}(2) & h_{3,1}(2) & h_{1,3}(2) & h_{2,1}(2) & h_{3,2}(2) \\ h_{1,2}(3) & h_{2,3}(3) & h_{3,1}(3) & h_{1,3}(3) & h_{2,1}(3) & h_{3,2}(3) \end{bmatrix} \quad (3-6) \\
 &= \begin{bmatrix} h_{1,2}(1) & h_{2,3}(1) & h_{3,1}(1) & h_{1,2}(1)+h_{2,3}(1) & h_{2,3}(1)+h_{3,1}(1) & h_{3,1}(1)+h_{1,2}(1) \\ h_{1,2}(2) & h_{2,3}(2) & h_{3,1}(2) & h_{1,2}(2)+h_{2,3}(2) & h_{2,3}(2)+h_{3,1}(2) & h_{3,1}(2)+h_{1,2}(2) \\ h_{1,2}(3) & h_{2,3}(3) & h_{3,1}(3) & h_{1,2}(3)+h_{2,3}(3) & h_{2,3}(3)+h_{3,1}(3) & h_{3,1}(3)+h_{1,2}(3) \end{bmatrix}
 \end{aligned}$$

The dimension of H matrix is $c \times \omega(\omega-1)$. Thus, H matrix is composed of $(\omega-1)$ sub-matrices, where the dimension of each sub-matrix is $c \times \omega$. Let $h_{k, (k+1) \bmod L_T}^{(L_T, \omega, \lambda_a, \lambda_c)}(i)$ be the basic element, which the basic element is located on the first sub-matrix. For example, the second sub-matrix of (3-6) is shown by

$$\begin{aligned}
 \mathbf{h}_2^{(L_T, 3, \lambda_a, \lambda_c)} &= \begin{bmatrix} h_{1,3}(1) & h_{2,1}(1) & h_{3,2}(1) \\ h_{1,3}(2) & h_{2,1}(2) & h_{3,2}(2) \\ h_{1,3}(3) & h_{2,1}(3) & h_{3,2}(3) \end{bmatrix} \\
 &= \begin{bmatrix} h_{1,2}(1)+h_{2,3}(1) & h_{2,3}(1)+h_{3,1}(1) & h_{3,1}(1)+h_{1,2}(1) \\ h_{1,2}(2)+h_{2,3}(2) & h_{2,3}(2)+h_{3,1}(2) & h_{3,1}(2)+h_{1,2}(2) \\ h_{1,2}(3)+h_{2,3}(3) & h_{2,3}(3)+h_{3,1}(3) & h_{3,1}(3)+h_{1,2}(3) \end{bmatrix} \quad (3-7)
 \end{aligned}$$

The property of i -th sub-matrices, where i is positive integer and $1 \leq i \leq \omega-1$, is that all of the elements in the i -th sub-matrix can be subdivided into i basic elements. For instance, $h_{1,3}(1)$ is equal to $h_{1,2}(1)+h_{2,3}(1)$, where $h_{1,2}(1)$ and $h_{2,3}(1)$ are basic elements in the first sub-matrix.

Let the element group consist of the elements with the same position of sub-matrices in H matrix. There are ω element groups in H matrix. For example, the first element group is $h_{1,2}(1)$ and $h_{1,3}(1)$ which are the first elements of each sub-matrix.

We assume that the first Hamming weight of the pseudo orthogonal codewords is located on the first pulse of codewords to simplify the calculation of low bound of the length of a POC. When the auto- and cross-correlation is calculated, all possible cyclic shifts of the pseudo orthogonal codewords should be considered. Therefore, this assumption is suitable to deduct the calculation complex.

3.2 Low bound of POC length with fixed cardinality

3.2.1 Case 1: Auto- and cross-correlation = 1

In [94], to calculate the low bound of the length of an optical orthogonal code (OOC) with $\lambda_a = \lambda_c = 1$, two distance matrices of H and V are considered, where H matrix shows the properties of auto-correlation and V matrix shows the properties of cross-correlation of a OOC. The maximum number of distinct elements of H or V matrix becomes the low bound of length of an OOC. However, in this chapter, the low bound of the length of a POC can be calculated by only considering H matrix. In other words, the characterizations of the cross-correlation between two different binary sequences are also showed by H matrix. In [94], there are four conditions to satisfy the condition $\lambda_a = \lambda_c = 1$ in any OOC. In this chapter, however, only one condition with $\lambda_a = \lambda_c = 1$ based on the distance matrix of H is considered.

Condition 1: As $\lambda_a = \lambda_c = 1$, all the elements of H matrix should be distinct each other.

Proof: This condition is the same as the Condition 1 and 3 in [94]. According to (3-6), each element of H matrix denotes the interval between two Hamming weights in the

pseudo orthogonal codeword. Because all the elements of H matrix are distinct as $\lambda_a = \lambda_c = 1$, all the intervals of two Hamming weights are the different. If the intervals are the same, two Hamming weights which are the both ends of the interval are overlapped each other as correlations are calculated by (3-1) and (3-3). Thus, in the same row, all the elements are distinct each other for the auto-correlation of 1. For the same reason, all the elements of the i -th row should be different to those of the other j -th row to satisfy that the cross-correlation is 1. In order to satisfy that the auto- and cross-correlation should be equal to 1, therefore all elements of H matrix are distinct each other.

Corollary 1: Based on *Condition 1* the lower bound of the length of the c -cardinality of a $(L_T, \omega, 1, 1)$ -POC is represented by

$$L_T = c \cdot \omega(\omega - 1) + 1. \quad (3-8)$$

Proof: From *Condition 1*, to satisfy the condition of $\lambda_a = \lambda_c = 1$, all the elements of H matrix are distinct each other. Therefore, the minimum value of L_T should be equal to the sum of the total number of elements in the H matrix and 1, which the additional one comes for the assumption that the first Hamming weight is located on the first pulse of codewords.

From the previous researches [35, 94], the low bound of the length of a POC with a given cardinality and Hamming weight of a POC can be derived. In the [94], the low bound of a POC is represented by

$$L_{T_1} \geq c \times \omega(\omega - 1) + 1, \quad (3-9)$$

$$L_{T_2} \geq c \times \omega^2, \quad (3-10)$$

$$L_T \geq \max\{L_{T_1}, L_{T_2}\}. \quad (3-11)$$

In this case, L_{T_2} is always larger than L_{T_1} , because the cardinality c and the Hamming weight ω are always positive integers in the POC. Thus, the low bound of the length of a POC in the [94] can be represented as

$$L_T \geq c \times \omega^2. \quad (3-12)$$

Although L_{T_1} is equal to the proposed analysis of (3-13), the low bound of L_T is different to the proposed analysis of (3-8). They did not need to consider two different conditions for auto- and cross-correlation, relatively, because *Condition 1* which is explained previously covers both the properties of auto- and cross-correlation.

From the other previous research [35], Johnson bound which is the upper bound of the cardinality of a POC with a given length and Hamming weight of a POC can be represented by

$$\phi(L_T, \omega, 1, 1) \leq \frac{(L_T - 1)}{\omega(\omega - 1)}. \quad (3-13)$$

From (3-13), the low bound of the length of a POC with a given cardinality can be derived by

$$L_T \geq \phi(L_T, \omega, 1, 1) \times \omega(\omega - 1) + 1, \quad (3-14)$$

where $\phi(L_T, \omega, 1, 1)$ is cardinality and equal to c . As a result, the proposed scheme has the same the low bound of the length of a POC as that of previous research [35]. Thus, this result illuminates that it is not necessary to consider the condition of L_{T_2} in the [94] and our approach is meaningful when the auto- and cross-correlation are “1”.

Table 3-1 shows the three cardinality of a $(L_T, \omega, 1, 1)$ -POC where each row denotes a pseudo orthogonal codeword, and the low bound of the length of a POC according to Hamming weight by computer simulation. All of the H matrices in *Table 3-2* generated from *Table 3-1* are satisfied to *Condition 1*, and the proposed low bound is illuminated by *Table 3-2*.

Table 3-1 According to Hamming weight, the low bound of the length of and the structure of the three cardinality of a $(L_T, \omega, 1, 1)$ -POC

ω	L_T	Pseudo Orthogonal Code
2	7	$\begin{bmatrix} 1 & 2 \\ 1 & 3 \\ 1 & 4 \end{bmatrix}$
3	19	$\begin{bmatrix} 1 & 2 & 5 \\ 1 & 3 & 10 \\ 1 & 6 & 12 \end{bmatrix}$
4	39	$\begin{bmatrix} 1 & 2 & 5 & 15 \\ 1 & 3 & 9 & 20 \\ 1 & 6 & 13 & 22 \end{bmatrix}$

Table 3-2 According to the three cardinality of a $(L_T, \omega, 1, 1)$ -POC, the structure of H matrix of POC

POC	H matrix
$\begin{bmatrix} 1 & 2 \\ 1 & 3 \\ 1 & 4 \end{bmatrix}$	$\begin{bmatrix} 1 & 2 \\ 1 & 3 \\ 1 & 4 \end{bmatrix}$
$\begin{bmatrix} 1 & 2 & 5 \\ 1 & 3 & 10 \\ 1 & 6 & 12 \end{bmatrix}$	$\begin{bmatrix} 1 & 3 & 15 & & 4 & 18 & 16 \\ 2 & 7 & 10 & & 9 & 17 & 12 \\ 5 & 6 & 8 & & 11 & 14 & 13 \end{bmatrix}$
$\begin{bmatrix} 1 & 2 & 5 & 15 \\ 1 & 3 & 9 & 20 \\ 1 & 6 & 13 & 22 \end{bmatrix}$	$\begin{bmatrix} 1 & 3 & 10 & 25 & & 4 & 13 & 35 & 26 & & 14 & 38 & 36 & 29 \\ 2 & 6 & 11 & 20 & & 8 & 17 & 31 & 22 & & 19 & 37 & 33 & 28 \\ 5 & 7 & 9 & 18 & & 12 & 16 & 27 & 23 & & 21 & 34 & 32 & 30 \end{bmatrix}$

3.2.2 Case 2: Auto- and cross-correlation ≥ 1

In the previous chapter, (3-8) represents the theoretical low bound of the length of a POC, when auto- and cross-correlation are equal to “1”. In this chapter, as the auto- and cross-correlation are not equal to “1”, the theoretical low bound of a POC is calculated by exploiting properties of H matrix. In addition, we assume that auto- and cross-correlation are the same to simplify the problem.

As the auto- and cross-correlation is not equal to 1, the properties of H matrix and the low bound of the length of a POC are different to (3-8). According to the auto- and cross-correlation, several elements of H matrix may have the same value, so that the low bound of the length of a $(L_T, \omega, \lambda_a, \lambda_c)$ -POC is also changed. To calculate the low bound of the length of a $(L_T, \omega, \lambda_a, \lambda_c)$ -POC with $\lambda_a \geq 1$ or $\lambda_c \geq 1$, we need to study the following properties of H matrix.

Chapter 3: Properties of Pseudo Orthogonal Code

Property 1: The sum of all elements of each row in the i -th sub-matrix is always equal to $i \times L_r$, where i is a positive integer and $1 \leq i \leq \omega - 1$.

Proof: At first, we focus on the first sub-matrix of H matrix. From (3-6), each element is the interval between two Hamming weights. Thus, the sum of all the intervals of the same row in the first sub-matrix are equal to the L_r . The elements of other sub-matrices are also composed of the sum of basic elements. We can easily extend this method to the i -th sub-matrix by using (3-6).

Corollary 2: The element group which consists of the elements with the same position of sub-matrices in H matrix indicates sequence. In other word, all of the elements in the element group have the same starting point of the intervals between two Hamming weights. In addition, the different element groups represent the different cyclic shifts of the pseudo orthogonal codeword.

Proof: H matrix is composed of the intervals between two Hamming weights. For example, in (3-6), $h_{1,2}(1)$ and $h_{1,3}(1)$ are the first elements of each sub-matrix. There is three Hamming weight in H matrix, so that $h_{1,2}(1)$ is the interval between the first and the second Hamming weight and $h_{1,3}(1)$ denotes the interval between the first and the third Hamming weight. The element group is composed of the distances from the first Hamming weight. Therefore, the element group is the different expression of the pseudo orthogonal codeword, which is the set of the distances from the represent point. The second element group of $h_{2,3}(1)$ and $h_{2,1}(1)$ is the set of the distances from the second Hamming weight, so that the second element group is the $h_{1,2}(1)$ cyclic shift of the first element group.

Property 2: As $\lambda_a \geq 1$, the number of the same valued elements in each row is less than or equal to λ_a .

Proof: As the auto-correlation λ_a is g and Hamming weight ω is n , we consider two assumptions;

1) One assumption is that g elements in the i -th row of H matrix are the same such as $h_{p_1 p_2}(i) = h_{p_3 p_4}(i) = \dots = h_{p_{2g-1} p_{2g}}(i)$, where $p_1 < p_2 < p_3 < p_4 < \dots < p_{2g-1} < p_{2g} \leq n$ and all the parameters are positive integers. In other words, all of the elements in the i -th row are distinct each other except for $h_{p_1 p_2}(i), h_{p_3 p_4}(i), \dots, h_{p_{2g-1} p_{2g}}(i)$.

Firstly, two element groups is defined; the first element group is composed of $[h_{p_1 p_2}(i) \ h_{p_1 p_3}(i) \ \dots \ h_{p_1 p_{n-1}}(i) \ h_{p_1 p_n}(i)]$ and the second element group is $[h_{p_2 p_3}(i) \ h_{p_2 p_4}(i) \ \dots \ h_{p_2 p_n}(i) \ h_{p_2 p_1}(i)]$. Because p_2 is the next Hamming weight of p_1 , the start element of the second element group should be next Hamming weight of the first element group. The pair of two elements are composed of the j -th and $(j+1)$ -th element in the first and second element group relatively, where j is positive integer and $1 \leq j \leq 2g-1$. Let $(h_{p_1 p_j} \ h_{p_2 p_{j+1}})$ be the pair of two elements. The element of $h_{p_1 p_j}$ can be divided into $h_{p_1 p_j} = h_{p_1 p_2} + h_{p_2 p_3} + \dots + h_{p_{j-1} p_j}$, and the element of $h_{p_2 p_{j+1}}$ can be divided into $h_{p_2 p_{j+1}} = h_{p_2 p_3} + h_{p_3 p_4} + \dots + h_{p_{j-1} p_j} + h_{p_j p_{j+1}}$. Except the same elements, if $h_{p_1 p_2}$ is equal to $h_{p_j p_{j+1}}$, $h_{p_1 p_j}$ is always equal to $h_{p_2 p_{j+1}}$. From the assumption of $h_{p_1 p_2}(i) = h_{p_3 p_4}(i) = \dots = h_{p_{2g-1} p_{2g}}(i)$, $h_{p_1 p_2}$ is equal to $h_{p_j p_{j+1}}$. Therefore, both elements in all the pairs are the same from $(h_{p_1 p_2} \ h_{p_2 p_4})$ to $(h_{p_1 p_{2g-1}} \ h_{p_2 p_{2g}})$ and the elements between

different pairs should be identified. The elements of other pairs after $\begin{pmatrix} h_{p_1 p_{2g-1}} & h_{p_2 p_{2g}} \end{pmatrix}$ should not be the same each other from the assumption of the same distance. Thus, there is g number of the same valued pairs in both element groups. From (3-1) and *Corollary 2*, if there are g number of the same pairs in the both element groups of $\begin{bmatrix} h_{p_1 p_2}(i) & h_{p_1 p_3}(i) & \cdots & h_{p_1 p_{n-1}}(i) & h_{p_1 p_n}(i) \end{bmatrix}$ and $\begin{bmatrix} h_{p_2 p_3}(i) & h_{p_2 p_4}(i) & \cdots & h_{p_2 p_n}(i) & h_{p_2 p_1}(i) \end{bmatrix}$, the auto-correlation is represented by g .

Secondly, two element groups consist of the first element group of $\begin{bmatrix} h_{p_1 p_2}(i) & h_{p_1 p_3}(i) & \cdots & h_{p_1 p_{n-1}}(i) & h_{p_1 p_n}(i) \end{bmatrix}$ and the third element group of $\begin{bmatrix} h_{p_3 p_4}(i) & h_{p_3 p_5}(i) & \cdots & h_{p_3 p_n}(i) & \cdots & h_{p_3 p_2}(i) \end{bmatrix}$. Let $\begin{pmatrix} h_{p_1 p_j} & h_{p_3 p_{j+2}} \end{pmatrix}$ be the pair of two elements where j is positive integer and $1 \leq j \leq 2g-1$. The element of $h_{p_1 p_j}$ can be divided into $h_{p_1 p_j} = h_{p_1 p_2} + h_{p_2 p_3} + \cdots + h_{p_{j-1} p_j}$, and the element of $h_{p_3 p_{j+2}}$ can be divided into $h_{p_3 p_{j+2}} = h_{p_3 p_4} + h_{p_4 p_5} + \cdots + h_{p_j p_{j+1}} + h_{p_{j+1} p_{j+2}}$. Except the same elements, if $h_{p_1 p_2} + h_{p_2 p_3}$ is equal to $h_{p_j p_{j+1}} + h_{p_{j+1} p_{j+2}}$, $h_{p_j p_{j+1}}$ is always equal to $h_{p_2 p_{j+1}}$. From the assumption of $h_{p_1 p_2}(i) = h_{p_3 p_4}(i) = \cdots = h_{p_{2g-1} p_{2g}}(i)$, $h_{p_1 p_2}$ is equal to $h_{p_j p_{j+1}}$ or $h_{p_{j+1} p_{j+2}}$. However, $h_{p_2 p_3}$ should not be equal to $h_{p_j p_{j+1}}$ or $h_{p_{j+1} p_{j+2}}$ from the assumption, which all of the basic elements are distinct except $h_{p_1 p_2}(i) = h_{p_3 p_4}(i) = \cdots = h_{p_{2g-1} p_{2g}}(i)$. Therefore, the number of the same valued pairs in both element groups is less than g .

Excluding the first and second element groups, the other pair of two element group is also distinct each other as above explanation. Therefore, as there is only g numbers of the same valued elements in i -th row, auto-correlation is equal to g .

2) The other assumption is that $(g + 1)$ elements in the i -th row of H matrix are the same such as $h_{p_1 p_2}(i) = h_{p_3 p_4}(i) = \dots = h_{p_{2g} p_{2g+1}}(i)$. two element groups is defined; the first element group is composed of $\left[h_{p_1 p_2}(i) \ h_{p_1 p_3}(i) \ \dots \ h_{p_1 p_{n-1}}(i) \ h_{p_1 p_n}(i) \right]$ and the second element group is $\left[h_{p_2 p_3}(i) \ h_{p_2 p_4}(i) \ \dots \ h_{p_2 p_n}(i) \ h_{p_2 p_1}(i) \right]$. In the same with the first assumption, let $\left(h_{p_1 p_j} \ h_{p_2 p_{j+1}} \right)$ be the pair of two elements. Each element is divided into basic element. As $h_{p_1 p_2}$ is equal to $h_{p_j p_{j+1}}$ except the same elements, $h_{p_1 p_j}$ is always equal to $h_{p_2 p_{j+1}}$. From the assumption of $h_{p_1 p_2}(i) = h_{p_3 p_4}(i) = \dots = h_{p_{2g} p_{2g+1}}(i)$, $h_{p_1 p_2}$ is equal to $h_{p_j p_{j+1}}$. Therefore, both elements in all the pairs are the same from $\left(h_{p_1 p_2} \ h_{p_2 p_4} \right)$ to $\left(h_{p_1 p_{2g}} \ h_{p_2 p_{2g+1}} \right)$. Thus, there are $(g + 1)$ number of the same valued pairs in both element groups. From (3-1) and *Corollary 2*, if there are $(g + 1)$ number of the same pairs in the both element groups, the auto-correlation is represented by $(g + 1)$. Thus, this does not satisfy the condition of $\lambda_a = g$.

Therefore, the same valued element in each row of H matrix is equal to and less than auto-correlation

Property 3: From *Property 2*, the number of the same valued element between the element groups in the i -th row and the j -th row are less than the correlation.

Proof: This is the general case of *Property 2*. The only difference is that element groups are located on different rows.

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Property 4: Elements in H matrix are cyclic shift symmetric with L_T on the basis of the center of H matrix.

Proof: In (3-6), for example, $h_{1,3}(k) = h_{1,2}(k) + h_{1,2}(k) = L_T - h_{3,1}(k)$ due to $h_{1,2}(k) + h_{1,2}(k) + h_{1,3}(k) = L_T$. Thus, the relationship of $h_{1,3}(k)$ and $h_{3,1}(k)$ is cyclic shift symmetric on L_T .

As the length of a $(L_T, \omega, \lambda, \lambda)$ -POC is minimized, the number of the elements in the first element group which have small integers such as “1” is maximized. In addition, H matrix of the $(L_T, \omega, \lambda, \lambda)$ -POC should satisfy *Properties 1* to *4*. To fulfill these conditions, therefore one row in H matrix of the $(L_T, \omega, \lambda, \lambda)$ -POC has λ numbers of k valued elements where k is an arbitrary positive integer, whereas the other rows in H matrix of the $(L_T, \omega, \lambda, \lambda)$ -POC have $(\lambda - 1)$ numbers of k valued elements. If *Properties 1* and *3* are only satisfied, different rows of H matrix have λ numbers of the same valued elements. However, H matrix should also satisfy *Properties 2* and *4*, so that the number of the same valued elements determines less than λ . Thus, the number of the same valued elements between i -th row and j -th row are less than or equal to $2\lambda - 1$. Therefore, in the case of c -cardinality of POC, the maximum number of the same valued elements in H matrix is $c(\lambda - 1) + 1$.

Corollary 3: Based on *Properties 2* and *3*, the lower bound of the length of c -cardinality of a $(L_T, \omega, \lambda, \lambda)$ -POC is represented by

$$L_T = \left\lfloor \frac{c \cdot \omega(\omega-1)}{c \cdot (\lambda-1) + 1} \right\rfloor + 1, \quad (3-15)$$

where $c \cdot \omega(\omega-1)$ comes from the dimension of H matrix.

Compared with (3-8) and (3-15), the low bound of the length of the c -cardinality a $(L_T, \omega, \lambda, \lambda)$ -POC is around $(\lambda-1)$ times as much as the c -cardinality of a $(L_T, \omega, 1, 1)$ -POC. In addition, the low bound of the length of the c -cardinality a $(L_T, \omega, \lambda, \lambda)$ -POC is not directly proportionate to the cardinality of c , in contrast with that of the c -cardinality of a $(L_T, \omega, 1, 1)$ -POC from (3-8). In the previous research [32], Johnson bound with $\lambda_a = \lambda_c \geq 1$ which they dealt with the upper bound of the cardinality of a POC can be represented by

$$\phi(L_T, \omega, \lambda, \lambda) \leq \frac{(L_T-1)(L_T-2) \cdots (L_T-\lambda)}{\omega(\omega-1) \cdots (\omega-\lambda)}. \quad (3-16)$$

In this case, the low bound of length of a POC with a given cardinality is equal to the solution of equation of higher degree. By contrast with $\lambda_a = \lambda_c = 1$ case, there are significant differences between the low bound of proposed scheme and Johnson bound. According to the increment of Hamming weight, the distinction between both the proposed scheme and Johnson bound scheme is increased. In the simulation result, the comparison of the low bound for the proposed scheme and the conventional schemes is illuminated according to the different parameters of a POC.

3.3 Simulation Results

Table 3-3 shows the low bound comparison of the length of a POC by the computer simulation, OOC [94], Johnson bound [32, 35] and the proposed scheme according to different Hamming weight, correlation properties, and cardinality. By using C programming, the structure of c -cardinality of $(L_T, \omega, \lambda_a, \lambda_c)$ -POC is generated for comparing with the theoretical low bound analysis from the conventional and proposed schemes, which is shown as *Table 3-4*. The generation of a POC in *Table 3-4* is conducted as follows: At first, the length of the POC with given Hamming weight and cardinality is started from the number of Hamming weight. At this length of the POC, all possible sets of positions of Hamming weights are checked symbol by symbol until the auto- and cross-correlation conditions are satisfied. If the correlation properties are not satisfied, the length of the POC is increased by one symbol. Until satisfying the correlation conditions, this process is iterated sequentially. In *Table 3-3*, the low bound of length of POC from the conventional and proposed schemes are calculated theoretically. The theoretical low bound of OOC [94] comes from (3-12), Johnson bound of [35] with both auto- and cross-correlation of “1” is from (3-14), Johnson bound of [32] comes from the solution of (3-16), and that of the proposed scheme is from (3-8) and (3-15), relatively. As the correlations of “1”, the theoretical low bound of the proposed scheme and Johnson bound is closely approximate to the computer simulation, but is not above the computer simulation due to the low bound. When the correlations are larger than 1, the low bound of the proposed scheme is more close to computer simulation compared with Johnson bound. Therefore, the proposed scheme outperforms the conventional schemes when the correlations is larger than 1.

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Table 3-3 According to Hamming weight, correlation and cardinality, the comparison of the minimum length of a $(L_T, \omega, \lambda_a, \lambda_c)$ -POC, which is calculated by computer simulation, OOC, Johnson bound and proposed theoretical analysis.

Parameters				Low bound of length of $(L_T, \omega, \lambda_a, \lambda_c)$ -POC				
ω	λ_a	λ_c	N	Computer simulation	OOC [94]	Johnson Bound [35]	Johnson Bound [32]	Proposed scheme
2	1	1	3	7	12	7	-	7
3	1	1	3	19	27	19	-	19
4	1	1	3	37	48	37	-	37
4	2	2	3	10	-	-	10	10
5	2	2	3	17	-	-	15	15
6	2	2	3	24	-	-	21	23
7	2	2	3	38	-	-	27	32
4	2	2	4	13	-	-	12	11
5	2	2	4	17	-	-	17	17

Table 3-4 By computer simulation, generating the structure of $(L_T, \omega, \lambda_a, \lambda_c)$ -POC.

Parameters					Structure of $(L_T, \omega, \lambda_a, \lambda_c)$ -POC with N -cardinality
L_T	ω	λ_a	λ_c	N	
7	2	1	1	3	[1, 2], [1, 3], [1, 4]
19	3	1	1	3	[1, 2, 5], [1, 3, 10], [1, 6, 12]
37	4	1	1	3	[1, 2, 5, 15], [1, 3, 9, 20], [1, 6, 13, 22]
10	4	2	2	3	[1, 2, 3, 7], [1, 2, 4, 5], [1, 3, 5, 8]
17	5	2	2	3	[1, 2, 3, 7, 14], [1, 2, 4, 10, 16], [1, 2, 5, 8, 9]
24	6	2	2	3	[1, 2, 3, 9, 14, 19], [1, 2, 4, 6, 7, 16], [1, 3, 7, 10, 18, 21]
38	7	2	2	3	[1, 2, 3, 5, 11, 31, 36], [1, 2, 8, 12, 24, 26, 27], [1, 3, 10, 18, 21, 24, 32]
13	4	2	2	4	[1, 7, 9, 13], [1, 7, 10, 12], [1, 8, 11, 12], [1, 9, 10, 11]
17	5	2	2	4	[1, 2, 3, 7, 14], [1, 2, 4, 10, 12], [1, 2, 5, 8, 9], [1, 3, 5, 10, 13]

Figure 3-1 depicts the performance comparison of the proposed and conventional schemes in the case of a $(L_T, \omega, 1, 1)$ -POC with three cardinality. The propose scheme and Johnson bound has the same low bound of length of POC. However, the low bound of OOC is not correct, because that of OOC is larger than the computer simulation.

Figure 3-1 In the case of $(L_T, \omega, 1, 1)$ -POC with three cardinality, the performance comparison of theoretical low bound analysis among the computer simulation, OOC [94], Johnson bound [35] and proposed scheme

Figure 3-2 also shows the comparison between the proposed scheme and Johnson bound in the case of a $(L_T, \omega, 2, 2)$ -POC with three cardinality. The theoretical low bound from the proposed scheme is more closely approximate to computer simulation compared with Johnson bound. Therefore, the proposed low bound calculation by using the distance matrix of H is more accurate approach than Johnson bound when the correlations is larger than 1.

Figure 3-2 In the case of $(L_T, \omega, 2, 2)$ -POC with three cardinality, the performance comparison of theoretical low bound analysis among the computer simulation, Johnson bound [32] and proposed scheme

3.4 Conclusions

In this chapter, the low bound of the c -cardinality of a $(L_T, \omega, \lambda_a, \lambda_c)$ -POC with arbitrary correlations is proposed by investigating the properties of H matrix on the c -cardinality of a $(L_T, \omega, \lambda_a, \lambda_c)$ -POC. The most of previous researches focus on the upper bound of cardinality of a POC. However, the low bound of length of a POC with a given cardinality is proposed in this chapter, which has advantages for the field of resource

allocation without feedback channel in the wireless system to analyze the system efficiency and mitigate interferences from the orthogonal properties.

In the previous research [94] on the low bound of the length of $(L_T, \omega, 1, 1)$ -POC, however it seems that the theoretical analysis of [94] is different from the computer simulation. Therefore, in this chapter, the theoretical analysis on the low bound of $(L_T, \omega, 1, 1)$ POC is modified by using the properties of the distance matrix H . Furthermore, the new theoretical analysis of the low bound of c -cardinality of a $(L_T, \omega, \lambda, \lambda)$ -POC is proposed. The simulation results verify that the theoretical low bound of the proposed scheme is better estimated than that of conventional schemes of OOC [94] and Johnson bound [32, 35].

Chapter 4

4. Application of Pseudo Orthogonal Code for Resource Allocation to Mitigate Interference with Limited Feedback Channel in a Wireless Body Area Network

In this chapter, the pseudo orthogonal resource allocation to mitigate interference among sensor nodes is proposed. In terms of the resource allocation, both the orthogonality of resource allocation patterns and the efficiency of data transmission are equally significant. By using the correlation properties in the previous chapter, the transmission efficiency of WBAN is theoretically calculated. In addition, the optimal amount of resource allocation in the WBAN system is proposed through the differential equation of transmission efficiency, which is exactly the ratio of the length of a POC to the number of WBANs in the system. In the simulation results, the proposed transmission efficiency of the objective WBAN is approximately close to the results from Monte Carlo method compared to the conventional schemes.

4.1 System model

In the WBAN, it is important to mitigate inter- and intra-interference due to the limitation of space, battery, and distributed system came from the characteristics of wireless sensor network. Especially, due to the limitation of the sensor nodes such as the limited battery capacity and no receiver antenna of sensor nodes, we assume the non-exchange of control signal among WBANs where the control signal for the information of resource allocation

such as frequency sub-channels and time slots is not broadcasted [132, 133]. Under this condition in order to mitigate inter-WBAN interference, we propose that each time domain has the specific resource allocation pattern based on different pseudo orthogonal codewords. We consider that there are N WBANs in a cell, and each WBAN has one transmitter and one receiver to exclude the impact of intra-interference.

As mentioned above, due to consider limited control signal channel among WBANs, the property of pseudo orthogonality is exploited for the resource allocation of WBANs to mitigate the inter-WBAN interference based on pseudo orthogonal code. The pseudo orthogonal resource allocation pattern code can be characterized by the c -cardinality of a $(L_T, \omega, \lambda_a, \lambda_c)$ -POC, where m is the number of frequency sub-channels in the direction of time domain, n is the number of time slots in the direction of frequency domain, ω is the Hamming weight, λ_a is the auto-correlation, and λ_c is the cross-correlation. Thus, each time domain has the same Hamming weights and properties of the correlation due to a codeword in the same POC [31, 94]. Time- and frequency-domains for resource allocation are shared by all WBANs, where the number of frequency sub-channels is L_T in the direction of time domain, and the number of time slots is c in the direction of frequency domain.

Furthermore, we assume that WBANs system is a slotted asynchronous environment due to a nonexistence of the control channel. The slotted asynchronization denotes that each WBAN has a different delay offset and sends a packet within the boundaries of a time slot. In other words, all WBANs start to send their packet with random integer time offset at the boundary of time slots. Therefore, in the slotted asynchronization, the resource patterns of WBANs in the direction of time domain may have different starting points and time offsets of each resource patterns in the WBANs system. Successful transmissions

denote that only one WBAN sends a packet in one resource slot as adjacent WBANs can't transmit any other packets at this resource slot. If two or more WBANs transmit in the same resource slot, a collision occurs.

4.2 Proposed Optimization Scheme of Pseudo Orthogonal Resource

Allocation in WBAN System

4.2.1 How to Allocate Time-Frequency Resources based on Pseudo Orthogonal Code

To maximize the efficiency of resource allocation, the c -cardinality of a $(L_T, \omega, \lambda_a, \lambda_c)$ -POC should be minimized. Because as the cardinality of a POC is increased, the length of code is also increased to maintain the property of auto- and cross-correlation, which are important to reduce the inter-WBAN interference. The number of overlapped slots, which are occupied by multiple WBANs at the same time as a function of the auto- and cross-correlation, is also decreased to optimize the resource allocation. Thus, we consider a POC reuse among different WBANs to increase the spectral efficiency. In this chapter, the cardinality of a POC is always equal to the number of WBANs in the system (i.e., $c = N$) and each time domain in the direction of frequency sub-channels has different pseudo orthogonal codeword, so that the number of time slots is also equal to the number of WBANs and the cardinality of a POC. Naturally, it is possible that the $L_T \times n$ resource area consists of one pseudo orthogonal codeword, by using the mapping scheme which 1-D sequence changes to 2-D sequence [78, 134, 135]. However, the rate of length increase of a POC is rapidly increased when the number of Hamming weight is increased under

the same property of auto- and cross-correlation. In addition, we also consider the slotted-asynchronous environment among WBANs, so that there is no interference from slightly overlapping the resource slot in the direction of time and frequency dimension. As a result, in order to maximize the efficiency of resource allocation in the WBAN system, the cardinality of a $(L_T, \omega, \lambda_a, \lambda_c)$ -POC should be equal to N .

the proposed scheme that configure the resources into slots on the two dimensional plane with time and frequency domain respectively, and each slot is assigned to sensor nodes for data transmission. Several WBANs share the same two-dimensional plane, where the occupied slots by the resource allocation of one WBAN have the diagonal line pattern and the shaded slots denote collisions. Thus, as the number of the shaded slots is increased, system throughput is decreased due to the inter-WBANs interference.

Figure 4-1 shows the proposed scheme that configures the resources into slots on the two dimensional plane with time and frequency domain respectively, and each slot is assigned to sensor nodes for data transmission. The resource slots are mapped with the matrix where the row of matrix denotes a time domain, and the column of matrix is a frequency domain. Three WBANs share the same resource area which is composed of 3 time slots and 13 frequency sub-channels, where the occupied slots by the resource allocation of one WBAN have the diagonal line pattern and the shaded slots denote collisions. As a result, as the number of the shaded slots is increased, system throughput is decreased due to the inter-WBANs interference. If the slot is allocated, the value of 1 is assigned to the corresponding element of the matrix and 0 otherwise. Thus, the matrix is represented by the position of the occupied resource slots in the two dimensional plane.

Therefore, *Figure 4-1* shows an example of WBANs system where there are three WBANs in the system and the resource allocation pattern of each WBAN can be

represented by the 3×13 matrix, which the time domain is 13 frequency sub-channels and the frequency domain is 3 time slots. The 3×13 matrix is comprised of three different pseudo orthogonal codewords based on the three cardinality of a (13,3,2,1)-POC to obtain pseudo-orthogonal property. For example, as the first row of $WBAN_1$ is [1 2 13], this means that the first, second, and thirteen frequency sub-channels in the first time domain are allocated by Hamming weights. Each row of the resource allocation for the WBANs, which denotes the time domain, can be any cyclic shift of the pseudo orthogonal codewords, which the starting points of the codewords are randomly generated. The order of the pseudo orthogonal codewords allocated to each row may be separated due to the slotted asynchronization of WBANs. Thus, the resource allocation patterns of WBANs are composed of the same POC, but the cyclic shift versions of each pseudo orthogonal codeword on time domain and the order of pseudo orthogonal codewords are different according to the specific WBANs. In the *Figure 4-1*, the same color row denotes the same pseudo orthogonal codeword, and the same color rows among different WBANs have the different cyclic shift of the same pseudo orthogonal codeword. And also, in the same WBAN, the order of pseudo orthogonal codewords is randomly allocated to three rows without the duplication of pseudo orthogonal codeword. Therefore, the auto- and cross-correlation of pseudo orthogonal codewords are represented as the collision of resource slots where more than two WBANs transmit their data at the same resource slot. As the number of overlapped slots is directly related to the performance of WBAN, the correlation function can be used to evaluate the performance of WBANs system.

Figure 4-1 Example of resource allocation pattern based on the pseudo-orthogonal code. The allocated resource slots are mapped with the corresponding elements of matrix.

4.2.2 Expected Performance of Resource Allocation

To evaluate the performance of the proposed pseudo orthogonal resource allocation in the WBAN system, the expected value for the number of overlapped slots which is related to the correlation properties is considered. To reduce computing complexity of expected value of the overlapped slots, we focus on one specific pseudo orthogonal codeword in the direction of time domain with interference from other WBANs. Given two binary sequences with the same length of L as $s_1[n]$ and $s_2[n]$, the sum of correlation which can be represented by [31, 136]

$$\sum_{k=0}^{L-1} Z_{s_1 s_2}[k] = \omega(s_1) \omega(s_2) \quad (4-1)$$

where k is a frequency sub-channel offset and arbitrary integer number and $\omega(s)$ is Hamming weight as $\omega(s) := \sum_{n=0}^{L-1} s[n]$. In the resource allocation based on the POC, the sum of correlation is equal to all possible number of overlapped slots taking account of all of the different cyclic shifts in the time domain between pseudo orthogonal resource patterns (i.e., pseudo orthogonal codewords due to the slotted asynchronization among WBANs) from two different WBANs. Notice that, if the resource allocation patterns between two WBANs are the same, (4-1) is the sum of the auto-correlation of two codewords. In the general case, (4-1) describes the sum of the cross-correlation of two codewords. Therefore, the total number of overlapped slots from two different WBANs is a function of the Hamming weights for both WBANs, regardless of the resource allocation pattern of WBANs.

In this chapter, the theoretical analysis of performance of WBANs is conducted by the expected number of overlapped slots, where N WBANs transmit their packets in the same time-frequency plane. To simplify the calculation of the expected value of the auto- and cross-correlation between codewords, the first pseudo orthogonal codeword of $WBAN_1$, which is according to the first time domain (the first row in the time-frequency domain), is considered as reference domain to evaluate the performance of the proposed scheme. Because we assume the slotted asynchronization, the interference does not occur in the direction of the frequency domain. Basically the process of calculating the expected overlapped resource slots is that the inter-WBAN interference comes from one WBAN and there is no interference from the other WBANs, where all WBANs before the

interfered WBAN don't affect interference to the objective WBANs and the influence from the other WBANs after the interfered WBAN is not considerable. To explain the concept of theoretical analysis of WBAN performance, we only consider three WBANs in the system. Afterwards, based on the theoretical analysis of three WBANs system, we extend the three WBANs to general case (i.e., $N \geq 3$) of the WBANs system.

4.2.2.1 Case 1: Three WBANs in the system ($N=3$)

In this section, we assume that there are only three WBANs in the system (i.e., $N=3$), which all WBANs transmit their packets at the same time-frequency plane based on the three cardinality of a $(L_T, \omega, \lambda_a, \lambda_c)$ -POC, so that each time domain has the same Hamming weight by the codewords. To simplify the calculation of the expected value of the overlapped slots based on the auto- and cross-correlation of the $(L_T, \omega, \lambda_a, \lambda_c)$ -POC, the first time domain of $WBAN_1$ is considered as reference domain to evaluate the performance of the proposed scheme. From the slotted asynchronization assumption, the interference does not occur in the direction of the frequency domain. Based on (4-1) and the properties of correlation, the sum of correlation among three binary sequences can be calculated by considering two different interference sources of $WBAN_2$ and $WBAN_3$; 1) $WBAN_2$ interferes with $WBAN_1$, which the resource slots of $WBAN_1$ are overlapped by those of $WBAN_2$, and 2) $WBAN_3$ interferes with $WBAN_1$, which the resource slots of $WBAN_1$ are overlapped by those of $WBAN_3$. Under the first condition, the resource slots of $WBAN_1$ are already in collision with those of $WBAN_2$ whether $WBAN_3$ interferes with

$WBAN_1$ or not. Therefore, in the first condition, the number of overlapped slots from $WBAN_2$, according to all possible frequency sub-channel offset, can be represented by

$$I_{s_1 s_2 s_3}^{WBAN_2} = \left(\sum_{k=0}^{L-1} Z_{s_1 s_2} [k] \right) L = \omega(s_1) \omega(s_2) L_T \quad (4-2)$$

where the index of I is an interference source, L_T is the number of frequency sub-channels, and $\omega(s_1)$, $\omega(s_2)$ and $\omega(s_3)$ are the amount of allocated resource slots of the same time domain from other WBANs, which is equal to the Hamming weight in the POC. In the second condition, as the resource slots of $WBAN_1$ are not influenced by $WBAN_2$, the resource slots of $WBAN_2$ should be interfered by $WBAN_3$ to arise the interference of $WBAN_1$. If the interference of $WBAN_1$ happens from $WBAN_2$, the number of overlapped slots is already calculated by (4-2). To obtain the number of overlapped slots under the second condition, thus the number of non-interference slots of $WBAN_1$ from $WBAN_2$ is calculated. Thus, the number of these non-interference slots from $WBAN_2$ according to all possible frequency sub-channel offset can be written by

$$I_{s_1 s_2}^{NA} = \omega(s_1) (L_T - \omega(s_2)) \quad (4-3)$$

where NA is the non-existence of interference from $WBAN_2$ and $WBAN_3$. Afterwards, these non-interference slots should be occupied by $WBAN_3$. Thus, the number of overlapped slots from $WBAN_3$ according to all possible frequency sub-channel offset can be written as

$$I_{s_1 s_2 s_3}^{WBAN_3} = \omega(s_1)(L_T - \omega(s_2))\omega(s_3). \quad (4-4)$$

Therefore, the total number of overlapped slots in each WBAN is the sum of (4-2), (4-3) and (4-4), and all possible cases of frequency sub-channel offset are L_T^2 . The expected value of total overlapped slots of the one specific time domain in each WBAN can be represented as

$$E[I_{s_1 s_2 s_3}^{ALL}] = \frac{I_{s_1 s_2 s_3}^{WBAN_2} + I_{s_1 s_2 s_3}^{WBAN_3}}{L_T^2} = \frac{\omega(s_1)\omega(s_2)L_T + \omega(s_1)(L_T - \omega(s_2))\omega(s_3)}{L_T^2}. \quad (4-5)$$

4.2.2.2 Case 2: General case of WBAN ($N \geq 3$)

Henceforward, we extend the proposed scheme to N WBANs for the general case of WBAN system. The process of calculating the expected overlapped resource slots in the general case is also similar to that of three WBANs in the system. Basically, when the expected number of overlapped resource slots is calculated, it is interested in single inter-WBAN interference which comes from only one WBAN. Concretely, all WBANs before the interfered WBAN don't affect interference to the objective WBANs. After then, the influence from the other WBANs after the interfered WBAN is not considered to calculate the expected number of overlapped resource slots, because the allocated resource slots are already occupied by the interfered WBANs. In detail, as there are N WBANs in the system, the objective WBAN is $WBAN_1$ and inter-WBAN interference comes from $WBAN_p$ where $1 < p \leq N$. Thus, as the inter-WBAN interference to $WBAN_1$ is calculated from $WBAN_2$ to $WBAN_N$ sequentially, $(p-2)$ WBANs before $WBAN_p$

don't interfere to $WBAN_1$, because we have an interest in the interference from $WBAN_p$. If the overlapped slot occurs by any of previous $(p-2)$ WBANs and also the same overlapped slot is interfered from $WBAN_p$, the interference from $WBAN_p$ is not under the consideration, because the overlapped slot is already occupied by the prior $(p-2)$ WBANs. For the same reason, the interference from $(N-p)$ WBANs after $WBAN_p$ is not considered because the overlapped slot is already occupied by $WBAN_p$. The average of the interference from $(N-1)$ WBANs is calculated to evaluate the performance of WBANs system. At first, as the interference which only comes from $WBAN_2$ regardless of the influences from the other $(N-p-1)$ WBANs, the number of overlapped slots caused by $WBAN_2$ can be represented as

$$I_{s_1 \dots s_N}^{WBAN_2} = \left(\sum_{k=0}^{L_T-1} Z_{s_1 s_2}[k] \right) L_T^{N-2} = \omega(s)^2 L_T^{N-2}. \quad (4-6)$$

For the subsequent step, we assume that $WBAN_2$ does not cause interference to $WBAN_1$ and the interference which only comes from $WBAN_3$ regardless of the influences from the other $(N-3)$ WBANs. Thus, the number of overlapped slots from $WBAN_3$ can be represented by

$$I_{s_1 \dots s_N}^{WBAN_3} = \omega(s_1)(L_T - \omega(s_2))\omega(s_3)L_T^{N-3}. \quad (4-7)$$

To generalize the formulation of the interference of $WBAN_1$, the interference which only comes from $WBAN_p$ without the interference from $WBAN_2$ to $WBAN_{p-1}$, and the

influence of $(N-p)$ WBANs are neglect. The number of overlapped slots from $WBAN_{p-1}$ can be shown as

$$I_{s_1 \dots s_N}^{WBAN_p} = \omega(s) \left(L_T - \omega(s) \right)^{p-2} \omega(s) L_T^{N-p} \quad (4-8)$$

when we assume that all the WBANs have the same Hamming weight $\omega(s_1) = \omega(s_2) = \dots = \omega(s_N) = \omega(s)$.

As a result, the objective time domain of target WBAN sequentially interferes from one of the WBANs in the system. Therefore, the total number of overlapped slots, which is the sum of all number of overlapped slots according to $(N-1)$ WBANs, can be represented by

$$I_{s_1 \dots s_N}^{ALL} = \sum_{p=2}^N \omega(s)^2 \left(L_T - \omega(s) \right)^{p-2} L_T^{N-p}. \quad (4-9)$$

Therefore, the total number of overlapped slots in each time domain is equal to (4-9), and all possible cases of frequency sub-channel offset are L_T^2 . The expected value of total overlapped slots of the one specific time domain in each WBAN can be represented by

$$E \left[I_{s_1 \dots s_N}^{ALL} \right] = \frac{I_{s_1 \dots s_N}^{ALL}}{L_T^2}. \quad (4-10)$$

As the resource area with time-frequency domain is shared by N WBANs, the expected value of the successful transmission in each time domain is the number of WBANs times as much as the expected value of total non-overlapped slots in each time domain. According to the number of WBANs in the system and the quantity of resource allocation of WBAN, the expected value of the successful transmission is changed, so that the

expected valued of successful transmission is not suitable for the evaluation of the performance of the WBAN system with different environment. Thus, transmission efficiency of the object WBAN is considered, which is the ratio of successful transmission slots over total resource slots. The transmission efficiency of the object WBAN can be represented by

$$p_{eff} = \left\{ \omega(s) - E \left[I_{s_1 \dots s_N}^{ALL} \right] \right\} \times \frac{N}{L_T}. \quad (4-11)$$

From (4-10), the expected value of number of overlapped slots is a function of the Hamming weight in each time domain. Therefore, it is necessary to find the optimal quantity of Hamming weight under the condition of given resources for the WBAN system.

4.2.3 Optimal Amount of Resource Allocations for Each WBAN

To maximize the performance of WBANs system, it is necessary to optimize the amount of resource allocation for each WBAN according to the number of WBANs and total resources in the time and frequency domain. In other words, this means that Hamming weight of each WBAN is optimized under the condition of the fixed length of codewords, because the objective of resource allocation is not only the minimization of interference properties, but also the maximization of the quantity of successful transmitted slots. In this section, by using the proposed theoretical analysis of the transmission efficiency for resource allocation in the WBAN system, the optimum Hamming weight with the fixed time-frequency resources is calculated.

The transmission efficiency of the object WBAN by considering the minimization of overlapped slots and the maximization of successful slots is already calculated by (4-11).

On differentiating the transmission efficiency of the object WBAN of (4-11), the maximum value of the transmission efficiency of the objective WBAN is obtained at

$\omega(s) = \frac{L_T}{N}$. Therefore, the optimal Hamming weight to maximize the transmission

efficiency is exactly the ratio of the length of a POC to the number of WBANs.

4.2.4 Performance Analysis of Pseudo-Orthogonal Resource Allocation

The objective of resource allocation in the WBAN system is different to that of the protocol sequence, so that pseudo orthogonal code takes account of both low correlation and spectral efficiency. Thus, although the property of correlation is degraded, the increment of the amount of Hamming weight may improve the spectral efficiency. According to the correlation, it is necessary to analyze the low bound of a POC to obtain the theoretical analysis of the spectral efficiency.

By using (4-11) and Corollary 3 in Chapter 4 which show the lower bound of the length of N -cardinality of a $(L_T, \omega, \lambda, \lambda)$ -POC, the transmission efficiency of the pseudo orthogonal resource patterns for the WBAN system can be modified by

$$p_{eff} = \left\{ \omega - E \left[I_{s_1, \dots, s_N}^{ALL} \right] \right\} \times \frac{N}{L_T} \\ = \left[\omega - \sum_{p=2}^N \left\{ \omega^2 (L_T - \omega)^{p-2} L_T^{N-p-2} \right\} \right] \times \frac{N}{L_T}, \text{ where } L_T = \left\lfloor \frac{N \cdot \omega (\omega - 1)}{N \cdot (\lambda - 1) + 1} \right\rfloor + 1. \quad (4-12)$$

Compared with the increment of inter-WBAN interference from the destruction of the orthogonal property among WBANs, therefore the considerable increment of the transmission efficiency in the WBAN system can be achieved.

4.3 Simulation Results

In this section, the theoretical analysis of pseudo orthogonal patterns for the resource allocation in the WBAN system is verified through the computer simulation. From (4-11) and (4-12), transmission efficiency, which is a similar to a function of a spectral efficiency without a digital modulation, evaluates the performance of resource allocation of the WBAN system in this section.

In the standard of IEEE 802.15.6 [137], the number of channels for WBAN is shown as Table 4-1. As the resource allocation pattern based on a POC is designed, therefore it is not necessary to consider the larger length of the POC than the number of channels in the direction of time domain.

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Table 4-1 Number of channels in the standard of IEEE 802.15.6 for WBAN

Frequency band (MHz)	The number of channels
402 to 405	10
420 to 450	12
863 to 870	14
902 to 928	60
950 to 958	16
2360 to 2400	39
2400 to 2483.5	29

According to different POCs, the proposed theoretical analysis of transmission efficiency from (4-12) is better estimated than OOC [94] and Johnson bound [32, 35]. As the actual length of a POC is known, the proposed theoretical analysis from (4-12) can approximate to the result of Monte Carlo method. The gap between the results from Monte Carlo method and the proposed scheme is caused from the estimated error of the minimum length of a POC as (3-15). In addition, in *Table 4-2*, the transmission efficiency is changed according to the ratio of Hamming weight and length of a POC. As Hamming

weight goes toward $\omega = \frac{L_r}{N}$, the transmission efficiency is maximized. Therefore, the

simulation results of *Table 4-2* illustrates that the proposed optimal amount of resource

allocation as $\omega = \frac{L_r}{N}$ is well derived.

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Table 4-2 According to Hamming weight, correlation and the minimum length of a $(L_T, \omega, \lambda_a, \lambda_c)$ -POC proposed theoretical analysis of transmission efficiency is verified by Monte Carlo method.

λ	ω	L_T	Transmission efficiency by simulation	Theoretical analysis from actual length of POC	Theoretical analysis from OOC [94]	Theoretical analysis from Johnson bound [32, 35]	Theoretical analysis from proposed low bound
1	2	7	0.437	0.437	0.347	0.437	0.437
1	3	17	0.359	0.359	0.422	0.359	0.359
1	4	39	0.248	0.248	0.323	0.248	0.248
2	4	10	0.432	0.432	-	0.432	0.432
2	5	17	0.439	0.440	-	0.444	0.444
2	6	24	0.422	0.422	-	0.437	0.428
2	7	38	0.368	0.368	-	0.427	0.401

Figure 4-2 depicts transmission efficiency in the fixed resource allocation quantity (i.e., a 13×3 frequency-time dimension and 17×3 frequency-time dimension) with three WBANs in the system. When Hamming weight is equal to 3, $(13,3,2,1)$ -POC and $(17,3,1,1)$ -POC are used for maximizing the pseudo orthogonal properties. To evaluate the proposed theoretical analysis of transmission efficiency according to the number of Hamming weight, however additional resource slots are inserted or a resource slot is removed in the $(13,3,2,1)$ -POC and $(17,3,1,1)$ -POC without considering pseudo orthogonal properties, which the location of inserted or removed slot is randomly decided. Thus, the pseudo orthogonal properties of POCs with different Hamming weights are

broken except Hamming weight of 3. In the *Figure 4-2*, the proposed theoretical analysis of transmission efficiency from (4-12) is well approximated by that of simulation result. Furthermore, the maximum values of transmission efficiency should be also located on $\omega = \frac{L_T}{N}$. If WBAN system allocates more than $\omega = \frac{L_T}{N}$ resources for each WBAN, the increment of collisions causes the degradation of the transmission efficiency. To further achieve both the orthogonal properties of a POC and the efficiency of resource allocation, it is necessary to consider the division of resource allocation, which whole resource allocation area of WBAN system should be divided by sub-groups. Because the length of a POC is rapidly increased by the increment of Hamming weight from (3-15).

Figure 4-2 Demonstration of the proposed analysis for transmission efficiency according to different amount of resource allocation when the frequency and the time domains are fixed.

4.4 Conclusions

In this chapter, the pseudo orthogonal resource allocation without feedback channel for the WBAN network are proposed. As the control signals among WBANs cannot be exchanged, the pseudo orthogonal resource allocation is one of the considerable solutions to mitigate inter-WBAN interferences. To maximize the transmission efficiency in the WBAN network, the orthogonal properties of a POC related to interferences are traded off against the dense resource assignment of sensor nodes. Based on the correlation

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properties of a POC, the expected value of overlapped slots of the pseudo orthogonal patterns is calculated, and then the optimal quantity of resource allocation of each WBAN is also analyzed from the expected value of overlapped slots, which is exactly the ratio of the length of a POC to the number of WBANs in the system. In addition, by exploiting the low bound of the length of a $(L_T, \omega, \lambda, \lambda)$ -POC with the c -cardinality in the previous chapter, the theoretical analysis on the transmission efficiency of the objective WBAN is proposed.

In the simulation results, the proposed transmission efficiency of the objective WBAN is approximately close to the results from Monte Carlo method compared to the conventional schemes. And also, the proposed optimal amount of resource allocation to maximize the transmission efficiency is well matched to the simulation results.

Chapter 5

5. Threshold based Charging Scheme for Reduction of Control Signaling Overhead in Electric Vehicle Charging Operation under Smart Grid System

In this chapter, in order to improve the EV charging performance, new threshold-based charging operation with historical charging data is proposed by minimizing control signaling overhead, instead of maximum power delivery to all EVs. In terms of the fairness of EV charging system, it is important to minimize the number of low battery state of charging (BSOC) level of EVs. Based on the predetermined threshold of BSOC, the EV charging system can be reduced the control signaling overhead, which EVs with high and fully BSOC level can't send their information to the central controller. Up to 47% of reduction in control signaling overhead is achieved by using the proposed threshold based charging scheme.

5.1 Methodology

Maximization of BSOC attained by EVs within network constraints is identified as the key trade-off for proposed TBCS to reduce control signaling overhead. Therefore, the smart charging system with cooperation (SCSC) which maximizes the percentage of EVs achieving full BSOC is modeled to serve as the basis of comparison for the overall performance of the proposed TBCS. In this section, the basic information and the methodology of SCSC and TBCS are delineated.

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5.1.1 Assumptions

Both SCSC and proposed TBCS assume EVs with battery capacity capped at 20kWh [25]. It is assumed that the users are incentivized to charge their EVs at off-peak times of the day, which is from 10pm to 6am (determined based on the consistency of previous research [25]) due to implementation of governmental policies. This is a reasonable duration since most EV batteries can be fully recharged in less than 8 hours, typically during the night. For this analysis, all EVs are assumed to be having similar lithium-ion battery. According to Zhang et al. (2012) [138], household typically charge at Mode 1 (at 4 kW) or Mode 2 (at 8 kW). Consumers do not usually require fast recharging since they have adequate time (up to 8 hours) to charge overnight at home. Hence, charging rate is set constant at 4kW per hour (Charging Mode 1) for this study. Besides, it also accounts for the worst case scenario since Mode 1 is the slowest charging mode.

For simplification purposes, it is also assumed that there will be no interruption in between charging duration (i.e. no additional EVs coming into the system for charging and none of the EVs would unplug from the network within that time slot). In addition, distance factor between customer point of charge (CPOC) and the transformer mentioned by Richardson et al. (2012) is not taken into account in both SCSC and the proposed TBCS [25]. Furthermore, the transformer and EV charging equipment are all assumed to have 100% efficiency rating. These assumptions allow the study to focus on the objective of determining the effect of reduction in control signaling loads by comparing the proposed scheme to the SCSC with all other conditions equal. Bi-directional flow of electricity to and from EV battery [24, 25, 138] is not considered in this study regardless of the existence of vehicle-to-grid system and vice versa. As suggested in previous research [25], although 50% market penetration rate seems to be overestimated when we consider EVs market of 2014, but this market penetration rate is appropriate to examine

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such a power demanding scenario in order to fully capture the main benefits from controlled charging strategies compared to uncontrolled charging.

Since the network distribution needs to meet the expectation of residential load while charging the EVs, it is necessary to consider how the residential load demand affects the power supply to EVs. Therefore, different cases of residential load is considered and discussed in the following section. Lastly, the present work considers 100,000 iterations of smart grids in order to obtain statistical power. To simplify the problem, we assume that the residential load is not changed according to the charging time-slots so that the residential load is constant value.

5.1.2 Difference between Selective Multiuser Diversity and EV Charging System

In the wireless communication, there are many previous researches on the opportunity scheduling techniques to achieve multiuser diversity (MUD). The problem of MUD is the burden of feedback overhead which is proportional to the number of all candidate users. To solve this problem, threshold based opportunity scheduling is introduced, which portion of candidate users with higher channel condition than the predetermined threshold only transmit their information to the central controller or base station.

However, the distribution variation of BSOC level in the EV charging system is different to that of the channel condition in the wireless communication such as signal to noise ratio (SNR) over time. The average of SNR is only a function of the distance between a base station and an end device. Thus, the average SNR is not changed as time passes, so that the threshold is also not changed according to the time. In contrast, the average of BSOC level for the same EV increases according to time, because EV has been still

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charged from the power distribution system. Therefore, the moving average technique by using historical BSOC data is considered to determine the threshold of BSOC over time.

5.1.3 Simulation Cases according to Residual Capacity

Three simulation cases will be analyzed for both SCSC and the proposed TBCS based on the different possibilities of residual capacity due to correlation between demand and supply power. The first simulation case happens when there is a balanced demand between the residential load and EV load within the network supply. Hence, first case describes where total supply of power distribution system meets the EV load demand.

The second possible simulation is conducted when the household load becomes demanding, thus the power supply, exclusive of the household load, is less than EV load requirements. Simulation for this case is modeled such that power supply is only sufficient to meet 80% of EV load demand.

Lastly, low residential load scenario is also considered. Therefore, there is more power supply delivered to EVs than required. In this case, an over-supply of 20% is modeled in the simulation.

5.1.4 Distribution Network and Load Modeling

The current chapter formulates simulation model with distribution network and load data broadly based on the work in P. Richardson et al. (2012) [25]. 100,000 sets of micro grids, each with 134 residential customers are simulated in MATLAB for analysis. Based on the 50% market penetration assumption, there will be 67 EVs charging at different CPOC for every micro grid simulated. Thus, in the EV charging system, total number of EVs N_{total} is 67.

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Load data for residential electricity demand obtained from charging service provider (CSP) typically consist of 15-minutes time-series demand data for high, medium, and low customers usage over a one-year period [25]. Hence, T_{ch} is the charging time-step used for simulation, analysis is conducted with 15 minutes interval for convenience of modeling of power distribution available for EVs which is based on the household load profiles. Thus, total of 32 time-steps for 8 hours of charging period are considered for simulation (from 10 pm to 6 am), $T_{ch} = 32$.

Based on [25], initial distribution of BSOC (i.e. at 10pm when all EVs first plugged in) is modeled with a normal distribution of mean(μ) and standard deviation(σ) as 10.75 kWh and 6 kWh respectively. Since BSOC distribution are random variables with real values and also the sample size of simulation is large enough for applicable central limit theorem, normal distribution is suitable for simulating EV charging system. For simulation purposes, the estimated amount of power supply which is available for EVs based on the third scenarios mentioned in Section 5.1.3 is calculated as below;

Estimated total energy demand of EV [kWh], $\hat{E}_D = (20[\text{kWh}] - \mu) \times N_{total}$

Estimated power demand per charging interval [kW], $\hat{P}_D = \hat{E}_D / T_{ch}$

Estimated power supply available per interval [kW], $\hat{P}_S = \hat{P}_D \times \omega$,

where weight factor; $\omega = \begin{cases} 1 & \text{for simulation case 1} \\ 0.8 & \text{for simulation case 2.} \\ 1.2 & \text{for simulation case 3} \end{cases}$

In the charging mode 1, P_{cpoc} is the maximum charging power for each EV, which is valued by 4 kW/hour per charging time-step = 1kW. Thus, the maximum number of EVs charged per time-step N_{max} is $\hat{P}_S / P_{cpoc} = \hat{P}_S / (1 \text{ kW})$.

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5.1.5 Smart Charging System with Cooperation (SCSC)

Since network transformer and main cables connecting transformer to network are assumed to operate at 100% efficiency in this analysis, voltage drop due to location of EV and thermal loading of network components are not considered. Furthermore, large variations in the charging rate over consecutive time steps are undesirable for current battery technology [139]. This problem is simplified by assuming constant charging rate at maximum of Mode 1 (i.e. 4 kW per hour). In order to retain the objective of reduction of feedback overhead and maximum energy delivery to all EVs while neglecting the network sensitivities including distance factor and thermal loading, the following methodology is developed.

At each time step, all EVs in the grid provide its own BSOC information feedback to the central controller. The BSOC profile is then sorted in ascending order and tabulated with information of respective CPOC. Based on collected information, the total energy demand, E_D is represented by

$$\tilde{E}_D = \sum_{i=1}^{N_{total}} (20[kWh] - BSOC_i) \quad (5-1)$$

where 20kWh is battery capacity, and $BSOC_i$ is the individual BSOC information of EVs.

According to the characteristic of normal distribution for generating initial BSOC, $\tilde{E}_D$ may not always be equal to $\hat{E}_D$.

Nevertheless, the average value of $\tilde{E}_D$ according to the iterations as E_D is the same as $\hat{E}_D$ stochastically. When P_s is the maximum power supply available for the EVs and P_{EV} is

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the power supply for charging EVs under the network constraints, from (5-1), P_{EV} can be expressed as

$$P_{EV} = E_D / T_{ch}. \quad (5-2)$$

Therefore, P_{EV} cannot exceed P_S as

$$P_{EV} \leq P_S. \quad (5-3)$$

If the power demand from the network does not exceed maximum supply, all EVs which are plugged into the distribution network will be charged. Otherwise, if EVs power demand from the network exceeds the feeder's maximum supply, charging system prioritizes EVs with lower BSOC in order to ensure no EVs are left with low BSOC at the end of the charging period. According to the BSOC level sorted in ascending order and the assumption of constant residential load, P_{EV} can be represented by

$$\begin{aligned} P_{EV} &= E_D / 32 \text{ time-slots} \\ &= \sum_{i=1}^M (20 - BSOC_i) / 1 \text{ time-slot} \end{aligned} \quad (5-4)$$

Table 5-1 Number of EVs in corresponding BSOC Level

BSOC level	0	1	...	Charging BSOC L_C	...	20
Number of EVs N_i	N_0	N_1	...	N_{L_C}	...	N_{20}

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where M is the number of EVs charged at each charging time-step under the network constraints. We denote that L_c is the highest charging level of BSOC at specific charging time-slot, and Table 5-1 shows the number of EVs according to each BSOC level. From (5-2) and (5-3), the number of EVs charged at each charging time-step can be represented by

$$\begin{cases} M = \sum_{i=0}^{L_c} N_i & \text{if } P_{EV} = P_S \\ M < \sum_{i=0}^{L_c} N_i & \text{if } P_{EV} < P_S \end{cases} \quad (5-5)$$

If $P_{EV} < P_S$, feeder selects M -EVs from low BSOC level. Therefore, constraint (5-3) and (5-4) is naturally satisfied as well. Under these conditions, control signals related to selected charging EVs broadcast to all EVs and those with BSOC below the threshold will be charged. Furthermore, based on Table 5-1, total number of EVs in the grid is represented by

$$N_{total} = \sum_{i=0}^{20} N_i \quad (5-6)$$

where N_i is the number of EVs according to each BSOC level.

After charging, the BSOC profile of all EVs is updated and provides feedback to the central controller again. That marks the end of a time step and the whole charging system repeats for 32 time steps from 10pm until 6am. With such process, the network is coordinated to ensure utilization for its fullest extent in terms of delivered energy. The charging process for each time slot is presented in a flow chart in *Figure 5-1*.

Figure 5-1 Operation flow of SCSC for each time step.

Figure 5-2 Schematic diagram of proposed TBCS.

5.1.6 Modeling of Proposed Threshold Based Charging Scheme

To significantly reduce control signaling overhead, intelligent nodes is proposed by exploiting the threshold, which decides the participation of the uplink feedback to charge

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each EV. The EVs under the threshold value will be charged whereas those above the threshold value will not be charged yet, and the threshold value will be increased as the number of charged EVs increase. The threshold is determined by moving average of historical BSOC data according to charging time-slots. *Figure 5-2* is the schematic diagram to show the method of the proposed TBCS according to the BSOC level. There are 67 EVs in the system and *Figure 5-2* shows the distribution of 67 EVs with different BSOC level. The dotted line indicates the threshold value which EVs with BSOC level below threshold value will be charged. Afterwards, the threshold value will be increased according to the power supply and the distribution of BSOC level of EVs at the prior charging time-slot. To update the threshold of BSOC level, the moving average of historical BSOC profile is considered. As the distribution of the BSOC level of EVs according to the charging time-steps is known, the threshold γ for charging EVs can be easily calculated by

$$\min_{\gamma} \sum_{i=0}^{\gamma} N_i > \frac{P_{EV}}{P_{cpoc}} \quad (5-7)$$

where P_{EV} , P_{cpoc} and N_i are the power supply for charging EVs, the maximum charging power for each EV and the number of EVs according to each BSOC level respectively. However, to reduce control signaling overhead, the proposed scheme cannot exchange control signals among a central controller and CPOCs in a real time so that the central controller cannot calculate the instantaneous threshold by using (5-7). Therefore, we consider moving average scheme to calculate the threshold based on the historical data of BSOC level of EVs.

Table 5-2 Sample of Charging Threshold according to Time-slots

Time-slot	1	8	16	24	32
Threshold [BSOC level]	9	11	14	16	19

Table 5-2 shows a sample of charging threshold according to several time-slots. *Figure 5-3* describes that the distribution of average historical BSOC level of EVs according to charging time-slots. The dotted line denotes charging threshold of each charging time-slot. By using the moving average scheme of historical BSOC level of EVs, the distribution of BSOC level of EVs is obtained to calculate the charging threshold of EVs according to charging time-slots.

(a) Charging time-slot: 1

(b) Charging time-slot: 21

Figure 5-3 Charging threshold and distribution of BSOC level of Smart Charging System with Cooperation according to charging time-slots.

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To further reduce the exchange of control signaling overhead, the central controller can transmit the information of charging threshold to CPOS periodically. In addition, it is not necessary that the charging threshold consists of every charging time-slots. In practical, the distribution of BSOC level of EVs and maximum power supply can be altered according to circumstance so that the redundancy of charging threshold is required to avoid performance degradation due to absence of EVs below threshold in the system. Therefore, the charging threshold can be updated periodically to reduce control signaling overhead and achieve the redundancy of charging threshold.

Figure 5-4 describes the operation flow of the proposed TBCS for a central controller and CPOC. The central controller calculates the charging threshold based on the historical data periodically, and in each time-slot, the central controller receives the requirement of charging power from EVs, which has less BSOC level than the charging threshold. If the number of feedback EVs is larger than the power supply, the central controller selects charging EVs under the limitation of the power supply and then sends acknowledgment and power to the determined EVs. In the CPOC side, as the current BSOC level of EV is less than the charging threshold, CPOC transmits the charging requirement to the central controller. After that, CPOC waits for receiving the permission from the central controller. As CPOC receives the permission, CPOC starts to charge EV and updates the current BSOC level of EV. Periodically CPOC updates the charging threshold from the central controller.

(a) Central controller

(b) Customer point of charge

Figure 5-4 Operation flow of the proposed TBCS for a central controller and CPOC.

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5.1.7 Hybrid Method of TBCS and Random Access for Further Reduction of Control Signaling Overhead

To further mitigate the control signal overhead, a hybrid method of threshold-based and random access schemes is necessary according to the charging time-slots and the BSOC of EVs. In case of threshold-based scheme determined by the distribution of BSOC level of EVs, near the end of charging period, almost of EVs participate in the transmission of their BSOC information to the central controller. Because most of EVs have the similar and high BSOC level due to sufficient power supply during charging period, and the concentrated distribution of BSOC level of EVs provokes the significant increment of request of EVs' charging. Thus, after the specific charging period, the random access method is exploited, which the EVs randomly transmit their BSOC information to the central controller with the predetermined access rate based on the number of EVs and the power supply in the power distribution system. As a result, by using the random access scheme, the further reduction of control signal overhead can be obtained when the distribution of EV charging is concentrated. *Figure 5-5* shows the schematic diagram of the random access scheme for charging EV. The charging time-slots with diagonal line pattern indicate the control signal transmission to participate in charging EV. Each EV sends its control signal randomly without considering whether the channel is empty or not. The access rate which each EV transmits the control signal is represented by

$$\lambda_{rdn} = \frac{P_D / P_{cpoc}}{N_{total}} \quad (5-8)$$

where P_{cpoc} is the maximum charging power for each EV and N_{total} is the total number of EVs in the EV charging system.

Figure 5-5 Schematic diagram of random access scheme for control signal transmission.

5.2 Simulation Results

5.2.1 Comparison of Charging Performance between SCSC and Proposed Schemes

Table 5-3 shows the summary of simulation environments. The overall trends of BSOC across the charging period for SCSC, proposed TBCS, and hybrid charging scheme (HCS) are very close to each other. Hence, in Figure 5-6, the charging threshold determined by the moving average of BSOC level in the proposed TBCS and HCS is proven to be appropriate. In addition, the proposed HCS is exploited after 24 charging time-slots to achieve further mitigation of the control signaling overhead. However, the charging performance of proposed HCS at the end of charging period is less than those of the other schemes due to the random access method.

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Table 5-3 Simulation Environment

Simulation parameters	Values
Number of EVs	67
Charging hour	10pm to 6am
Charging time-slot	15 mins
Charging rate	1kW / time-slot
Capacity of EV	20 kWh
Iteration	100,000
Control signal frame length	1024 bits
Distribution of residential loads	constant

(a) Simulation Case 1

(b) Simulation Case 2

(c) Simulation Case 3

Figure 5-6 Distribution function of the battery state of charge for all EVs at end of charging periods according to different power supply and power demand.

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For the simulation case 1 ($\hat{P}_S = \hat{P}_D$), all EVs which are plugged into the distribution network are almost fully charged (ranging from 17-20 kWh) at the end of the charging period for SCSC. Meanwhile, in the proposed TBCS and proposed HCS, the distribution of BSOC of EVs is less than that of SCSC. In the proposed TBCS, the charging performance is approximated to that of SCSC. About 9% of the EVs with BSOC of 18 kWh are observed at the end of the charging period. For the PHCS, 97.05% of the EVs achieve high BSOC level with ranging from 17-18 kWh and only 2.95% of EVs have 15-16 kWh.

For the simulation case 2 ($\hat{P}_S = 0.8\hat{P}_D$), all EVs cannot fully be charged due to $P_S < P_{EV}$. Similar to the simulation of case 1, overall charging performance of the proposed TBCS and HCS shows lower charging performance than that of SCSC. However, there are no EVs which have BSOC level of below 15 kWh and only 10% of EVs has BSOC level of 15-16 kWh in the proposed HCS. Therefore, irrespective of cases, the charging performance of the proposed charging schemes are lower than that of SCSC, but the performance difference between the proposed schemes and SCSC is negligible.

For the simulation case 3 ($\hat{P}_S = 1.2\hat{P}_D$), the proposed TBCS is that 100% of the EVs have their BSOC fall in the range of 17-20 kWh at the end of charging session, and also 99.94% of the EVs has BSOC of 17-20 kWh in the proposed HCS. Only 0.06% of the EVs has BSOC of 16 kWh. For the SCSC, all EVs are located in BSOC of 20 kWh at the end of charging period. The overall result is considered satisfactory for such scenario.

5.2.2 Comparison of Control Signaling Overhead

According to Yoon et al. (2008), the efficient uplink resource allocation for power saving is found to be 1024 bits per frame for each subscriber [140]. Hence, each EV is assumed

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to send their information packet at 1024 bits per time slot at least. Since SCSC requires all EVs in the network distribution to send uplink feedback signals at every interval, the amount of information packet sent per interval is $67 \text{ EVs} \times 1 \text{ frame} \times 1024 \text{ bits} = 68,608$ bits. Therefore, a total of 2,195,456 bits are involved for the entire 8 hours of SCSC so that the control signaling overhead is significantly large. Meanwhile, the amount of uplink feedback control signals for the proposed TBCS and HCB corresponds to number of EVs within the threshold category which varies for each time interval. *Table 5-4* shows the comparison of control signalling overhead including SCSC, the proposed TBCS and the proposed HCS. Average total uplink feedback signals sent to central controller in the proposed TBCS are 1,582,704, 1,323,860 and 1,456,685 bits for scenario 1, 2 and 3 respectively which decrease up to 39% uplink data load compared to SCSC. In the Chapter 5.2.5, the proposed TBCS designs that only portion of EVs which have the BSOC is below the predetermined threshold can participate to transmit their charging request to the central controller. Therefore, the simulation result illuminates that the proposed scheme can reduce the feedback overhead. Furthermore, the proposed HCS by combining the random access scheme can achieve the further reduction of control signaling overhead, which is 1,201,134, 1,160,518 and 1,227,479 bits for different scenarios respectively. Thus, the control signaling overhead decreases up to 47% compared to SCSC.

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Table 5-4 Performance Comparison of SCSC, Proposed Threshold based Charging Scheme (PTBCS) and Proposed Hybrid Charging Scheme (PHCS)

	Charging Performance [%]			Reduction of Feedback Overhead [%]		
	SCSC	PTBCS	PHCS	SCSC	PTBCS	PHCS
Simulation case 1 (% of EV at 17-20kWh)	100%	100%	97.05%	0%	27.91%	45.29%
Simulation case 2 (% of EV at 17-20kWh)	100%	96.63%	66.98%	0%	39.70%	47.14%
Simulation case 3 (% of EV at 17-20kWh)	100%	100%	99.94%	0%	33.65%	44.09%

5.2.3 Comparison of Overall Performance

The proposed TBCS reduces the quantity of control signaling overhead by about 30% compared with SCSC. However, the proposed schemes arise the slight drop in percentage of EVs achieving close to full BSOC as shown in Table 5-4. The reduction of control signal overhead decreases as the charging time-slots increases. Because the charging threshold increases according to the increment of the charging time-slots, the number of EVs which have the BSOC level below the charging threshold increases cumulatively. Thus, the proposed HCS has more reduction of control signaling overhead since the charging participation of EVs is limited by the random access method after 24 charging time-slot. However, the charging performance of HCS decreases 30% by final BSOC level ranged from 17 to 20 kWh and 7% by final BSOC level ranged from 16 to 20 kWh compared with the proposed TBSC, so that this performance decrement might be endurable.

5.2.4 Capability of Stochastic Model

In the queuing theory from Arlitt et al. (1997) [141], Poisson process counts events that happen at a constant rate. Poisson process is characterized by a rate parameter λ , so that the number of events in time interval $(t, t + \tau]$ follows a Poisson distribution with associated parameter $\lambda\tau$ by

$$P[(N(t + \tau) - N(t) = k)] = \frac{e^{-\lambda\tau} (\lambda\tau)^k}{k!} \quad (5-9)$$

where k is arbitrary positive integer numbers. Therefore, we assume that EV charging system is Poisson process as λ decreases according to charging time-slots. λ is the mean of Poisson distribution, in other words, the average value of charging demand of the EV system is represented by

$$\begin{aligned} \lambda &= \frac{1}{N_{total}} \sum_{i=1}^{N_{total}} (20 - BSOC_i) \\ &\approx \frac{1}{N_{total}} \sum_{i=1}^{T_{ch}} (T_{ch} - i) P_{EV} \end{aligned} \quad (5-10)$$

(a) Charging time-slot 1

(b) Charging time-slot 11

(c) Charging time-slot 21

(d) Charging time-slot 31

Figure 5-7 Relationship between CSCS and Poisson process according to charging time-slots.

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where $BSOC_i$, N_i , T_{ch} , and P_{EV} represent the individual BSOC information of EVs, the number of EVs according to each BSOC level, the charging time-steps, and the power supply for charging EVs respectively. For example, in the beginning of charging time-slots, the charging demand and request of EVs is higher than that of the late charging time-slot. On the other hand, in the late of charging time-slot, most of EVs are already charged so that the number of event for charging EVs is decreased. In addition, as P_{EV} is consistently provided according to charging time-slots, the average of BSOC is also increased. *Figure 5-7* shows the relation between the synthetic data from CSCS and the estimation of EV charging system based on Poisson process. To simplify the problem, the parameter of λ is only considered. According to the time-slots, the overall trends of SCSC and Poisson estimation across the charging period are very close to each other. However, the graph generated for SCSC is generally observed to have sharper peak while the graph of Poisson estimation has broader and flatter distribution. For further investigation, the stochastic model which can separate the mean and the standard deviation of the BSOC in the EV charging system should be considered.

5.3 Conclusions

In SCSC, the enormous amount of control signaling overhead for real time monitoring of all EVs in the system can cause the performance degradation of EVs charging system. To resolve this problem, in this chapter, the new threshold-based charging operation based on historical charging data is proposed to minimize control signaling overhead. In addition, to further mitigate the control signaling overhead, the hybrid charging scheme of threshold-based and random access schemes is proposed according to the charging time-slots and the BSOC of EVs.

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In the computer simulations, the proposed TBCS and HCS can reduce control signaling overhead up to 39% or 47% of what is required in the SCSC. The proposed schemes is the slight drop in percentage of EVs achieving close to full BSOC, but most of EVs have over 80% of the full BSOC. Therefore, the proposed TBCS and HCS schemes have shown substantial reduction of the control signaling overhead produces and the satisfactory performance of EV charging system in the simulation cases.

Finally, the possibility of stochastic model for the EV charging system is shown to calculate the threshold according to time. The overall trends of Poisson estimation can be approximated according to time, but the graph shape of Poisson estimation has broader and flatter distribution. For further work, it is necessary for the stochastic model to consider separating the mean and the variance of BSOC levels.

Chapter 6

6. Conclusions and Future Work

6.1 Conclusion

Sensor network is a spatially distributed system, which are widely used for many applications such as military, emergency alarm and health monitoring system. However, the sensor node has some constraints such as limited amount of battery, short communication range, and limited processing capabilities, spacing and storage compared with conventional sensors. These limitations of sensor nodes present the cross layer optimization in this dissertation. The cross layer optimization eliminates strict boundaries between layers in the OSI communications model, which permits information exchange and interaction through the layer boundaries dynamically to enable the compensation for overload, latency or other mismatch of requirements and resources. Therefore, in the sensor network, by considering the cross layer optimization to solve the limitations of the sensor nodes, the optimization of the sensor network can be achieved. In this thesis, link layer and MAC layer applications have been investigated for the cross layer optimization. The representative systems for link layer and MAC layer select the pseudo orthogonal resource allocation pattern in the WBAN system and the smart EV charging system respectively, and afterwards the optimizations of the representative systems for each layer are studied.

In the case of link layer, a pseudo orthogonal resource allocation scheme for the mitigation of interference without feedback channel is researched for the wireless body area network (WBAN) applications. Wireless sensors for WBAN have some constraints

due to limited battery life, the mobility of human, small spacing, and haphazard interference environment. Under these conditions, the pseudo orthogonal resource allocation scheme to mitigate interferences among WBAN is proposed through the orthogonal properties of a POC.

In Chapter 3, the low bound of the length of the c -cardinality of a $(L_T, \omega, \lambda_a, \lambda_c)$ -POC is calculated by exploiting the properties of the distance matrix of H matrix on the POC. The relationship among the length, correlation and Hamming weight of a POC is closely connected with the spectral efficiency of the WBAN system. Thus, it is necessary to analyze the low bound of the length of a POC under the conditions of prefixed correlation properties, Hamming weight and cardinality for evaluating the performance of the WBAN system theoretically. The simulation results show that the theoretical low bound of the proposed scheme is well approximate to the computer simulation compared to the conventional schemes of OOC [94] and Johnson bound [32, 35]. However, in this chapter, the limitation of calculation on the low bound of the length of a POC is that the auto-correlation should be equal to the cross-correlation.

In Chapter 4, by using the properties of a POC, the pseudo orthogonal resource allocation pattern is proposed for the mitigation of inter-WBAN interferences without feedback in the WBAN system. To optimize spectral efficiency of the resource allocation, the trade-off between the orthogonal properties of a POC and the quantity of resource allocation of WBAN is considered. To optimize the quantity of resource allocation and orthogonal properties, two dimensional resource allocation patterns are constructed by several pseudo orthogonal codewords. To mitigate the collisions, codewords are randomly assigned to time domain and frequency sub-channel offsets are also randomly assigned. Based on the properties of correlation and cyclic shift on a POC, the successful

transmission efficiency of objective WBAN is calculated. In addition, the optimal quantity of resource allocation of each WBAN is proposed by differentiating the transmission efficiency, which is exactly the ratio of the length of a POC to the number of WBANs in the system. Furthermore, from the low bound the length of the c -cardinality of a $(L_T, \omega, \lambda_a, \lambda_c)$ -POC, a theoretical transmission efficiency of WBANs system can be analyzed according to the number of WBANs, and the quantity of resource allocation. However, in this chapter, the transmission efficiency of WBANs system is only considered. For further research, it is necessary to theoretically analyze the system reliability on resource allocation in the whole system, such as outage probability.

In Chapter 5, to reduce control signaling overhead in the electric vehicle charging system, new threshold-based distributed technique for the smart EV charging system is proposed for the application of MAC layer. As an electric vehicle charging system is uncoordinated in the conventional power distribution system, the penetration of EVs is a burden on the conventional network especially when the demand of residential loads and EVs is concentrated. Thus, it is necessary to mitigate the negative effect of the penetration of EVs through a smart sensor network, which is a demand response model via a bi-directional real time monitoring system of the conventional power distribution system. However, as the bi-directional real time monitoring causes the significant control signal overhead in the network, it will cause the performance degradation in the whole EV charging system. This dissertation presents the development of the new threshold based charging scheme to reduce control signaling overhead, which only EVs with low level of battery state of charge below the predetermined charging threshold can transmit their charging request to controller. Therefore, the proposed threshold based charging scheme has shown the reduction of the control signaling overhead and the endurable decrement of

charging performance in the simulation results. In addition, the stochastic model for the distribution of BSOC level according to time is proposed to simply calculate the charging threshold. However, the proposed stochastic model based on Poisson process is somewhat different to the computer simulation results in terms of the standard deviation of BSOC levels.

6.2 Future work

In the future work, the cross layer optimization for the sensor network is implemented by combining each optimization scheme for link layer and MAC layer. In the EV charging system, each charging request transmitted from charging point of customer to the central controller does not have bulk data, but the problems are that charging requests are frequently transmitted and lots of transmitters are existed in the system. To alleviate these problems, a contention based random access channel [142] for uplink control signaling based on reference signal [143] and pseudo orthogonal code will be presented. Conventional contention based random access schemes are designed for the packet based transmission as shown in *Figure 6-1*. To avoid collisions, different arbitration inter-frame space (AIFS) and different contention window (CW) for multiclass access categories (ACs) is considered for random back-off time which waits random time slots before data transmission. Request-to-send/clear-to-send (RTS/CTS) is related to the start of data transmissions. Thus, in the contention based random access channel, the frame is used in transmission units appropriate for the large volume of data. *Figure 6-2* shows that there are smaller units of data transmission in the frame structure [144]. In addition, different from the packet based transmission, the structure of a reference signal pattern, which is for channel estimation in wireless communication, is designed by symbols and subcarriers

as the *Figure 6-3* [143]. Thus, it is possible to share the limited resource area by multiple users compared with the packet based data transmission.

By using the properties of a POC, we will design the contention based access protocol similar to protocol sequences, which is pseudo orthogonal resource allocation patterns consisted of the resource blocks and slots or the slots and resource blocks, instead of the CW in the conventional contention based schemes. In addition, the length of pseudo orthogonal patterns and number of occupied resource block is optimized according to the number of EVs participated to feedback and the predetermined threshold of EV charging system. Because, the quantity of symbols and sub-carriers is a function of the number of EVs which are participated to send charging requests, and also the amount of charging requests is depended on the predetermined EVs' charging threshold and the charging period.

Figure 6-1 The structure of contention based random access channel.

Figure 6-2 The structure of frame structure in the long term evolution system.

Figure 6-3 The structure of reference signals for common pilot.

There are several issues to further modify the proposed schemes in each chapter. In Chapter 3, the low bound of the length of a POC with fixed cardinality is calculated by exploiting the properties of the distance matrix of the POC. However, we only consider that the auto-correlation is equal to the cross-correlation to calculate the low bound of the length of a POC. In the future work, the low bound of the length of a POC with different correlation properties and Hamming weight can be investigated [32-34, 36, 145]. In addition, these properties of the distance matrix H can easily extend to analyze the structure of OOC, and design user identification [146] and frame synchronization [147, 148].

In Chapter 4, all of the WBANs have the same Hamming weight with the same auto- and cross-correlation. It is possible to extend the different Hamming weight according to WBANs can be configured and established to analyze the influence of the different Hamming weight to the interference mitigation of the WBAN system [32-34].

Finally, in Chapter 5, the stochastic model for the distribution of BSOC level is proposed according to time. In the proposed stochastic model, the mean value is close to that of the simulation result. However, the standard deviation of the proposed model is significant large compared to the simulation result, because the distribution of BSOC of EV charging system over time is not Poisson process, which Poisson process should have the same mean and standard deviation. Therefore, the stochastic model with different mean and standard deviation should be developed to increase the accuracy of estimation of the BSOC distribution in the EV charging system.

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