Doctoral Thesis

Neighbor Discovery Schemes for Multichannel Wireless Networks and Opportunistic Networks

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2011

다중 채널 무선 네트워크와
기회적 네트워크를 위한
이웃 탐색 기법에 관한 연구

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by

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A dissertation submitted to the faculty of the Pohang University of Science and Technology in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Division of Electrical and Computer Engineering.

Pohang, Korea

12. 21. 2010

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DECE 20033327

양 동 민, Dongmin Yang, 다중 채널 무선 네트워크와 기회적 네트워크를 위한 이웃 탐색 기법에 관한 연구, Neighbor Discovery Schemes for Multichannel Wireless Networks and Opportunistic Networks, Department of Computer Science and Engineering
Division of Electrical and Computer Engineering, 2011, 92 p, Advisor: 김치하 (Cheeha Kim). Text in English

Abstract

Recently, there has been a growing interest in new networking paradigms such as opportunistic networks and cognitive networks. Various applications of ubiquitous networking and cloud computing are at the heart of such development (e.g. military, vehicular, rescue, medical, and multimedia transfer service). These networks are typically deployed without any communication infrastructure and are required to configure themselves. Neighbor discovery is one of the first steps in the self-configuration. To enable reliable exchange of data or control information, two nodes in physical contact must recognize each other and establish a link in a common channel. If a node fails to accomplish it, it misses the contact and experiences very long delivery latency or a failure of data delivery. Moreover, since it is difficult to predict when a node gets and how long it keeps in contact with another node, it is very challenging to discover neighbor nodes. In this thesis, we focus on the problem of discovering neighbor nodes in a fully distributed and deterministic manner.

In the first topic of this thesis, we propose a channel rendezvous scheme in multi-channel access networks. Nodes must establish a link on a common channel before data transmission begins. We focus on the distributed channel rendezvous problem without a separate control channel. Our scheme determines the order, in which two nodes visit available channels to rendezvous within $2N + 1$ slots, where N is the number of channels and a slot is the minimum interval required for establishing a link between any pair of nodes that are in a common channel. The best bound known so far is $N^2 + N - 1$ slots. By Jain's fairness index, we justify the claim that all channels are fairly accessed. More notably, our scheme can be implemented without slot synchronization which is hard to accomplish in a distributed manner.

In the second topic of this thesis, we propose an optimal energy-efficient neighbor discovery scheme for opportunistic networks. Opportunistic networks are one of the most interesting evolutions of MANETs (Mobile Adhoc Networks). For a practical MANET, links may be intermittently established due to short transmission range and high user mobility, which is not the case where most previous works have implicitly assumed that the network is connected and there is a contemporaneous end-to-end path between any two nodes. For prompt neighbor discovery, a node is assumed to broadcast continuously probing messages to discover another in its vicinity. This kind of persistent probing consumes too much energy for battery-operated devices to afford. In order to minimize the energy consumption for persistent probing, a node must be able to turn off its radio, thus setting it to sleeping mode, during non-contact times and be able to turn it on only for neighbor discovery and data exchange. We design a probing schedule which provides a bounded delay with the minimal miss probability of a contact. Then, we derive an energy-efficient probing and associated listening schedule. The proposed neighbor discovery scheme is optimal in the sense that it provides a bounded delay with the minimal energy consumption as well as with the minimal miss probability of a contact. The performance of the proposed neighbor discovery scheme is evaluated by an extensive theoretical analysis and simulation results. Performance metrics, such as energy consumption, and loss probability of a contact are compared with those of existing schemes. The theoretical analysis and simulation results are also used to show the performance of the proposed scheme could be improved. In opportunistic networks where contact between two nodes occurs infrequently, we show that the proposed scheme achieves more significant energy-efficiency and provides much higher successful neighbor discovery probability than existing schemes.

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CHAPTER 1

Introduction

The vision of "Anytime, Anywhere from Any device" for computing and communication anytime is the global hottest trends in today's development. Especially, mobile ad hoc networking (MANET) has attracted much interest from many researchers and the advance of wireless communication technology has made it possible to achieve the vision to some extent. However, there are still so many challenges to overcome when it will be deployed the practically and incrementally in a real world.

To resolve the scarcity of wireless resource and increase the network capacity and utilization, multi-channel networks, instead of single-channel, have extensively been studied during the last some decades. In multi-channel networks, to enable reliable data exchange, two nodes should arrive on one common channel commonly available to them. In this context, neighbor discovery means that two nodes access a channel during a certain period of time which is long enough to establish a reliable link. It is worth noting that some previous work on the topic refers to this process as ”rendezvous” rather than ”neighbor discovery”. The rendezvous process for multi-channel networks is necessary for data transmission and can be achieved in centralized, or distributed manner. The use of a dedicated control channel or a central unit simplifies the rendezvous process, but may still act as a bottleneck and single point of failure is still a concern. Therefore, we focus on rendezvous when there are no control channels or centralized controllers, and all vacant channels are potentially available for the exchange of control and data, which we call it as the blind rendezvous problem.

Recently, interesting evolutions of MANETs, (eg. opportunistic networks and delay tolerant networks) have attracted a lot of attention. This networking is an emerging technology with a wide range of potential applications (e.g., military, vehicular, rescue, medical, and multimedia transfer service). Such networks are characterized by intermittent connectivity. There is no contemporaneous end-to-end path between any two nodes, called network partitioning. Links may be intermittently established due to their short transmission range and high user mobility. In the absence of a fixed infrastructure for connectivity, instead of maintaining network connectivity with the high cost of control messages, data must be exchanged during every opportunistic contact when the device happens to come into transmission range of others. Because the contact duration may be short, it is necessary for any neighboring nodes to recognize each other as quickly as possible to ensure a sufficient time to exchange data. Until the destination node is reached, data can be delivered in a store-and-forward manner, where, if a node with data to be forwarded has no destination node in the vinicity, data is buffered into an intermediate node and sent at a later time to the destination or to another intermediate node. Therefore, if a node fails to recognize another within its transmission range, it misses the contact, and experiences very long delivery latency or a failure of data delivery. And, these battery-operated devices cannot afford persistent and battery-draining probing, so it is very important for such devices to discover a neighbor in contact with minimum energy consumption.

The remainder of the dissertation is organized as follows. This dissertation consists of two parts. Chapter 2 proposed Deterministic Rendezvous Scheme in Multi-channel Access Networks. Chapter 3 presents Optimal Energy-Efficient Neighbor Discovery Scheme in Opportunistic Networks. Finally, conclusion is given in Chapter 4.

CHAPTER 2

Deterministic Rendezvous Scheme in Multi-channel Access Networks

2.1 Introduction

To enable reliable data exchange, 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. The rendezvous process for multi-channel access networks is necessary for data transmission and can be achieved in centralized, or distributed manner [1]. The rendezvous process for multi-channel access networks is necessary for data transmission and can be achieved in centralized, or distributed manner [1]. In the former, a control channel is adopted for control information exchange [2, 3, 4], or a central unit is responsible for the link establishment between nodes [5]. The use of a dedicated control channel or a central unit simplifies the rendezvous process, but may result in a bottleneck, or create a single point of failure. We focus on the distributed approach in which all channels are accessed in a predetermined order to rendezvous.

Few results for the distributed rendezvous schemes can be found in literature [1, 6, 14, 15]. The best probabilistic solution is the Anderson-Weber strategy which solves the rendezvous search problem on a complete graph [6, 14]. The expected rendezvous time is asymptotic to $0.82888497N$ where N is the number of available channels, but it does not guarantee a bounded time to rendezvous. In contrast, deterministic solutions predefining a rule of visiting channels provide a bounded time to rendezvous [1, 15]. The best bound known so far is $N^2 + N - 1$ slots. A slot is the minimum interval required to establish a link between any pair of nodes that are in a common channel. They are assumed to accomplish slot synchronization.

In this chapter, we propose a novel approach to find the deterministic rendezvous sequence that bounds the maximum rendezvous time to $2N + 1$ slots.

We first describe the necessary backgrounds. Second, we present the algorithm which generates the deterministic rendezvous sequence. Third, we prove that the maximum rendezvous time is $2N + 1$ slots. Finally, we show that this solution can be extended to an asynchronous communication which does not require slot synchronization. We believe that the key contribution of our proposed solution is threefold;

- To the best of our knowledge, we are the first to propose the deterministic rendezvous process with the smallest bound for rendezvous time of $2N + 1$ slots.
- The rendezvous process provides fair channel access in multi-channel environment.
- All nodes operate with an identical rendezvous sequence in fully distributed manner.

2.2 Previous works

2.2.1 Centralized approach [2, 3, 4, 5]

Since, in cognitive networks, the rendezvous process needs to be carried out in a distributed manner, a central entity, such as a base station, is not available. To address this difficult problem, the vast majority of the existing MAC protocols for cognitive networks rely on a dedicated global or group control channel [5, 2, 3, 4]. Assuming a common control channel certainly simplifies the rendezvous process as well as other medium access-related issues. However, relying on a common control channel has a number of important drawbacks. A common control channel may become a bottleneck or create a single point of failure. More importantly, the dynamically changing availability of spectrum may make it impossible to maintain a common control channel. In cognitive networks, the availability of any channel cannot be guaranteed, thus making it impossible to guarantee the availability of the common control channel.

2.2.2 Anderson-Weber [6]

Two friends have become separated in a building or shopping mall and and wish to meet as quickly as possible. There are n possible locations where they might meet. However, the locations are identical and there has been no prior

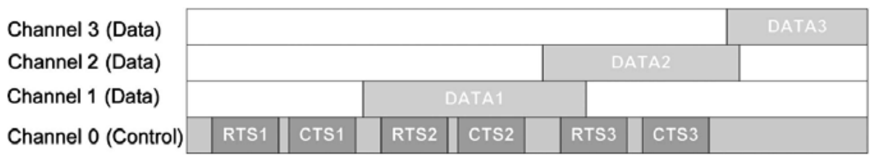


Fig. 2.1 Dedicated Control Channel Approach

agreement where to meet or how to search. Hence they must use identical strategies and must treat all locations in a symmetrical fashion. Suppose their search proceeds in discrete time. Since they wish to avoid the possibility of never meeting, they will wish to use some randomizing strategy. If each person searches one of the n locations at random at each step, then rendezvous will require n steps on average. It is possible to do better than this: although the optimal strategy is difficult to characterize for general n, there is a strategy with an expected time until rendezvous of less than $0.829n$ for large enough n. For $n = 2$ and 3 the optimal strategy can be established and on average 2 and $8/3$ steps are required respectively. There are many tantalizing variations on this problem, which we discuss with some conjectures.

2.2.3 Dedicated Control Channel [7] [8] [9]

Every device has two radios. One radio is tuned to a channel dedicated to control messages and the other radio can tune to any other channel. In principle, all devices can overhear all the agreements made by other devices, even during data exchange. This system's efficiency is limited only by the contention for the control channel and the number of available data channels.

Fig. 2.1 illustrates the operations of Dedicated Control Channel. In the figure, channel 0 is the control channel and channels 1, 2, and 3 are for data transmission. When device A wants to send to device B, it transmits a request-to-send (RTS) packet on the control channel. That RTS specifies the lowest numbered free channel. Upon receiving the RTS, B responds with a clear-to-send (CTS) packet on the control channel, confirming the data channel suggested by A. The RTS and CTS packets also contain a Network Allocation Vector (NAV) field, as in 802.11, to inform other devices of the duration for which the sender, the receiver, and the chosen data channel are busy. Since all devices listen to the control channel at all times, they can keep track of the busy status of other devices and channels, even during data exchange. Devices avoid busy channels when selecting a data channel.

Examples of this approach include Dynamic Channel Allocation (DCA) [7], DCA with Power Control (DCA-PC) [8], and Dynamic Private Channel (DPC) [9].

The major advantage of Dedicated Control Channel is that it does not require time synchronization: Rendezvous always happen on the same channel. The main disadvantage of this protocol is that it requires a separate dedicated

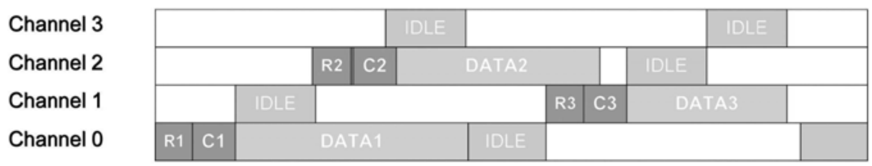


Fig. 2.2 Common Hopping Approach

control radio and a dedicated channel, thereby increasing cost and decreasing spectral efficiency when few channels are available.

2.2.4 Common Hopping [10] [11]

In this approach, devices have only one radio. Devices not exchanging data hops through all channels synchronously. A pair of devices stop hopping as soon as they make an agreement for transmission and rejoin the common hopping pattern subsequently after transmission ends.

The Common Hopping protocol improves on Dedicated Control Channel in two respects: 1) it uses all the channels for data exchange and 2) it requires only one transceiver per device. As shown in Fig. 2.2, the hopping pattern cycles through channels 0, 1, 2, and 3. When device A wants to send to device B, it sends an RTS to B on the current common channel. If B receives the RTS properly, then it returns a CTS on the same channel. Devices A and B then pause hopping and remain on the same channel during data transfer, whereas the other idle devices continue hopping. When they are finished, devices A

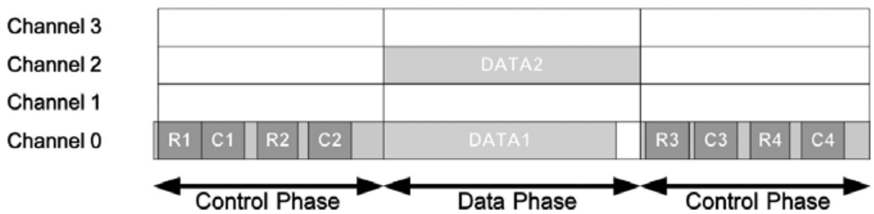


Fig. 2.3 Split Phase Approach

and B rejoin the Common Hopping sequence with all the other idle devices. It is possible that the Common Hopping sequence wraps around and visits the channel that A and B are using before they finish data exchange. Idle devices sense the carrier and refrain from transmitting if it is busy.

While A and B are exchanging data, they are unaware of the busy status of the other devices. Hence, it is possible that a sender sends an RTS to a device that is currently busy on a different channel. Another issue with this approach is that devices hop more frequently. Examples of this design approach include channel hoping multiple access (CHMA) [10] and Channel Hopping multiple Access with packet Trains (CHAT) [11].

2.2.5 Splite Phase [12] [13]

In this approach, devices use a single radio. Time is divided into an alternating sequence of control and data exchange phases, as shown in 2.3. During a control phase, all devices tune to the control channel and attempt to make agreements for channels to be used during the following data exchange phase.

If device A has some data to send to device B, then it sends a packet to B on the control channel with the ID of the lowest numbered idle channel, say, i. Device B then returns a confirmation packet to A. At this point, A and B have agreed to use channel i in the upcoming data phase. Once committed, a device cannot accept other agreements that conflict with earlier agreements.

In the second phase, devices tune to the agreed channel and start data transfer. The protocol allows multiple pairs of devices to choose the same channel because each pair might not have enough data to use up the entire data phase. As a result, the different pairs must either schedule themselves or contend during the data phase. In the analysis, we assume that at most one device pair can be assigned to each channel, so there is no need for scheduling or contention. In the simulation section, we assume random access, as suggested in [12] where multiple pairs can share the same channel during a data phase.

The advantage of this approach is that it requires only one radio per device. However, it requires time synchronization among all devices, though the synchronization can be looser than in Common Hopping because devices hop less frequently. Examples of this approach are MMAC and Multichannel Access Protocol (MAP) [13] Their main difference is that the duration of the data phase is fixed in MMAC, whereas it is variable in MAP and depends on the agreements made during the control phase.

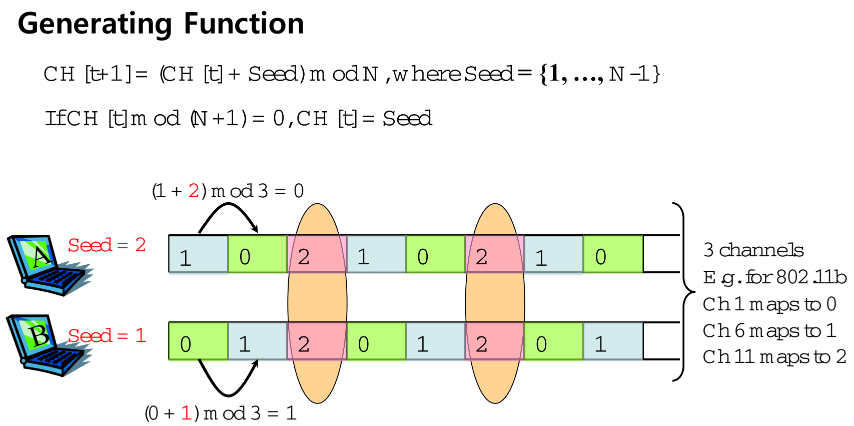


Fig. 2.4 Generating function and an example in case of 3 channels [15]

2.2.6 SSCH [15]

To alleviate congestion caused by bottleneck, another approach which allows different pairs to rendezvous simultaneously on different channels was proposed. In [15], each node is allowed to have one or multiple (channel, seed)-pairs to determine its channel hopping sequences. Each sequence period includes a parity slot at which time instant all nodes with the same seed are guaranteed to rendezvous on a channel indicated by the seed value. When each node selects one (channel, seed)-pair, the resulting sequence period is $N + 1$ slots, and each pair of sequences rendezvous exactly once within a period. Thus, the maximum time to rendezvous of SSCH is $N + 1$ slots. By design, SSCH is a synchronous channel hopping system, although results in [15] show that it can tolerate moderate clock skew. The amount of clock skew used in [15] to evaluate

SSCH is very small relative to one slot duration. If the clock skew is larger than one slot duration, SSCH cannot guarantee that two nodes rendezvous exactly once within a period of $N + 1$ slots. In fig. 2.4 shows the generating function of SSCH and a sequence example in case of 3 channels.

2.2.7 McMAC [16]

Parallel Rendezvous protocols are efficient in that multiple device pairs can make agreements simultaneously on distinct channels. The main goal is to overcome the single control channel bottleneck. However, since there are multiple rendezvous channels, special coordination is required so that two devices can rendezvous on the same channel. One solution is for each idle device to follow a “home” hopping sequence and for the sending device to transmit on that channel to find the intended receiver. McMAC [16] is among examples of this approach.

As illustrated in Fig. 2.5, each device picks a seed to generate a different pseudorandom hopping sequence. When a device is idle, it follows its “home” hopping sequence. Each device puts its seed in every packet that it sends, so its neighbors eventually learn its hopping sequence. For simplicity of analysis and simulation, devices are assumed to hop synchronously in this study. However, nodes are not required to align their hopping boundaries in practice. The hopping can be made less frequent than in the Common Hopping protocol to reduce the channel switching penalty and synchronization overhead. When device A has data to send to B, A flips a coin and transmits with some probability p during each time slot. If it decides to transmit, then it tunes to the current channel of B and sends an RTS. If B replies with a CTS, then both A and B stop hopping to exchange data. Data exchange normally takes place over several time slots. After the data exchange is over, A and B return to their original hopping sequence, as if no pause in hopping had happened.

SSCH and McMAC are similar in that they allow devices to rendezvous simultaneously on different channels. However, there are subtle differences. In SSCH, each node chooses four different hopping sequences and time multiplexes them to form a single hopping sequence. Nodes adapt their hopping sequences over time to the traffic but are not allowed to deviate from their hopping sequences. In McMAC, each node has one hopping sequence, which never changes. However, nodes are allowed to deviate from their default hopping sequence temporarily to accommodate sending and receiving.

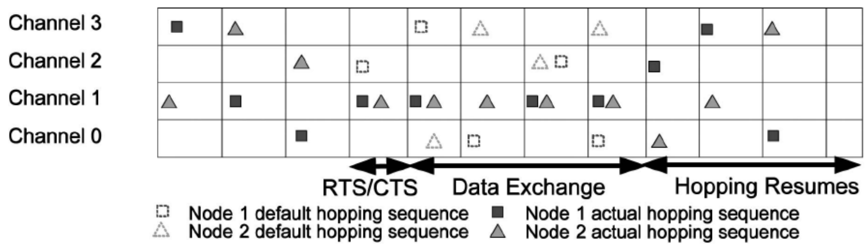


Fig. 2.5 McMAC

2.2.8 A frequency rendezvous approach for decentralized dynamic spectrum access networks [17]

They propose a transmission frequency rendezvous approach for secondary users deployed in decentralized dynamic spectrum access networks. The solution is accomplished via a combination of receiver pilot tones, a tone scanning protocol, and transmitter/receiver handshaking process. In the proposed rendezvous algorithm, the most important step is pilot tone detection and receiver query. In order to realize a shortest search time for the target receiver, an efficient scanning rule should be employed. Three scanning rules have been proposed and evaluated, namely: frequency sequence scanning, pilot tone strength scanning, and cluster scanning. The proposed network framework operates as follows: One radio is designated as the transmitter, which we refer to as TX1. The other three radios are all defined as receivers, namely RX1, RX2, and RX3. All radios within the vicinity are transmitting their own unmodulated pilot tones at different center frequencies in order to signal their frequency locations to other wireless nodes. The flow diagram in fig. 2.6 shows how the proposed algorithm operate. Because there is no centralized control in this network, the transmitter is responsible for locating a target receiver and sending data to it.

2.2.9 Sequence-based rendezvous (SeqR) [1]

While still not requiring any synchronization between radios, they proposed a deterministic solution to guarantee rendezvous within an upper bound. Each sequence generated by the SeqR scheme has a period of $N(N+1)$ slots. Fig. 2.7 shows how to build sequence. This scheme builds the initial sequence, u, by first selecting a permutation of elements in Z_N. The permutation is used contiguously N times, and once the permutation is interspersed with the other N permutations. For example, when $N = 3$, one can select a permutation such as $\{0, 2, 1\}$. The entire sequence would be $\{\mathbf{0}, 0, 2, 1, \mathbf{2}, 0, 2, 1, \mathbf{1}, 0, 2, 1\}$ and it is repeated. Note that the elements in the permutation $\{0, 2, 1\}$ is interspersed with the three replications of the same permutation. This sequence is k-shift-invariant (see Theorem 2.4.2). The sequence period is $N(N + 1)$ slots and its maximum time to rendezvous is $N^2 + N - 1$ slots.

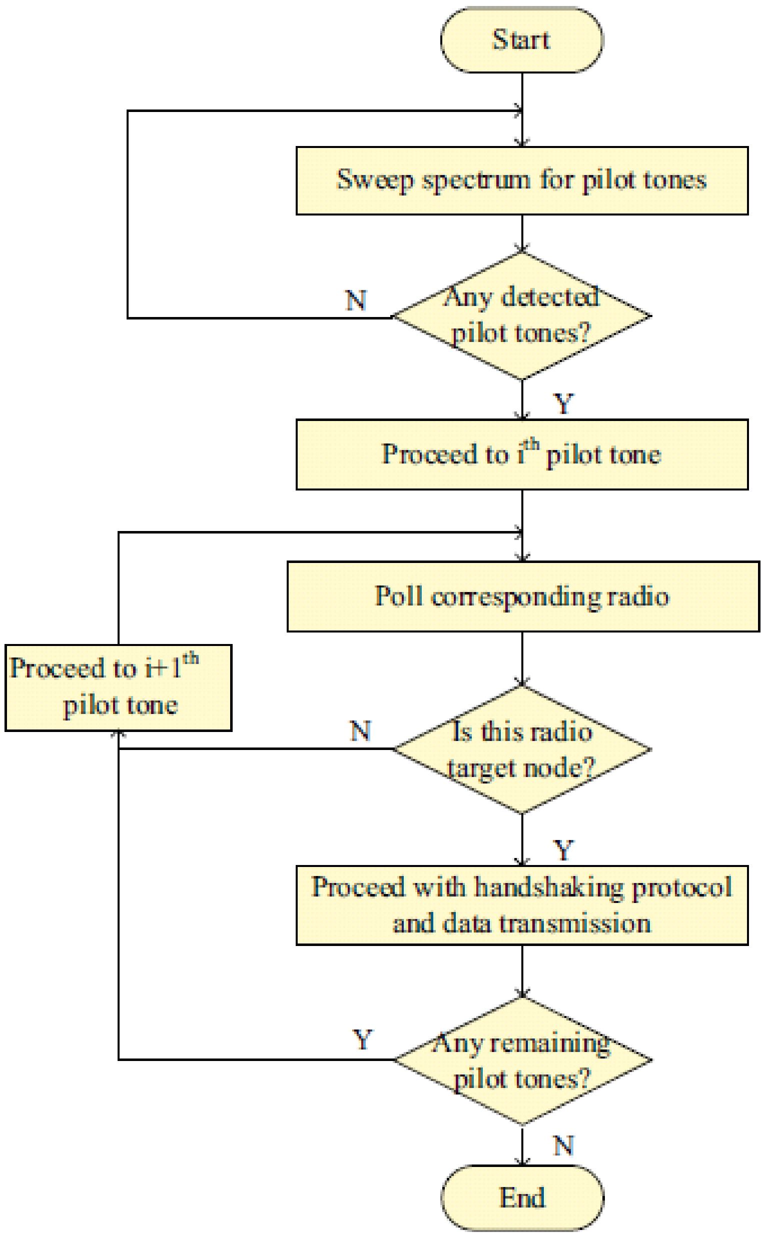


Fig. 2.6 Flow diagram [17]

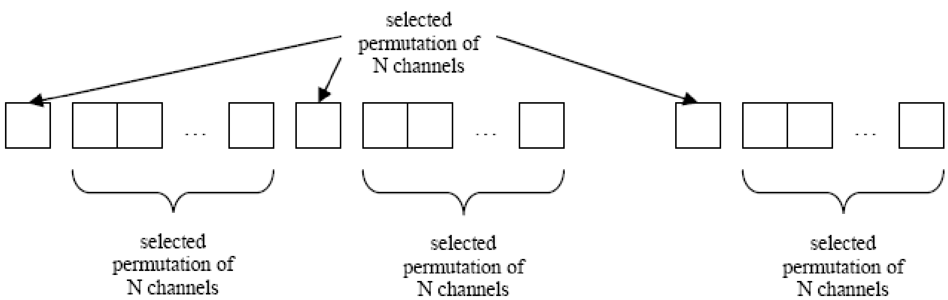


Fig. 2.7 Building the sequence [1]

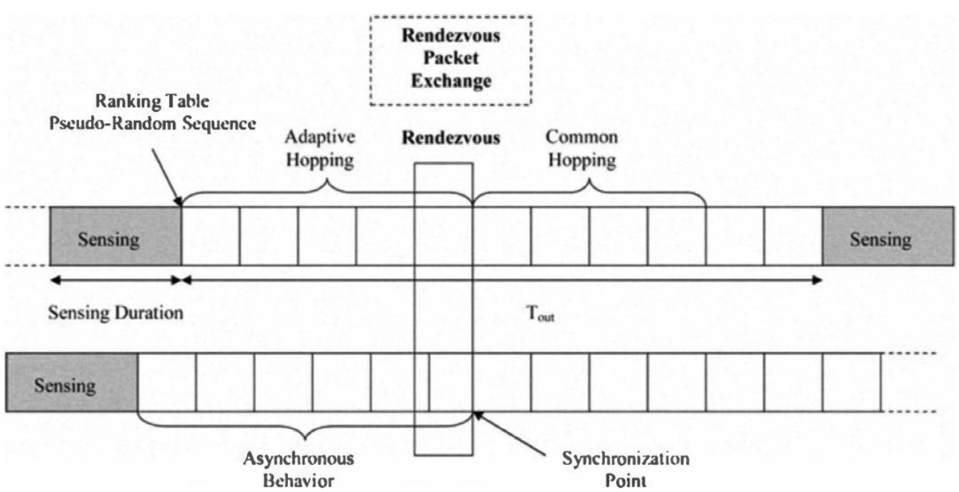


Fig. 2.8 Overview of the protocol behavior

2.2.10 AMRCC [18]

The adaptive multiple rendezvous control channel (AMRCC) scheme maximally spreads control signalling and data transmission among channels compared to [1]. In fact, the adaptive MRCC scheme builds the channel hopping sequences based on sensing information in order to hop across the different channels by minimizing the interference to licensed users. The main differences with [1] is that the sequences are chosen adaptively to combat the problem of PU interference. The hopping sequences are built in such a way that the channels with minimum interference to other devices occur a higher number of times than the others. Additionally, the start and stop times of each slot do not have to be rigidly synchronized. In fig. 2.8 the entire protocol behavior within a period of the sensing cycle is shown. The contribution made in AMRCC is twofold: Firstly, a frequency hopping scheme is proposed that allows altering the hopping sequence based on the PU(Primary User) activity in the channels, and secondly, a simple and low-overhead procedure is developed to aid new node-join and leave events.

2.2.11 Rendezvous for cognitive networks [19]

They presented an ivestigation into the rendezvous problem, provides a taxonomy of the types of rendezvous in Fig. 2.9, and identifies a spectrum of sys-

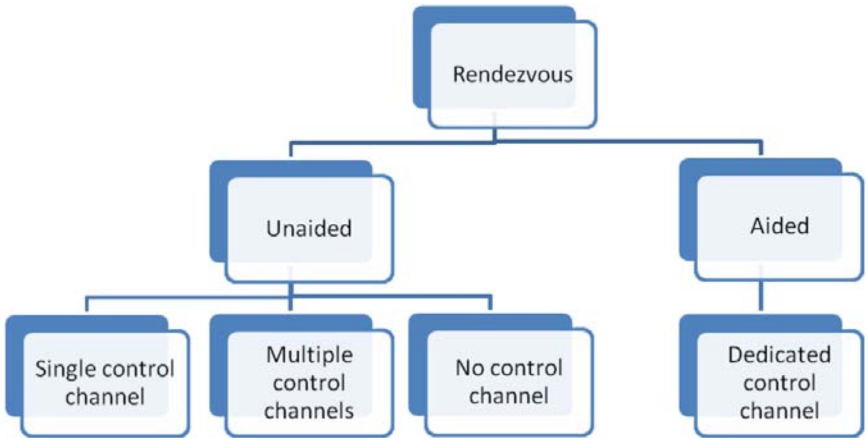


Fig. 2.9 Taxonomy of rendezvous techniques

tem models under which rendezvous can occur. Then, they proposed several rendezvous algorithms to communicating in a Dynamic Spectrum Access environment, providing diferent performance guarantees depending on the assumptions of the system model. The focus is on rendezvous when there are no control channels or centralized controllers, which is termed the blind rendezvous problem. In random rendezvous, a radio wishing to join a network visits the potential communications channels in random order. The random algorithms provides robust operation under all condition models. Generated orthogonal sequence-based rendezvous is identical with [1]. The modulara clock algorithm is a rendezvous algorithm that uses prime number modular arithmetic to make TTR (Time To Rendezvous) guarantees under several different rendezvous models. It, while unbounded, provides a potential speedup in expected TTR, while requiring less pre-coordination and the flexibility to operate in both the shared and individual models.

2.3 Preliminaries

In order to demonstrate the rendezvous sequence, we first assume the setup in Fig. 2.10 where time is divided into equal slots of time t and slots are numbered from 0. We 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, in which a_i denotes the visiting channel number, is defined to be the order of channels a node visits and it is repeated. We see that 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. For a moment, we assume two nodes are slot-synchronized. Afterwards we will remove this assumption. Although slots are well synchronized, nodes may start their sequence at different time as shown in Fig. 2.11. 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.

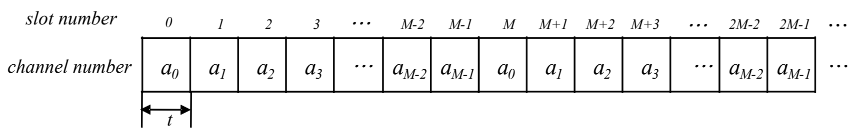


Fig. 2.10 Structure of Rendezvous Sequence

To examine this requirement, we formalize the effect of misalignment distance k by defining the k-*shift-invariant* for SEQ.

Definition 2.3.1. The rendezvous sequence $SEQ = (a_0, a_1, \ldots, a_{M-1})$ is k-*shift-invariant* ($k = 0, 1, \cdots, M-1$), if there exists slot $I \in \{k, k+1, \ldots, k+(M-1)\}$ such that $a^A_{\{i=I \bmod M\}} = a^B_{\{j=(I-k) \bmod M\}}$.

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. 2.11, 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. We will show how to find such a rendezvous sequence $SEQ = (a_0, a_1, \ldots, a_{M-1})$ for a multi-channel access network in the next section.

2.4 Deterministic Rendezvous Sequence ($DRSEQ$)

We introduce the algorithm generating a rendezvous sequence for a multi-channel access network and prove that it is *k-shift-invariant* for all k. We also show that all channels are fairly accessed and extend it to an asynchronous communication.

2.4.1 Algorithm

A rendezvous sequence 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.

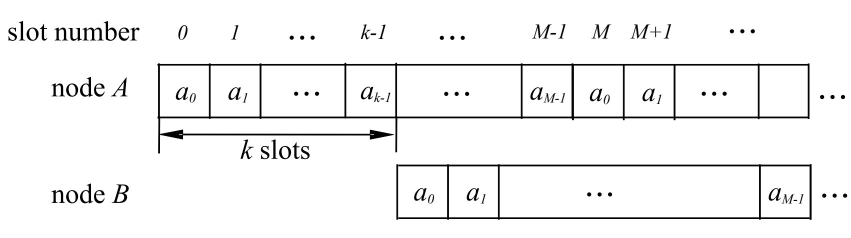


Fig. 2.11 Alignment of two sequences

We call such sequence $DRSEQ$, the number of whose elements is $2N+1$ as shown in Fig. 2.12. An example of $DRSEQ$ for $N=5$ is illustrated in Fig. 2.13. Theorem 2.4.1 states that with $DRSEQ$, two nodes can rendezvous within $2N+1$ slots for N available channels.

Theorem 2.4.1. For N available channels, $DRSEQ$ is *k-shift-invariant* for $k = 0, 1, \ldots, 2N$ so that nodes A and B rendezvous within $2N+1$ slots.

Proof. *For the sake of simplicity, let node A start at slot 0 and B start at slot k. Then we need look into slots k through $k+2N$.*

For $k=0$, it is trivial.

For odd k, at slot $2N + \frac{k+1}{2}$, we have a common channel such as $\frac{k+1}{2}$, since $a^A_{\{(2N+\frac{k+1}{2}) \bmod 2N+1\}} = a^A_{\{\frac{k-1}{2}\}} = \frac{k-1}{2}+1 = \frac{k+1}{2}$ by (2.1) and $a^B_{\{(2N+\frac{k+1}{2}-k) \bmod 2N+1\}} = a^B_{\{2N-\frac{k-1}{2}\}} = 2N - \{2N - \frac{k-1}{2}\} + 1 = \frac{k+1}{2}$ by (2.1).

For even k ($\neq 0$), at slot $N + \frac{k}{2}$, we have a common channel such as $N + 1 - \frac{k}{2}$, since $a^A_{\{(N+\frac{k}{2}) \bmod 2N+1\}} = a^A_{\{N+\frac{k}{2}\}} = 2N - \{N + \frac{k}{2}\} + 1 = N - \frac{k}{2} + 1$ by (2.1) and $a^B_{\{(N+\frac{k}{2}-k) \bmod 2N+1\}} = a^B_{\{(N-\frac{k}{2}) \bmod 2N+1\}} = N - \frac{k}{2} + 1$ by (2.1).

Therefore, for each k ($= 0, 1, \ldots, 2N$), there exists at least one slot $I \in \{k, k+$

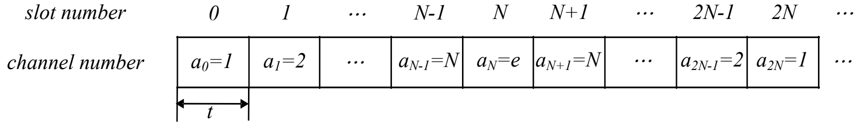


Fig. 2.12 Structure of $DRSEQ$

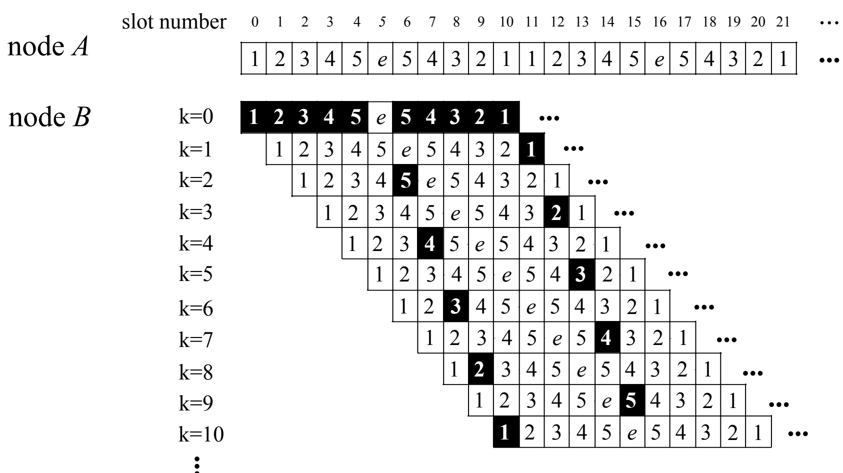


Fig. 2.13 Illustration of $DRSEQ$ with $(N = 5)$

$1, \ldots, k+2N\}$ *such that* $a^A_{\{I \bmod 2N+1\}} = a^B_{\{(I-k) \bmod 2N+1\}}$. $\square$

In order to show that all channels are fairly accessed, Jain's fairness index [21] is used. The probability $Pr(c)$ $(c = 1, 2, \ldots, N)$ that two nodes visiting channels according to $DRSEQ$ rendezvous at channel c is derived as

$$Pr(c) = \begin{cases} \dfrac{4N+4}{(2N+1)^2} & ,(1 \leq c \leq N-1) \\ \dfrac{4N+5}{(2N+1)^2} & ,(c = N), \end{cases}$$

and the fairness index is obtained as

$$
\begin{aligned}
\text{Fairness index} &= \frac{\{\sum_{c=1}^{N} Pr(c)\}^2}{N\sum_{c=1}^{N}\{Pr(c)\}^2} \\
&= \frac{16N^4 + 32N^3 + 24N^2 + 8N + 1}{16N^4 + 32N^3 + 24N^2 + 9N} \\
&\cong 1.
\end{aligned}
$$

The result indicates that $DRSEQ$ is perfectly fair.

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 $DRSEQ$ as shown in Fig. 2.14. 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 2.4.2 states that the rendezvous can be achieved without slot synchronization if the slot time for the case of slot-synchronization is doubled.

Theorem 2.4.2. *If new slot time $t' = 2t$, then $DRSEQ$ guarantees A and B to rendezvous within $2N + 1$ slots without slot synchronization.*

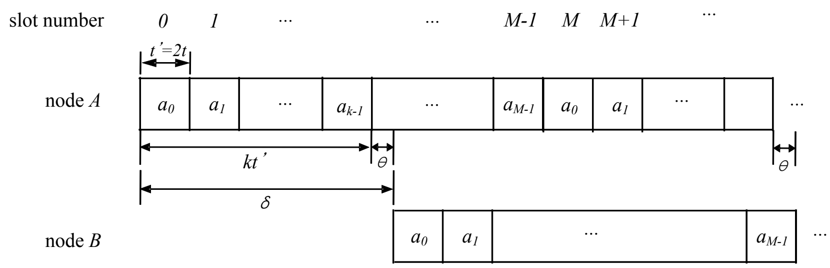


Fig. 2.14 Asynchronous interaction between two nodes

Proof. *As shown in Fig 2.14, 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 $2N + 1$ 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 $2N + 1$ slots.*

Therefore, $DRSEQ$ guarantees A and B to rendezvous within $2N + 1$ slots without slot synchronization if the slot time for the case of slot-synchronization is doubled. □

2.5 Summary

In this chapter, we introduce a distributed channel rendezvous scheme excluding any centralized control approach for multi-channel access networks. It is noteworthy that the proposed scheme achieves the smallest bound of $2N + 1$ slots for rendezvous time if N channels are available and provides fair access opportunities to all channels. Also, we have shown that our scheme can be implemented without slot synchronization. The proposed scheme can be used in various applications, such as cognitive radio networks and multi-channel adhoc networks.

CHAPTER 3

Optimal Energy-Efficient Neighbor Discovery Scheme in Opportunistic Networks

3.1 Introduction

Opportunistic networking is an emerging technology with a wide range of potential applications (e.g., military, vehicular, rescue, medical, and multimedia transfer service) [22, 23, 24]. Opportunistic networks are one of the most interesting evolutions of MANETs (Mobile Adhoc Networks) which have been extensively studied during the last few years. For a practical MANET, links may be intermittently established due to short transmission range and high user mobility, which is not the case where most previous works have implicitly assumed that the network is connected and there is a contemporaneous end-to-end path between any two nodes [25, 26, 27, 28, 29, 30, 31, 32]. Mobile devices (e.g., PDAs, UMPCs, and laptops) with short range wireless network interfaces (e.g., Bluetooth, WiFi, and DSRC) can exchange data only in close proximity of each other. Before exchanging data, two nodes in physical contact must recognize each other by the operation of probing and responding [33, 34, 35, 36, 37, 38, 39]. Even with multiple responses, only one node must be designated as the receiver [34, 35, 36, 37, 38, 39]. If a node fails to recognize another within its transmission range, it misses the contact, and experiences very long delivery latency or a failure of data delivery. One of the main challenges in deploying an opportunistic network is how to find such a neighbor in contact. In this dissertation, we focus on the neighbor discovery problem for the intermittently connected networks.

Since most mobile devices are battery-operated and their radio coverage is limited, it is necessary to discover a neighbor in contact first before data exchange. However, these battery-operated devices cannot afford persistent probing, so it is very important for such devices to discover a neighbor in contact with minimum energy consumption. Various studies such as 802.11 Power

Save Mode [40], S-MAC [41], T-MAC [42], and P-MAC [43] have introduced the sleeping mode, in which the radio is turned off for as long as possible when there is no data to forward. Similarly, an energy saving scheme for opportunistic networking must be able to turn off the radio, thus setting a sleeping mode, during non-contact time and be able to turn it on only for neighbor discovery and data exchange. Even if it is difficult to predict when the nodes encounter each other and how long they remain in contact, it is crucial to find such figures for successful data exchange and energy saving.

In [33] and [34], a neighbor discovery scheme was proposed without a sleeping mode. In contrast, a wake-up mechanism with a sleeping mode has been designed in [35, 36, 38, 39]. Especially, in [35, 36], the quorum-based protocol and the birthday protocol have provided a scheme where two nodes awake for a certain period of time within a given interval. They dealt with two operation modes: sleep and wake-up. Note that they did not specify what to do during the wake-up mode. We believe the wake-up mode must be elaborated depending on the action the node takes. In this dissertation, we divide the wake-up mode into the probing mode and the listening mode. In opportunistic networks, a node can be in one of 3 operation modes, probing, listening, or sleeping. In probing mode, it sends probing messages. In listening mode, it listens to probing messages and responds to the probing messages. And in sleeping mode, it shuts down its radio to save energy and turns it on when the sleeping interval expires.

Since all nodes in ad-hoc networking are considered to be homogeneous, they behave in a symmetric manner. In addition, since they cannot afford to maintain synchronous clocks and align slot boundaries, it is natural for opportunistic networks to operate in an asynchronous manner. That is, all the nodes in the network follow the same sequence of actions for neighbor discovery and their actions take place asynchronously. As long as they are symmetric, they may miss physical contact with non-zero probability. Consider two neighboring nodes alternating between probing and listening modes in order to eliminate any chances of missing a contact. However, when their probing periods are exactly overlapped, they fail to recognize each other. This happens, even when the non-overlapping interval is less than the smallest interval δ which is required to recognize a probing message. Note that, in [40, 44], the recognition of a probing message is referred to as a CCA (Clear Channel Assessment), which determines whether the medium is busy or idle. According to the configurations of the system, the recognition time δ of a probing message is determined by 4 and 15 μs in [40], and 102.4, 1600, and 3200 μsin [44]. This simple observation leads us to the conclusion that there is no symmetric neighbor discovery algorithm with perfect contact discovery. For symmetric neighbor discovery, we aim to design a neighbor discovery scheme which guarantees the minimum miss probability.

Furthermore, we propose an asynchronous neighbor discovery within a bounded delay D. The bounded delay D is given as the desired discovery delay, the time difference between the instant of discovering the contact and the beginning instant of physical contact. D is usually determined as follows. If neighbor discovery succeeds within D, data exchange can be completed through this contact. D can be given as a constant [37, 45] or probabilistically derived [33, 46, 47]. If D is a probabilistic threshold which may be obtained from the contact duration distribution, the optimal solution probabilistically guarantees that two neighbor nodes discover each other within D. We also show that it is energy-optimal in the sense that the proposed scheme minimizes the energy required to discover a neighbor within D with the minimum miss probability of a contact.

3.2 Previous works

The wide spread use of small mobile devices in the recent years has been observed by researchers and many are interested in exploring content distribution using these devices. The properties of these devices, such as small size, wireless interfaces, limited storage etc., combined with the manner in which they are used and transported, defines an opportunistic networking. Opportunistic networks are one of the most interesting evolutions of MANETs which have been extensively studied during the last few years. Generally, in opportunistic networks, nodes are randomly deployed, move around arbitrarily, and exchange data only during contact, that is, in proximity of each other as shown in Fig. 3.1. The opportunistic networks are characterized by

- Intermittent Connectivity: There is no contemporaneous end-to-end path between any two nodes, called *network partitoining*. Links may be intermittently established due to their short transmission range and high user mobility. In the absence of a fixed infrastructure for connectivity, data could be exchanged between devices during opportunistic contacts that arise whenever the device happens to come into transmission range of others.

- Opportunistic Contacts: In opportunistic networking, data is transferred

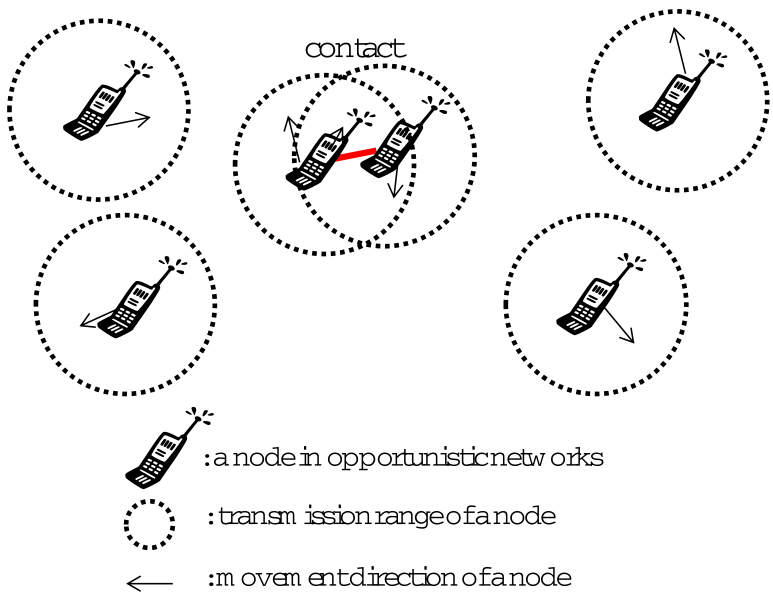


Fig. 3.1 Structure of Rendezvous Sequence

through contacts which occur infrequently. The contact duration directly influences the capacity of opportunistic networks because it limits the amount of data that can be transferred between nodes. Because the contact duration is generally brief, it is necessary for any neighboring nodes to recognize each other as quickly as possible to ensure a sufficient time to exchange data.

- Long Data Delivery Latency: If a node with data to be forwarded has no destination node in the vinicity, until the destination node is reached, data can be delivered in a similar manner to store-and-forward. Data is buffered into an intermediate node and sent at a later time to the destination or to another intermediate node. Therefore, if a node fails to recognize another within its transmission range, it misses the contact, and experiences very long delivery latency or a failure of data delivery. Furthermore, if the destination node has to acknowledge it, the delivery latency is much longer.

These features make existing MANET protocols unsuitable for opportunistic networks because most previous works have implicitly assumed that the network is connected and that there is a contemporaneous end-to-end path between any two nodes. Considering these properties, an energy-efficient neighbor discovery scheme with which a node can recognize another in the neighborhood with the minimum miss probability of a contact is needed.

In opportunistic networks, the neighbor discovery is a continuous and therefore, battery draining process. Many researchers have studied works in order for the neighbor discovery to achieve energy-efficiency.

3.2.1 STAR [33]

In [33], the trade-off between the probability of missing a contact and the contact probing frequency was investigated. First, via theoretical analysis, they characterize the trade-off between the probability of a missed contact and the contact probing interval for stationary processes. Next, for time varying contact arrival rates, an optimization framework was provided to compute the optimal contact probing interval as a function of the arrival rate. They characterize real world contact patterns via Bluetooth phone contact logging experiments and show that the contact arrival process is self-similar. STAR was designed as a contact probing algorithm which adapts to the contact arrival process. Via trace driven simulations on our experimental data, it is shown that STAR consumes three times less energy when compared to a constant contact probing interval scheme.

3.2.2 Adaptive energy conserving algorithm [34]

Novel adaptive schemes for neighbor discovery were introduced and evaluated in Bluetooth-enabled ad-hoc networks. In order to save energy consumed for neighbor search when the device is unlikely to encounter a neighbor, they adaptively choose parameter settings depending on a mobility context to decrease the expected power consumption of Bluetooth-enabled devices. For this purpose, they first determined the mean discovery time and power consumption values for different Bluetooth parameter settings through a comprehensive exploration of the parameter space by means of simulations validated by experiments on real devices.

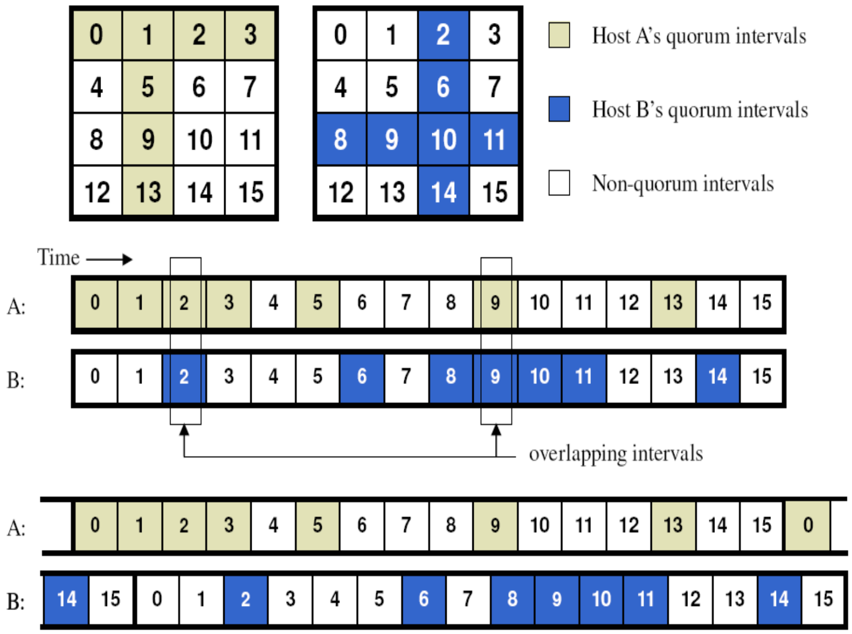


Fig. 3.2 Examples of the Quorum-Based Protocol [50]

3.2.3 Quorum-based protocol [35]

In [35], they proposed a quorum-based protocol for multi-hop ad-hoc networks. Their protocol divides time into a sequence of beacon intervals which are grouped into sets of m^2 contiguous intervals, where m is a global parameter. In each group, the m^2 intervals are arranged as a two-dimensional $m \times m$ array in a row major manner. A node arbitrarily picks one column and one row of entries to transmit and receive, respectively, for a total of $2m - 1$ intervals, in each group of m^2 intervals. Since m is a global parameter, all nodes use the same duty cycle, which limits flexibility. Fig. 3.2 shows an example with m =

16. Host A picks intervals along the first row and the second column as its beacon intervals. Host B, which does not coordinate with A, picks the third row and the third column. In the middle, we show the case where A's and B's clocks are perfectly synchronized, in which case intervals 2 and 9 of A and B are fully covered by each other. On the bottom, we show the case where A and B are asynchronous in time. The beacon windows of intervals 0 and 13 of A are fully covered by the duration when B is active. On the contrary, the beacon windows of intervals 2 and 8 of B are fully covered by the duration when A is active. In [50], this result is generalized to any quorum protocol that satisfies a rotation closure property. We note that both sampling protocols, like B-MAC and X-MAC, and scheduled protocols, like S-MAC, implicitly use quorum-based neighbor discovery. Their use differs only in the details of what happens during each interval and whether transmissions are row major and listening is column major in each group of m^2 intervals as is the case for sampling protocols or the reverse for slotted ones.

3.2.4 Birthday protocol [36]

The birthday protocol addressed two problems associated with static ad-hoc wireless networks: methods of saving energy during a deployment of the nodes, and efficient methods of performing adjacent neighbor discovery. To meet these

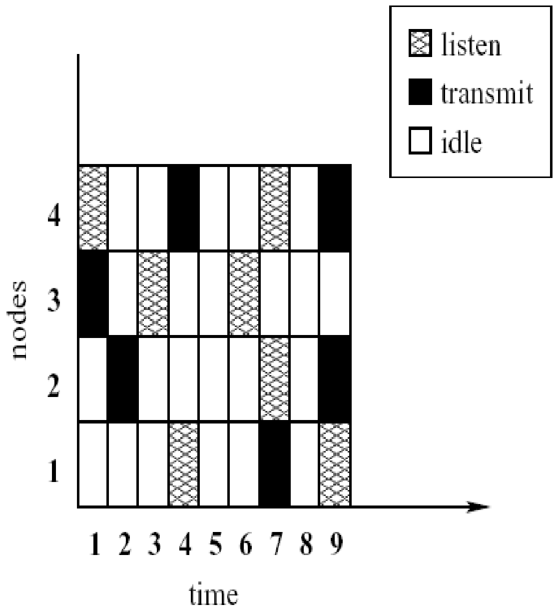


Fig. 3.3 Example of the Birthday protocol [36]

goals, they introduce a family of birthday protocols which use random independent transmissions to discover adjacent nodes. As illustrated in Fig. 3.3, four nodes, all within range of each other, have just entered birthday-listen-transmit mode, performing discovery over 9 slots. Link discovery occurs when a single node transmits, and one or more nodes are listening. A node transmits probing messages with the probability of p_t, listens to the probing messages with the probability of p_l and sleeps with the probability of p_s. Various modes of the birthday protocol are used to solve the two problems. They provide a mathematical model and analysis of the two modes of the protocol and are led to a third mode which is the probabilistic analog of the deterministic round robin scheduling algorithm. They show by analysis and simulation that the birthday protocols are a promising tool for saving energy during the deployment of an ad-hoc networks as well as an efficient and flexible means of having the nodes discover their neighbors.

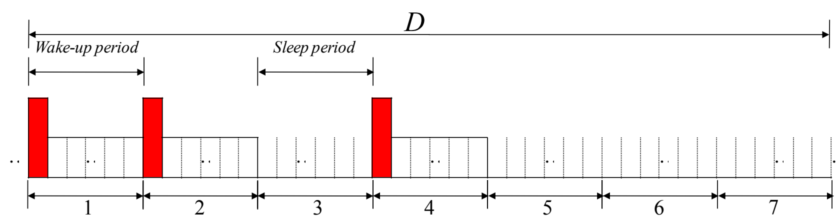


Fig. 3.4 Wake-up schedule structure of WSF-(7,3,1)

3.2.5 Wake-up function using optimal block design [38]

They consider the problem of designing optimal asynchronous wake-up schedules to facilitate distributed power management and neighbor discovery in multihop wireless networks. They first formulate it as a block design problem and derive the fundamental trade-offs between wake-up latency and the average duty cycle of a node. After the theoretical foundation is laid, they then devise a neighbor discovery and schedule bookkeeping protocol that can operate on the optimal derived wake-up schedule. To demonstrate the usefulness of asynchronous wake-up, they investigate the efficiency of neighbor discovery and the application of on demand power management, which overlays a desirable communication schedule over the wake-up schedule mandated by the asynchronous wake-up mechanism. Simulation studies demonstrate that the proposed asynchronous wake-up protocol has a short discovery time which scales with the density of the network.

In [38], they proposed a wake-up schedule for neighbor discovery, $WSF-(n_t, n_a, n_c)$. It provides a method that can guarantee nc opportunities for communication within nt periods by waking up for na periods out of nt periods. A node probes at the start of each wake-up period and listens for the remaining wake-up period. $WSF-(n_t, n_a, n_c)$, for a given delay bound D, offers a feasible set of wake-up schedule functions which can guarantee neighbor discovery within D using a polynomial form of function proposed in [38]. In Fig. 3.4, $WSF-(7,3,1)$ is illustrated.

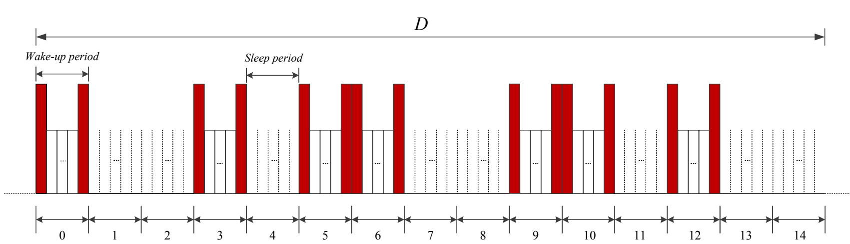


Fig. 3.5 Wake-up schedule structure of Disco-(3,5)

3.2.6 Disco [39]

Disco is an asynchronous neighbor discovery and rendezvous protocol that allows two or more nodes to operate their radios at low duty cycles and yet still discover and communicate with one another during infrequent, opportunistic encounters without requiring any prior synchronization information. The key challenge is to operate the radio at a low duty cycle but still ensure that discovery is fast, reliable, and predictable over a range of operating conditions. Disco nodes pick a pair of prime numbers such that the sum of their reciprocals is equal to the desired radio duty cycle. Each node increments a local counter with a globally fixed period. If a node's local counter value is divisible by either of its primes, then the node turns on its radio for one period. This protocol ensures that two nodes will have some overlapping radio on-time within a bounded number of periods, even if nodes independently set their own duty cycle. Once a neighbor is discovered, and its wake-up schedule known, rendezvous is just a matter of being awake during the neighbor's next wake-up period, for synchronous rendezvous, or during an overlapping wake period, for asynchronous rendezvous. Fig. 3.5 illustrates the structure the wake-up schedule when 3 and 5 are picked as a pair of prime numbers.

3.3 Problem Statements and Research Goals

Generally, in opportunistic networks, nodes are randomly deployed, move around arbitrarily, and exchange data only during contact. Before exchanging data, nodes in physical contact should recognize each other by the operation of probing and responding. Since nodes are homogeneous and cannot afford to maintain synchronous clocks and align slot boundaries, they behave in a symmetric manner and their actions take place asynchronously.

Because of the properties of opportunistic networks, a major problem to be solved is to devise an energy-efficient neighbor discovery with minimum miss probability of a contact. The major properties of opportunistic networks are as follows:

- Limited battery capacity: Nodes in opportunistic networks operate with limited battery power. While most subsystems on nodes have seen a great deal of progress in recent years, power still remains a scarce resource and must be conserved as much as possible. The discovery process, being a continuous process run by the device, needs to be energy-efficient in order to lengthen the lifespan of battery-operated devices.
- Guarantee a bounded delay: Communication opportunities within such networks are usually brief, in the order of a few seconds. Two users car-

rying devices that have a radio range of 10 m, such as that of Bluetooth and walking towards each other at a normal speed of 2 m/s will have an opportunity of only 5s to discover each other's presence and establish communication. Hence, the discovery process needs to guarantee a bounded delay in order to enable nodes to take advantage of random encounters.

- Loss probability of a contact: All the nodes in the network follow the same sequence of actions for neighbor discovery and their actions take place asynchronously. As long as they are symmetric, they may miss physical contact with non-zero probability. Consider two neighboring nodes alternating between probing and listening modes in order to eliminate any chances to miss a contact. However, when their probing periods are exactly overlapped, they fail to recognize each other. This happens, even when the non-overlapping interval is less than the period which is required to recognize a probing message.

The goal is to propose the optimal energy-efficient neighbor discovery scheme that minimizes the energy consumed to discover a neighbor within D with the minimum miss probability of a contact by means of keeping nodes' radio off as long as possible.

3.4 Preliminaries

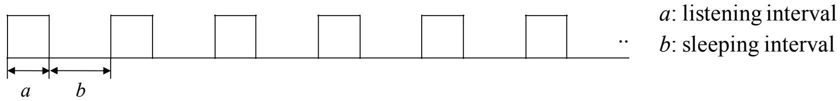


Fig. 3.6 Listening and sleeping modes

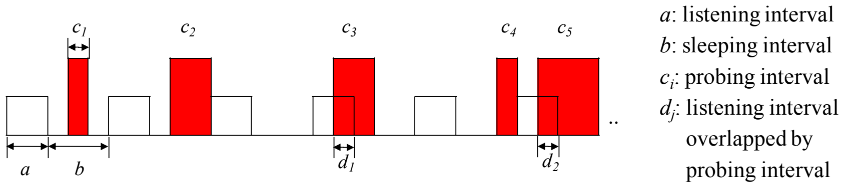


Fig. 3.7 Listening and probing modes

To illustrate the neighbor discovery process, we first consider the setup in Fig. 3.6, where a node periodically performs listening and sleeping. The node listens to receive probing messages for interval a_i $(i = 1, \ldots, N)$ and then sleeps for interval b_i $(i = 1, \ldots, N)$ [48]. We define the duty cycle q as $\frac{\sum_{i=1}^{N} a_i}{\sum_{i=1}^{N}(a_i+b_i)}$. To detect encountering nodes, the node must send probing messages in addition. As shown in Fig. 3.7, probing intervals c_i $(i = 1, \ldots, M)$ may be placed arbitrarily. Then, any listening intervals overlapped by probing intervals are no longer in listening mode and are denoted by d_i $(i = 1, \ldots, K)$. Let E_P, E_L, and E_S $(E_P > E_L >> E_S)$ denote respectively the power consumed in probing, listening, and sleeping modes. Then, the total energy E_{total} consumed by a single node for the whole operation time T can be expressed as

$$
\begin{aligned}
E_{total} &= E_P \sum_{i=1}^{M} c_i + E_L(\sum_{i=1}^{N} a_i - \sum_{i=1}^{K} d_i) \\
&\quad + E_S(\sum_{i=1}^{N} b_i - (\sum_{i=1}^{K} c_i - \sum_{i=1}^{M} d_i)).
\end{aligned} \tag{3.1}
$$

Without loss of generality, we can assume $T = \sum_{i=1}^{N} (a_i + b_i)$, where N is the number of listening intervals. M and K are the number of probing intervals and listening intervals overlapped by probing intervals in T, respectively. The problem is to find how to schedule probing, listening and sleeping intervals, such that any node can detect physical contact with a neighbor node within D while not only the total energy consumption but also the miss probability of the contact is minimized. In order to guarantee that a node discovers another within D, it must transmit probing messages every D period and its probing interval must be longer than the maximum sleeping interval. This requirement leads to $T = M * D$ and $c_i = \max_{j=1,\cdots,N}(b_j) + \mu$ $(\mu > 0)$ for all i.

3.5 Optimal Listening Schedule for Given Duty Cycle

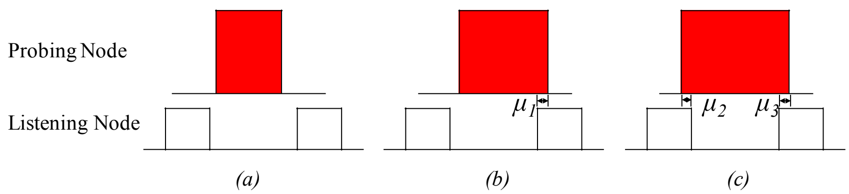


Fig. 3.8 Three operation modes at a node

For duty cycle q, we can obtain the minimum bound for E_{total} if we can schedule sleeping intervals to satisfy

$$\min\big(\max_{j=1,..,N} b_j\big) = b, \tag{3.2}$$

where $b = \frac{\sum_{j=1}^{N} b_j}{N}$. With duty cycle q, the energy consumed by listening and sleeping modes is fixed. The total energy consumed by a single node must be bounded by $\min(\max_{j=1,..,N} b_j)$. To find the value of $\min(\max_{j=1,..,N} b_j)$, let us arrange b_1,..., b_N in an ascending order. Then, we have the new sequence of $b_1^{'}$,..., $b_N^{'}$ ($b_1^{'} \leq ... \leq b_N^{'}$), where $b_N^{'} = \max_{j=1,..,N}(b_j)$. Since $b_N^{'} \geq b_i^{'}$ for $\forall i = 1, ..., N$, we have $\frac{\sum_{i=1}^{N} b_N^{'}}{N} \geq \frac{\sum_{i=1}^{N} b_i}{N}$. Therefore, $b_N^{'} = \max_{j=1,..,N}(b_j) \geq \frac{\sum_{i=1}^{N} b_i}{N} \geq \min\big(\frac{\sum_{i=1}^{N} b_i}{N}\big) = b$, where equality only holds when $b_1 = ... = b_N = b$. It leads to $a_i = \frac{\sum_{j=1}^{N} a_j}{N} = a$ and $K = M$ for all i. Fig. 3.8 shows how to associate three operations modes with given D when a node operates in all of them.

3.6 Probing Interval for the Minimum Miss Probability of a Contact

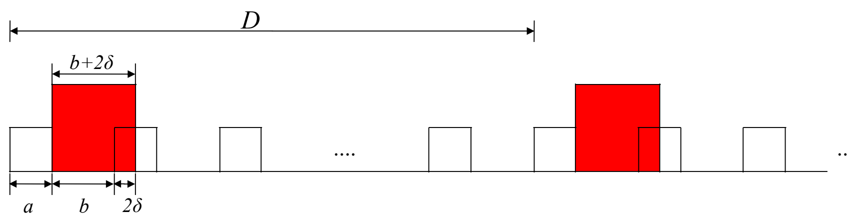


Fig. 3.9 Various probing intervals

To achieve neighbor discovery within given D, a node must perform probing at least once within every D period. Even with this constraint, two nodes in physical contact may fail to recognize each other. Fig. 3.9 illustrates how to miss probing messages. If a probing interval fits in a sleeping interval as shown in Fig. 3.9(a), sending node fails to be recognized by its sleeping neighbor node. Although a probing interval is longer than a sleeping interval, it is not sufficient to be recognized if the difference between those two intervals, denoted by μ_1, μ_2, and μ_3 as in Fig. 3.9(b) and (c), is less than δ. Therefore, a node must transmit a probing message every D period or less, and its interval must be long enough to avoid the cases shown in Fig. 3.9. Thus the probing interval must be longer than or equal to $b + 2\delta$.

Next we need to see what happens when two nodes operating. Since they are symmetric, it is possible for them to miss probing messages if they are perfectly synchronized. As long as they operate asynchronously, it is practically impossible that their probing intervals are exactly overlapping. However, if their probing intervals are misaligned by less than δ back and forth from the exactly aligned instant, they cannot recognize each other. This leads to the conclusion that the achievable minimum miss probability of a contact is $2\delta/D$. To validate this claim, we assume that the starting instant of a period of one node is uniformly distributed over the period D of the other node where it is enclosed ($0 < X < D$). From Fig. 3.10, the miss probability of a contact is simply $P[X < \delta] + P[D - \delta < X] = \delta/D + \delta/D = 2\delta/D$.

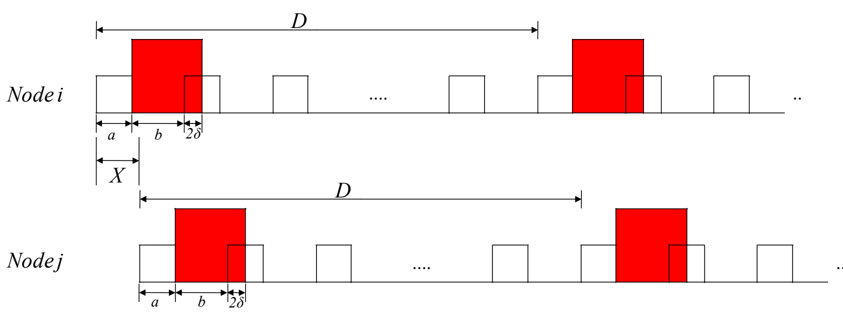


Fig. 3.10 Asynchronous interaction of two approaching nodes

3.7 Energy-Efficient Probing Schedule for Given Duty Cycle

In this section, for duty cycle q, we derive the schedule of the probing, listening, and sleeping intervals with minimum energy consumption. From (3.1) and the probing interval of section 3.6, it leads to $d_i = \delta$, and $c_i = b + 2\delta$, for all i. Then, the total energy consumption is expressed by

$$\begin{aligned} E_{total} &= E_P \sum_{i=1}^{M} (b + 2\delta) + E_L(N \cdot a - \sum_{i=1}^{M} \delta) \\ &\quad + E_S(N \cdot b - \sum_{i=1}^{M} (b + \delta)) \\ &= E_P \cdot M(b + 2\delta) + E_L(N \cdot a - M \cdot \delta) \\ &\quad + E_S(Nb - M(b + \delta)) \\ &= \frac{T^2(1-q)(E_P - E_S)}{N \cdot D} \\ &\quad + \frac{T(2E_P - E_L - E_S)\delta}{D} \\ &\quad + T(E_L \cdot q + E_S(1-q)) \end{aligned} \tag{3.3}$$

using $b = (1-q)\frac{T}{N}$.

In (3.3), E_{total} is a function of N. So, the minimum bound for E_{total} can be determined when N is maximized. As described in Fig. 3.11, with duty cycle q, in order to maximize N, every listening interval a is set to δ, then $b = \delta\frac{1-q}{q}$. As a result, achievable minimum energy is

$$E_{total}^{min} = \frac{T\delta\{(E_P - E_S)(1-q) + q(2E_P - E_L - E_S)\}}{D \cdot q} + T(E_L \cdot q + E_S(1-q))$$

using $N = \frac{Tq}{\delta}$.

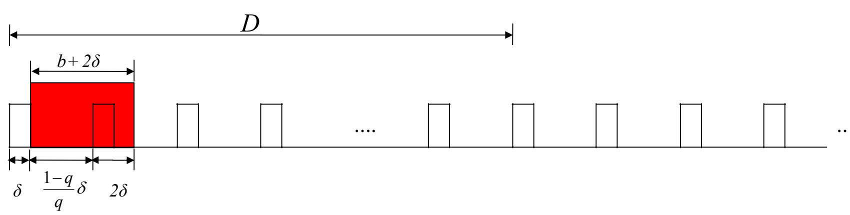


Fig. 3.11 Optimal probing and listening schedule given duty cycle q

3.8 Optimal Duty Cycle

In previous sections, we presented an optimal neighbor discovery scheme that discovers the adjacent nodes within D and consumes the minimum energy for achieving the minimum miss probability of a contact, which is dependent on duty cycle q. In this section, we introduce a method to determine the optimal duty cycle for a node. Fig. 3.12 illustrates how the optimal duty cycle can be obtained. When the duty cycle is small, the listening energy decreases, but the probing energy increases (see Fig. 3.12(a)). In contrast, when the duty cycle is large, the listening energy increases, but the probing energy decreases (see Fig. 3.12(b) and (c)).

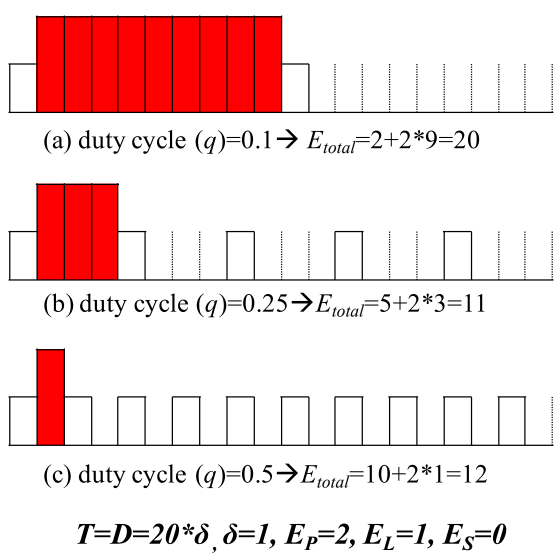


Fig. 3.12 How to obtain the optimal duty cycle

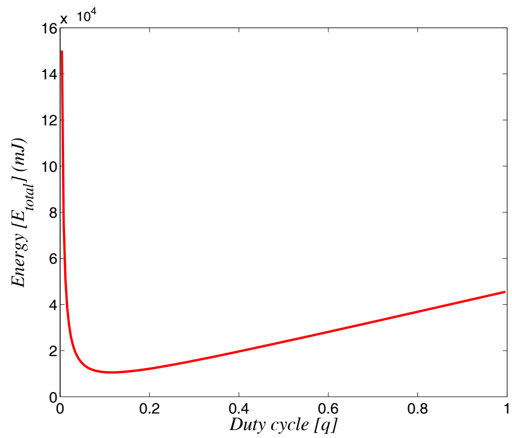


Fig. 3.13 Determining the optimal duty cycle

Therefore, we can obtain the optimal value of a duty cycle by setting the derivative of E_{total}^{min} with respect to q to zero:

$$E_{total}^{min'} = T[(E_L - E_S) - \frac{(E_P - E_S)\delta}{Dq^2}].$$

The minimum value of E_{total}^{min} is proved to exist by using the second derivative test:

$$E_{total}^{min''} = \frac{2 \cdot (E_P - E_S) \cdot \delta \cdot T}{D \cdot q^3} > 0.$$

Hence, the optimal duty cycle is determined by

$$q_{opt} = \sqrt{\frac{(E_P - E_S)\delta}{(E_L - E_S)D}}.$$

In Fig. 3.13, the optimal duty cycle (0.115499) is determined at the point where E_{total}^{min} (= $1.05541 \times 10^4\ mJ$) is minimal. Each variable is set to $T = 1000000 \times \delta\ ms$, $D = 100 \times \delta\ ms$, $\delta = 1\ ms$, $E_L = 45\ mW$, $E_S = 0.09\ mW$, and $E_P = 60\ mW$.

3.9 Fixing Duty Cycle q_p in terms of Probing

In this section, we consider the case that a node periodically performs probing and sleeping with duty cycle q_p. In a similar manner to the case of fixing duty cycle q in term of listening, the schedule of probing, listening, and sleeping intervals is derived as shown in Fig. 3.14. The schedule also provides a bounded delay D for neighbor discovery with the minimum miss probability of a contact. The schedule outperforms the previous one only if E_L is greater than E_P. Generally, since E_L is less than E_P, this schedule always has a poorer performance than the schedule with the duty cycle q in terms of listening.

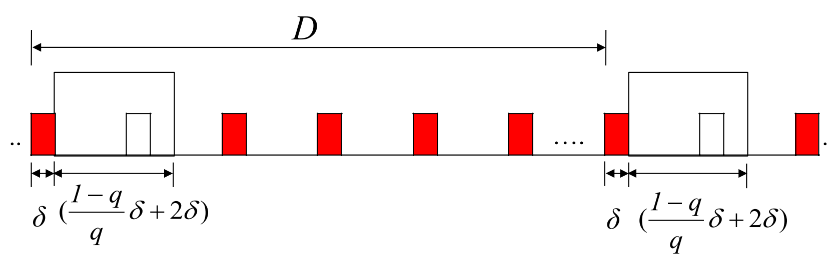


Fig. 3.14 Fixing duty cycle q_p in terms of probing

3.10 Theoretical Analysis

In this section, we evaluate the performance of our scheme and the schemes proposed in [38] and [39] through theoretical analysis. Performance metrics for theoretical analysis are energy consumption and miss probability of a contact. In [38] and [39], they have introduced the neighbor discovery schemes which provide a bounded discovery delay with sleeping mode for energy saving. In [38], they proposed a wake-up schedule for neighbor discovery, WSF-(n_t, n_a, n_c), which provides a method that can guarantee n_c opportunities for communication within n_t periods by waking up for n_a periods out of n_t periods. A node probes at the start of each wake-up period and listens for the remaining wake-up period. WSF-(n_t, n_a, n_c), for a given delay bound D, offers a feasible set of wake-up schedule functions which can guarantee neighbor discovery within D using a polynomial form of function proposed in [38]. In Fig. 3.4, WSF-(7,3,1) is illustrated .

In [39], Disco-(p_1, p_2) was designed as a wake-up schedule using two prime numbers, p_1 and p_2. Time is divided into fixed-width reference periods and consecutive periods are labeled with consecutive integers. A node awakes if the integer of the period is divisible by p_1 or p_2. If all nodes pick up the same two prime numbers, Disco-(p_1, p_2) provides a wake-up schedule to guarantee one overlapping period within $p_1 * p_2$ periods. The node probes at the start and end of each wake-up period and listens for the remaining duration of the wake-up period. Given D, Disco-(p_1, p_2) provides a feasible set of wake-up schedules with different combinations of two prime numbers. Disco-(3,5) is illustrated in Fig. 3.5.

WSF-(n_t, n_a, n_c) provides a wake-up schedule only if n_t is a polynomial function of a power of a prime. And, two primes of Disco-(p_1, p_2) must be chosen such that $p_1 \neq p_2$. The prime number theorem [49] states that if you randomly select a number nearby some large number N, the probability that a prime number is selected is about $\frac{1}{\ln N}$. For example, near 10,000, about one in nine numbers is prime, whereas near $1,000,000,000$, only one in every 21 numbers is prime. In other words, as the number increases, the prime number more rarely appears. Due to this property of primes, both WSF-(n_t, n_a, n_c) and Disco-(p_1, p_2) do not have the fine granularity for providing a wake-up schedule for a delay bound D. In other words, as a required delay bound increases, it it more difficult to find the optimal primes to guarantee neighbor discovery within D. Therefore, we consider a feasible set of all possible wake-up schedule functions for relatively short delay bounds and compare them to the proposed scheme. System parameters such as slot time, frame size or windows size are different depending on existing communication protocols. Without loss of generality, we assume that a delay bound D is given with units of ms and a minimum slot unit for probing or listening, δ, is $1ms$. As illustrated in Fig. 3.4, in WSF-(n_t, n_a, n_c), a node probes at the start of each wake-up period for δ and listens to a probing message for the remainder of the wake-up period, which must be at least δ or more. Therefore, one period $\frac{D}{n_t}$ must be equal to or longer than 2δ $(= 2ms)$. Using multiplier theorem, they proved that WSF-$(k^2+k+1, k+1, 1)$ provides a wake-up schedule only if k is a power of a prime. Given a delay bound D, we obtain one feasible set of all WSF-$(k^2 + k + 1, k + 1, 1)$s that satisfy $\frac{D}{n_t} \geq 2\delta$ $(= 2ms)$ and compare them to the proposed scheme. For example, for a delay bound 100ms, a feasible set includes WSF-(7,3,1), WSF-(13,4,1), WSF-(21,5,1), and WSF-(31,6,1), where k is 2, 3, 4, and 5, respectively. Since $k = 6$ is not a power of a prime and $k = 7$ does not satisfy $\frac{D}{n_t} \geq 2\delta$ $(\frac{100}{7^2+7+1} < 2)$, they are not included in the feasible set. As shown in Fig. 3.5, in Disco-(p_1, p_2), a node probes at the start and end of each wake-up period for δ and listens to a probing message for the remainder of the wake-up period, which must be longer than δ $(= 1ms)$. Therefore, one period $\frac{D}{p_1 * p_2}$ must be equal to or longer than 3δ $(= 3ms)$. In a similar manner to WSF-(n_t, n_a, n_c), for a given delay bound D, we compare the proposed scheme to a feasible set of all Disco-(p_1, p_2) functions which satisfy $\frac{D}{p_1 * p_2} \geq 3\delta$. For example, for a delay bound 100 ms, a feasible set includes Disco-(2,3), Disco-(2,5), Disco-(2,7), Disco-(2,11), Disco-(2,13), Disco-(3,5), Disco-(3,7), and Disco-(3,11). Since Disco-(2,17) and Disco-(3,13) do not satisfy $\frac{D}{p_1 * p_2} \geq 3\delta$ $(\frac{100}{2*17} < 3$, $\frac{100}{3*13} < 3)$, they are not in the feasible set.

Schedules of all three schemes have the period of D. To compare the energy consumption for discovering neighbors, we use the average energy consumed during a delay bound D. Energy consumed in the proposed scheme, WSF-(n_t, n_a, n_c), and Disco-(p_1, p_2) are denoted by E_{Prop}, E_{WSF}, and E_{Disco}, respectively. They can be easily expressed as

$$
\begin{aligned}
E_{Prop} &= E_P\left(\frac{(1-q_{opt})\delta}{q_{opt}} + 2\delta\right) - E_L\delta \\
&\quad - E_S\left(\frac{(1-q_{opt})\delta}{q_{opt}} + \delta\right) \\
&\quad + D(E_L \cdot q_{opt} + E_S(1-q_{opt})) \\
E_{WSF} &= n_a\delta E_P + n_a E_L\left(\frac{D}{n_t} - \delta\right) \\
&\quad + (n_t - n_a)\frac{D}{n_t}E_S \\
E_{Disco} &= 2\delta(p_1 + p_2 - 1)E_P \\
&\quad + (p_1 + p_2 - 1)\left(\frac{D}{p_1 p_2} - 2\delta\right)E_L \\
&\quad + (p_1 - 1)(p_2 - 1)E_S\frac{D}{p_1 p_2}.
\end{aligned}
$$

Then, to compare the miss probability of a contact for discovering neighbors, we derive the miss probabilities for three schemes. They are denoted by P_{LP_Prop}, P_{LP_WSF}, and P_{LP_Disco} respectively and are expressed as

$$\begin{aligned} P_{LP\_Prop} &= \frac{2\delta}{D} \\ P_{LP\_WSF} &= \frac{2n_t\delta}{D} \\ P_{LP\_Disco} &= \frac{2p_1p_2\delta}{D}. \end{aligned}$$

Miss probability of the proposed scheme is always lower than those of WSF-(n_t, n_a, n_c) and Disco-(p_1, p_2) because n_t, p_1, and p_2 are equal to or larger than 2. In contrast, the energy consumption of each wake-up schedule in the feasible sets of WSF-(n_t, n_a, n_c) and Disco-(p_1, p_2), varies depending on n_t, n_a, p_1, and p_2.

Given a delay bound D, we obtain two wake-up schedules with a minimum miss probability from the feasible sets of WSF-(n_t, n_a, n_c) and Disco-(p_1, p_2), respectively, and compare the proposed scheme to them. There exists a tradeoff between energy consumption and miss probability. Therefore, of the wake-up schedules of a feasible set, WSF-(7,3,1) with the smallest n_t $(= 7 = 2^2 + 2 + 1)$ has the minimum miss probability. And, of wake-up schedules of a feasible set of Disco-(p_1, p_2)s, Disco-(2,3) with 2 and 3 of the smallest and the second smallest primes has the minimum miss probability. Fig. 3.15 shows the miss probability of the proposed scheme, WSF-(7,3,1), and Disco-(2,3). Miss probability of the proposed scheme is nearly 0 and always lower than WSF-(7,3,1), and

Table 3.1: Wake-up schedules of WSF-(n_t, n_a, n_c) and Disco-(p_1, p_2), which minimize energy consumption for each delay bound

		DelayBound(ms)													
		350	400	450	500	550	600	650	700	750	800	850	900	950	1000
WSF	(n_t, n_a, n_c)	(7,13)	(7,19)	(11,13)			(11,17)	(11,19)	(13,17)	(13,19)			(13,23)		(17,19)
Disco	(p_1, p_2)	(133,12,1)	(183,14,1)			(273,17,1)		(307,18,1)			(381,20,1)				

Disco-(2,3). Fig. 3.16 shows the energy consumption of the proposed scheme, WSF-(7,3,1), and Disco-(2,3) as a function of delay bound D. When the proposed scheme is compared to WSF-(7,3,1), and Disco-(2,3), we observe a significant energy saving using the proposed scheme. From Fig. 3.15 and Fig. 3.16, we conclude that although WSF-(n_t, n_a, n_c) and Disco-(p_1, p_2) use more energy, their miss probability is much higher than that of the proposed scheme.

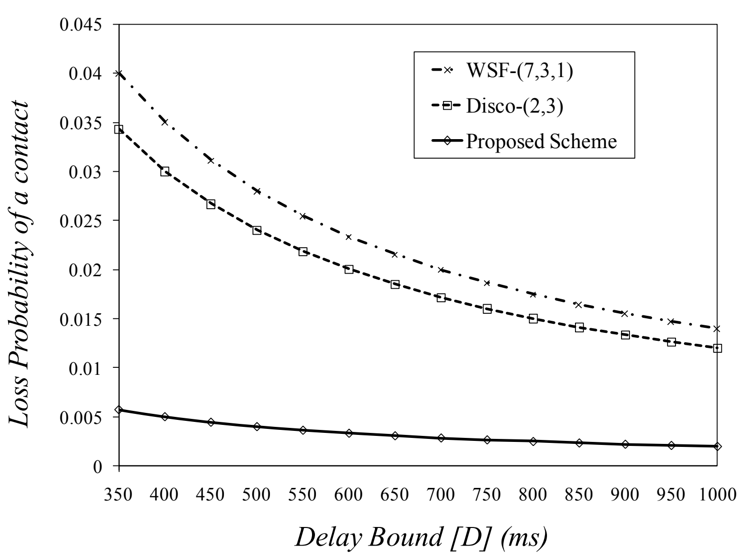


Fig. 3.15 Miss probability of the proposed scheme, WSF-(7,3,1), and Disco(2,3)

Table 3.1 shows the wake-up schedules of WSF-(n_t, n_a, n_c) and Disco-(p_1, p_2),

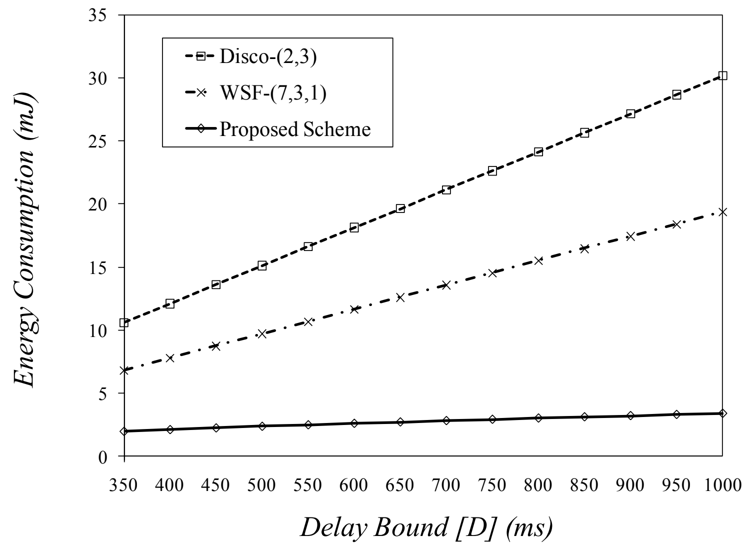


Fig. 3.16 Energy consumption of the proposed scheme, WSF-(7,3,1), and Disco(2,3)

which minimize the energy consumption for each delay bound. As n_t or $p_1 * p_2$ increases, the number of sleep periods increases and energy consumption is reduced. So, the wake-up schedules with a maximum n_t and $p_1 * p_2$ in each feasible set of WSF-(n_t, n_a, n_c) and Disco-(p_1, p_2) are chosen. Fig. 3.17 shows energy consumption of the proposed scheme and wake-up schedules in Table 3.1. A feasible set of WSF-(n_t, n_a, n_c) includes some wake-up schedules with less energy consumption than the proposed scheme. In contrast, for a delay bound, Disco-(p_1, p_2) provides no wake-up schedules which consume less energy than the proposed scheme. Fig. 3.18 shows the miss probability as a function of delay bound D. Wake-up schedules of WSF-(n_t, n_a, n_c) and Disco-(p_1, p_2) listed in

Table 3.1 miss a contact with a probability of more than 0.5. The miss probability is too high to deploy the wake-up schedules in real networks. In contrast, the proposed scheme offers a much lower probability of a contact than WSF-(n_t, n_a, n_c) and Disco-(p_1, p_2), which are nearly 1.

As shown in Fig. 3.17 and Fig. 3.18, fluctuations in energy consumption and miss probability of WSF-(n_t, n_a, n_c) and Disco-(p_1, p_2) appear. A feasible set for a delay bound D is restricted by the number of available primes. For example, WSF-(307,18,1) is selected as a wake-up schedule with minimum energy consumption at delay bounds of 650, 700, 750 ms. A feasible set of WSF-$(k^2+k+1, k+1, 1)$ is determined by a power of a prime, k, such that $\frac{D}{n_t}$ $(= \frac{D}{k^2+k+1})$ is equal to or larger than 2δ. Of elements of the set, the wake-up schedule with a maximum k is selected as the one with the minimum energy consumption. The maximum k is 17 at all delay bounds of 650, 700, and 750ms because the next prime 19 does not satisfy $\frac{D}{k^2+k+1} \geq 2$. Since miss probability $\frac{2(k^2+k+1)\delta}{D}$ is inversely proportional to D, the miss probability of a contact decreases from 650 to 750 ms as shown in Fig. 3.18.

All three schemes, for a given delay bound D, propose wake-up schedules which discover a neighbor within D. WSF-(n_t, n_a, n_c) and Disco-(p_1, p_2) offer a feasible set of several wake-up schedules, respectively, and the proposed scheme suggests one schedule. Although the wake-up schedules of WSF-(n_t, n_a, n_c) and

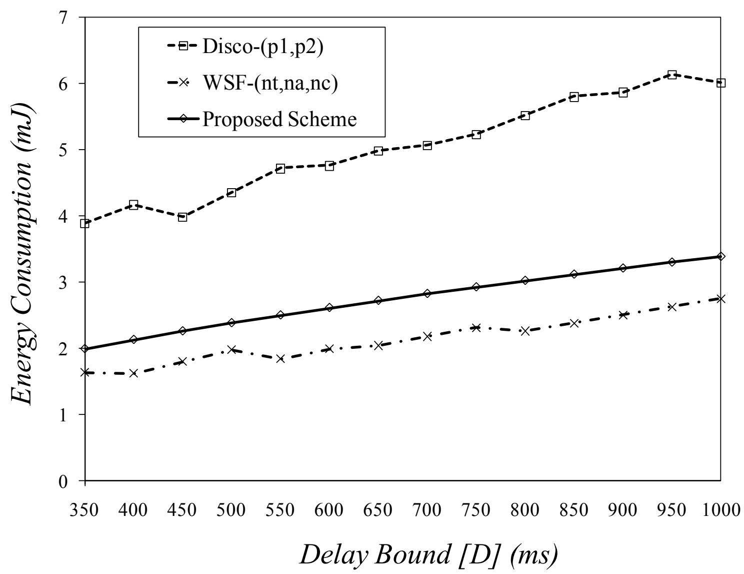


Fig. 3.17 Energy consumption of wake-up schedules which minimize energy consumption for each delay bound and the proposed scheme

Disco-(p_1, p_2) consume the maximum energy to minimize the miss probability, their miss probabilities still are higher than that of the proposed scheme. As shown in Fig. 3.17, a feasible set of WSF-(n_t, n_a, n_c) includes wake-up schedules which consume less energy than the proposed scheme. But, the miss probability of the schedule is too high for the schedule to be deployed into opportunistic networks. And wake-up schedules in a feasible set of Disco-(p_1, p_2) have a performance with a higher miss probability and higher energy consumption rate than the proposed scheme. We provide the theoretical analysis for the limited ranges from 350 to 1000 ms, since it is cumbersome to obtain a feasible set for WSF-(n_t, n_a, n_c) and Disco-(p_1, p_2) for a given delay bound. However, the performance tendency of energy consumption and miss probability of a contact will continue in all ranges of delay bounds.

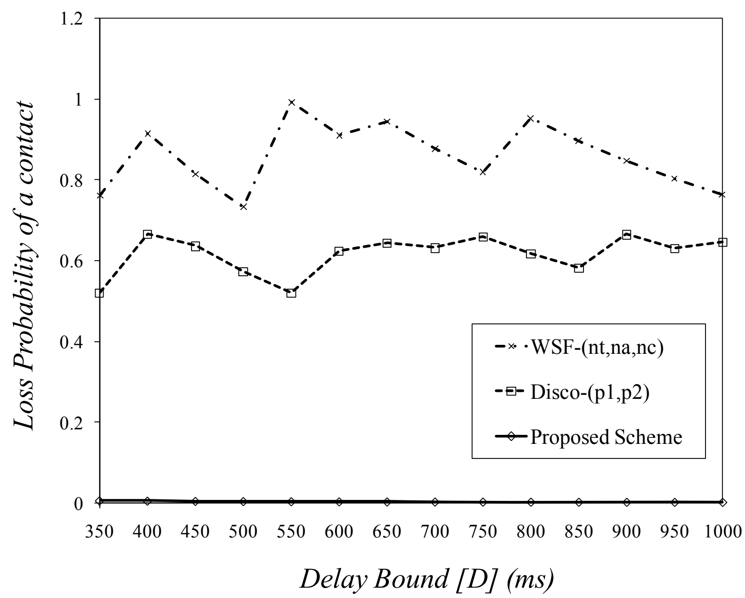


Fig. 3.18 Miss probabilities of wake-up schedules which minimize energy consumption for each delay bound and the proposed scheme

3.11 Performance Evaluation

To validate the proposed scheme, we conducted simulations. Metrics for performance evaluation were the energy consumption and the success probability of neighbor discovery. To clarify the performance evaluation of the three schemes, we summarize the simulation model as follows. The simulated network consists of 30 nodes which are randomly placed over a $500m \times 500m$ grid. Power consumptions of probing, listening and sleeping are $60mW$, $45mW$ and $0.09mW$, respectively [51]. Wireless transmission range is set to $50m$. Node velocity is uniformly distributed at $(3m/s, 5m/s)$. Each node moves according to the random walk mobility model. Schedules are divided into equal periods of sending or receiving probing messages, which are set to 1 ms $(= \delta)$.

3.11.1 Energy Consumption and Failure Probability of Neighbor Discovery

We define the energy consumption as the amount of average energy that is consumed during D and the failure probability of neighbor discovery as the ratio of the number of contacts not successfully discovered by adjacent nodes to the total number of contacts.

In [38], only WSF-(7,3,1) and WSF-(73,9,1) were described in detail. For performance evaluation through the simulation, we compare the proposed scheme with WSF-(7,3,1), WSF-(73,9,1), Disco-(2,3), and the wake-up schedules of Disco-(p_1, p_2) listed in Table 3.1. For the failure probability of neighbor discovery, we conduct simulations excluding the wake-up schedules of Disco-(p_1, p_2) listed in Table 3.1, since the failure probabilities of them are too high. As shown in Fig. 3.19, simulation results closely match theoretical analysis. Fig. 3.19 (a) and Fig. 3.19 (b) show the energy consumption and the failure probability of neighbor discovery.

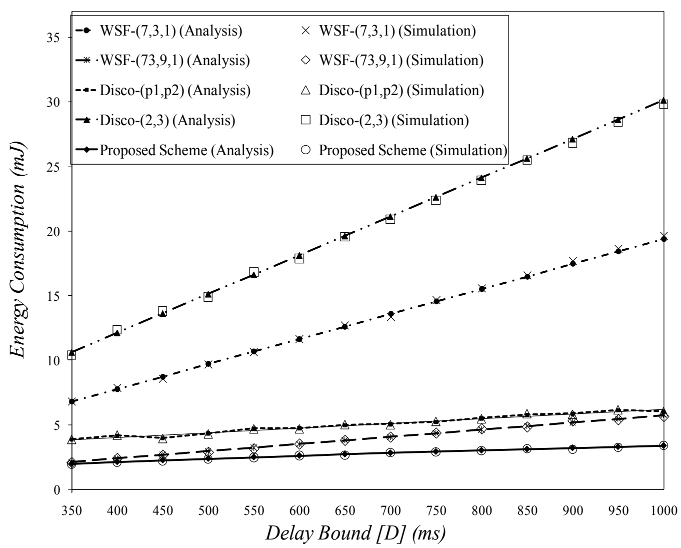
3.11.2 Discovery Time

We defined the discovery time as the time elapsed between the instant the devices are in communication range and the instant they discover each other. Fig. 3.20 shows the cumulative distribution functions of the discovery times obtained from simulation with a delay bound of 400 ms and 700 ms, respectively.

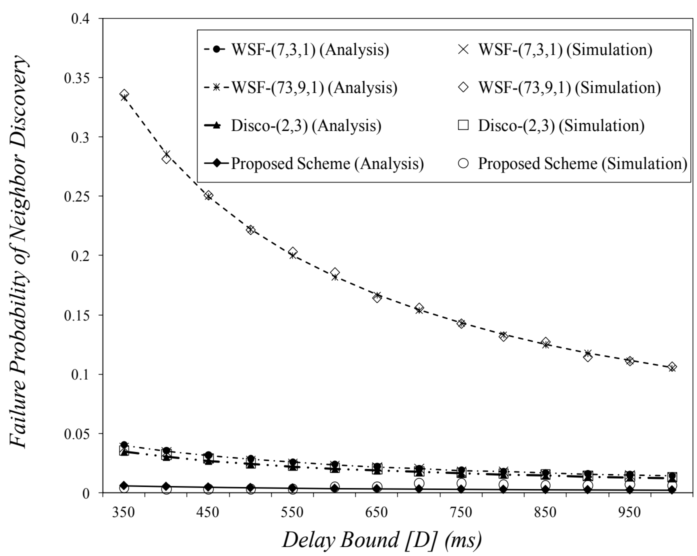
To compare with Disco, at delay bounds of 400 ms and 700 ms, we use two wake-up schedules, the most successful neighbor discovery probability and the most energy-efficient consumption among all possible combinations of two prime numbers. They are Disco-(2,3) and Disco-(7,19) at 400 ms, and Disco-(2,3) and Disco-(7,11) at 600 ms. WSF-(7,3,1) and WSF-(73,9,1) discover neighbors with almost the same speed as the proposed scheme. In contrast, Disco discovers neighbors much more quickly. In Disco-(p_1, p_2), if two nodes choose the same prime number, they may never discover each other if they wake up with the same period but different phase. In order to allow each node to choose different prime numbers, all nodes are required to pick two prime numbers and awake for more periods. For this reason, nodes do not control neighbor discovery within D and find neighbors much faster. Disco-(2,3) consumes more than 6 times the energy of the proposed scheme, and Disco-(7,19) and Disco-(7,11) more than 2 times. WSF-(7,3,1) and WSF-(73,9,1) consume energy more than 2 and 1.5 times proposed scheme, respectively.

3.12 Summary

In opportunistic networking, networks are sparse and nodes are mobile. In addition, nodes must continuously probe their neighborhood in order to not miss an opportunity for data delivery. This persistent probing imposes a significant burden on battery-operated devices. Therefore, we have proposed the neighbor discovery scheme which provides a bounded delay with the minimum of energy consumption required to achieve the minimal miss probability. We derived the probing schedule and the associated listening schedule with the minimal miss probability of a contact. And we elaborated it to energy-efficient. Then, through extensive theoretical analysis and simulations, we validated the performance of the proposed scheme. Results demonstrate that the proposed scheme achieves a significant energy-efficiency and provides excellent successful neighbor discovery.



(a) Energy consumption
(simulation results)



(b) Failure probability of a contact
(simulation results)

Fig. 3.19 Comparison of energy consumption and miss probability of a contact through simulation

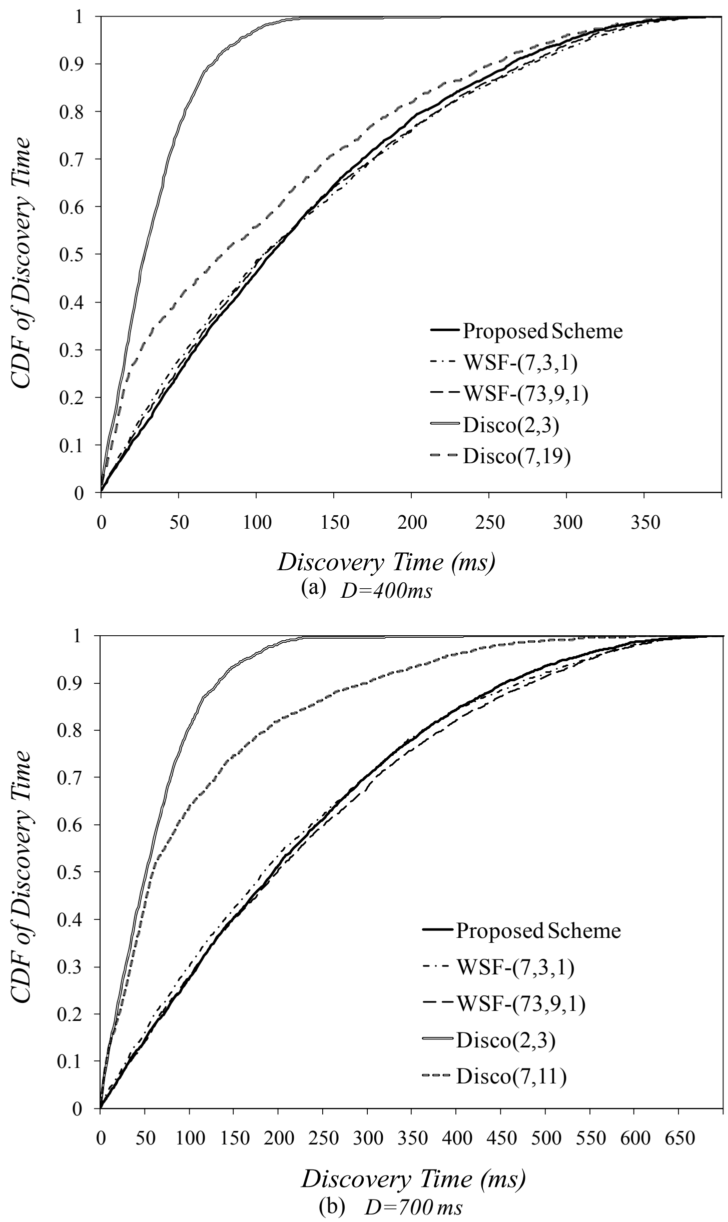


Fig. 3.20 Cumulative distribution functions of the discovery time (D = 400 ms and D = 700 ms)

CHAPTER 4

Conclusion

This chapter conclude the dissertation by summarizing the major contributions of the thesis and suggesting some key directions for future work.

4.1 Thesis Summary

In chapter 2, we introduced a distributed channel rendezvous scheme excluding any centralized control approach for multi-channel access networks. Establishing a control channel for medium access control is a challenging problem in multi-channel access networks. The use of a dedicated global control channel simplifies the rendezvous process but may not be feasible due to the bottleneck of a single control channel. We showed that proposed scheme achieves the smallest bound of $2N+1$ slots for rendezvous time if N channels are available. It was proved to provide fair access opportunities to all channels. And we suggested how to implement it without slot synchronization and proved it.

In chapter 3, we proposed optimal energy-efficient neighbor discovery scheme in opportunistic networks. In opportunistic networking, networks are sparse and nodes are mobile. In addition, nodes must continuously probe their neighborhood in order to not miss an opportunity for data delivery. This persistent probing imposes a significant burden on battery-operated devices. We derived the probing schedule and the associated listening schedule with the minimal miss probability of a contact. And we elaborated it to energy-efficient. Then, we conducted an extensive theoretical analysis and simulations.

4.2 Contribution

4.2.1 Deterministic Rendezvous Scheme in Multi-channel Access Networks

We believe that the key contribution of our proposed solution is as follows. We are the first to propose the deterministic rendezvous process with the smallest bound for rendezvous time of $2N + 1$ slots. The best bound known so far is N^2+N1 slots. And the rendezvous process provides fair channel access in multi-channel environment and all nodes operate with an identical rendezvous sequence. It is noteworthy that both fairness and simplification are the most challenging problems in distributed systems. And it can be implemented without slot synchronization. Because synchronization is a highly resource-consuming task, battery-operated mobile nodes does not afford it.

4.2.2 Optimal Energy-Efficient Neighbor Discovery Scheme in Opportunistic Networks

We have proposed the neighbor discovery scheme which provides a bounded delay with the minimum of energy consumption required to achieve the minimal miss probability. Previous researches dealt with two operation modes (sleep and wake-up) while they did not specify what to do in the wake-up mode. It is important to design wake-up mode mode becasue energy-consumption differs depending on the action the node takes in wake-up mode. We divide the wake-up mode into probing and listening mode and derive an energy-optimal neighbor discovery scheme.

And we aim to design a neighbor discovery scheme which guarantees the minimum miss probability. As long as they operate asynchronously, it is practically impossible that their probing intervals are exactly overlapping. However, if their probing intervals are misaligned by less than δ back and forth from the exactly aligned instant, they cannot recognize each other. Achievable minimum miss probability of a contact is $2\delta/D$. The proposed scheme provide the minimum miss probability of $2\delta/D$.

The proposed neighbor discovery scheme is optimal in the sense that it discovers a neighbor within a bounded delay with the minimal energy consumption as well as with the minimal miss probability of a contact.

4.3 Future Direction

There are a few interesting future research directions for two parts of proposed schemes.

First, as an extension of DRSEQ, we will study a scheme which guarantees a rendezvous within a bounded time without synchronization as long as a commonly available channel exists. we 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.

Secondly, as an extention of energy-efficient neighbor discovery scheme, we will propose a scheme which makes multiple nodes energy-efficiently operate. When multiple nodes are within their transmission range, they may not recognize each other because of collisions of probing message. To alleviate it, we will design an enegy-efficient MAC protocol.

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다중 채널 무선 네트워크와 기회적 네트워크를 위한 이웃 탐색 기법에 관한 연구

최근에, 기회 네트워크 (opportunistic network)나 인지 네트워크 (cognitive network)와 같은 새로운 유형의 이동 애드혹 네트워크 (mobile ad hoc network) 가 많은 관심을 받고 있다. 군사, 차량, 의료, 멀티미디어 전송 등 다양한 서비스에 응용될 수 있다. 이러한 네트워크는 일반적으로 기간 통신없이 자가 구성 (self-configuration) 을 할 수 있어야 한다. 이 자가 구성의 제일 첫번째 단계가 이웃 탐색이다. 전송거리 내에 있는 두 노드들은 데이타를 교환하기 전에, 서로를 인식하고 연결을 설정해야 한다. 만약 서로를 인식하지 못한다면, 통신 기회를 놓치게 되고, 전송 지연이 길어져 결국 데이타 전송을 하지 못하게 된다. 이웃 탐색하는 방법을 찾는 것은 노드들이 서로 언제 얼마나 오랫동안 만날지 모르기 때문에 상당히 어려운 문제이다. 본 연구에서는 분산적 (distributed)이고 결정적인 (deterministic) 방식으로 이웃 노드를 탐색하는 문제를 다루고자 한다.

본 연구의 첫 번째 주제에서는, 다중 채널 액세스 네트워크에서 채널 랑데뷰 기법을 제안한다. 노드들은 데이터 전송을 시작하기 전에 하나의 공통된 채널에서 링크를 설정해야 한다. 그런 공통의 채널을 찾는 방법은 중앙 처리 또는 분산 처리 방식으로 이루어 질 수 있다. 본 연구에서는 별도의 제어 채널 없이 완전 분산 처리 (fully distributed) 방식으로 이루어지는 채널 랑데뷰 문제에 대해 초점을 맞춘다. 제안된 방식은 두개의 노드들이 $2N + 1$ 슬롯 내에 랑데뷰할 가용 채널을 방문하는 순서를 제공한다. 여기서 N은 채널의 수이고 슬롯은 공통 채널에서 두 노드가 링크를 설정하는데 필요한 최소의 시간 간격을 나타낸다. 지금까지 알려진 가장 좋은 방식으로

는 $N^2 + N - 1$ 슬롯 내에 랑데뷰한다고 알려져 있다. 그리고, 제안된 기법은 슬롯의 동기화 없이도 구현가능하다는 것을 증명하였다.

본 연구의 두 번째 주제에서는, 기회 네트워크에서 최적의 에너지 효율적인 이웃 탐색 방식을 제안한다. 기회 네트워크는 이동 애드혹 네트워크가 가장 흥미롭게 진화된 형태이다. 실제 이동 애드혹 네트워크에서는 노드의 짧은 전송거리와 사용자의 빠른 이동으로 인하여 빈번하게 연결이 끊긴다. 그러므로, 전체 네트워크는 연결되어 있고 노드들 사이에는 단대단 (end-to-end) 경로가 존재한다고 가정하고 있는 기존의 이동 애드혹 네트워크에 대한 연구들은 적용할 수 없다. 신속한 이웃 탐색을 하기 위해서, 노드는 지속적으로 주변에 있는 다른 노드를 탐색하기 위해 probing 메시지를 broadcasting하고 있다. 이런 종류의 지속적인 probing은 너무 에너지 소모가 크기 때문에, 배터리로 동작하는 장치에게는 적합하지 않다. 에너지 소비를 최소화하기 위해서 다른 노드를 만나지 않을 때에는 radio 전원을 꺼서 sleeping mode로 설정하고, 오직 이웃 탐색과 데이타를 교환할 때에만 radio 전원을 켜야 한다. 우선, 에너지 효율적이고 최소의 missing 확률과 고정 지연 시간을 제공하는 probing 스케쥴 방식을 설계한다. 이후 제안된 probing 스케쥴과 함께 최적의 에너지 효율적인 listening 스케쥴 방식을 제안한다. 제안된 이웃 탐색 기법은 최소의 에너지 소모와 최소의 missing 확률을 제공하면서 고정 지연 시간을 제공한다는 점에서 최적의 알고리즘이라고 할 수 있다. 또한, 이론적 분석과 시뮬레이션 결과를 통해서 기존의 기법들과 성능을 비교하였다. 이 비교를 통해서 제안된 기법이 에너지 소모 및 contact의 missing 확률 측면에서 기본의 기법들보다 우수한 에너지 효율성과 높은 이웃 탐색 확률을 제공한다는 것을 보여 준다.

감 사 의 글

오늘의 결실을 맺기까지 저에게 도움을 주셨던 모든 분들께 이 지면을 빌어 진심으로 감사드리며, 소중했던 포항에서의 추억을 항상 마음 속에 간직하고 그리워하며 살아가겠습니다.

먼저, 학자로서 지녀야 할 논리적인 사고 뿐만 아니라 사람으로서 지녀야 하는 인생에 가치관까지 가슴에 새겨 주신 김치하 교수님께 진심으로 감사드립니다. 대학교 입학땐 존경의 대상이셨고, 대학원 입학시에는 연구의 목표이셨고, 지금은 인생의 스승님이십니다. 한없이 부족한 저에게 애정어린 지도와 큰 가르침 교수님께 다시 한번 감사드립니다. 또한, 소중한 시간을 할애하여 본 논문의 심사를 위해 자리해셨던 박찬익 교수님, 서영주 교수님, 송황준 교수님, 그리고 바쁘신 가운데 포항까지 오셔서 논문 심사와 조언을 주신 경북대 컴퓨터공학과 한기준 교수님께 감사드립니다. 또한, 철없이 입학했을 때부터 아낌없는 조언과 충고를 주신 포항공과대학교 컴공과 교수님들께 감사의 말씀드립니다.

박사과정 기간이 길어지면서 박사 학위에 대한 확신을 하기 힘든때도 있었습니다. 그럴 때마다 저에게 많은 힘이 주신 분이 부모님과 동생입니다. 걱정과 근심으로 힘드셨지만 무한한 신뢰로 항상 저를 위해 묵묵히 눈물로 기도해 주신 아버님, 어머님, 그리고 저의 동생에게 진심으로 감사하고 사랑한다는 말을 전해드리고 싶습니다.

저의 인생에서 가장 소중한 추억을 함께한 연구실 선후배님들께 감사드립니다. 특히, 먼저 졸업하신 정종식 박사님, 김근형 박사님, 박태근 박사님, 허윤구 박사님, 김정규 박사님, 곽동호 박사, 태수형, 덕희형, 상욱형, 욱이형, 봉규형, 찬필형, 규영형, 미정누나, 성용형, 종혁형, 성열형, 주현형, 영진형, 한림, 경숙, 미호, 윤림, 영숙, 구지준, 미애, 지현, 승규, 상익, 지혜, 선배님들과 연구했던 시간들이 너무나 소중한

추억으로 남아 있습니다.

연구실에서 가장 행복했던 시간과 가장 힘든 시간을 같이 보낸 파트너 종민이, 언제나 독특한 생각과 밝은 웃음으로 선배들과 후배들의 사랑을 받았던 순목이, 누구에게나 넓은 마음을 내어 주는 기석이, 같이 있으면 행복한 기운을 나누어 주는 승열이, 짧은 기간이었지만 마치 10년을 알아 왔던거처럼 느껴지는 현목이, 후배지만 많은 면에서 항상 조언을 얻고 싶은 재훈이, 연구실 마스코트에서 이제는 주축으로 자리잡고 있는 지선이, 연구실 차세대 주자들 중휘, 철민, 건휘 모두에게 감사하다는 말 전하고 싶습니다. 앞으로 더욱 번창하고 발전해가는 연구실이 되기를 바라겠습니다. 마지막으로, 오랜기간 동안 부족한 제 옆자리를 큰 힘과 사랑으로 채워준 수현이에게 진심으로 감사드립니다.

저와 같이 부족함이 많은 사람이 오늘의 결실을 맺은 것은 여러분들의 도움이 없었다면 불가능한 일이었을 겁니다. 이러한 감사의 마음을 변함없이 가슴속 깊은 곳에 지니고 새로운 삶을 다시 시작하겠습니다.

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Multi-Path routing 기반 네트워크에서 동작하는 **RSVP** 확장 방안**(An RSVP Extension for Multi-Path Routing Networks)**

Advisor: Prof. 김 치 하

Mar.2003 Sep.2010: Ph.D. in Computer Science and Engineering

Division of Electrical and Computer Engineering, POSTECH

Thesis Title :

다중 채널 무선 네트워크와 기회적 네트워크를 위한 이웃 탐색 기법에 관한 연구**(Neighbor Discovery Schemes for Multichannel Wireless Networks and Opportunistic Networks)**

Advisor: Prof. 김치하 (Cheeha Kim)

Publications

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