Doctoral Thesis

Neighbor Discovery for Cognitive Radio Channels and Directional Antenna Networks

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인지무선 채널 환경과 지향성 안테나 네트워크를 위한 이웃 탐색 기법에 관한 연구

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by

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The undersigned have examined this dissertation and hereby certify that it is worthy of acceptance for a doctoral degree from POSTECH

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Abstract

Cognitive radio networks and 60GHz wireless networks are emerging technologies for future wireless communications. Cognitive radio networks allow the secondary nodes to share the wireless channel with primary users of the spectrum in an opportunistic manner. Cognitive radio technology offers a solution to current spectrum usage inefficiencies based on its ability to dynamically adapt operating frequencies to occupy spectrum white spaces. The unlicensed 60GHz band brings the promise of multi-gigabit data rates to support new applications such as high-definition video streaming over wireless links and ultra high speed content download. The dynamically changing availability of the channels in cognitive radio environments and the properties of 60GHz radio create new research challenges for neighbor discovery. This dissertation presents an investigation into the neighbor discovery problem which is a process of finding one hop neighbors to establish links with each other and is the first step towards the design of MAC and network layer protocols.

We first propose a neighbor discovery scheme for cognitive radio networks. Cognitive radio networks need to utilize available spectrum in a dynamic and opportunistic fashion without causing interference to co-located primary nodes. Before data transmission begins, secondary nodes must establish a link on a channel which is not occupied by primary nodes. Unfortunately, in cognitive radio networks, the set of available channels can be different for each node, since it is determined by the relative locations of nodes to primary nodes. We are the first to present a distributed channel rendezvous scheme which finds a commonly available channel between any two nodes in a bounded time without synchronization. Our scheme determines the order, in which two nodes visit channels to find a common channel, if any, within a bounded time.

To support neighbor discovery for 60GHz wireless networks, we propose a neighbor discovery scheme for directional antenna networks. Directional antennas are employed for realizing the multi-gigabit wireless communications in the unlicensed 60GHz band. We consider the problem of neighbor discovery for self-organization of a 60GHz network with directional antennas. Directional communications complicate the discovery process since discovery is only achieved when nodes are facing each other within their antenna beams. Moreover, a significant challenge here is the distributed nature of nodes, which implies that nodes are not time synchronized or have different antenna beamwidths.

We are the first to present a deterministic neighbor discovery scheme even when nodes have different antenna beamwidths or nodes are not synchronized.

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CHAPTER 1

Introduction

1.1 Background

Cognitive radio networks and 60GHz wireless networks are emerging technologies for future wireless communications. Recent technological advances have resulted in the development of wireless ad hoc networks composed of devices that are self-organizing and can be deployed without infrastructure support.

These devices generally have small form factors, and have embedded storage, processing and communication ability. While ad hoc networks may support different wireless standards, the current state of the art has been mostly limited to their operations in the 900MHz and the 2.4GHz industrial, scientific and medical (ISM) bands. With the growing proliferation of wireless devices, these bands are increasingly getting congested. By a static spectrum allocation policy, the governmental agencies assign wireless spectrum to license holders on a long term basis for large geographical regions. Recently, because of the increase in spectrum demand, this policy faces spectrum scarcity in particular spectrum bands. In contrast, a large portion of the assigned spectrum is used sporadically, leading to under-utilization ($< 5.2\%$) of a significant amount of spectrum [43]. There are several frequency bands licensed to operators, such as in the 400-700MHz range, that are used sporadically or under-utilized for transmission [43]. In order to address the critical problem of spectrum scarcity, the FCC has recently approved the use of unlicensed devices in licensed bands. Consequently, dynamic spectrum access (DSA) techniques are proposed to solve these current spectrum inefficiency problems. This new area of research foresees the development of cognitive radio (CR) networks to further improve spectrum efficiency.

The basic idea of CR networks is that the unlicensed devices (also called cognitive radio users or secondary users) need to vacate the band once the licensed device (also known as a primary user) is detected. CR networks, however, impose unique challenges due to the high fluctuation in the available spectrum as well as diverse quality of service (QoS) requirements [44]. Specifically, in CR ad hoc networks, the distributed multi-hop architecture, the dynamic network topology, and the time and location varying spectrum availability are some of the key distinguishing factors. These challenges necessitate novel design techniques that simultaneously address a wide range of communication problems spanning several layers of the protocol stack.

The ultimate objective of the cognitive radio is to obtain the best available spectrum through cognitive capability and reconfigurability. Since most of the spectrum is already assigned, the most important challenge is to share the licensed spectrum without interfering with the transmission of other licensed users as illustrated in Fig. 1.1. The cognitive radio enables the usage of temporarily unused spectrum, which is referred to as spectrum hole or white space [45]. If this band is further utilized by a licensed user, the cognitive radio moves to another hole or stays in the same band, altering its transmission power level or modulation scheme to avoid interference as shown in Fig. 1.1. The owner of a licensed channel is referred to as primary user and all other users of the channel as secondary users.

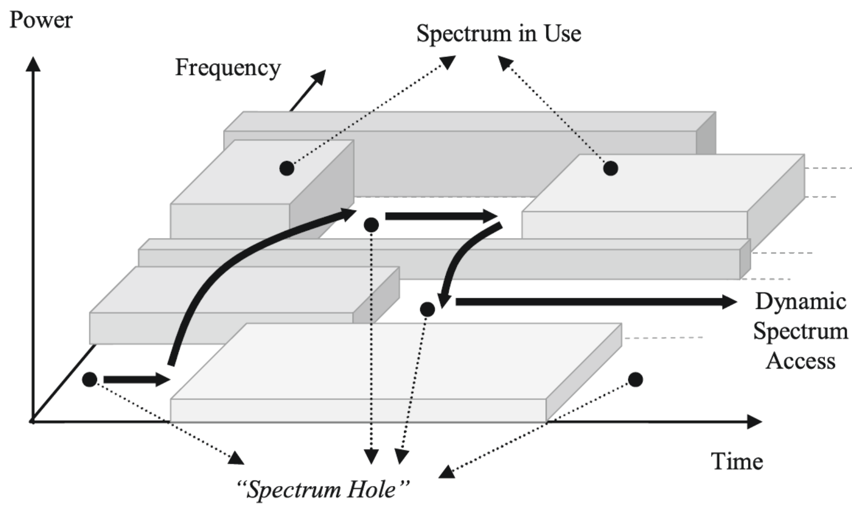

Fig. 1.1 Spectrum hole concept [42]

The large swath of available spectrum in the unlicensed 57-66GHz band (60GHz band in short) represents one of the largest unlicensed bands being allocated and harmonized around the world. This directly translates into the potential to achieve multi-gigabit wireless communication performance [12]. Recent advances of using SiGe and CMOS to build inexpensive 60GHz transceiver components has created intense commercial interest to productize and standardize 60GHz radio technology for bandwidth demanding mass market wireless applications. High end consumer electronic industry is among the first embracing this technology for High-Definition Multimedia Interface (HDMI) cable replacement. A very thin HDTV that can be hung on the wall without a trailing cable has huge aesthetic appeal to the consumers. The required raw data rate to support transmission of the uncompressed video mode 1080p with resolution 1920 $times$ 1080, is as high as 2.986 gigabits per second (Gbps) (with 60 frames per second and 24 bits per pixel). HDMI is devised to transmit the uncompressed HD audio/video over a single cable. The typical HDMI cable usage length is within 10m without using the repeater. The maximum supported bandwidth for HDMI version 1.0 is up to 4.9 Gbps, and the HDMI version 1.3 increased the bandwidth to 10.2 Gbps [12]. Only 60GHz can provide the bandwidth needed for uncompressed HDTV content streaming from the set top box to the TV. PC and Handheld industries are also interested in the potential of using 60GHz for usages such as sync-and-go, wireless docking, etc. Such intense commercial interest led to multiple industrial efforts including WirelessHD [13], WiGig [14], and standard development efforts including ECMA TC48 [15], IEEE 802.15.3c [16] and IEEE 802.11ad [17]. WirelessHD is the first industrial consortium developing a specification to transmit uncompressed HDMI signal over 60GHz radio link. The specification has been designed and optimized for HDMI cable replacement. WiGig is an industrial SIG (Special Interest Groups) with the objective of developing a unified 60GHz specification that has the flexibility to support a broader range of applications including but not limited to uncompressed HDMI cable replacement.

60GHz radio technology is very attractive for broadband mobile telecommunication. Radio operating on this frequency band has some unique properties that make them substantially different from radio on the 2.4GHz or 5GHz frequency band (e.g. license-free, oxygen absorption, high path loss, small size wavelength). To overcome high path loss, high-gain directional antennas are recommended to be used in 60GHz systems. The main advantages of directional antennas (e.g. transmission range extension, capacity increase, spatial reuse, multi-path dispersion reduction, security) are introduced in [25].

Until now, the main research effort related to cognitive radio and 60GHz radio is at the physical layer design and channel model investigation. However, the unique properties of cognitive and 60GHz radio also create new research challenges for networking. Hence the aim of this dissertation is to provide an in-depth view on the neighbor discovery design which is the key operation of self organizing networks. Self-organization is the ability of ad-hoc networks to create and maintain themselves without relying on any external infrastructure, central dedicated control entity, system administrator, or users. Hence, a device should be capable to detect or organize a network without the awareness from the user's aspect. So, neighbor discovery is not only the most basic issues for a wireless system to achieve self-organization, but also crucial factor that decide the performance of the system. Devices should discover their neighbors as quickly as possible as rapid discovery of neighbors often translates into energy efficiency, since devices have to spend less energy for discovering neighbors. Also, rapid discovery allows for other protocols to quickly start their execution.

1.2 Problem Statement and Research Goals

Neighbor discovery is an initial step to enable self-organization in wireless ad-hoc networks. It allows in-range devices to link with each other and form a connected network. On neighbor discovery, the difficulty for the cognitive radio network is the radios locating each other and getting the network started. Before any transmission can occur, all radios must survey the spectrum to determine where the available holes (frequency reuse opportunities) are located. However, each receiver sensor will perceive the spectrum slightly differently because each will see different objects shadowing different primary user transmitters, and will either see each primary transmitter with different signal strengths, or will not see some primary transmitters that other nodes are able to see. So while node A may see an open frequency, node B may consider that frequency to be in use by a distant primary node or primary network. To neighbor discovery, the cognitive radios must agree on a protocol to find each other on a free frequency (i.e. channel). A pair of nodes wishing to communicate with each other have to exchange control information on an unoccupied channel that will enable the establishment of a link. Unfortunately, in cognitive radio networks, the set of available channels sensed by a node depends on its location relative to primary nodes, so it may be different for each node [4]. To enable reliable exchange of control information, two nodes should rendezvous in one channel commonly available to them. Here rendezvous means that two nodes access a channel during a certain period of time which is long enough to establish a reliable link. This rendezvous process for cognitive radio networks is required and can be achieved in a centralized, or distributed manner. Applying the distributed neighbor discovery on cognitive radio networks is challenging due to the dynamic nature of nodes. Specifically, a neighbor discovery scheme for cognitive radio networks is required to operate when:

- We assume an infrastructureless environment. The use of a dedicated control channel or a central unit simplifies the rendezvous process, but it may result in a bottleneck, or create a single point of failure [35]. Moreover, the dynamically changing availability of spectrum may make it impossible to maintain a control channel [50].
- The discovery should be achieved even if each node may sense different sets of available channels.
- All nodes are not globally synchronized, so the neighbor discovery scheme should be operated in asynchronous environments.

One of the major impacts from the 60GHz wireless network is the use of directional antennas. To setup a directional communication, a node is expected to know its neighbor and the position of its neighbor. Therefore, a conventional neighbor discovery mechanism that employs omni-directional antennas cannot effectively support directional neighbor discovery. How to support the use of directional antennas and how to schedule directional transmissions within a network are open issues. Additionally, applying the distributed neighbor discovery on directional antennas is challenging due to the dynamic nature of nodes. Specifically, a neighbor discovery scheme for 60GHz directional antenna networks is required to operate when:

- Directional transmission and reception are accomplished only when the antenna beams mutually cover each other for any two nodes.
- The beam pattern of nodes which use directional antennas might be different depending on their antenna design [27]. The discovery should be achieved even if any two nodes have different antenna beamwidths.
- All nodes are not globally synchronized, so the neighbor discovery scheme should be operated in asynchronous environments.
- Nodes have no compass.

In the above mentioned environments, only probabilistic solutions are found in the literature [4, 33, 35, 28, 29, 30]. Although the probabilistic approaches are simple and straightforward, they do not guarantee a bounded time for discovery. Deterministic solutions are proposed in [35, 34, 11, 30, 31, 32] for guaranteeing the discovery within a bounded time. However, they have more restricted assumptions. The goal of this research is to propose two neighbor discovery schemes which achieve discovery within a bounded time for cognitive radio channels and 60GHz directional antenna networks.

1.3 Main Idea and Research Methodologies

For a neighbor discovery scheme which is suitable for cognitive radio channels, we focus on a distributed approach where each node accesses all channels in a predetermined order which guarantees rendezvous if there is an available channel in common. The rendezvous means that any two nodes are in the same channel for enough time to exchange control messages each other. All nodes access the channels in a predetermined sequence as channel hopping. Also, all nodes operate with an identical rendezvous sequence in a fully distributed manner. We propose a sequence which guarantees the periodic overlap between any two nodes so that a pair of nodes that wish to establish a link can rendezvous. The nodes are not synchronized, so the rendezvous should be achieved even when nodes may start their sequence at different times. Also, each node may sense different sets of available channels, we should guarantee the rendezvous as long as a commonly available channel exists. We find a sequence which guarantees the rendezvous within a bounded time, and propose a generating function that produces the sequence for a given N where N is the total number of channels. Mathematical proofs are given in the dissertation to prove the correctness of the algorithms. We believe that the key contributions of our proposed scheme are twofold:

- First, to the best of our knowledge, we are the first to propose a deterministic rendezvous process which guarantees rendezvous within a bounded time even when each node senses different sets of available channels.
- Second, all nodes operate with an identical rendezvous process in a fully distributed manner.

Next, we propose a deterministic neighbor discovery scheme for directional antenna networks. We focus to achieve discovery even when any two nodes may have different antenna beamwidths. The above-mentioned existing solutions select a direction and decide to transmit or listen in that direction, or use a hopping sequence to decide the pointing direction. We simply share a given constant value T for all nodes in the network. And we use the shared T value for the steering strategy of the antenna beam, which performs the neighbor discovery regardless of the different antenna beamwidths. Also, two modes are defined. First, in the beaconing mode, node A probes in all directions by transmitting beacon messages during time T. Here, T is the turnaround time for sweeping all directions in clockwise order. Second, in listening mode, the antenna behaves like a sector antenna. If we easily label the sectors as $0, 1, \ldots, \frac{2\pi}{\theta_B} - 1$. Then, node B stays on sector 0 for time T while waiting for reception of a beacon message. After time T, node B switches to the next sector, and stays on sector 1 for time T while waiting for reception of a beacon message, and so on. If node B receives a beacon message from an arbitrary direction, it responds directionally with an ACK message. This exchange of messages completes the discovery between the two nodes A and B. Suppose that nodes A and B are trying to discover each other. If one node (node B) is in the listening mode for period of $\frac{2\pi}{\theta_B} \times T$ (when the beamwidth of node B is θ_B) and the other node (node A) is in the beaconing mode during the same time period, or vice versa, then the neighbor discovery between two nodes is achieved within a bounded time of $\frac{2\pi}{\theta_B} \times T$. Through this basic idea, we propose the whole neighbor discovery scheme. We believe that the key contribution of our proposed scheme is that:

- To the best of our knowledge, we are the first to propose a deterministic neighbor discovery scheme which guarantees discovery within a bounded time even when nodes have different antenna beamwidths.

1.4 Dissertation Overview

The dissertation is organized as follows.

Chapter 2 presents the proposed neighbor discovery scheme for cognitive radio channels. The properties for accomplishing neighbor discovery in cognitive radio channels environments are described, and the rendezvous sequence which ensures the deterministic discovery for any pair of nodes is presented. The function for generating a rendezvous sequence is given and mathematical proofs are described to prove the correctness of the generating function.

Chapter 3 presents the proposed neighbor discovery scheme for 60GHz directional antenna networks. First, the applications of the unlicensed 60GHz band are described. And the neighbor discovery scheme for antenna networks are described. To guarantee a bounded discovery time, a token passing scheme and a election scheme which uses a unique identifier are described.

Chapter 4 presents a summary of the dissertation, with some concluding remarks.

CHAPTER 2

A Channel Rendezvous Scheme for Cognitive Radio Networks

2.1 Introduction

Cognitive radio technology offers a solution to current spectrum usage inefficiencies based on its ability to dynamically adapt operating frequencies to occupy spectrum white spaces [37]. The issue of the channel rendezvous arises as the availability of these white spaces may change dynamically in frequency, time and space [50]. A pair of nodes wishing to communicate with each other have to exchange control information on an unoccupied channel that will enable the establishment of a link. Unfortunately, in cognitive radio networks, the set of available channels sensed by a node depends on its location relative to primary nodes, so it may be different for each node [4]. To enable reliable exchange of control information, two nodes should rendezvous in one channel commonly available to them. Here rendezvous means that two nodes access a channel during a certain period of time which is long enough to establish a reliable link. This rendezvous process for cognitive radio networks is required and can be achieved in a centralized, or distributed manner. The use of a dedicated control channel or a central unit simplifies the rendezvous process, but it may result in a bottleneck, or create a single point of failure [35]. Moreover, the dynamically changing availability of spectrum may make it impossible to maintain a control channel [50]. We focus on a distributed approach where each node accesses all channels in a predetermined order which guarantees rendezvous if there is an available channel in common.

Few results for distributed rendezvous schemes can be found in the literature. Probabilistic solutions were proposed in [4, 33]; one is based on the Chinese Remainder Theorem (CRT) [7] and the other is not. But they do not guarantee a bounded time for rendezvous. In contrast, deterministic solutions are proposed under the assumptions that all nodes know the total number of channels and use same channel labels [35, 34]. They create a channel hopping sequence using a generating function which bounds the rendezvous time. Note that they also assume that all the channels are available at a time. This assumption is not suitable for solving the channel rendezvous problem in a cognitive radio environment, since the available channel set for each node can be different and *a priori* knowledge of other channel status information cannot be assumed in the rendezvous problem. If any two nodes have at least one commonly available channel, then they can rendezvous and reliably exchange control information in it. We propose a scheme which guarantees a rendezvous within a bounded time without synchronization as long as a commonly available channel exists.

In this paper, we first describe the system model. Then, we present an algorithm which generates a deterministic rendezvous sequence under the assumption that two nodes are synchronized with respect to slots. A slot is defined as the minimum interval required to exchange control information between a pair of nodes. Next, we prove that the maximum time to find a commonly available channel between two nodes is $\mathbf{N}(3\mathbf{N}-1)$ slots, where $\mathbf{N}$ $(= N + O(N^{2/3}))$ is the smallest prime number greater than or equal to the total number of channels N. Finally, we show that this solution can be extended to asynchronous communication which does not require slot synchronization. We believe that the key contributions of our proposed scheme are twofold:

- First, to the best of our knowledge, we are the first to propose a deterministic rendezvous process which guarantees rendezvous within a bounded time even when each node senses different sets of available channels.
- Second, all nodes operate with an identical rendezvous process in a fully distributed manner.

2.2 Previous works

The following is a collection of solutions to the rendezvous problem from a wide variety of sources. Some of the sources are based in cognitive radio/cognitive network literatures, some is from traditional communications literature, while others are crossovers from applied statistics and operations research.

2.2.1 Random Channels

The random channel visitation is one of the more popular solutions to the rendezvous problem. The strategy is analyzed by Balachandran in [47] and suggested for implementation by Silvius in [46]. Random channel visitation has the desirable property that rendezvous can occur with a calculable probability at any time slot t. If the available spectrum between two radios is the same, then a truly random visitation of available space will yield expected time to rendezvous in linear, or $O(m)$ time, where m is the number of channels. The problem with expected rendezvous time in a random approach is that rendezvous is not guaranteed in any time. No matter what value t is chosen, there also exists a non-zero probability that rendezvous will not occur by it. In a similar implementation, Silvius proposes the use of pseudo-random sequences in [48]. Note that the expected rendezvous time of different pseudo-random sequences would match the expected time for truly random visitation. However, there exists a probability that the same sequence is chosen by both radios with the sequence beginning at different points, resulting in a potentially orthogonal sequence. Orthogonal sequences have different values at every point of the sequence, preventing rendezvous from occurring. We would need to predefine a timeout in order to recover from these rendezvous failures under the pseudo-random sequence approach. For any value of t that could be chosen as a maximum time, there exists a positive probability that rendezvous will occur but has not yet by t, which makes establishing a timeout difficult.

2.2.2 Anderson-Weber Strategy

The applied statistics world has examined the rendezvous problem at some length. Anderson and Weber's [33] symmetric discrete locations rendezvous problem formulation most closely represents the channel rendezvous problem for multi-channel access networks. In this paper, agents exist within a certain discrete location (channel) at every point of time. Movement between locations is instantaneous, and occurs at the same discrete time intervals for all agents. Agents can only observe the location they are currently in, and the game ends when the two agents find each other. In the graph formulation of Anderson's model, rendezvous must occur at a vertex and cannot occur on an edge. The graph must also be complete so that the agents can travel to any vertex at any-time step. In Anderson and Weber's paper, for a problem with m vertices the algorithm that every channel is visited in the randomized permutation guarantees rendezvous if one agent searches while the other remains in place. The probability of choosing to remain in place for m time steps instead of following a randomized permutation for m time steps is denoted by θ. Anderson concludes that the optimal θ value, or percentage of time that a agent will stay in place for m time steps (rather than randomly permute through the channels) is 0.2475 as m gets infinitely large, and the expected rendezvous time is approximately $0.828m$. Note that like the random channel approach, there is no bound on the maximum time.

2.2.3 Dynamic Control Channels

In contrast to previously mentioned solutions which solve for rendezvous in an infrastructureless environment, Jeong and Yoo [49] introduce an algorithm which allows rendezvous with the base station over any available data spectrum, rather than just a specific, predefined control channel. This implementation eliminates the need for a predefined, reserved control channel between the master controller and the cognitive radios, frees up spectrum, and eliminates the control channel spectrum bottleneck. However, the master controller (base station) itself still acts as a bottleneck, and the hardware requirements of the base towers are quite steep as it would potentially need to be listening and broadcasting over the entire dynamic spectrum.

2.2.4 Sequence based Rendezvous

DaSilva and Guerreiro [35] propose the use of generated non-orthogonal channel sequences in order to achieve rendezvous. The use of non-orthogonal sequences guarantees that a rendezvous will occur regardless of the time that two radios begin searching for one another (bounding the maximum rendezvous time). In order to create a sequence that is guaranteed to be non-orthogonal, a generalized permutation of the available channels is created and distributed amongst all radios in the network. When a radio seeks to rendezvous, it begins to execute the generated sequence. The generator provided by DaSilva works by creating a permutation of channels and then embedding this permutation within a supersequence of the permutation. Fig. 2.1 illustrates this for n possible channels. For instance, assume the permutation generated and distributed to all radios is $3, 2, 5, 1, 4$. The generated sequence then is $3, (3, 2, 5, 1, 4)$, $2, (3, 2, 5, 1, 4)$, $5, (3, 2, 5, 1, 4)$, $1, (3, 2, 5, 1, 4)$, $4, (3, 2, 5, 1, 4)$. The rendezvous process is bounded by $m^2 + m - 1$, where m is the number of channels. This is one of the only benchmarks in open literature to date for a bounded time. The largest issue with the use of generated non-orthogonal sequences is that it requires

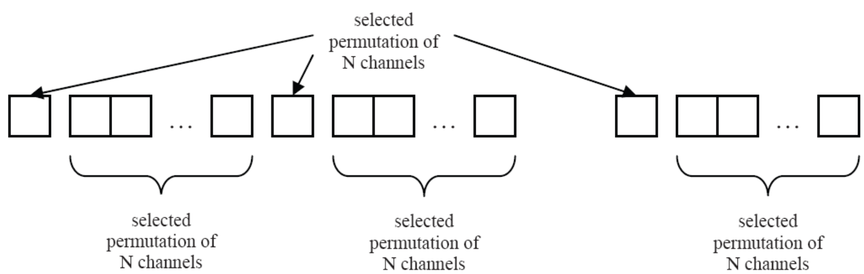

Fig. 2.1 Sequence based Rendezvous

pre-coordination of the generator and permutations in advance. Furthermore, both radios need to start with the same initial set of channels. As the available spectrum changes, the radios would need to receive updates, unless the sequences were implemented as a generic schema. In order to perform this pre-coordination, a control channel or out-of-band coordinator would need to be available.

2.2.5 Quorum based Channel hopping

Bian [50] presents a systematic approach, based on quorum systems, for designing and analyzing channel hopping protocols for the purpose of control channel establishment. The proposed approach, called Quorum-based Channel Hopping (QCH) system, can be used for implementing rendezvous protocols in CR networks that are robust against link breakage caused by the appearance of incumbent user signals. Bian describes two optimal QCH systems under the assumption of global clock synchronization: the first system is optimal in the sense that it minimizes the time to rendezvous between any two channel hopping sequences; the second system is optimal in the sense that it guarantees the even distribution of the rendezvous points in terms of both time and channel, thus solving the rendezvous convergence problem.

2.2.6 Deterministic Rendezvous Sequence ($DRSEQ$)

In [11], the authors propose a deterministic rendezvous scheme assuming that all channels are available. The rendezvous process is bounded by $2N + 1$ slots. We present the scheme in detail since it is highly related to our work.

System model

In order to demonstrate the rendezvous sequence, the authors assume the setup in Fig. 3.4 where time is divided into equal slots of time t and slots are numbered from 0. Also assume that N channels are available numbered 1 through N. The rendezvous sequence $SEQ = (a_0, a_1, \ldots, a_{M-1})$ with the size of M slots,

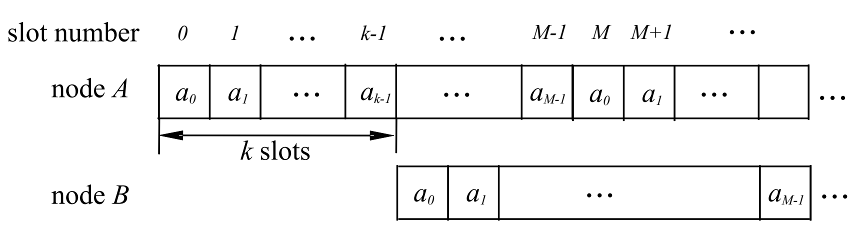

Fig. 2.2 Alignment of two sequences

in which a_i denotes the visiting channel number, is defined to be the order of channels a node visits and it is repeated. The relation between the slot number I and the channel number a_i in SEQ can be expressed as $a_{\{i=I \bmod M\}}$ for $i = 0, \ldots, M-1$ and $I = 0, 1, 2, \cdots$. When two nodes visiting channels according to SEQ are in a common channel during time t, the rendezvous is achieved. For the sake of convenience, the sequence element for node A and B is denoted by a_i^A and a_j^B, respectively and A starts first. Note that $a_i^A = a_i^B$ for all i. Although slots are well synchronized, nodes may start their sequence at different time as shown in Fig. 2.2. For node B, the channel number in slot I is $a^B_{\{j=(I-k) \bmod M\}}$ where k is the misalignment distance less than M which represents that nodes A and B start apart as far as k slots. Note that the misalignment distance k can be any non-negative integer, but by cutting off leading part of the sequence of node A, k can be adjusted to be less than M. Even with this kind of misalignment, SEQ must guarantee the rendezvous. To examine this requirement, the authors formalize the effect of misalignment distance k by defining the k*-shift-invariant* for SEQ. See [11]. Suppose that nodes A and B visit channels according to $SEQ = (a_0, a_1, \ldots, a_{M-1})$ which is k*-shift-invariant* as shown in Fig. 2.2, there exists slot $I \in \{k, k+1, \ldots, k+(M-1)\}$ in which they visit the common channel c $(= a^A_{\{i=I \bmod M\}} = a^B_{\{j=(I-k) \bmod M\}})$. When SEQ is k*-shift-invariant* for all k, then SEQ guarantees that node B can rendezvous with A within M slots.

***DRSEQ* algorithm**

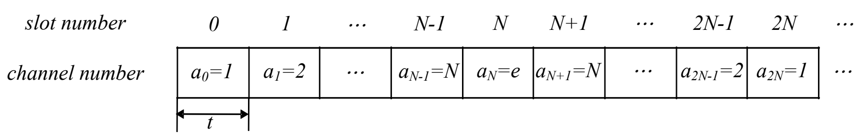

Fig. 2.3: Structure of $DRSEQ$

A rendezvous sequence $DRSEQ$ for N available channels can be generated using the following.

$$a_i = \begin{cases} i+1 & for\ 0 \leq i \leq N-1 \\ e & for\ i = N \\ 2N-i+1 & for\ N+1 \leq i \leq 2N \end{cases} \tag{2.1}$$

where e denotes empty slot. An example of $DRSEQ$ for $N = 5$ is illustrated in Fig. 2.4. Theorem 1 in [11] states that with $DRSEQ$, two nodes can rendezvous within $2N + 1$ slots for N available channels.

2.2.7 Analysis of *DRSEQ*

The $DRSEQ$ provide the best known absolute guarantee of maximum rendezvous time. However, a number of assumptions presented must be evaluated further to truly understand whether the algorithm is robust enough for

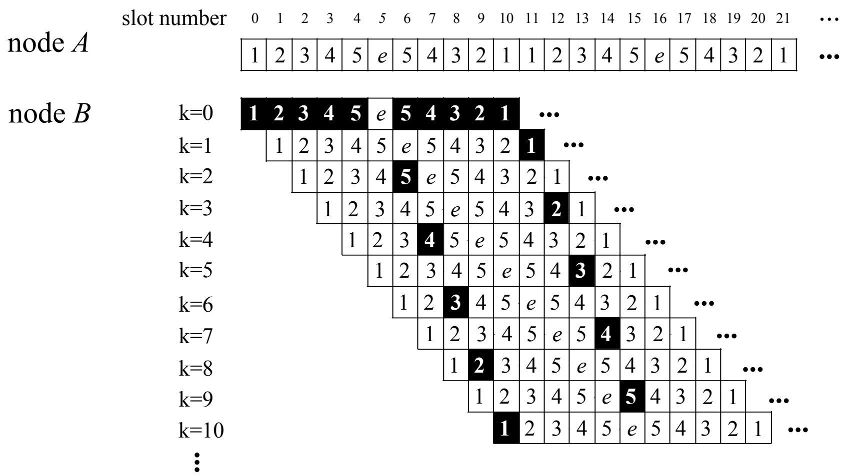

Fig. 2.4: Illustration of $DRSEQ$ with ($N = 5$)

implementation for cognitive radio networks. $DRSEQ$ does not handle the rendezvous problem when the two nodes observe different available channel sets. In the case where node A's available channel set is $\{1, 2, 3, 4, 5\}$ and node B's available channel set is $\{1, 2, 3, 4\}$, then nodes A and B do not rendezvous at $k = 2$ as shown in Fig. 2.4. To overcome this problem, we propose a simple remedy which uses the Chinese Remainder Theorem and can be applied to $DRSEQ$. The Chinese Remainder Theorem [41] states that for any set of n pairwise prime numbers $p = \{p_1, p_2, \ldots, p_n\}$, then for any set of integers $a_1, a_2, \ldots, a_n$

for which $a_i < p_i$, there exists a solution to the set of equations.

$$x \equiv a_1 \pmod{a_1}$$

$$x \equiv a_2 \pmod{a_2}$$

$$\cdots$$

$$x \equiv a_n \pmod{a_n}$$

The theorem proves that there exists a solution to the set of equations, and regardless of which values of a_i are desired. Our main concern in applying the theorem is that the moduli are pairwise prime, so that regardless of the starting integers given we will have a solution. The use of absolute primes guarantees that the set p will also be pairwise co-prime. If the numbers chosen were not absolute primes, coordination would need to occur to ensure that no common factors exist between chosen p values. This restriction raises some challenges. First, we must choose a moduli that is greater or equal than the number of channels that are available for each node. Second, the moduli should be chosen independently by the nodes, however such choices could lead to values of m_A, m_B that are not co-prime. Fig. 3.1 shows the rendezvous procedure when the node A's available channel set is $\{1, 2, 3\}$ and node B's available channel set is

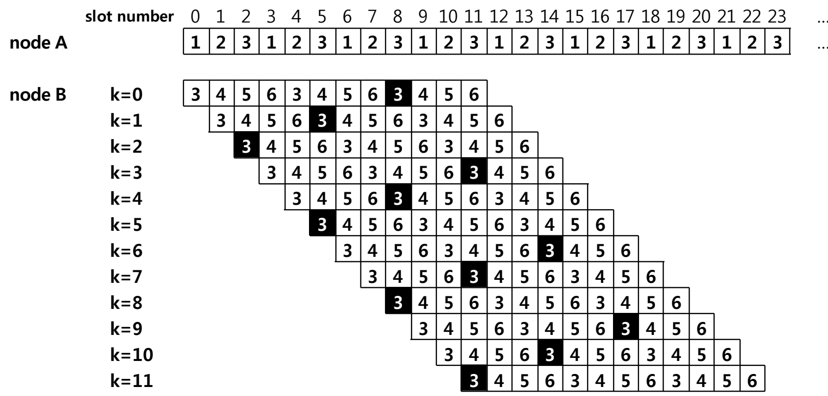

Fig. 2.5 Rendezvous Sequence with Chinese Remainder Theorem

$\{3, 4, 5, 6\}$. This solution is simple and practical when the available channel set size for each node is small, however it does not guarantee a bounded rendezvous time. In the next section, we propose a rendezvous scheme which uses the Chinese remainder theorem and it is deterministic in nature.

2.3 System Model

In order to demonstrate the rendezvous process, we first assume the setup in Fig. 3.4 where time is divided into equal slots of t and slots are numbered from 0. We also assume total N channels numbered 1 through N. The rendezvous sequence $SEQ = (a_0, a_1, \ldots, a_{M-1})$ with the size of M slots, in which a_i denotes the visiting channel number, is defined to be the order of channels a node visits repeatedly. Note that the channel number a_i in SEQ for node A can be expressed as $a_{\{i=I \bmod M\}}$ for $i = 0, \ldots, M-1$ and slot number $I = 0, 1, 2, \cdots$. For the sake of convenience, the sequence element for node A and B is denoted by a_i^A and a_j^B, respectively and A starts first. Also note that $a_i^A = a_i^B$ for all i. For a moment, we assume two nodes are slot-synchronized. Afterwards we will remove this assumption. The set of available channels observed by node A and B is denoted by S^A and S^B, respectively, where $S^A, S^B \subset \{1, 2, \cdots, N\}$. When $S^A \cap S^B \neq \emptyset$ and two nodes visiting channels according to SEQ meet in a common channel ($\in S^A \cap S^B$) during slot time t, the rendezvous is achieved. Although slots are well synchronized, nodes may start their sequence at different times as shown in Fig. 3.4. For node B, the channel number in slot I is $a^B_{\{j=(I-k) \bmod M\}}$ where k is the misalignment distance less than M which represents that node A and B start apart as far as k slots. Note that the misalignment distance k can be any non-negative integer, but by cutting off the leading part of the sequence of node A, k can be adjusted to be less than M. Even with this kind of misalignment, SEQ must guarantee the rendezvous. To examine this requirement, we analyze the effect of misalignment distance k by defining the *k-shift-rendezvous property* for SEQ.

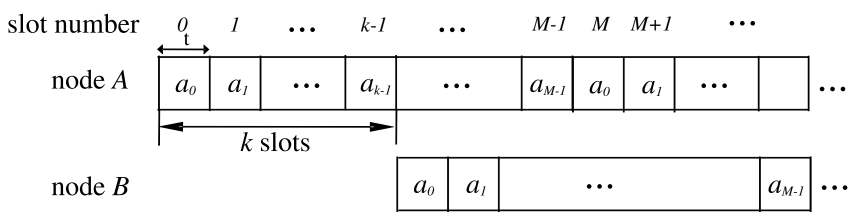

Fig. 2.6 System model

Definition. *The rendezvous sequence* $SEQ = (a_0, a_1, \ldots, a_{M-1})$ *has the* k-shift-rendezvous property ($k = 0, 1, \cdots, M-1$)*, if, for all* $c \in \{1, 2, \cdots, N\}$*, there exists at least one slot* $I \in \{k, k+1, \ldots, k+(M-1)\}$ *such that* $a^A_{\{i=I \bmod M\}} = a^B_{\{j=(I-k) \bmod M\}} = c$*, where* c *denotes channel number.*

Suppose that node A and B visit channels according to $SEQ = (a_0, a_1, \ldots, a_{M-1})$ which has the *k-shift-rendezvous property* as shown in Fig. 3.4, there exists at least one slot $I \in \{k, k+1, \ldots, k+(M-1)\}$ in which they visit a common channel c $(= a^A_{\{i=I \bmod M\}} = a^B_{\{j=(I-k) \bmod M\}})$, for all $c \in (S^A \cap S^B)$. When SEQ has the *k-shift-rendezvous property* for all k and $S^A \cap S^B \neq \emptyset$, then SEQ guarantees that B can rendezvous with A in a common channel within M slots. To satisfy the lower bound, which is proven in Theorem 2 of [9], for all channels

$c \in \{1, 2, \cdots, N\}$, the lower bound of SEQ's size $(= M)$ is N^2. We will show how to find a rendezvous sequence $SEQ = (a_0, a_1, \ldots, a_{M-1})$ which is $M = O(N^2)$ in the next section.

2.4 Channel Rendezvous Sequence

We introduce the algorithm generating a rendezvous sequence for cognitive radio networks and prove that it has the *k-shift-rendezvous property* for all k.

2.4.1 Algorithm

We propose two rendezvous sequences which are used for channel rendezvous and link establishment in this section. First, we present a rendezvous sequence which is called $CRSEQ$. The generation algorithm of $CRSEQ$ is based on the properties of triangular numbers and the Chinese Remainder Theorem (CRT) [7]. Next, we present a rendezvous sequence which is called $CRSEQadv$. $CRSEQadv$ is an advanced version of $CRSEQ$. To easily understand the basic idea of the sequences, we first explain the mechanism of $CRSEQ$ in detail and then present the generation algorithm of $CRSEQadv$ directly.

We explain the properties of triangular numbers and the Chinese Remainder Theorem. For triangular numbers ($T_n = \frac{n(n+1)}{2}$), $T_{n_1+n_2} = T_{n_1} + T_{n_2} + n_1 n_2$ holds true where n, n_1, and n_2 are integers. We can let $T_n^\alpha = T_{n+\alpha} - T_n$ for a given integer α (similar to the concept of misalignment distance k), then $T_n^\alpha = T_{n+\alpha} - T_n = \alpha n + T_\alpha$. The sequence of T_n^α for $n = 1, 2, \ldots$ is an arithmetic progression with common difference α. If N is a prime number and $0 < \alpha < N$, then any N consecutive members of the sequence form a complete set of residues modulo

N by CRT. If we suppose that two nodes visit channels according to $SEQ = (T_0 \bmod N+1, (T_0+1) \bmod N+1, \ldots, (T_0+(2N-1)) \bmod N+1, T_1 \bmod N+1, (T_1+1) \bmod N+1, \ldots, (T_1+(2N-1)) \bmod N+1, \cdots)$ and the misalignment distance k is $2N\cdot\alpha-\beta$, then, for $(0 \le \beta < N, 0 < \alpha < N)$ case, there exists $n \in \{0, 1, \ldots, (N-1)\}$ such that $T_{n+\alpha} \bmod N = (T_n+\beta) \bmod N$. And also the set $\{T_{n+\alpha} \bmod N+1 (= (T_n+\beta) \bmod N+1), (T_{n+\alpha}+1) \bmod N+1 (= (T_n+\beta+1) \bmod N+1), \ldots, (T_{n+\alpha}+(N-1)) \bmod N+1 (= (T_n+\beta+(N-1)) \bmod N+1)\}$ is same as the channel set $\{1, 2, \ldots, N\}$. Therefore, for all $\alpha\ (= 1, \ldots, \beta-1)$ and for all $\gamma\ (= 0, 1, \ldots, \beta-1)$, there exists $n \in \{0, 1, \ldots, \beta-1\}$ such that $T_n \bmod \beta = (T_{n+\alpha}+\gamma) \bmod \beta$. And the set $\{T_n \bmod \beta, (T_n+1) \bmod \beta, \ldots, (T_n+(\beta-1)) \bmod \beta\}$ is same as the set $\{0, 1, \ldots, \beta-1\}$. Using the above property, we derive a rendezvous sequence which is *k-shift-invariant* for all k. The generation algorithm for total $N\ (\ge 2)$ channels is as follows.

$$a_i = \begin{cases} ((\frac{1}{2}\lfloor\frac{i}{2\mathbf{N}}\rfloor(\lfloor\frac{i}{2\mathbf{N}}\rfloor+1)+i) \bmod \mathbf{N}) \bmod N+1 & for\ 0 \le i < 2\mathbf{N}(2\mathbf{N}-1) \\ \lfloor\frac{i-2\mathbf{N}(2\mathbf{N}-1)}{2\mathbf{N}}\rfloor \bmod N+1 & for\ 2\mathbf{N}(2\mathbf{N}-1) \le i < 2\mathbf{N}(3\mathbf{N}-1) \end{cases} \quad (2.2)$$

where $\mathbf{N}$ is the smallest prime number greater than or equal to N. By the known results about the distribution of primes [10], it is known that $\mathbf{N}\ (= N + O(N^{2/3}))$.

We call such sequence $CRSEQ$, the number of whose elements is $M = 2\mathbf{N}(3\mathbf{N}-1)$. Theorem 2.4.1 states that with $CRSEQ$, two nodes can rendezvous at least once in all channels within $M = 2\mathbf{N}(3\mathbf{N}-1)$ slots.

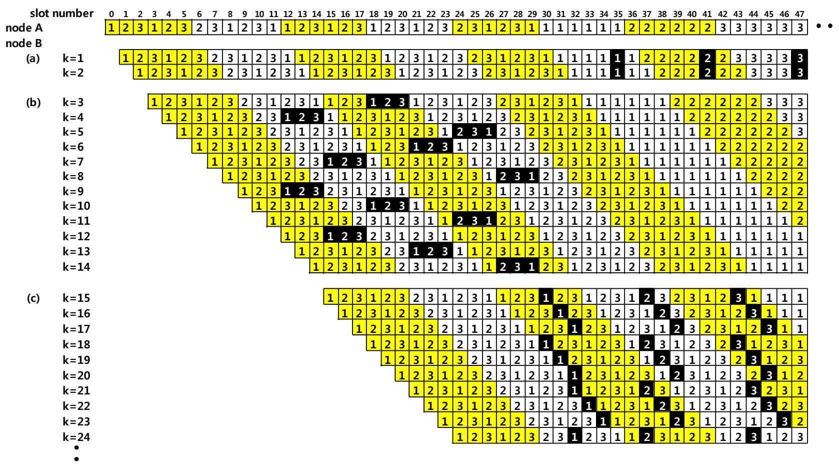

Fig. 2.7 Sketch of proof ($CRSEQ$ with $N = 3$)

Theorem 2.4.1. *For* N (≥ 2) *channels,* $CRSEQ$ *is* k-shift-invariant *for* $k = 0, 1, \ldots, (M-1)$ *so that nodes* A *and* B *rendezvous in all channels* $c = 1, 2, \ldots, N$ *within* $M = 2\mathbf{N}(3\mathbf{N}-1)$ *slots.*

Proof. At slot $I_{k,c}$, nodes A and B visit channel $a^A_{\{I_{k,c} \bmod M\}}$ and $a^B_{\{(I_{k,c}-k) \bmod M\}}$, respectively. We prove, for all $k = 0, 1, \ldots, (M-1)$ and for all $c = 1, 2, \ldots, N$, there exist slots $I_{k,c} \in \{k, k+1, \ldots, k+(M-1)\}$ such that $a^A_{\{I_{k,c} \bmod M\}} = a^B_{\{(I_{k,c}-k) \bmod M\}} = c$.

For $0 \le k < \mathbf{N}$ (with reference to Fig. 2.7(a)), at slots $I_{k,c} = 2\mathbf{N}(2\mathbf{N} + c - 1) - 1$, we have an identical channel such as c for all $1 \le c \le N$, since $a^A_{\{(2\mathbf{N}(2\mathbf{N}+c-1)-1) \bmod M\}} = a^A_{\{2\mathbf{N}(2\mathbf{N}+c-1)-1\}} = \lfloor \frac{2\mathbf{N}c-1}{2\mathbf{N}} \rfloor \bmod N + 1 = (c-1) \bmod N + 1 = c$ by (2.4) and $a^B_{\{(2\mathbf{N}(2\mathbf{N}+c-1)-1-k) \bmod M\}} = a^B_{\{2\mathbf{N}(2\mathbf{N}+c-1)-1-k\}} = \lfloor \frac{2\mathbf{N}c-1-k}{2\mathbf{N}} \rfloor \bmod N + 1 = (c-1) \bmod N + 1 = c$ by (2.4).

For $\mathbf{N} \le k < 2\mathbf{N}^2 - \mathbf{N}$ (with reference to Fig. 2.7(b)), we look into slots $I_{k,c} \in \{k, k+1, \ldots, 2\mathbf{N}(2\mathbf{N}-1) - 1\} \subset \{k, k+1, \ldots, k + (M-1)\}$. At slot $I_{k,c}$, node A visits channel $a^A_{\{I_{k,c} \bmod M\}} = ((\frac{1}{2}\lfloor \frac{I_{k,c}}{2\mathbf{N}} \rfloor (\lfloor \frac{I_{k,c}}{2\mathbf{N}} \rfloor + 1) + I_{k,c}) \bmod \mathbf{N}) \bmod N + 1$ by (2.4), and node B visits channel $a^B_{\{(I_{k,c}-k) \bmod M\}} = ((\frac{1}{2}\lfloor \frac{I_{k,c}-k}{2\mathbf{N}} \rfloor (\lfloor \frac{I_{k,c}-k}{2\mathbf{N}} \rfloor + 1) + I_{k,c} - k) \bmod \mathbf{N}) \bmod N + 1$ by (2.4). Two cases should be considered.

1. $I_{k,c} \bmod 2\mathbf{N} < \mathbf{N} \le k \bmod 2\mathbf{N}$: $\lfloor \frac{I_{k,c}-k}{2\mathbf{N}} \rfloor = \lfloor \frac{I_{k,c}}{2\mathbf{N}} \rfloor - \lfloor \frac{k}{2\mathbf{N}} \rfloor - 1$, since $k \bmod 2\mathbf{N} - 2\mathbf{N} < I_{k,c} \bmod 2\mathbf{N} < k \bmod 2\mathbf{N} \Leftrightarrow k - 2\mathbf{N}\lfloor \frac{k}{2\mathbf{N}} \rfloor - 2\mathbf{N} < I_{k,c} - 2\mathbf{N}\lfloor \frac{I_{k,c}}{2\mathbf{N}} \rfloor < k - 2\mathbf{N}\lfloor \frac{k}{2\mathbf{N}} \rfloor \Leftrightarrow \lfloor \frac{I_{k,c}}{2\mathbf{N}} \rfloor - \lfloor \frac{k}{2\mathbf{N}} \rfloor - 1 < \frac{I_{k,c}-k}{2\mathbf{N}} < \lfloor \frac{I_{k,c}}{2\mathbf{N}} \rfloor - \lfloor \frac{k}{2\mathbf{N}} \rfloor$. Substituting $\lfloor \frac{I_{k,c}-k}{2\mathbf{N}} \rfloor = \lfloor \frac{I_{k,c}}{2\mathbf{N}} \rfloor - \lfloor \frac{k}{2\mathbf{N}} \rfloor - 1$ into $a^B_{\{(I_{k,c}-k) \bmod M\}}$ yields $a^B_{\{(I_{k,c}-k) \bmod M\}} = ((\frac{1}{2}(\lfloor \frac{I_{k,c}}{2\mathbf{N}} \rfloor - \lfloor \frac{k}{2\mathbf{N}} \rfloor - 1)((\lfloor \frac{I_{k,c}}{2\mathbf{N}} \rfloor - \lfloor \frac{k}{2\mathbf{N}} \rfloor)) + I_{k,c} - k) \bmod \mathbf{N}) \bmod N + 1$. Then, $((\frac{1}{2}\lfloor \frac{I_{k,c}}{2\mathbf{N}} \rfloor (\lfloor \frac{I_{k,c}}{2\mathbf{N}} \rfloor + 1) + I_{k,c}) - (\frac{1}{2}(\lfloor \frac{I_{k,c}}{2\mathbf{N}} \rfloor - \lfloor \frac{k}{2\mathbf{N}} \rfloor - 1)(\lfloor \frac{I_{k,c}}{2\mathbf{N}} \rfloor - \lfloor \frac{k}{2\mathbf{N}} \rfloor) + I_{k,c} - k) = (\lfloor \frac{k}{2\mathbf{N}} \rfloor + 1)\lfloor \frac{I_{k,c}}{2\mathbf{N}} \rfloor - \frac{\lfloor \frac{k}{2\mathbf{N}} \rfloor (\lfloor \frac{k}{2\mathbf{N}} \rfloor + 1)}{2} + k) \bmod \mathbf{N} = 0$ satisfies $a^A_{\{I_{k,c} \bmod M\}} = a^B_{\{(I_{k,c}-k) \bmod M\}}$. Let $x = \lfloor \frac{k}{2\mathbf{N}} \rfloor$ $(0 \le x < \mathbf{N} - 1)$ and $y = \lfloor \frac{I_{k,c}}{2\mathbf{N}} \rfloor$ $(\mathbf{N} - 1 \le y < 2\mathbf{N} - 1)$. First, we show that there exists y $(\mathbf{N} - 1 \le y < 2\mathbf{N} - 1)$ such that $((x+1)y - \frac{x(x+1)}{2} + k) \bmod \mathbf{N} = 0$ by CRT. We suppose a pair of

simultaneous congruences as (2.3), where $x+1$, $\mathbf{N}$ are positive integers which are coprime and $-\frac{x(x+1)}{2}+k$, 0 are integers.

$$\begin{aligned} &Y \equiv -\tfrac{x(x+1)}{2}+k \pmod{(x+1)} \\ &Y \equiv 0 \pmod{\mathbf{N}} \end{aligned} \tag{2.3}$$

By CRT, there exists an integer Y solving the congruences and Y is of the form $Y=(x+1)\mathbf{N}t+Y_0$ for all integers t, and Y_0 can be obtained using the Extended Euclidean algorithm [7]. From (2.3), Y can be expressed as $(x+1)t'-\frac{x(x+1)}{2}+k$ for some integer t'. To satisfy $Y=(x+1)\mathbf{N}t+Y_0=(x+1)t'-\frac{x(x+1)}{2}+k$, t' should be of the form $t'=\mathbf{N}t+Y_0'$, where $Y_0'=\frac{Y_0-(-\frac{x(x+1)}{2}+k)}{(x+1)}$ is an integer since $(x+1)(t'-\mathbf{N}t)=Y_0-(-\frac{x(x+1)}{2}+k)$. If $t'=\mathbf{N}t+Y_0'$, then $((x+1)t'-\frac{x(x+1)}{2}+k)$ is an integer multiple of $\mathbf{N}$ by (2.3). To satisfy $((x+1)y-\frac{x(x+1)}{2}+k) \bmod \mathbf{N}=0$, there should exist at least one y ($\mathbf{N}-1\le y<2\mathbf{N}-1$) such that $y=t'=\mathbf{N}t+Y_0'$. Since $\mathbf{N}-1\le y=\mathbf{N}t+Y_0'<2\mathbf{N}-1 \Rightarrow 1-\frac{1}{\mathbf{N}}-\frac{Y_0'}{\mathbf{N}}\le t<2-\frac{1}{\mathbf{N}}-\frac{Y_0'}{\mathbf{N}}$, so $t=\lceil 1-\frac{1}{\mathbf{N}}-\frac{Y_0'}{\mathbf{N}}\rceil$. Then, $y=\mathbf{N}\lceil 1-\frac{1}{\mathbf{N}}-\frac{Y_0'}{\mathbf{N}}\rceil+Y_0'$ satisfies $a^A_{\{I_{k,c} \bmod M\}}=a^B_{\{(I_{k,c}-k) \bmod M\}}$. Let $y'=\mathbf{N}\lceil 1-\frac{1}{\mathbf{N}}-\frac{Y_0'}{\mathbf{N}}\rceil+Y_0'$. Therefore, at slots $I_{k,c}=2\mathbf{N}y'+(c-1-\frac{y'(y'+1)}{2}) \bmod \mathbf{N}$, we have an identical channel such as c for all $1\le c\le N$, since $a^A_{\{I_{k,c} \bmod M\}}$ $(=a^B_{\{(I_{k,c}-k) \bmod M\}})=((\frac{y'(y'+1)}{2}+\mathbf{N}(2y'+1)+(c-1-\frac{y'(y'+1)}{2}) \bmod \mathbf{N}) \bmod \mathbf{N}) \bmod N+1=c$ by (2.4).

2. $k \bmod 2\mathbf{N} < \mathbf{N} \leq I_{k,c} \bmod 2\mathbf{N}$: From case 1), we assume that $a^A_{\{I'_{k',c} \bmod M\}} = a^B_{\{(I'_{k',c}-k') \bmod M\}} = c$ (for all $1 \leq c \leq N$) where $I'_{k',c} \bmod 2\mathbf{N} < \mathbf{N} \leq k' \bmod 2\mathbf{N}$. Let $k = k' + \mathbf{N}$ ($k \bmod 2\mathbf{N} < \mathbf{N}$) and $I_{k,c} = I'_{k',c} + \mathbf{N}$ ($I_{k,c} \bmod 2\mathbf{N} \geq \mathbf{N}$). Then, at slots $I_{k,c}$, we have an identical channel such as c for all $1 \leq c \leq N$, since $a^A_{\{I_{k,c} \bmod M\}} = a^A_{\{(I_{k,c}-\mathbf{N}) \bmod M\}}$ ($\because$ by (2.4) and $I_{k,c} \bmod 2\mathbf{N} \geq \mathbf{N}$) $= a^A_{\{I'_{k',c} \bmod M\}} = c$ and $a^B_{\{(I_{k,c}-k) \bmod M\}}) = a^B_{\{((I'_{k',c}+\mathbf{N})-(k'+\mathbf{N})) \bmod M\}}) = a^B_{\{(I'_{k',c}-k') \bmod M\}} = c$.

For $2\mathbf{N}^2 - \mathbf{N} \leq k < 4\mathbf{N}^2 - \mathbf{N}$ (with reference to Fig. 2.7(c)), two cases should be considered.

1. $k \bmod 2\mathbf{N} < \mathbf{N}$: At slots $I_{k,c} = 2\mathbf{N}(2\mathbf{N} + c - 2) + (c - 1 - \frac{u(u+1)}{2}) \bmod \mathbf{N} + k \bmod \mathbf{N}$ where $u = 2\mathbf{N} + c - 2 - \lfloor \frac{k}{2\mathbf{N}} \rfloor$, we have an identical channel such as c for all $1 \leq c \leq N$, as follows. First, $a^A_{\{I_{k,c} \bmod M\}} = a^A_{\{I_{k,c}\}} = \lfloor \frac{2\mathbf{N}(2\mathbf{N}+c-2)+(c-1-\frac{u(u+1)}{2}) \bmod \mathbf{N}+k \bmod \mathbf{N}-2\mathbf{N}(2\mathbf{N}-1)}{2\mathbf{N}} \rfloor \bmod N + 1 = (c-1) \bmod N+1 = c$ by (2.4). Second, $a^B_{\{(I_{k,c}-k) \bmod M\}} = a^B_{\{I_{k,c}-k\}} = ((\frac{1}{2}\lfloor \frac{I_{k,c}-k}{2\mathbf{N}} \rfloor(\lfloor \frac{I_{k,c}-k}{2\mathbf{N}} \rfloor + 1) + I_{k,c} - k) \bmod \mathbf{N}) \bmod N + 1$ by (2.4). Since $I_{k,c} - k = (2\mathbf{N}(2\mathbf{N} + c - 2) + (c - 1 - \frac{u(u+1)}{2}) \bmod \mathbf{N} + k \bmod \mathbf{N}) - (\lfloor \frac{k}{2\mathbf{N}} \rfloor 2\mathbf{N} + k \bmod \mathbf{N})$($\because k \bmod 2\mathbf{N} < \mathbf{N}$), so $\lfloor \frac{I_{k,c}-k}{2\mathbf{N}} \rfloor = 2\mathbf{N} + c - 2 - \lfloor \frac{k}{2\mathbf{N}} \rfloor = u$. Substituting $\lfloor \frac{I_{k,c}-k}{2\mathbf{N}} \rfloor = u$ into $a^B_{\{(I_{k,c}-k) \bmod M\}}$ yields $a^B_{\{(I_{k,c}-k) \bmod M\}} = ((\frac{u(u+1)}{2} + 2\mathbf{N}u + (c-1-\frac{u(u+1)}{2}) \bmod \mathbf{N}) \bmod \mathbf{N}) \bmod N + 1 = (c-1) \bmod N + 1 = c$ by (2.4).

2. $k \bmod 2\mathbf{N} \geq \mathbf{N}$: At slots $I_{k,c} = 2\mathbf{N}(2\mathbf{N}+c-2) + (c-1-\frac{v(v+1)}{2}) \bmod \mathbf{N} + k \bmod \mathbf{N}$ where $v = 2\mathbf{N}+c-3-\lfloor\frac{k}{2\mathbf{N}}\rfloor$, we have an identical channel such as c for all $1 \leq c \leq N$, as follows. First, $a^A_{\{I_{k,c} \bmod M\}} = a^A_{\{I_{k,c}\}} = \lfloor\frac{2\mathbf{N}(2\mathbf{N}+c-2)+(c-1-\frac{v(v+1)}{2}) \bmod \mathbf{N}+k \bmod \mathbf{N}-2\mathbf{N}(2\mathbf{N}-1)}{2\mathbf{N}}\rfloor \bmod N+1 = (c-1) \bmod N+1 = c$ by (2.4). Second, $a^B_{\{(I_{k,c}-k) \bmod M\}} = a^B_{\{I_{k,c}-k\}} = ((\frac{1}{2}\lfloor\frac{I_{k,c}-k}{2\mathbf{N}}\rfloor(\lfloor\frac{I_{k,c}-k}{2\mathbf{N}}\rfloor+1) + I_{k,c}-k) \bmod \mathbf{N}) \bmod N+1$ by (2.4). Since $I_{k,c}-k = (2\mathbf{N}(2\mathbf{N}+c-2) + (c-1-\frac{v(v+1)}{2}) \bmod \mathbf{N} + k \bmod \mathbf{N}) - (\lfloor\frac{k}{2\mathbf{N}}\rfloor 2\mathbf{N} + \mathbf{N} + k \bmod \mathbf{N}) = (2\mathbf{N}(2\mathbf{N}+c-3-\lfloor\frac{k}{2\mathbf{N}}\rfloor) + \mathbf{N} + (c-1-\frac{v(v+1)}{2}) \bmod \mathbf{N}$ ($\because$ $k \bmod 2\mathbf{N} \geq \mathbf{N}$), so $\lfloor\frac{I_{k,c}-k}{2\mathbf{N}}\rfloor = 2\mathbf{N}+c-3-\lfloor\frac{k}{2\mathbf{N}}\rfloor = v$. Substituting $\lfloor\frac{I_{k,c}-k}{2\mathbf{N}}\rfloor = v$ into $a^B_{\{(I_{k,c}-k) \bmod M\}}$ yields $a^B_{\{(I_{k,c}-k) \bmod M\}} = ((\frac{v(v+1)}{2} + 2\mathbf{N}v + \mathbf{N} + (c-1-\frac{v(v+1)}{2}) \bmod \mathbf{N}) \bmod \mathbf{N}) \bmod N+1 = (c-1) \bmod N+1 = c$ by (2.4).

For $4\mathbf{N}^2-\mathbf{N} \leq k < 2\mathbf{N}(3\mathbf{N}-1)-\mathbf{N}$, the proof is similar to the case (for $\mathbf{N} \leq k < 2\mathbf{N}^2-\mathbf{N}$). We look into slots $I_{k,c} \in \{2\mathbf{N}(3\mathbf{N}-1), 2\mathbf{N}(3\mathbf{N}-1)+1, \ldots, 2\mathbf{N}(4\mathbf{N}-1)-1\} \subset \{k, k+1, \ldots, k+(M-1)\}$. At slot $I_{k,c}$, node A visits channel $a^A_{\{I_{k,c} \bmod M\}} = a^A_{\{I_{k,c}-M\}} = ((\frac{1}{2}\lfloor\frac{(I_{k,c}-M)}{2\mathbf{N}}\rfloor(\lfloor\frac{(I_{k,c}-M)}{2\mathbf{N}}\rfloor+1) + (I_{k,c}-M)) \bmod \mathbf{N}) \bmod N+1$ by (2.4), and node B visits channel $a^B_{\{(I_{k,c}-k) \bmod M\}} = ((\frac{1}{2}\lfloor\frac{I_{k,c}-k}{2\mathbf{N}}\rfloor(\lfloor\frac{I_{k,c}-k}{2\mathbf{N}}\rfloor+1)+I_{k,c}-k) \bmod \mathbf{N}) \bmod N+1$ by (2.4). Two cases should be considered.

1. $I_{k,c} \bmod 2\mathbf{N} < \mathbf{N} \leq k \bmod 2\mathbf{N}$: Let $\lfloor\frac{I_{k,c}-k}{2\mathbf{N}}\rfloor = \lfloor\frac{I_{k,c}}{2\mathbf{N}}\rfloor - \lfloor\frac{k}{2\mathbf{N}}\rfloor - 1$, $x = \lfloor\frac{k}{2\mathbf{N}}\rfloor$ $(2\mathbf{N}-1 \leq x < 3\mathbf{N}-2)$, and $y = \lfloor\frac{I_{k,c}}{2\mathbf{N}}\rfloor$ $(3\mathbf{N}-1 \leq y < 4\mathbf{N}-1)$ similar to the case (for $\mathbf{N} \leq k < 2\mathbf{N}^2-\mathbf{N}$). Then, $((x-2\mathbf{N}+2)y + \mathbf{N}y - \frac{x(x+1)}{2} + \frac{9\mathbf{N}(\mathbf{N}-1)}{2} -$

$2\mathbf{N}(3\mathbf{N}-1)+1+k) \bmod \mathbf{N} = 0$ and also $((x-2\mathbf{N}+2)y - \frac{x(x+1)}{2} + \frac{9\mathbf{N}(\mathbf{N}-1)}{2} + 1 + k) \bmod \mathbf{N} = 0$ satisfies $a^A_{\{I_{k,c} \bmod M\}} = a^B_{\{(I_{k,c}-k) \bmod M\}}$. We show that there exists y $(3\mathbf{N}-1 \le y < 4\mathbf{N}-1)$ such that $((x-2\mathbf{N}+2)y - \frac{x(x+1)}{2} + \frac{9\mathbf{N}(\mathbf{N}-1)}{2} + 1 + k) \bmod \mathbf{N} = 0$ by CRT [7]. $x-2\mathbf{N}+2$, $\mathbf{N}$ are positive integers which are coprime and $-\frac{x(x+1)}{2} + \frac{9\mathbf{N}(\mathbf{N}-1)}{2} + 1 + k$, 0 are integers. The rest of the proof is similar to the case (for $\mathbf{N} \le k < 2\mathbf{N}^2 - \mathbf{N}$), so we omit it.

2. $k \bmod 2\mathbf{N} < \mathbf{N} \le I_{k,c} \bmod 2\mathbf{N}$: The proof is same as case (for $\mathbf{N} \le k < 2\mathbf{N}^2 - \mathbf{N}$).

For $2\mathbf{N}(3\mathbf{N}-1) - N \le k < 2\mathbf{N}(3\mathbf{N}-1)$, at slots $I_{k,c} = 2\mathbf{N}(5\mathbf{N}+c-3)$, we have an identical channel such as c for all $1 \le c \le N$, since $a^A_{\{(2\mathbf{N}(5\mathbf{N}+c-3)) \bmod M\}}$ $= a^A_{\{2\mathbf{N}(2\mathbf{N}+c-2)\}} = \lfloor \frac{2\mathbf{N}(c-1)}{2\mathbf{N}} \rfloor \bmod N + 1 = (c-1) \bmod N + 1 = c$ by (2.4) and $a^B_{\{(2\mathbf{N}(5\mathbf{N}+c-3)-k) \bmod M\}} = a^B_{\{2\mathbf{N}(5\mathbf{N}+c-3)-k\}} = \lfloor \frac{2\mathbf{N}(3\mathbf{N}+c-2)-k}{2\mathbf{N}} \rfloor \bmod N + 1 = (c-1) \bmod N + 1 = c$ by (2.4).

□

Next, we present the generation algorithm of $CRSEQadv$. Node A and B visit channels according to the rendezvous sequence. The generation algorithm of the rendezvous sequence is also based on the properties of triangular numbers and CRT [7]. For triangular numbers, $T_n = \frac{n(n+1)}{2}$ where n is an integer. We assume temporarily that N is a prime number. The rendezvous sequence for total N channels consists of N subsequences. The j-th subsequence starts with T_j and it has $3N-1$ elements in it. The l-th element in the first $2N-1$ elements is computed as $(T_j+l) \bmod N+1$ and any element in the remaining part is $j+1$. With this construction, the rendezvous sequence can be ensured to have k*-shift-rendezvous property* for all k. Identically, we can identify the channel number a_i for slot i using the Eq. (2.4). An example for $N = 3, k = 6$ is shown in Fig. 3.6. At slot 16, A visits channel $(T_2 + 0) \bmod 3 + 1 = 1$ and also B visits channel $(T_1 + 2) \bmod 3 + 1 = 1$. At slot 17, A visits channel $(T_2 + 1) \bmod 3 + 1 = 2$ and also B visits channel $(T_1 + 3) \bmod 3 + 1 = 2$. At slot 18, A visits channel $(T_2 + 2) \bmod 3 + 1 = 3$ and also B visits channel $(T_1 + 4) \bmod 3 + 1 = 3$, and so on. Using Eq. (2.4), we can derive the same sequence as in Fig. 3.6. The generation algorithm for total N (≥ 2) channels is formulated as follows.

$$a_i = \begin{cases} z \bmod N+1, & for\ 0 \leq y < 2\mathbf{N}-1 \\ x \bmod N+1, & for\ 2\mathbf{N}-1 \leq y < 3\mathbf{N}-1 \end{cases} \tag{2.4}$$

where $z = (\frac{x(x+1)}{2} + y) \bmod \mathbf{N}$, $x = \lfloor \frac{i}{3\mathbf{N}-1} \rfloor$, $y = i \bmod (3\mathbf{N}-1)$, and $0 \leq i < \mathbf{N}(3\mathbf{N}-1)$. Note that $\mathbf{N}$ is the smallest prime number greater than or equal to N. By the known results about the distribution of primes [10], it is known that $\mathbf{N}$ $(= N + O(N^{2/3}))$. We call such sequence $CRSEQadv$, the number of whose elements $M = \mathbf{N}(3\mathbf{N}-1)$. Theorem 2.4.1 states that with $CRSEQadv$, two nodes can rendezvous within $M = \mathbf{N}(3\mathbf{N}-1)$ slots.

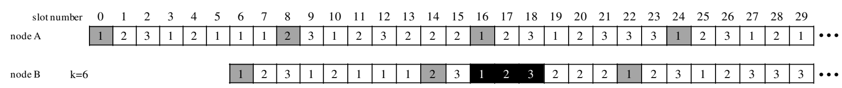

Fig. 2.8 Illustration of the rendezvous process with ($N = 3$)

Theorem 2.4.1. *For* N (≥ 2) *channels,* $CRSEQadv$ *has the* k-shift-rendezvous property *for all* k $(= 0, 1, \ldots, (M-1))$ *so that node* A *and* B *rendezvous in a common channel* $c \in S^A \cap S^B$ *within* M $(= \mathbf{N}(3\mathbf{N}-1))$ *slots, where* $S^A \cap S^B \neq \emptyset$*.*

Proof. At slot I, node A and B visit a channel $a^A_{\{I \bmod M\}}$ and a channel $a^B_{\{(I-k) \bmod M\}}$, respectively. We prove that, for all $k = 0, 1, \ldots, (M-1)$ and for all $c = 1, 2, \ldots, N$, there exists a slot $I \in \{k, k+1, \ldots, k+(M-1)\}$ such that $a^A_{\{I \bmod M\}} = a^B_{\{(I-k) \bmod M\}} = c$.

For $0 \leq k < \mathbf{N}$, at slot $I = (3\mathbf{N}-1)c - 1$, we have a common channel such as c for all $1 \leq c \leq N$, since $a^A_{\{((3\mathbf{N}-1)c-1) \bmod M\}} = a^A_{\{(3\mathbf{N}-1)c-1\}} = \lfloor \frac{(3\mathbf{N}-1)c-1}{3\mathbf{N}-1} \rfloor \bmod N + 1 = (c-1) \bmod N + 1 = c$ by (2.4) and $a^B_{\{((3\mathbf{N}-1)c-1-k) \bmod M\}} = a^B_{\{(3\mathbf{N}-1)c-1-k\}} = \lfloor \frac{(3\mathbf{N}-1)c-1-k}{3\mathbf{N}-1} \rfloor \bmod N + 1 = (c-1) \bmod N + 1 = c$ by (2.4).

For $\mathbf{N} \leq k < \mathbf{N}(3\mathbf{N}-1) - \mathbf{N} + 1$ and $\mathbf{N} \leq k \bmod (3\mathbf{N}-1) < 2\mathbf{N}$, from slot $I = (3\mathbf{N}-1)c - \mathbf{N} + k$ to slot $I + (\mathbf{N}-1) = (3\mathbf{N}-1)c + k - 1$, we have a common channel such as c for all $1 \leq c \leq N$, as follows. First, at slots $I = (3\mathbf{N}-1)c - \mathbf{N} + k$, $I + 1 = (3\mathbf{N}-1)c - \mathbf{N} + k + 1$, $\ldots$, $I + (\mathbf{N}-1) = (3\mathbf{N} -$

$1)c+k-1$, node A visits all channels $1 \leq c \leq N$, since $a^A_{\{I \bmod M\}} = ((\frac{1}{2}(c+\lfloor\frac{k}{3\mathbf{N}-1}\rfloor)(c+\lfloor\frac{k}{3\mathbf{N}-1}\rfloor+1)+k \bmod (3\mathbf{N}-1)-\mathbf{N}) \bmod \mathbf{N}) \bmod N+1$, $a^A_{\{(I+1) \bmod M\}}$ $= ((\frac{1}{2}(c+\lfloor\frac{k}{3\mathbf{N}-1}\rfloor)(c+\lfloor\frac{k}{3\mathbf{N}-1}\rfloor+1)+k \bmod (3\mathbf{N}-1)-\mathbf{N}+1) \bmod \mathbf{N}) \bmod N+1$ $,\ldots, a^A_{\{(I+(\mathbf{N}-1)) \bmod M\}} = ((\frac{1}{2}(c+\lfloor\frac{k}{3\mathbf{N}-1}\rfloor)(c+\lfloor\frac{k}{3\mathbf{N}-1}\rfloor+1)+k \bmod (3\mathbf{N}-1)-\mathbf{N}+(\mathbf{N}-1)) \bmod \mathbf{N}) \bmod N+1$ by (2.4). Second, node B visits only the channel c from slot I to slot $I+(\mathbf{N}-1)$, since $a^B_{\{(I-k) \bmod M\}} = \lfloor\frac{((3\mathbf{N}-1)c-\mathbf{N}}{3\mathbf{N}-1}\rfloor \bmod N+1 = c$, $a^B_{\{(I+1-k) \bmod M\}} = \lfloor\frac{((3\mathbf{N}-1)c-\mathbf{N}+1}{3\mathbf{N}-1}\rfloor \bmod N+1 = c$ $,\ldots, a^B_{\{(I+(\mathbf{N}-1)-k) \bmod M\}} = \lfloor\frac{((3\mathbf{N}-1)c-\mathbf{N}+(\mathbf{N}-1)}{3\mathbf{N}-1}\rfloor \bmod N+1 = c$ by (2.4).

For $\mathbf{N} \leq k < \mathbf{N}(3\mathbf{N}-1)-\mathbf{N}+1$ and $0 \leq k \bmod (3\mathbf{N}-1) < \mathbf{N}$, we look into slots which are $I \geq k$ and $\mathbf{N}-1 \leq I \bmod (3\mathbf{N}-1) < 2\mathbf{N}-1$. At slot I, node A visits channel $a^A_{\{I \bmod M\}} = ((\frac{1}{2}\lfloor\frac{I}{3\mathbf{N}-1}\rfloor(\lfloor\frac{I}{3\mathbf{N}-1}\rfloor+1)+I \bmod (3\mathbf{N}-1)) \bmod \mathbf{N}) \bmod N+1$ by (2.4), and node B visits channel $a^B_{\{(I-k) \bmod M\}} = ((\frac{1}{2}\lfloor\frac{I-k}{3\mathbf{N}-1}\rfloor(\lfloor\frac{I-k}{3\mathbf{N}-1}\rfloor+1)+(I-k) \bmod (3\mathbf{N}-1)) \bmod \mathbf{N}) \bmod N+1$ by (2.4) and $0 \leq (I-k) \bmod (3\mathbf{N}-1) < 2\mathbf{N}-1$. We can let $\lfloor\frac{I-k}{3\mathbf{N}-1}\rfloor = \lfloor\frac{I}{3\mathbf{N}-1}\rfloor - \lfloor\frac{k}{3\mathbf{N}-1}\rfloor$, since $k \bmod (3\mathbf{N}-1) \leq I \bmod (3\mathbf{N}-1)$. Substituting $\lfloor\frac{I-k}{3\mathbf{N}-1}\rfloor = \lfloor\frac{I}{3\mathbf{N}-1}\rfloor - \lfloor\frac{k}{3\mathbf{N}-1}\rfloor$ into $a^B_{\{(I-k) \bmod M\}}$ yields $a^B_{\{(I-k) \bmod M\}}$ $= ((\frac{1}{2}\lfloor\frac{I}{3\mathbf{N}-1}\rfloor - \lfloor\frac{k}{3\mathbf{N}-1}\rfloor(\lfloor\frac{I}{3\mathbf{N}-1}\rfloor - \lfloor\frac{k}{3\mathbf{N}-1}\rfloor+1)+(I-k) \bmod (3\mathbf{N}-1)) \bmod \mathbf{N}) \bmod N+1$. Then, $(\lfloor\frac{k}{3\mathbf{N}-1}\rfloor\lfloor\frac{I}{3\mathbf{N}-1}\rfloor - \frac{\lfloor\frac{k}{3\mathbf{N}-1}\rfloor(\lfloor\frac{k}{3\mathbf{N}-1}\rfloor-1)}{2} + I \bmod (3\mathbf{N}-1) - (I-k) \bmod (3\mathbf{N}-1)) \bmod \mathbf{N} = 0$ satisfies $a^A_{\{I \bmod M\}} = a^B_{\{(I-k) \bmod M\}}$. Let $p = \lfloor\frac{k}{3\mathbf{N}-1}\rfloor$ $(1 \leq p < \mathbf{N})$ and $q = \lfloor\frac{I}{3\mathbf{N}-1}\rfloor$ $(p \leq q < p+\mathbf{N})$. Then p, $\mathbf{N}$ are positive integers which are coprime and $-\frac{p(p-1)}{2} + I \bmod (3\mathbf{N}-1) - (I-k) \bmod (3\mathbf{N}-1)$ is an integer.

There exists q such that $a^A_{\{I \bmod M\}} = a^B_{\{(I-k) \bmod M\}}$ by CRT, and we denote it q'. Then, at slots $I = (3\mathbf{N}-1)q' + \mathbf{N}-1$, $I+1 = (3\mathbf{N}-1)q' + \mathbf{N}-1+1$, $\ldots$, $I+(\mathbf{N}-1) = (3\mathbf{N}-1)q' + \mathbf{N} - 1 + (\mathbf{N}-1)$, we have a common channel such as c for all $1 \leq c \leq N$, since $a^A_{\{I \bmod M\}}$ $(= a^B_{\{(I-k) \bmod M\}}) = ((\frac{q'(q'+1)}{2} + \mathbf{N} - 1) \bmod \mathbf{N}) \bmod N+1$, $a^A_{\{(I+1) \bmod M\}}$ $(= a^B_{\{(I+1-k) \bmod M\}}) = ((\frac{q'(q'+1)}{2} + \mathbf{N} - 1 + 1) \bmod \mathbf{N}) \bmod N + 1$, $\ldots$, $a^A_{\{(I+(\mathbf{N}-1) \bmod M\}}$ $(= a^B_{\{(I+(\mathbf{N}-1)-k) \bmod M\}}) = ((\frac{q'(q'+1)}{2} + \mathbf{N} - 1 + (\mathbf{N}-1)) \bmod \mathbf{N}) \bmod N + 1$ by (2.4).

For $\mathbf{N} \leq k < \mathbf{N}(3\mathbf{N}-1) - \mathbf{N} + 1$ and $2\mathbf{N} \leq k \bmod (3\mathbf{N}-1) < 3\mathbf{N}-1$, the proof is similar to the case (for $\mathbf{N} \leq k < \mathbf{N}(3\mathbf{N}-1) - \mathbf{N} + 1$ and $0 \leq k \bmod (3\mathbf{N}-1) < \mathbf{N}$), so we omit it.

For $\mathbf{N}(3\mathbf{N}-1) - \mathbf{N} + 1 \leq k < \mathbf{N}(3\mathbf{N}-1)$, the proof is similar to the case (for $0 \leq k < \mathbf{N}$), so we omit it. □

2.4.2 Asynchronous communication

In this section, we make a fundamental extension to an asynchronous communication. Suppose that nodes A and B visit channels according to $CRSEQadv$ as shown in Fig. 2.9. Without slot synchronization, the slot boundaries for nodes A and B may not be aligned. To cope with this, the slot time is doubled to be $2t$ in order to ensure that two nodes stay in a common channel for at least time t. Note that t is the minimum time required to establish a link between two nodes. Theorem 2.4.1 states that the rendezvous can be achieved without slot synchronization if the slot time for the case of slot-synchronization is doubled. We present only the case of $CRSEQadv$.

Theorem 2.4.1. *If new slot time $t' = 2t$, then $CRSEQadv$ guarantees A and B to rendezvous in a common channel $c \in S^A \cap S^B$ within $\mathbf{N}(3\mathbf{N}-1)$ slots without slot synchronization, where $S^A \cap S^B \neq \emptyset$.*

Proof. The proof is the same as that of Theorem 2 in [11]. As shown in Fig 2.9, if the misalignment distance of nodes A and B is $\delta = kt' + \theta$ $(0 \leq \theta < t')$ for $k = 0, \ldots, 2N$, only two cases must be considered.

- Case 1: For $0 \leq \theta < t$, every slot from the beginning for B overlaps the corresponding one for A during $(t' - \theta)$ which is long enough to establish the link if they have a common channel. By Theorem 2.4.1, we conclude that nodes A and B rendezvous within $\mathbf{N}(3\mathbf{N}-1)$ slots.

- Case 2: For $t \leq \theta < t'$, every slot from the beginning for B overlaps the next slot for A during θ which is long enough to establish the link if they have a common channel. By Theorem 2.4.1, we conclude that nodes A and B rendezvous within $\mathbf{N}(3\mathbf{N}-1)$ slots.

□

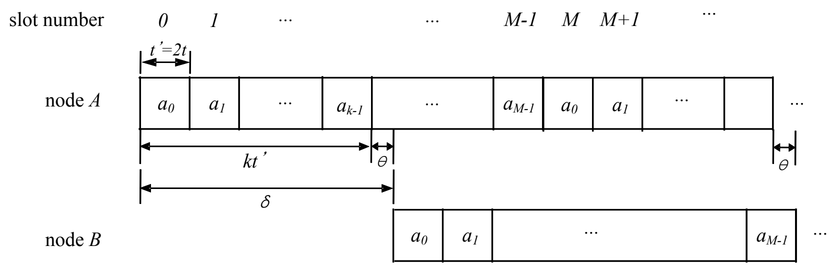

Fig. 2.9 Asynchronous interaction between two nodes

2.5 Summary

In this paper, we propose a deterministic channel rendezvous scheme which provides a bounded rendezvous time, even when each node senses different sets of available channels and nodes are not synchronized.

CHAPTER 3

A Deterministic Neighbor Discovery Scheme for Directional Antenna Networks

3.1 Introduction

The unlicensed 60GHz band brings the promise of multi-gigabit data rates to support new applications such as high-definition video streaming over wireless links and ultra high speed content download [26]. The 60GHz band is very attractive for achieving very high data rates. However, it experiences much higher path loss compared to 2.4GHz and 5GHz radio. To overcome high path loss, the 60GHz systems employ directional antennas to increase the signal's effective radiated power from the transmitter to receiver [27]. Although directional antennas exhibit many advantages compared to omni-directional antennas, their deployment is very challenging for neighbor discovery. Neighbor discovery is a process of finding one hop neighbors to establish links with each other and is the first step towards the design of MAC and network layer protocols [28]. To set-up a directional communication, a node not only needs to know who its neighbor is, but also where its neighbor is. Hence, it is necessary for nodes to determine the direction of each other before setting up directional communications.

Additionally, applying the distributed neighbor discovery on directional antennas is challenging due to the dynamic nature of nodes. Specifically, a neighbor discovery scheme is required to operate when:

- All nodes are not globally synchronized, so the neighbor discovery scheme should be operated in asynchronous environments.
- The beam pattern of nodes which use directional antennas might be different depending on their antenna design [27]. The discovery should be achieved even if any two nodes have different antenna beamwidths.
- Nodes have no compass.

Many neighbor discovery protocols have been proposed for wireless networks that use directional antennas. Probabilistic solutions were proposed and analyzed in [28, 29, 30]. In [28] and [29], each node listens in a random direction for a random time and then transmits a hello message in a random direction and goes back to listening in another random direction. In [30], each node randomly decides whether to be in scan mode (probes a predefined sequence of directions by transmitting hello messages) or listen mode (waits for a specified direction) with equal probability $(1/2)$. Although these approaches are simple and straightforward, they do not guarantee a bounded time for discovery. Deterministic solutions are proposed in [30, 31, 32]. For guaranteeing the discovery within a bounded time, the existing schemes assume omnidirectional antennas [31], time synchronization [30], or pre-assigned roles [26, 32].

In this paper, we propose a neighbor discovery scheme that ensures all nodes in the network will discover their neighbors in a deterministic time without the above-mentioned assumptions. The rest of the paper is organized as follows. We first describe the system model. Then, we present the neighbor discovery scheme and conclude this paper. We believe that the key contribution of our proposed scheme is that:

- To the best of our knowledge, we are the first to propose a deterministic neighbor discovery scheme which guarantees discovery within a bounded time even when nodes have different antenna beamwidths.

3.2 Related works

3.2.1 60GHz radio

60GHz radio is the frontier to enable ultra high quality wireless transmission of multimedia applications. The vision of 60GHz radio is not only the replacement of cable without sacrifice data rate and QoS, but is also envisioned as the hinge to realize smart home, for instance, transport of HD video throughout the Ambient Intelligence home with sufficient QoS. Therefore, 60GHz radio has tremendous commercial values. 60GHz radio technology is very attractive for broadband mobile telecommunication. Radio operating on this frequency band has some unique properties that make them substantially different from radio on the 2.4GHz or 5GHz frequency band. The properties are as follows:

- License free: Abundant unlicensed bandwidth has been allocated worldwide for 60GHz radio. As shown in Fig. 3.1, up to 7GHz bandwidth is allocated for Europe, Japan, North America, and up to 3.5GHz bandwidth is allocated for Australia [19, 20]. Compared with other license-free applications, this is the largest contiguous block of radio spectrum ever allocated.

- Oxygen absorption: The millimeter wave region of the electromagnetic spectrum is characterized by high levels of atmospheric radio frequency energy absorption. This means that transmitted energy is quickly absorbed by oxygen molecules in the atmosphere over long distances, like 15 dB/km. In small scale networks, e.g. home network, oxygen absorption is not a big issue.

- High path loss: Friis free-space propagation model [18] indicates the fundamental relation between the transmitting power P_t, receiving power P_r and the radio wavelength λ as $\frac{P_r}{P_t} = G_t \times G_r(\lambda/4\pi d)^2$ where G_t and G_r are the transmitting and receiving antenna gain respectively, and d is the distance between the transmitting and receiving antennas. Therefore, a free-space path loss derived from Friis model can be expressed as $20\log_{10}(4\pi d/\lambda)$, according to which, the free-space path losses at 1m for 2.4GHz, 5GHz and 60GHz are 40.05 dB, 46.42 dB and 68 dB, respectively. Therefore, 60GHz experiences much higher path loss compared to 2.4GHz and 5GHz radio.

- Small Size Wavelength: Due to the fundamental relationship between the signal wavelength and the antenna size, the wavelength of 60GHz is in the order of millimeter (around 5mm), which makes it possible to design small size antennas at 60GHz band. Therefore, it is convenient to integrate 60GHz featured transceivers with portable consumer electronic devices.

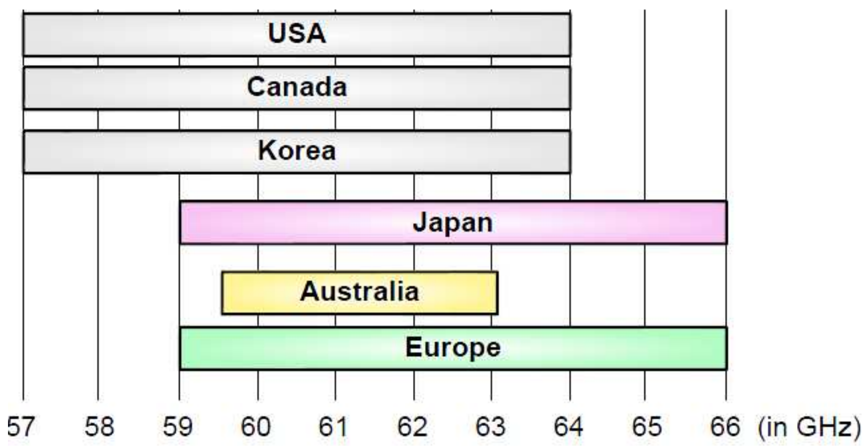

Fig. 3.1 60GHz worldwide spectrum allocation [21]

3.2.2 Directional antennas

To overcome high path loss, high-gain directional antennas are recommended to be used in 60GHz systems. The main advantages of directional antennas are introduced as follows [22].

- Transmission range extension: According to the Friis free-space model mentioned above, it is easy to understand that an increased transmitting or receiving antenna gain results in a longer transmission distance.

- Capacity increase: The capacity of a radio link is directly related to the Signal to Interference plus Noise Ratio (SINR). Interference is mainly because of the communications from other close by users. With directional antennas, it is possible to reduce interference levels by nullifying signals from undesired directions. Therefore, transmission capacity can be increased by increased antenna gain and decreased interference level.

- Spatial reuse: Because directional antennas focus the transmission power on a certain direction and nullify interference from the other directions, more transmission pairs can be accommodated within a certain area.
- Multi-path dispersion reduction: For indoor applications, the multi-path propagation causes delay spread, which limits the maximum bit rate due to inter symbol interference. Using directional antennas suppresses the multi-path dispersion by limiting the transmission power emitting directions.
- Security: Omni-directional transmitted signals are easily tapped by intruders. Directional antennas make the interception of broadcasting more difficult, since it limits the effective reception range only to the desired direction.

3.2.3 60GHz standards and consortiums

IEEE 802.15.3 defines a MAC and PHY standardization for high rate WPANs, which aims to enable wireless connectivity of high-speed, low-power, low-cost, multimedia-capable portable consumer electronic devices [23]. In March 2005, the IEEE 802.15.3 Task Group 3c (TG3c) [24] was formed to develop a 60GHz based alternative PHY for the existing IEEE 802.15.3 standard. It was approved as a standard in Sept. 2009. Three different PHY modes are specified in IEEE 802.15.3 c. The first one is single carrier mode, which aims for low power and low complexity devices. The second is high-speed interface mode, which is for the low-latency bidirectional data transfer. The third one is Audio/video (A/V) mode for the delivery of uncompressed high-definition video and audio. Therefore, 60GHz radio technology can be adopted for a wide range of consumer devices and applications.

The IEEE 802.11 standardization group successfully drives the development of wireless technology in the commercial market. Within the Gigabit gold rush, the IEEE 802.11 formed task group IEEE 802.11 ad [12] to enable 60GHz WLAN. IEEE 802.11 ad is developed from the IEEE 802.11 VHT (Very High Throughput) study group. It is envisioned to be the successor of IEEE 802.11n but it provides ten times higher data rate. The main feature being different from IEEE 802.15.3c is that, IEEE 802.11 ad aims to challenge Gigabit WiFi. The IEEE 802.11ad featured devices are expected to be compatible with the existing IEEE 802.11 services, facilities, and network structures.

The WirelessHD Consortium was formed in 2006 to define a specification for the next generation wireless digital network interface for consumer electronics and personal computing products [13]. WirelessHD is an industry-led organization which consists of several leading technology and consumer electronics companies, (e.g. Broadcom Corporation, Intel Corporation, LG Electronics Inc., Panasonic Corporation, NEC Corporation, etc.) They joined to specify 60GHz technology based mobile and stationary consumer and enterprise applications. Their main focus is to enable wireless HDMI for streaming compressed and uncompressed A/V at up to 1080p resolution.

The Wireless Gigabit Alliance (WiGig) [14] is another industry-led organization promoting multi-Gbps based wireless communications operating over the unlicensed 60GHz spectrum. WiGig was launched in May 2009 and it is comprised of more than fifteen leading companies that include semiconductor vendors, consumer electronic and personal computer manufacturers. Being different with WirelessHD, WiGig aims to provide a wide range of applications. Many WiGig members are also Wi-Fi Alliance members. It is possible that WiGig aligns itself with IEEE 802.11ad to promote Gigabit Wi-Fi.

3.2.4 Existing neighbor discovery solutions

Random algorithms [30, 29, 28]

Under this algorithm, if a node decides to transmit, it will transmit directionally in a random direction in the first mini-slot. When a node decides to listen, it listens during the first mini-slot directionally in a random direction. Suppose that node B decides to listen at the start of the slot and receives a message successfully in the first mini-slot from some node, say node A, it sends back an acknowledgement directionally to node A in the second mini-slot. If node A receives the acknowledgement from node B, it sends a confirmation message to node B directionally in the third minislot. The neighbor discovery process is then completed. In the above algorithms, nodes decide whether to transmit/receive and which direction to transmit/receive completely randomly. There is no coordination among all the nodes. In [28], the authors proposed a mathematical model to analyze a class of neighbor discovery strategies in ad hoc networks with directional mode only antennas. Using the model, they analyze the p parameter which is the probability whether to transmit or receive. $p = 1/2$ in the random case. For high density (i.e. 1000 nodes over 3000m by 3000m field with 200m transmission range), optimal p is 0.22 as shown in Fig. 3.2 since collisions are considered.

Scan based algorithms [30]

In the scan-based algorithms, at the start of each scan, each node is in one of two modes, transmitting or listening. When transmitting (scanning), a node probes a pre-defined sequence of directions for potential neighbors, by transmit-

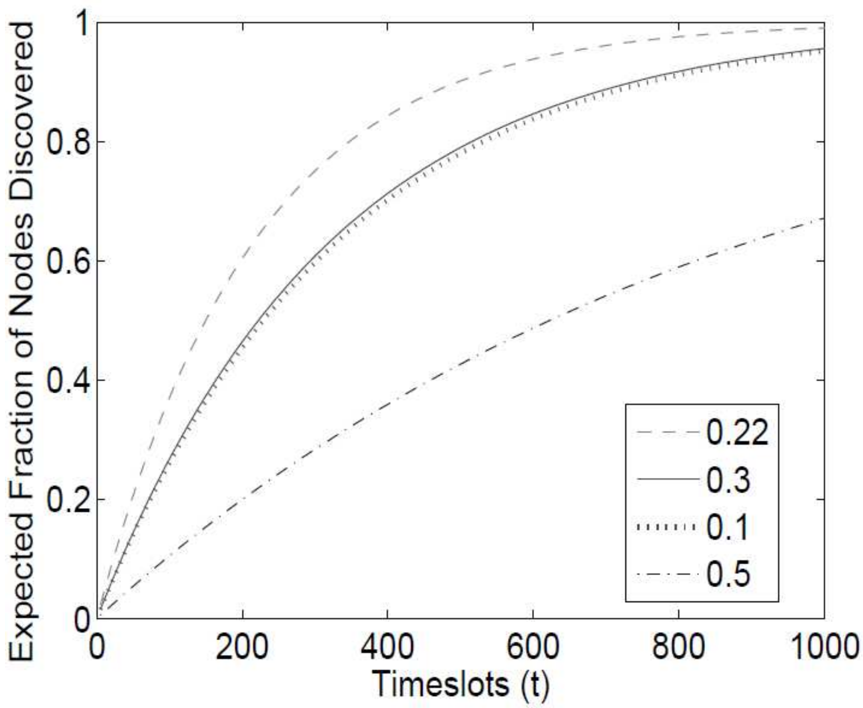

Fig. 3.2 Performance comparison using different p parameters

ting an advertisement in each specified direction. When listening, a node waits for advertisements also in a specified direction. If a listening node receives an advertisement, it responds directionally with its own advertisement, and expects to receive a confirmation in return, all within a timeslot. There are two modes. Under the deterministic mode selection algorithm, they assume that nodes are time synchronized and have unique identifiers. Then, each node is initialized with parameters M and j, where $j \in \{0, \ldots, M-1\}$ (its unique identifier) and M is the maximum number of nodes in the network. Each node's ID, j, is coded into a binary form. If the number of digits is less than $\lceil \log_2 M \rceil$, 0's are added to the left, up to $\lceil \log_2 M \rceil$ digits. For example, if $M = 16$, and $j = 3$, its binary form is 0011 (00 is added in front of 11). For scan i (the i-th scan within a search cycle), if the ith digit of the node ID is 0, it chooses listening mode and if it is 1, it chooses scan mode. For example, node 3 (with binary code of 0011), will choose the scan mode in the first 2 scans and the listen mode in the 3rd and 4th scan. Thus, during the first scan, a node has the opportunity of detecting one-half of its neighbors in the network (if they are within the reachable range, as half of the i-th digit of the node ID is 0s and half is 1s). Under the random mode selection algorithm, at the start of each scan, a node decides randomly whether to be in the scan mode or listen mode with equal probability (1/2), independently the decisions made in previous scans. Fig. 3.3 shows that scan

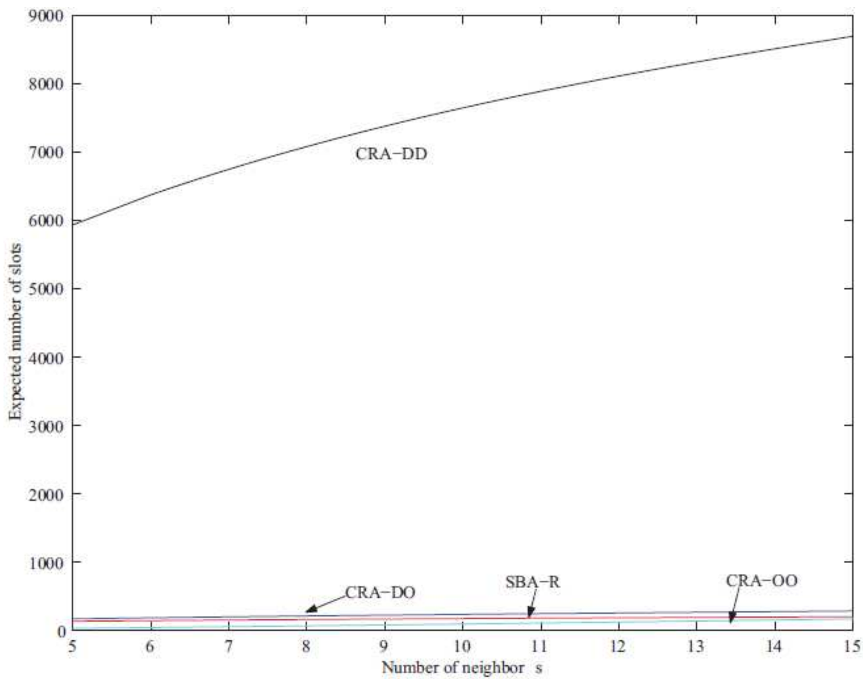

Fig. 3.3 Performance comparison between random and scan based algorithms

based algorithms outperform random algorithms. (beamwidth of each node is 10 degree, CRA-DD is a random algorithm with $p = 1/2$, CRA-DO is a random algorithm with directional transmit and omni-directional receive modes, CRA-OO is a random algorithm with omni-directional transmit and omni-directional receive modes, and SBA-R is a random scan based algorithm)

3.3 System Model

We consider only nodes which are equipped with a directional antenna with beamwidth θ ($0 < \theta \leq 2\pi$) and are covered by each other's beam. We assume that each antenna is steerable so that it can rotate an angle of θ in each step, and that it revolves once in fixed time T. Also, we assume that a two way handshaking procedure (transmitting a HELLO message and receiving back an ACK message between two nodes) can be achieved within each step. As shown in Fig. 3.4, the antenna beamwidth of nodes may be different (e.g. $\theta_A = 30$ degree for node A, $\theta_B = 45$ degree for node B). Our neighbor discovery scheme allows antenna systems that perform either transmission or reception at a time. Directional transmission and reception are accomplished only when the antenna beams mutually cover each other for node A (if sender) and node B (if receiver) as shown in Fig. 3.4. We also assume that each node is distinguishable by a unique identifier like a MAC address.

The beam pattern of nodes which use directional antennas might be different depending on their antenna design [27]. High gain directional antenna technology is utilized to overcome high path loss at 60GHz. Various antenna architectures can be implemented to achieve $10 \sim 20$ dB directional antenna gain. Antennas at the transmitter and the receiver can provide combined $20 \sim 40$ dB gain. Large aperture single antenna designs, such as horn, yagi, and tapper

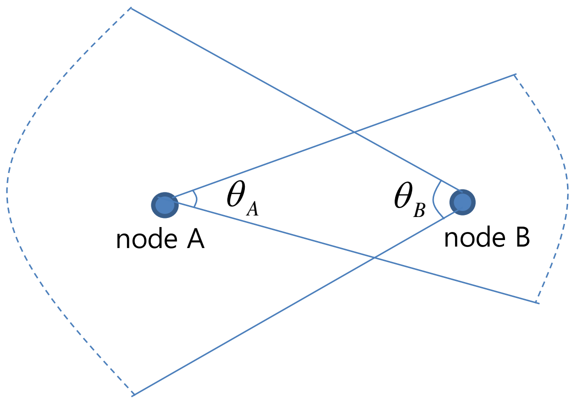

Fig. 3.4 Directional communications

slot antenna (TSA) can celiver high gain in a fixed direction. On the other hand, multiple large aperture high gain antennas can cover different directions and provide broader spatial area coverage. This is called a sector switch antenna system. Alternatively, a phased array antenna technology uses electronically scanning array antenna (ESAA), which automatically tunes the phase of each antenna element to achieve adaptive spatial beam forming. The size of the phased array antenna is compact and can provide broad scanning capability. In the phased array antenna design, there are many possible antenna array arrangements. Different antenna array configuration provides unique array characteristics in terms of peak array gain, array radiation pattern, side lobe level (SLL) and other parameters. The 16 element phased array antenna was designed with linear 1×16, rectangular 2×8, and square 4×4 array configurations. The antenna element in the array was excited with different phases to

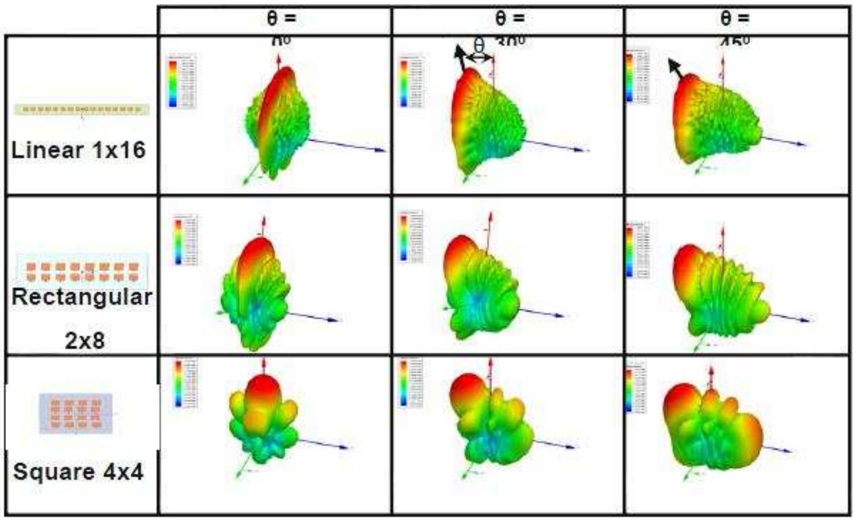

Fig. 3.5 Linear, rectangular and square 16 element array configurations and their radiation pattern at scanning angle $0, 30, 40$ degrees [27]

scan from 0 degree to 45 degree, as shown in Fig. 3.5. The linear array achieves higher array peak gain, narrower beamwidth (5 degree). The square 4×4 antenna array has pencil shape beam pattern and the beamwidth of the square antenna array is ~ 21 degree and is much broader than the linear array. The rectangular 2×8 antenna array is a compromise between the linear and the square array antennas with 12 degree beamwidth.

Our neighbor discovery scheme allows antenna systems that perform transmission and reception only in a directional mode. Directional transmission and reception are accomplished only when the antenna beams mutually cover each other for node A (if sender) and node B (if receiver) as shown in Fig. 3.4. In reality, the directional antenna pattern consists of a mainlobe and several smaller sidelobes [27]. However, we ignore sidelobes for simplicity. We also assume that each node is distinguishable by a unique identifier like a MAC address, and collision and link errors are not considered here.

3.4 Neighbor Discovery Scheme

For neighbor discovery with directional antennas, our key idea is to share a given constant time T for all nodes in the network. We use the shared T value for the steering strategy of the antenna beam, which performs the neighbor discovery regardless of the different antenna beamwidths. The antenna behaves like a sector antenna. The entire omnidirectional 360 degree range is composed of $\frac{2\pi}{\theta}$ non overlapping sectors, the size of which is the same as beamwidth θ (when the beamwidth of a node is θ). We may label the sectors as $0, 1, \ldots, \frac{2\pi}{\theta} - 1$. Every node operates in two modes; scan and listen modes. In the scan mode, node A stays on sector 0 for $\frac{\theta_A}{2\pi} \times T$ and switches to the next sector (when the beamwidth of node A is θ_A). In each sector, node A transmits a HELLO message and waits for an ACK reply. As shown in Fig. 3.6(a), node A resolves probing in all directions for T which is the turnaround time for sweeping all sectors. In listen mode, node B stays on sector 0 for T waiting for reception of a HELLO message. Then, node B switches to the next sector, and stays for T waiting for reception of a HELLO message, and so on. If node B receives a HELLO message from a direction, it responds directionally with an ACK message. This exchange of messages completes the discovery between the nodes A and B.

Suppose that nodes A and B are trying to discover each other. If node B is in the listen mode for period of $\frac{2\pi}{\theta_B} \times T$ and node A is in the scan mode during the

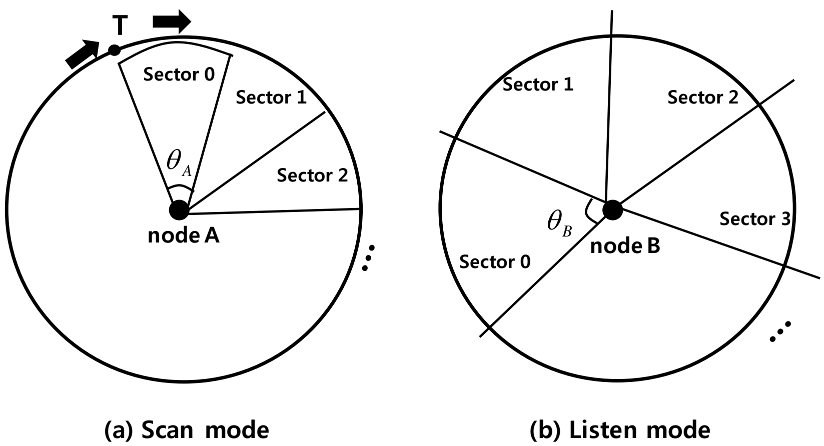

Fig. 3.6 Discovery of two nodes

same period, then the neighbor discovery between two nodes is achieved within a bounded time of $\frac{2\pi}{\theta_B} \times T$ (when the beamwidth of node B is θ_B).

To extend the current scheme for 3-dimensional operation, we assume a directional antenna with horizontal beamwidth θ^h $(0 < \theta^h \leq 2\pi)$ and vertical beamwidth θ^v $(0 < \theta^v \leq 2\pi)$. Horizontal beamwidth refers to the width of the antenna's beam along a plane that is parallel to the horizon, and vertical beamwidth refers to the height of the antenna's beam along a plane that is perpendicular to the horizon. Node A which is in scan mode performs the z-axis rotation as shown in Fig. 3.7(a). It rotates an angle of θ_A^h in each sector, and that it revolves once in $\frac{\theta_A^v}{\pi} \times T$. In each sector, node A stays for $\frac{\theta_A^h}{2\pi} \times \frac{\theta_A^v}{\pi} \times T$ while transmitting a HELLO message and waiting for an ACK reply. After $\frac{\theta_A^v}{\pi} \times T$, the x and z axes have been rotated about the origin through angle θ_A^v to produce the

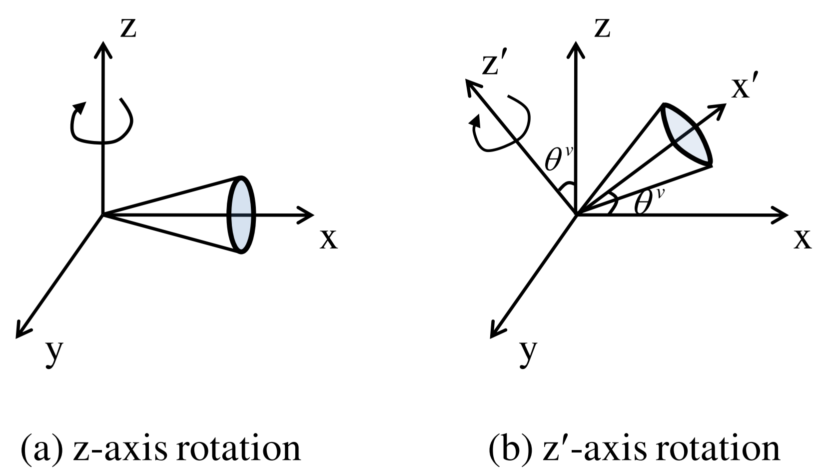

Fig. 3.7 3-dimensional operation

x' and z' axes as shown in Fig. 3.7(b). Then node A performs the z'-axis rotation in the same way. Node A resolves probing in all directions for T which is the turnaround time for sweeping all sectors $(0, 1, \ldots, \frac{2\pi}{\theta_A^h} \times \frac{\pi}{\theta_A^v} - 1)$. Node B which is in listen mode rotates the beam in the same way as node A, but it stays on each sector for T waiting for reception of a HELLO message. Then, node B switches to the next sector, and stays for T waiting for reception of a HELLO message, and so on. If node B receives a HELLO message from a direction, it responds directionally with an ACK message. This exchange of messages completes the discovery between the nodes A and B. Suppose that nodes A and B are trying to discover each other. If node B is in the listen mode for period of $\frac{2\pi}{\theta_B^h} \times \frac{\pi}{\theta_B^v} \times T$ and node A is in the scan mode during the same period, then the neighbor discovery between two nodes is achieved within a bounded time of $\frac{2\pi}{\theta_B^h} \times \frac{\pi}{\theta_B^v} \times T$. Through this basic idea, we show the more specific neighbor discovery scheme. Note that we only explain for the 2-dimensional case.

The neighbor discovery scheme operates in the joining order of nodes to the network in a sequential form. Now, we assume that nodes do not join the network simultaneously and later we remove the assumption. When a new node is ready to join the network, it starts with the listen mode. There are two cases:

- case 1) If other nodes already exist in the network, the new node can receive HELLO messages from all of them within a period of $\frac{2\pi}{\theta} \times T$ when the beamwidth of the new node is θ. As mentioned above, the new node replies to its discovered neighbors using ACK messages. The new node discovers all existing nodes within a bounded time $\frac{2\pi}{\theta} \times T$. After that, the new node switches to the scan mode.

- case 2) If the new node does not hear anything during $\frac{2\pi}{\theta} \times T$, then the new node switches to the scan mode.

To handle the problem when several nodes join the network simultaneously, we consider also two cases:

- case 1) If no node exists in the network, then before switching to the scan mode, it proceeds as follows. It uses the bit streams of its MAC address.

For a 1 bit, it performs the scan mode for $2 \times \frac{2\pi}{\theta} \times T$, and for a 0 bit, it performs the listen mode for $2 \times \frac{2\pi}{\theta} \times T$ (when the beamwidth of the new node is θ). After the 48 bits of the MAC address, it performs the listen mode for $2 \times \frac{2\pi}{\theta} \times T$ once again, and after that, the new node switches to the scan mode.

- case 2) If other nodes already exist in the network, only the newly joining nodes may not discover each other. This case can be easily solved by assistance of existing nodes, so we skip this procedure.

Next, we show that nodes can discover each other within a bounded time. Suppose that nodes A and B are joining the network at time t_A and t_B respectively, and node A joins first (i.e. $t_A < t_B$). Two cases should be considered:

- case 1) If $t_B - t_A \leq \frac{2\pi}{\theta} \times T$, it can be easily proved that nodes A and B can discover each other since there is at least one different bit in their unique MAC address.

- case 2) If $t_B - t_A > \frac{2\pi}{\theta} \times T$, then node A switches to the scan mode first and node B switches to the scan mode after at least $\frac{2\pi}{\theta} \times T$, so two nodes can discover each other.

To cope with that nodes have different beamwidths, we simply include the step for the newly joining node to restart with the listen mode after being in the scan mode for $\frac{2\pi}{\theta} \times \mathbf{T}$, where $\mathbf{T}$ is an application dependent period.

3.5 Summary

In this paper, we have proposed a deterministic neighbor discovery scheme which ensures a bounded time, even when nodes have different antenna beamwidths and nodes are not synchronized.

CHAPTER 4

Conclusions

In this dissertation, we proposed two neighbor discovery schemes which are processes of finding one hop neighbors to establish links with each other and are the first step towards the design of self-organization, MAC and network layer protocols. The first scheme solves the channel rendezvous problem and can be used for cognitive radio networks where the channel availability between nodes can be different. Cognitive radios devices which alter their behavior based on perception and programming, can help solve many spectrum and waveform adaptation issues. In particular, cognitive radios have been envisioned as a chief enabler for Dynamic Spectrum Access (DSA), a mechanism for allowing secondary spectrum users (SUs) to share spectrum with primary spectrum users (PUs). For opportunistic channel access, SUs must dynamically sense a potentially large number of frequency channels; if a channel is not occupied by a PU, it may be available for two or more SUs to establish a communication link. However, there may be a large number of observed open channels (and at any given time PUs may be active in some of these), making the problem of finding a common channel for SU radios to communicate difficult. This dissertation presented an investigation into the channel rendezvous problem, where two or more radios attempt to find one another in a cognitive radio environment consisting of a set of frequency channels shared opportunistically with multiple PUs. Also, it is a challenging problem to apply the distributed neighbor discovery on cognitive radio networks due to the dynamic nature of nodes. Specifically, a neighbor discovery scheme for cognitive radio networks is required to operate when:

- We assume an infrastructureless environment. The use of a dedicated control channel or a central unit simplifies the rendezvous process, but it may result in a bottleneck, or create a single point of failure [35]. Moreover, the dynamically changing availability of spectrum may make it impossible to maintain a control channel [50].

- The discovery should be achieved even if each node may sense different sets of available channels.

- All nodes are not globally synchronized, so the neighbor discovery scheme should be operated in asynchronous environments.

We believe that the key contributions of our proposed scheme are twofold:

- First, to the best of our knowledge, we are the first to propose a deterministic rendezvous process which guarantees rendezvous within a bounded time even when each node senses different sets of available channels.

- Second, all nodes operate with an identical rendezvous process in a fully distributed manner.

The other scheme solves the neighbor discovery with directional antennas and can be applied to 60GHz radio applications. The principle usage for the 60GHz radio technology is its applicability in networked future homes, where various types of multimedia applications are highly expected. 60GHz consumer products are emerging in the market since 2009, such as wireless HDMI replacement solution. However, simply replacing a 10m HDMI cable may not provide a bright future for the 60GHz technology. Wireless HDMI replacement may be the killer application for 60GHz radio, but it is not the only strength to motivate the research on 60GHz radio. Lot of efforts are taking place to apply

60GHz radio in a wider range of applications. For instance uncompressed video streaming, multi uncompressed video streaming, office desktop, conference ad-hoc, and kiosk file-downloading. To achieve these goals,the issues like neighbor discovery, self organization, medium access, system coexistence, etc., need to be addressed. Also, it is a challenging problem to apply the distributed neighbor discovery on directional antennas due to the dynamic nature of nodes. Specifically, a neighbor discovery scheme for 60GHz directional antenna networks is required to operate when:

- Directional transmission and reception are accomplished only when the antenna beams mutually cover each other for any two nodes.
- The beam pattern of nodes which use directional antennas might be different depending on their antenna design [27]. The discovery should be achieved even if any two nodes have different antenna beamwidths.
- All nodes are not globally synchronized, so the neighbor discovery scheme should be operated in asynchronous environments.
- Nodes have no compass.

We believe that the key contribution of our proposed scheme is that:

- To the best of our knowledge, we are the first to propose a deterministic neighbor discovery scheme which guarantees discovery within a bounded time even when nodes have different antenna beamwidths.

Future works include research on MAC protocols for cognitive radio channels and 60GHz wireless networks.

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인지무선 채널 환경과 지향성 안테나 네트워크를 위한 이웃 탐색 기법에 관한 연구

본 논문은 미래 통신을 위한 신기술로 주목 받고 있는 인지 무선 네트워크 (Cognitive Radio Network) 기술과 60GHz 주파수 대역 기반 무선 네트워크 기술에 관해 기술한다. 기하급수적으로 증가하는 방송 및 통신 시스템으로 인해 무선 주파수 자원의 고갈 문제가 심각하게 대두되고 있다. 이와 같은 주파수 고갈 문제의 해결을 위해 유휴 주파수를 사용하는 인지 무선 기술이 많은 관심을 받고 있다. 인지 무선 네트워크 기술은 단말 기기 및 네트워크의 지능화를 통해 동적으로 변화하는 주파수 상태를 인지하여 유휴 주파수 자원을 최적으로 활용하고자하는 기술이다. 또한, 60GHz 주파수 대역 기반 무선 네트워크 기술은 HD 급의 고화질 동영상 무선 전송, 대용량 무선 데이터 전송 등의 응용을 서비스하기 위한 기가급 무선 전송 속도를 제공할 수 있는 기술이다. 이웃 탐색 기법은 자기의 이웃 노드들을 탐색하여 서로 연결 링크를 설정하는 기법으로, 무선 네트워크를 형성하기 위한 핵심 기초 기술이라고 할 수 있다. 최근에, 채널 환경이 동적으로 변하는 인지 무선 네트워크의 특성과 지향성 안테나를 사용해야만 하는 60GHz 주파수 대역의 특성을 고려한 이웃 탐색 기법을 개발하는 것이 새로운 연구 과제이다.

먼저 본 논문은, 인지무선 네트워크에서의 이웃 탐색 기법을 기술한다. 인지 무선 네트워크는 허가된 주파수 대역에서 활동하는 주 사용자 (Primary node)의 주파수 점유 권리를 보장하면서 비허가 사용자 (Secondary node)가 유휴 주파수를 효율적으로 사용할 수 있도록 운용된다. 비허가 사용자들은 주 사용자가 점유하고 있지 않은 채널을 선택하여 이웃 탐색을 시도한다. 각 비허가 사용자와 주 사용자들의 상대

적인 위치에 따라 각 비허가 사용자가 사용 가능한 채널들의 집합이 다를 수 있다. 이러한 성질이 이웃 탐색을 어렵게 한다. 본 논문에서는 비허가 사용자가 접근하는 채널 순서를 정하여, 임의의 두 사용자가 일정한 시간내에 서로 사용 가능한 채널에서 통신이 이루지는 것을 보장하는 방법에 관하여 기술한다. 또한, 두 사용자는 서로간의 시간 동기화를 요구하지 않는다.

본 논문은 지향성 안테나를 사용하는 60GHz 주파수 대역 기반 네트워크에서의 이웃 탐색 기법에 관해여 기술한다. 60GHz 무선 통신에서는 주파수의 특성에 의해 기가급의 무선 전송 속도를 제공하기 위해 지향성 안테나의 사용이 불가피하다. 지향성 안테나를 사용하는 경우에는 통신을 시작하려는 두 사용자의 안테나가 서로 마주보고 있는 경우에만 통신이 가능하다. 이러한 성질이 이웃 탐색을 어렵게 한다. 또한, 각 사용자가 서로 다른 안테나 빔폭을 가지거나, 두 사용자가 서로간의 시간 동기화가 이루어 지지 않은 상태에서도 이웃 탐색이 가능해야 한다. 본 논문에서는 지향성 안테나 네트워크에서 정해진 시간내에 이웃 탐색을 보장하는 기술에 관하여 기술한다.

감 사 의 글

오랜 시간의 흔적들과 함께 나의 발자취들이 녹아있는 연구실 자리에 앉아, 학위논문의 마지막 장을 감사의 글로 작성하려는 순간 여러 감정이 가슴 벅차게 밀려오는 것 같습니다. 대학을 졸업하고 대학원 학생으로서 첫발을 포항이라는 땅에 설레임과 기대감에 충만하여 내딛었던 순간이 생생히 소중한 기억으로 먼저 떠오릅니다. 출발하는 순간에 품었던 의지를 가끔씩 기억해 왔기에 연구 과정 중에 어려움들을 이겨나가며 성장해왔던 것 같습니다. 하지만, 이러한 초발심의 힘보단 저에게 직접적인 도움을 주신 분들이 너무 많기에, 제가 새로운 도전의 시작을 출발할 수 있는 시점에 도달할 수 있었던 것 같습니다. 그분들께 작으나마 감사의 마음을 글로 전하려고 합니다.

부족한 저를 대학원생으로 받아주시고, 8년 동안 아주 큰 가르침을 주신 김치하 교수님께 진심으로 감사 드립니다. 항상 큰 그림을 가지고 연구를 시작할 수 있도록 격려와 질책을 통해 가르쳐 주신 스승님 뜻에 어긋나지 않는 제자가 될 수 있도록 항상 가르침을 마음 속 깊이 새기겠습니다. 바쁘신 와중에도 논문 심사와 진심으로 조언을 해주신 박찬익 교수님, 서영주 교수님, 송황준 교수님, 그리고 한기준 교수님께 감사를 드립니다. 훌륭하신 교수님들 덕분에 많은 것을 배우고 학교를 졸업하게 된 것 같습니다.

공부한다는 이유로 자주 찾아 뵙지 못한 부모님께 항상 죄송한 마음과 걱정만 끼쳐드렸는데, 저를 믿어주시고 공부할 수 있도록 물심양면으로 신경 써주시고 기도해주셔서 항상 감사하는 마음을 가지고 있습니다. 앞으로는 효도하는 아들이 되겠습니다. 더 큰 꿈을 가지고 미국으로 유학 가셔서 나보다도 더 힘든 생활을 하고 있을 누나에게 멀리서나마 항상 응원과 기도를 보내고 있습니다. 아버지, 엄마, 누나 존경하고 사랑합니다. 그리고, 공부 중에 하늘나라로 떠나신 외할머니께 논문을 바

칩니다.

NDS 연구실에서의 추억은 영원히 잊지 못할 것 같습니다. 항상 연구의 열기가 뜨거운 NDS 연구실이란 작은 삶의 공간에서 함께 연구하며, 서로의 생각을 나누며, 서로 도와주며 함께 뜻 깊게 즐거운 시간을 보냈던 것 같습니다. 제가 처음 연구실에 왔을 때 밝게 맞이해주시고 연구실 시작의 부푼 기대를 주신 근형이형, 정말 따뜻한 시선과 격려를 통하여 저의 가능성을 펼칠 수 있게 도움을 주신 종식이형, 연구실에서 성실한 모습을 몸소 실천으로 보여주시며 새로운 가르침을 주신 태근이형, 신입생 때 많은 꾸지람과 관심으로 랩 생활의 기본을 가르쳐 주신 윤구형, 항상 뒤에서 힘이 되는 버팀목으로 저를 바라보시며 인도해주신 덕희형, 힘들 때마다 가까이 기댈 수 있는 형으로 듬직하게 맞이해주셨던 찬필이형, 아무것도 몰랐던 저에게 항상 세심하게 가르쳐 주셨던 규영이형, 유일한 동갑내기 선배로 가까울 수 있었던 영숙이, 관심 깊은 대화로 가르침을 주셨던 한림형, 말로는 표현할 수 없을 만큼 너무나도 많은 정신적 도움을 주셨던 영진이형, 함께 일하며 호흡이 잘 맞던 미애, 자기 색이 분명해서 좋았던 지현이, 기대가 컸던 안타까운 승규, 랩 사람들에게 어머니와 같은 사랑을 주셨던 미정 누나, 대한민국 군인으로서 자랑스러웠던 종혁이형, 성용이형, 그리고 주현이형, 사회인으로서의 가르침을 주셨던 성열이형, 독특한 사고를 바탕으로 다른 분야에서도 열심인 상익이, 친동생 같은 친근감을 주었던 지혜, 따뜻한 인간미를 바탕으로 함께 연구하는 방법을 가르쳐주신 정규형, 좋은 연구 성과를 함께 이룩할 수 있어 가장 고마운 동민형, 석사 때부터 함께 연구할 수 있어 가장 행복했던 동호형, 자랑스러운 후배 순목이, 현 랩장으로서 가장 고생이 많은 후배 기석이, 연구실의 즐거움을 가장 많이 주며 내가 아끼는 후배 승열이, 성실함의 자세가 보기 좋은 후배 재훈이, 가장 친한 친구 현목이, 산학 공동 연구의 가르침을 주신 용수형, NDS 연구실 첫 여성박사의 주인공이 될 후배 지선이, 연구실의 궂은 일을 도맡아 솔선수범인 사랑스러운 후배 중휘, 미래가 가장 기대되는 두 신입생 철민, 건희, 모든 연구실 선후배들에게 감사를 드리며 연구실의 빛나는 발전을 통하여

모두 세상의 주인공이 되기를 희망합니다.

졸업을 한지 오래되었지만, 언제나 서로의 발전을 위하여 관심을 가지는 홍익대학교 컴퓨터공학과 사람들에게 감사를 드리고 싶습니다. 함께 대학 공부를 시작한 경찬이형, 명현, 재식, 준일, 효원 ,시명, 민욱에게 고맙고, 영어회화 동아리 사람들에게도 감사의 뜻을 전합니다.

마지막으로, 영원히 고마운 마음을 잊을 수 없는 미안함이 먼저인 그녀 박수정에게 이 논문을 바칩니다.

Curriculum Vitae

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Education

Mar.1998 Feb.2003: B.S. in Computer Science and Engineering, Hongik University

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Thesis Title :

M-ary 검색 알고리즘을 이용한 다수의 **RFID** 태그 식별에 관한 연구**(Multiple RFID Tags Identification with M-ary Search Algorithm)**

Advisor: Prof. 김 치 하

Mar.2005 Feb.2011: Ph.D. in Computer Science and Engineering

Division of Electrical and Computer Engineering, POSTECH

Thesis Title :

인지무선 채널 환경과 지향성 안테나 네트워크를 위한 이웃 탐색 기법에 관한 연구(Neighbor Discovery for Cognitive Radio Channels and Directional Antenna Networks)

Advisor: Prof. 김치하 (Cheeha Kim)

Publications

International Journal

1. Jongmin Shin, Dongmin Yang and Cheeha Kim, "A Channel Rendezvous Scheme for Cognitive Radio Networks" *IEEE Communications Letters*, vol. 14, no. 10, pp. 954 - 956, Oct. 2010", Oct. 2010.

2. Dongmin Yang, Jongmin Shin and CheeHa Kim, "Deterministic Rendezvous Scheme in Multi-channel Access Networks" *IET Electronics Letters*, vol. 46, no. 20, pp. 1402 - 1404, Sep. 2010, Sep. 2010.

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3. 직교 주파수 분할 다중 시스템에서의 목표 데이터 전송률과 에너지 제약을 만족하는 최적의 채널별 변조기법 선택 방법, 출원인: 포항공과대학교 산학협력단, 특허, 출원번호: 10-2009-0106276, 발명인: 고현목, 김치하, 양동민, 신종민, 오승열 (2009-11-05)

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