THE UNIVERSITY OF CALGARY

PEER-TO-PEER WIRELESS SYSTEM

by

Wilson Pak-Wang Lee

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR

THE DEGREE OF MASTER OF SCIENCE

DEPARTMENT OF ELECTRICAL AND COMPUTER
ENGINEERING

CALGARY, ALBERTA

JULY, 1996

THE UNIVERSITY OF CALGARY
FACULTY OF GRADUATE STUDIES

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "Peer-to-Peer Wireless System" submitted by Wilson Pak-Wang Lee in partial fulfillment of the requirements for the degree of Master of Science.

Michel Fattouche

Supervisor, Dr. Michel Fattouche
Dept. of Electrical and Computer Engineering

Dr. Spence Nichols
Dept. of Electrical and Computer Engineering

Dr. Abraham Fapojuwo
Nortel Wireless Networks

H. Zaghloul

Dr. Hatim Zaghloul
President and C.E.O., Wi-LAN Inc.

Date: July 29, 96

ABSTRACT

Currently, telephone companies provide the basic telephone service to many small communities in Northern Canada by installing local switching and transmission facilities. The new mobile satellite systems offer a potential alternative of serving the rural areas. However, local calling within a community will require double satellite hops for the communication link. A simple peer-to-peer wireless system is proposed to provide local calling within a small community. This reduces the use of the mobile satellite channels for local calls. Also, the telephone companies can reduce the cost of installing and maintaining local switching and transmission facilities in these remote locations. A single-hop peer-to-peer wireless system is specified, and its performance is simulated to ensure all the requirements are met. The two-hop system using a repeater is also examined.

ACKNOWLEDGMENTS

I would like to thank Northwestel Inc. who have sponsored my study and research during the past two years. I hope this research will benefit them in the future. I also wish to express my appreciation to Dr. M. Fattouche and the TRLabs staff for their expert advice in pointing me to the right direction in my research. Finally, I wish to thank my wife, Daisy, and our daughter, Joelle, for their constant support during my study.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1
INTRODUCTION

1.1 Overview

From the time of Alexander Graham Bell until about the middle of the twentieth century, American telephony was defined by the physical challenge of wiring the continent [1]. The installation and maintenance of copper to provide telephone service represent a major investment of the telephone companies. The costs of copper-based local access rise rapidly as a function of declining population density [2]. Hence, providing telephone service to the rural areas is expensive.

A common method to provide the telephone service in rural areas of Northern Canada is to install a local fixed satellite earth station with a telephone switch. This centralized configuration is required for common access to the telephone network and ease of maintenance for the telephone company. The use of a wireless access system such as subscriber radios to serve fixed-location (i.e. non-mobile) users began in the 1970's in Canada [1]. Such a system consists of a central station and multiple subscriber stations. The wireless network provides an alternative for telephone access compared to the conventional wired network. However, both the wired and wireless networks require a centralized configuration with a local switch or central station.

The new mobile satellite systems, either geostationary (GEO) or low earth orbit (LEO), provide an alternative for wireless access to the telephone network. Each subscriber only needs a terminal with an antenna pointing to the satellite to have telephone service. Such systems can provide telephone service especially in rural areas. However, all calls, whether local or long-distance, have to route through the mobile satellite systems. The subscriber has to pay the air-time charges even for local calls. To alleviate this problem, a peer-to-peer wireless system consisting of a group of identical terminals can be used in rural areas for local calling. The use of a peer-to-peer wireless system with a mobile satellite system presents a completely distributed architecture to provide telephone service in rural areas.

Current peer-to-peer wireless systems described in [3] and [4] are designed for the military use and for the mobile users. The jamming threat concern and the terminal mobility requirement increase the complexity of the systems. They are not applicable for the rural area local communications. A simple peer-to-peer wireless system developed for commercial use is described in this thesis.

1.2 Scope of Thesis

Chapter 2 will describe the existing configuration to provide telephone service in rural areas of Northern Canada and the problem of local calling within a community using the mobile satellite systems. Chapter 3 proposes a peer-to-peer wireless system to provide local calling within a small community. The system design approach and other potential applications are also discussed. Chapter 4 presents the system specifications. Chapter 5 examines the system performance. Conclusions and future work are described in chapter 6.

CHAPTER 2

PROVIDING TELEPHONE SERVICE IN RURAL AREAS OF NORTHERN CANADA

2.1 Existing Configuration

A typical configuration for providing telephone service in many small communities with less than 200 subscriber lines in the Yukon Territory and the Northwest Territories, Canada is shown in Fig. 2.1. The telephone company provides the local switching and satellite transmission facilities, as well as the supporting infrastructure such as building and power. This centralized architecture is also used in urban areas with other types of transmission facilities such as fiber or digital radios. Such an architecture is expensive to install and maintain especially in areas with small population density and minimal subscribers growth. Therefore, serving the rural areas may cost five to ten or more times per line as compared to urban areas [5].

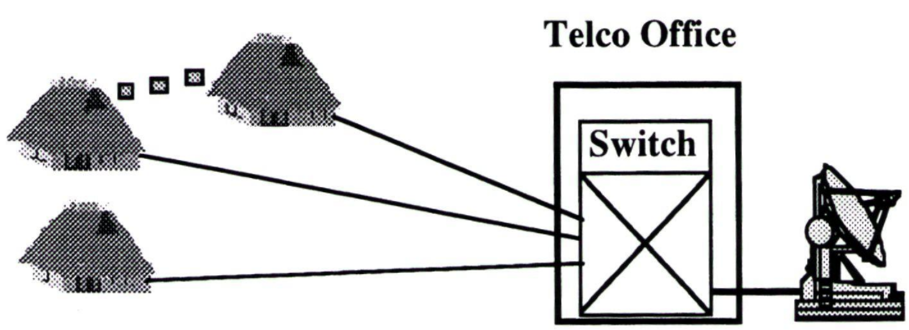

Figure 2.1 *A typical (simplified) telephone network configuration in rural areas of Northern Canada*

2.2 Mobile Satellite Systems

The World Administrative Radio Conference in 1992 had allocated spectrum in the 2 GHz band for the mobile satellite service [6]. Several mobile satellite systems provide voice grade telephone service including the MSAT from Telesat Mobile Inc., the upcoming Iridium from Motorola, and the proposed Globalstar from Qualcomm. A user only needs a terminal to access the telephone network through a satellite gateway station as shown in Fig. 2.2. Mobile satellite systems provide an alternative for subscribers in rural areas to access the telephone network. Local switching and transmission facilities provided by the telephone company can be replaced by the mobile satellite terminals. This distributed architecture allows the telephone company to eliminate the maintenance of their own facilities.

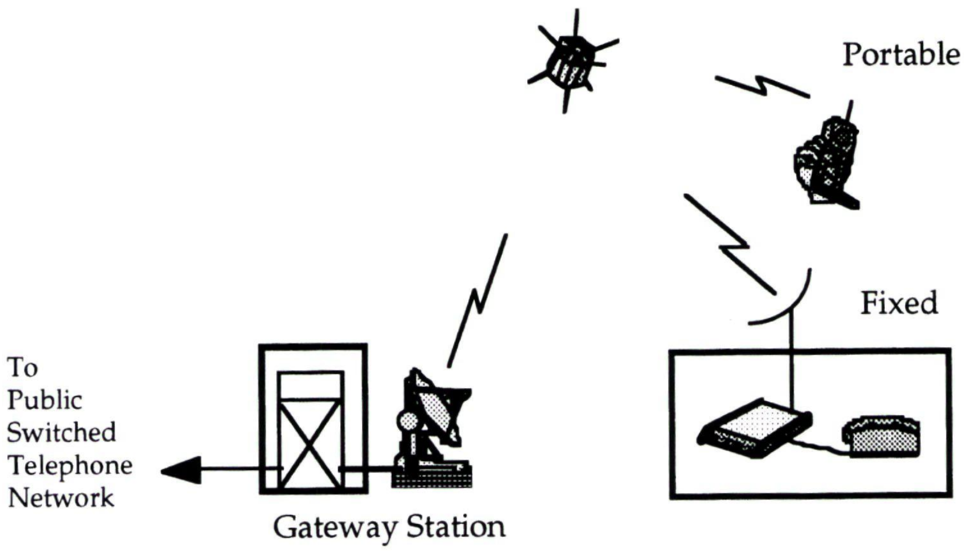

Figure 2.2 *Using the Mobile Satellite System to access the telephone network*

2.3 Local Calling using the Mobile Satellite System

Although the mobile satellite system can provide telephone service in rural areas, all calls including local and long-distance must route to the satellite and sometimes to the gateway station. Therefore, local calling within a community needs to use two satellite channels as shown in Fig. 2.3.

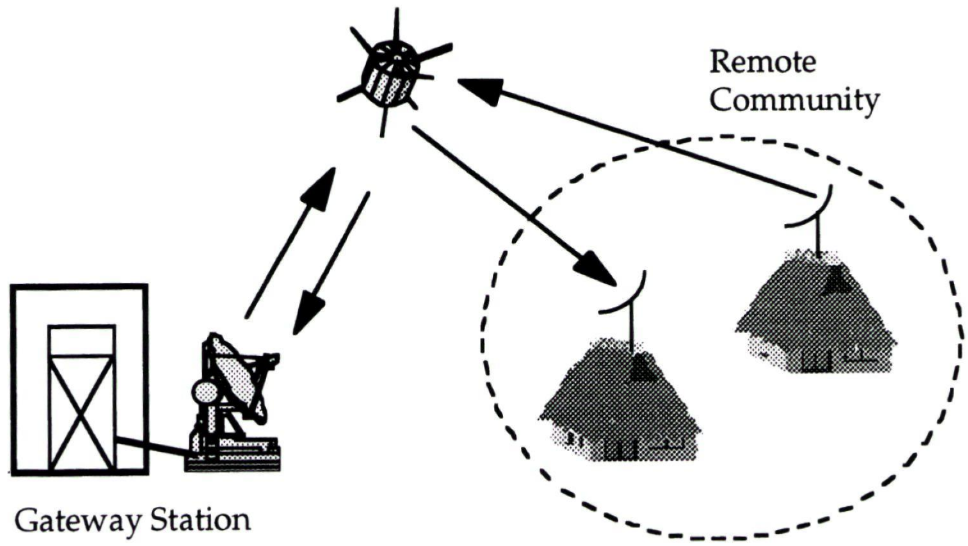

Figure 2.3 *Local Calling within a community using the Mobile Satellite System*

To avoid this problem, one solution is to install a private branch exchange (PBX) on site to route the local calls as shown in Fig. 2.4. But this is a change back to the centralized configuration, and the telephone company still has to maintain its local facilities. An alternative is required and discussed in the next chapter.

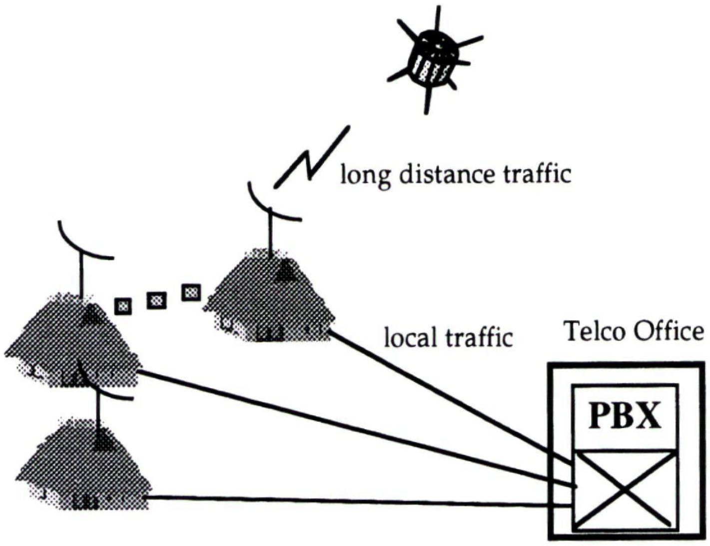

Figure 2.4 *Using a Private Branch Exchange on site for the local calls*

CHAPTER 3

THE SOLUTION OF PROVIDING TELEPHONE SERVICE IN RURAL AREAS

3.1 Local Calling using the Peer-To-Peer Wireless System

A peer-to-peer wireless system is proposed to handle the local calls while the long-distance calls route to the mobile satellite as shown in Fig. 3.1.

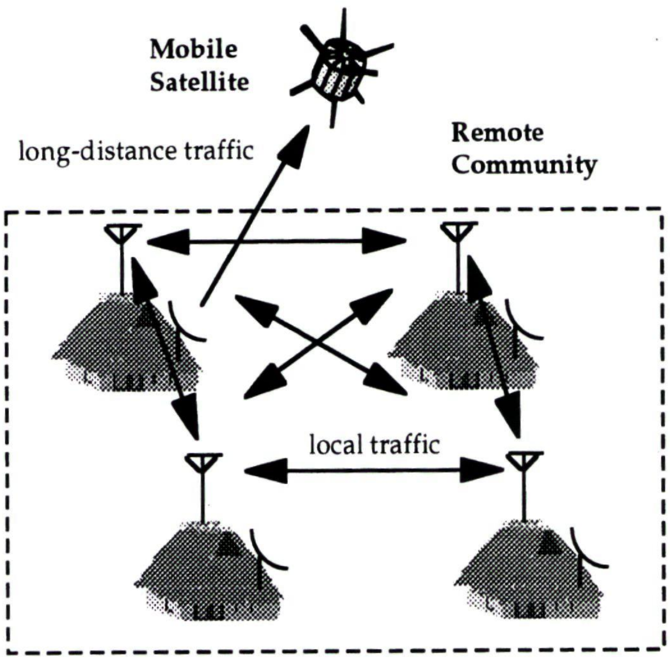

Figure 3.1 *Using a Peer-To-Peer Wireless System for Local Calling within a community*

This architecture offers several advantages.

(1) The use of a local wireless system eliminates the use of copper in rural areas. Also, the system does not require installation of either switching

hardware and related infrastructure such as building and power. This allows timely set up of local communications. This feature is also important in areas where no telecommunication infrastructure exists such as mining and exploration camps, or in the search and rescue operations.

(2) No installation and maintenance of the local switching and transmission facilities is required by the telephone company. Providing telephone service is simply done by distributing the terminals. This reduces the cost of serving the rural areas.

(3) No satellite channel is used for the local calls. This reduces the use of expensive air-time usage which translates to additional cost savings for the users or the telephone company.

Therefore, using a peer-to-peer wireless system in conjunction with a mobile satellite system is a low-cost option for serving the rural areas from the telephone company perspective.

3.2 Other Potential Applications

Besides providing the local communications in rural areas, a peer-to-peer wireless system can provide other applications such as wireless local loop and cordless extension of cellular.

3.2.1 Wireless Local Loop

Wireless local loop service can be provided by attaching a gateway switch with an interface to the public switched telephone network as shown in Fig. 3.2. Since local calling within the serving area will be peer-to-peer, the gateway switch only needs to route the calls to the telephone network. If a peer-to-peer wireless system already exists in an area, the service provider only needs to install a gateway switch for the users to access the telephone network.

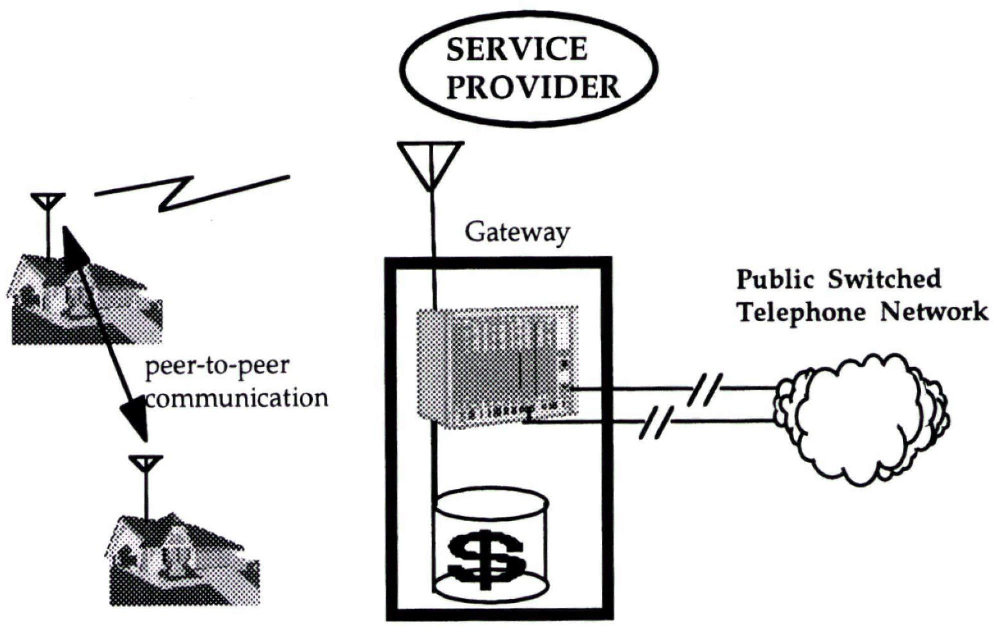

Fig. 3.2 Wireless Local Loop

Figure 3.2 *Wireless Local Loop*

3.2.2 Cordless Extension of Cellular

If a cellular terminal is integrated with a peer-to-peer wireless terminal, it could be used as a long-range cordless phone at home as shown in Fig. 3.3. The user can activate the home base station using the peer-to-peer wireless link to access the telephone network. If the peer-to-peer wireless link operates in the unlicensed band, the user can save the cellular air-time charges by using the handheld terminal acting as a cordless extension.

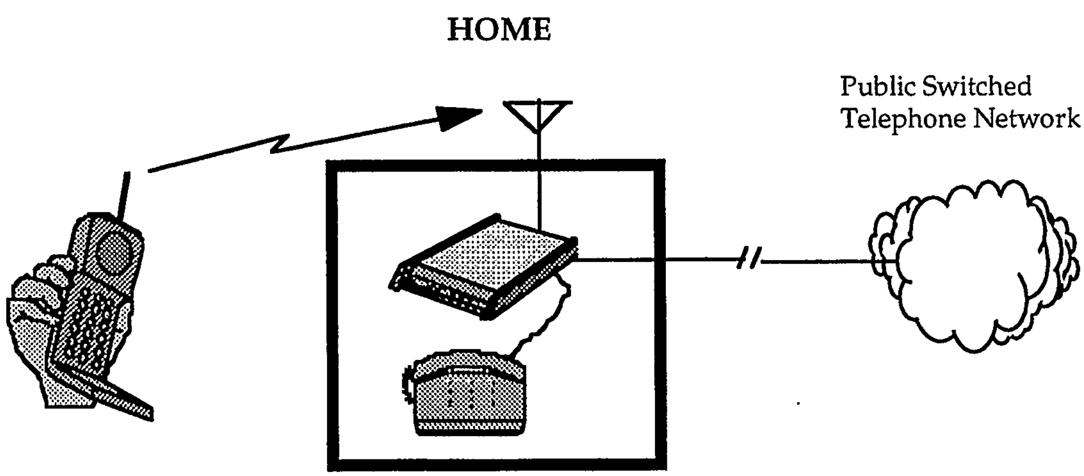

Figure 3.3 *Cordless Extension using Cellular*

3.3 System Design Approach

Any system design generally involves the definition of service requirements which translate into system specifications. However, we are also designing a wireless system that operates in a certain frequency band. Therefore, the radio standards set by the Industry Canada or the Federal Communications Commission (FCC) must be met. We also need to examine other similar systems to determine if some of their features should be incorporated or avoided in our system. Also, since the system is designed to be used in rural areas, a simple and low cost system is almost mandatory. Once the system is specified, its performance needs to be examined to ensure all service requirements are met. The system design approach is illustrated in Fig. 3.4.

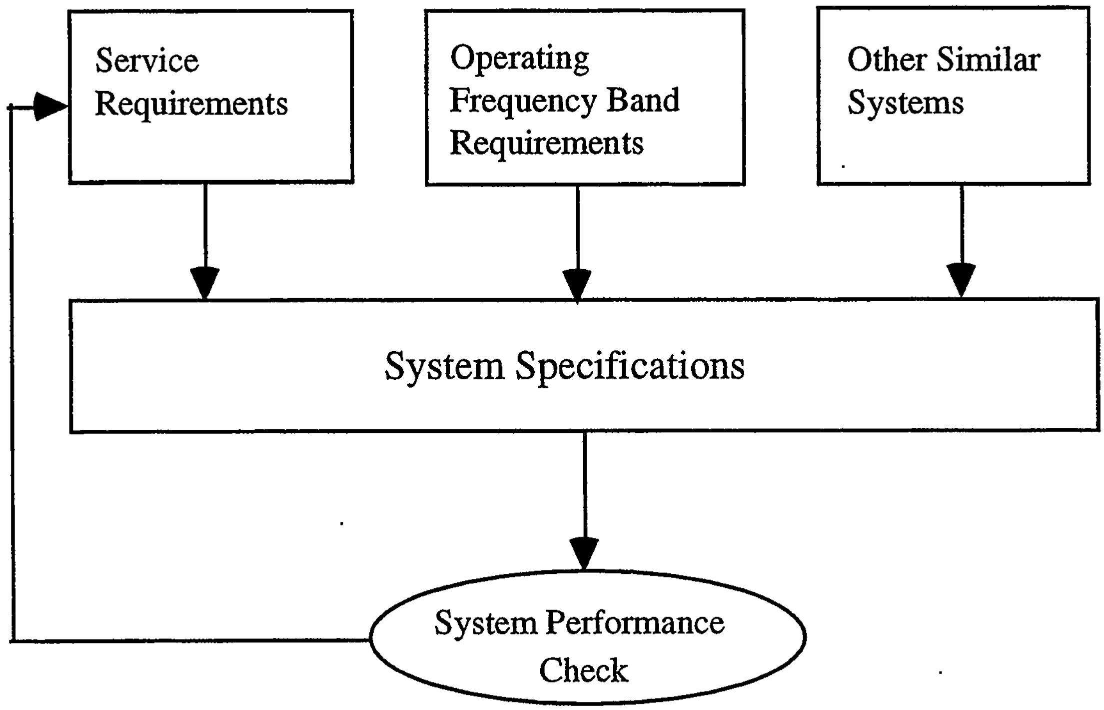

Figure 3.4 *System Design Approach*

The service requirements, operating frequency band requirements, and other similar system design criteria are discussed in sections 3.4 to 3.7. The system specifications are discussed in chapter 4 and the system performance is examined in chapter 5.

3.4 Service Requirements in Rural Areas

The basic service requirements in rural areas including traffic pattern and service quality are listed in table 3.1 [5]. Other optional services such as call forwarding, call waiting, and voice mail are not addressed in the system design since the demand varies in different communities. The payphone service requires special signaling format. It can be implemented using the gateway switch of the mobile satellite system. If the local peer-to-peer wireless system fails, the emergency calls can be handled by the mobile satellite system.

Categories	Requirements
Basic Service	Voice telephony capable of supporting Group 3 fax and low speed data
Coverage Area	within 2 km radius
Traffic Volume	0.05 - 0.09 erlang per line
Service Quality	Probability of blocking during busy hour ≤ 1%

Table 3.1 *Summary of Service Requirements in Rural Areas*

Since many small communities in Northern Canada have less than 200 subscribers, the maximum system capacity is chosen from 150 to 200 subscribers (terminals).

3.5 Operating Frequency Band Requirements

Since the system is designed for the local communications within an area which is similar to a wireless local area network (LAN), the unlicensed or ISM (industrial, scientific, and medical) bands under the Industry Canada RSS-210 [7] or FCC Part 15 in the United States are possible operating frequency bands. The frequency bands include 902-928 MHz, 2400 - 2483.5 MHz, and 5725 - 5850 MHz. All these unlicensed bands require the use of spread spectrum. Specifically, the 902-928 MHz band is chosen for the following two reasons:

(1) This band can be supported by devices relying on silicon-based devices with low fabrication cost, where the other higher frequency bands require more expensive gallium arsenide (GaAs) technology in power amplifier and receiver front-end circuits [8].

(2) Because of low frequency, this band allows the maximum transmission range between terminals.

3.5.1 Spread Spectrum Techniques

Two types of spread spectrum can be used in the 902-928 MHz band: direct sequence and frequency hopping.

In many direct sequence systems, a pseudo-random binary sequence is used to modulate the transmitted signal. The relative rate between the pseudo-random sequence and the user data, also known as the processing gain, is typically between 10 and 100 for commercial systems [8]. The received radio frequency signal is demodulated, and the resulting signal is correlated with the same pseudo-random sequence to recover the end user data.

In frequency hopping systems, both the transmitter and the receiver hop from one frequency to the next synchronously in a pre-determined hopping pattern. If the hopping rate is higher than the data rate, the system is a fast frequency hopping system. However, such systems are costly to build. Slow frequency hopping systems, in which the hopping rate is slower than the data rate, are more often used.

Since the system supports a number of users in a common frequency band, this type of multiple access communication scheme, using direct sequence or frequency hopping, is also known as code division multiple access.

3.5.2 Direct Sequence vs. Frequency Hopping Code Division Multiple Access

Although both the direct sequence and frequency hopping code division multiple access (CDMA) schemes can combat multipath interference, there are two important differences.

(1) Direct sequence CDMA systems are highly sensitive to differences in received signal power levels due to the non-zero cross correlation of the pseudo-random(PN) sequences assigned to individual users [9]. This is known as the near-far problem. One solution to this problem is the use of power control which attempts to ensure that all signals from the mobiles within a given cell arrive at the base of that cell with equal power. Such a method can be implemented in a centralized configuration using a base station for coordination. In a distributed configuration such as the peer-to-peer wireless system, power control is extremely difficult to implement. On the other hand, in frequency hopping CDMA, the near-far problem will only cause the adjacent channel interference and can be resolved by filtering instead of using power control.

(2) Synchronization of the direct sequence systems is more difficult to achieve than the frequency hopping systems because direct sequence systems synchronize at a higher chip rate.

Therefore, frequency hopping is chosen over direct sequence CDMA to be used in the peer-to-peer wireless system.

3.5.3 Frequency Hopping System Requirements in 902 - 928 MHz

The requirements of a frequency hopping system operating in the 902-928 MHz band [7] are listed below.

-- Minimum number of hopping frequencies = 50.

-- Average time occupancy on any frequency cannot exceed 0.4 second within a 20 second period.

-- Maximum peak output power = 1 W.

-- Maximum 20 dB bandwidth of the hopping channel = 500 kHz.

-- Minimum hopping channel carrier frequencies separation is 25 kHz or the 20 dB bandwidth of the hopping channel, whichever is greater.

3.6 Other Similar Systems

A peer-to-peer wireless system using frequency hopping spread spectrum is described in [3]. The system is a multi-hop packet radio network operating in the HF (3 to 30 MHz) band. Since the system is designed for the U.S. Navy, it must resist a variety of jamming threats, and therefore, the frequency hopping CDMA is used. Also, each node can be fixed or mobile all the time. The constant change in the network topology requires each node to periodically update the information of its one-hop neighbours and neighbours' neighbours. Each node is also assigned its own code for transmitting traffic either in point-to-point or point-to-multipoint configuration.

Another peer-to-peer wireless system, Wireless Adaptive Mobile Information System, using direct sequence CDMA is described in [4]. This is also a multi-hop mobile packet radio network supporting multimedia traffic including voice, data, and video. Again because of the terminal mobility requirement, each node must periodically update its one-hop neighbours.

These two peer-to-peer wireless systems require constant network initializations which increase the system complexity. Also, both systems transmit information in packet form. Each packet may route through different nodes to the destination. This is equivalent to packet switching. For real time traffic such as voice, the stringent delay requirement makes packet switching difficult to implement especially in a mobile network. Therefore, to maintain the simplicity of each terminal in the system, the network should have no or minimum network initialization. Also, circuit switching is preferred to easily accommodate the real time traffic. This means a dedicated link is set up either between two nodes or through several nodes for the message transmission.

3.7 Summary

The use of a peer-to-peer wireless system in conjunction with a mobile satellite system is proposed for providing telephone service in rural areas. The peer-to-peer wireless system can also be used in other applications such as wireless local loop and cordless extension of cellular. We have adopted a system design approach by first listing the rural area basic service requirements. Then, we have chosen the operating frequency band of 902-928 MHz and decided to use the frequency hopping spread spectrum. By examining other similar systems, we have decided that our system should use circuit switching with no or little network initialization to maintain the system simplicity. We can now proceed to specify the system in the next chapter.

CHAPTER 4

PEER-TO-PEER WIRELESS SYSTEM SPECIFICATIONS

4.1 Overview

After listing the service requirements, choosing the operating frequency band, and examining other similar systems in the last chapter, we can start specifying the system. The peer-to-peer wireless system consists of three components including the network organization, channel access scheme, and physical layer communications as shown in Fig. 4.1

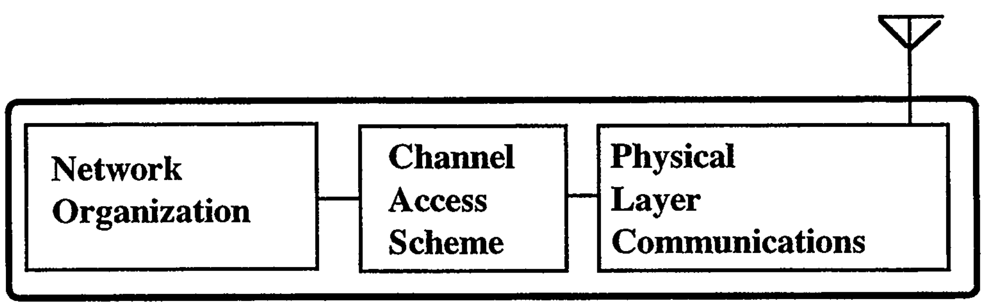

Figure 4.1 *Peer-to-Peer Wireless System components*

The network organization consists of a system initialization scheme that allows a group of identical terminals to set up the links among themselves and to exchange the routing information. The channel access scheme allows multiple terminals to access and share a common frequency band. The physical layer communications enables the information exchange between terminals over the wireless channel. This chapter will specify each of these three components to meet the service and operating frequency band requirements.

4.2 Network Organization

The network organization allows the terminals to discover the network connectivity (i.e. who they can connect to). This is a key component in the multi-hop network. However, since we concentrate on the single and two-hop systems, network organization can essentially be avoided. Fig. 4.2 lists the areas to be examined in the network organization.

Network Organization
-- Single-hop (no system initialization)
-- Two-hop (no system initialization by using the paging scheme)

Figure 4.2 *Network Organization components*

In the single-hop systems, we assume the network connectivity exists with each terminal being able to communicate with the other terminals in the system. Hence, no network initialization is required. This means no terminal initially knows its neighbours. Each node (terminal) only requires a unique address in the system.

In the two-hop systems, initialization can still be avoided by using the repeater paging scheme. The two-hop system will be examined at the end of this chapter. In the rural area application, since the single-hop system does not require any network initialization, we desire to use it to serve the whole community.

4.3 Channel Access Scheme

To allow multiple terminals sharing the same frequency band, we divide the 902-928 MHz band into signaling and message channels, as shown in Fig. 4.3. The signaling channel occupies two frequencies with one used for call request and the other used for call acknowledgment. The Call Request channel uses time-division multiple access (TDMA) with 50 slots per frame, and there are 50 message channels representing 50 frequency hopping patterns.

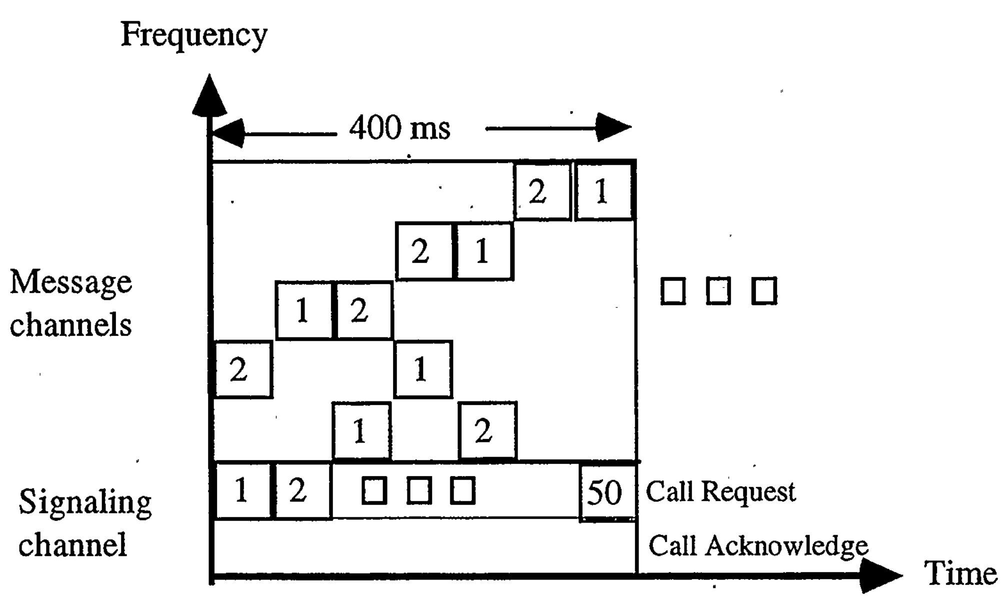

Figure 4.3 *Channel Access Scheme*

Each time slot of the Call Request signaling channel corresponds to a message channel (hopping pattern). The Call Request channel is used for the call set up and synchronization. The Call Acknowledge channel is used for the call acknowledgment. A media access control (MAC) protocol is developed to allow a terminal to access a time slot on the Call Request channel. When a terminal obtains a time slot on the Call Request channel, a message channel (hopping pattern) is automatically assigned. Two users exchange information on the assigned hopping pattern and synchronize using the time slot on the Call Request channel.

The components of the channel access scheme are shown in Fig. 4.4.

Channel Access Scheme
-- Signaling channel (broadcast channel usage & synchronize a user-pair)
-- MAC protocol (access an idle time slot on the Call Request channel)
-- Message channels (exchange information)

Figure 4.4 *Channel Access Scheme components*

This channel access scheme meets two of the ISM band requirements.

(1) Since the frame time of the signaling (Call Request) channel is chosen to be 400 ms, each of the 50 time slots has a duration of 8 ms. Each message channel (hopping pattern) contains 49 distinct frequencies. During a period of 400 ms, a user-pair hops on 49 distinct frequencies on the message channel and on the signaling channel once. This brings the total number of hopping frequencies to 50 which is the minimum requirement of the ISM band.

(2) The dwell time of each frequency of the message channel is 8 ms within a period of 400 ms. Therefore, within a 20-second period, a user-pair occupies each frequency for a total of 400 ms. This also meets the ISM band requirement.

Another important feature is the use of a dedicated link (hopping pattern) for the information exchange. As mentioned in section 3.6, this can easily accommodate the real time traffic such as voice. Sections 4.4, 4.5 and 4.6 will discuss the signaling channel, the MAC protocol, and the message channels respectively as part of the channel access scheme.

4.4 Signaling Channel

As mentioned in section 4.3, the signaling channel is divided into the Call Request and Call Acknowledge channels with each channel occupying a dedicated frequency. Here, we limit our discussion for a single-hop system only. The two-hop system requires additional packet types which will be discussed at the end of this chapter.

4.4.1 Call Request Channel

The Call Request channel uses time-division multiple access on a dedicated frequency. It is divided into 50 time slots with a period of 400 ms as shown in Fig. 4.5.

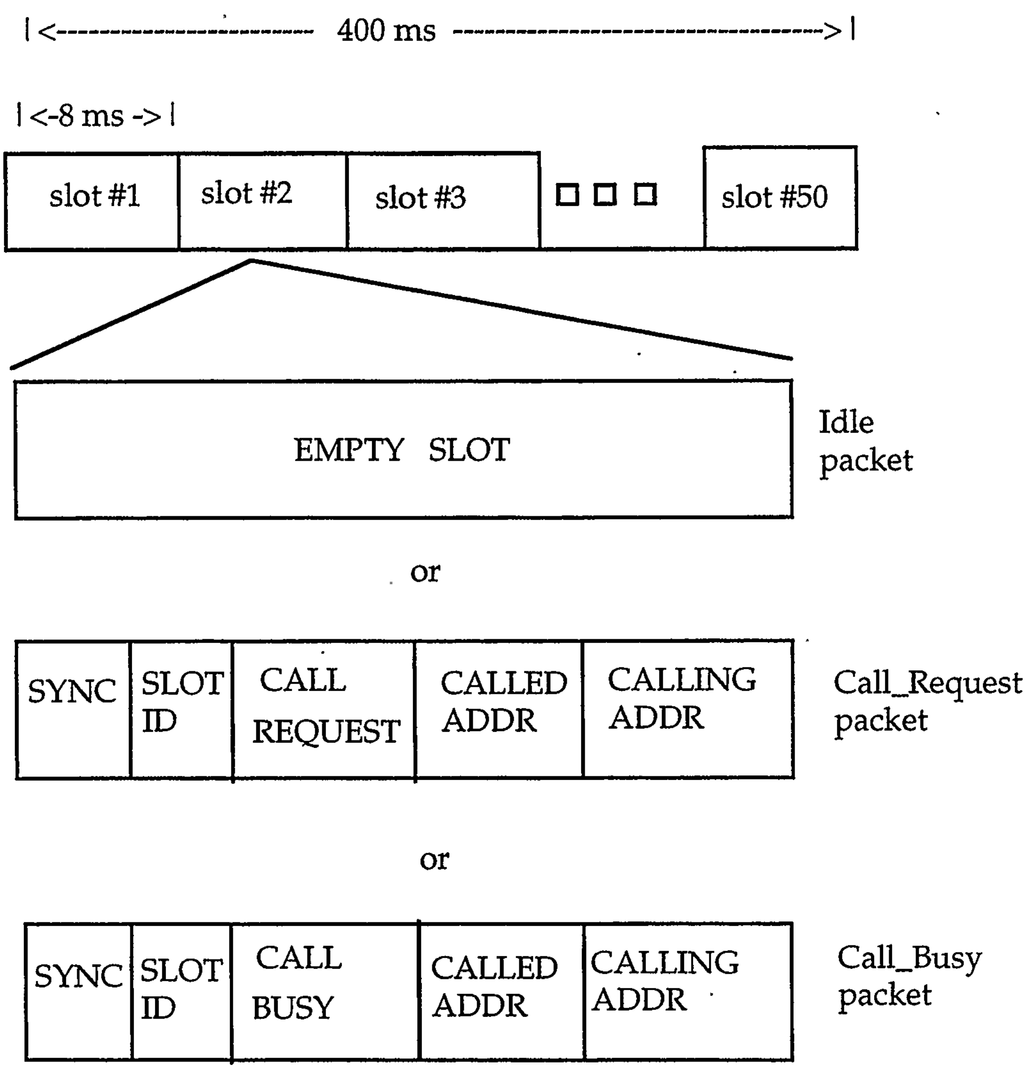

Figure 4.5 *Call Request Channel*

Each time slot has one of three packet types:

(1) idle packet (an empty slot),

(2) call_request packet, or

(3) call_busy packet.

An empty slot (idle packet) indicates that it is available for use. A slot with a call_request packet indicates a call being set up. A slot with a call_busy packet indicates a call in progress, and its corresponding hopping pattern is used. It is also used for synchronization of a user-pair. The slot ID of either the call_request or call_busy packet links to a frequency hopping pattern (message channel). Therefore, any user who seizes a slot will automatically acquire a message channel.

4.4.2 Call Acknowledge channel

The Call Acknowledge channel uses another dedicated frequency and contains 8ms bursts of call_ack packets (with a frame time of 400 ms) as shown in Fig. 4.6.

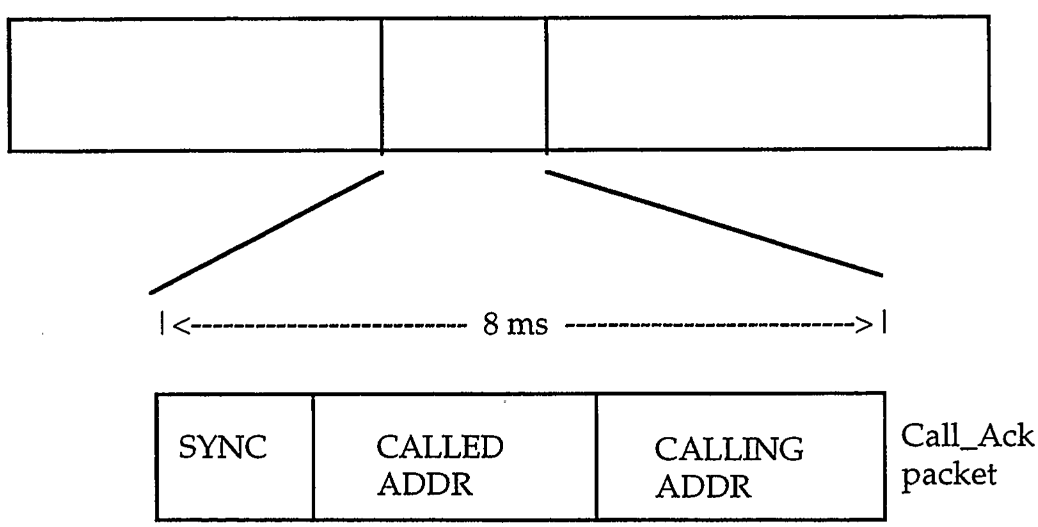

Figure 4.6 *Call Acknowledge channel*

4.5 Media Access Control Protocol

As mentioned in section 4.3, a media access control (MAC) protocol is required for a terminal to access an idle time slot on the Call Request channel. The MAC protocol is basically a set of rules applying to any user (terminal) who initiates a call. Two protocols are presented here. The second protocol is a slight variation of the first one.

4.5.1 MAC Protocol #1

After the user goes off-hook, the terminal must:

(1) tune to the Call Request channel and scan for 400 ms (1 frame), and

(2) determine which slots contain the call_request or call_busy packets by decoding all the used slots ID.

Two different situations occur on the Call Request channel.

4.5.1.1 Empty Call Request channel

If the entire Call Request channel is empty at the end of the scan (400 ms), the terminal will scan for an additional 8ms to ensure that no used slot occurs near the end of the scan. The terminal must transmit the call_request packet at 408 ms using slot ID #1 as shown in Fig. 4.7.

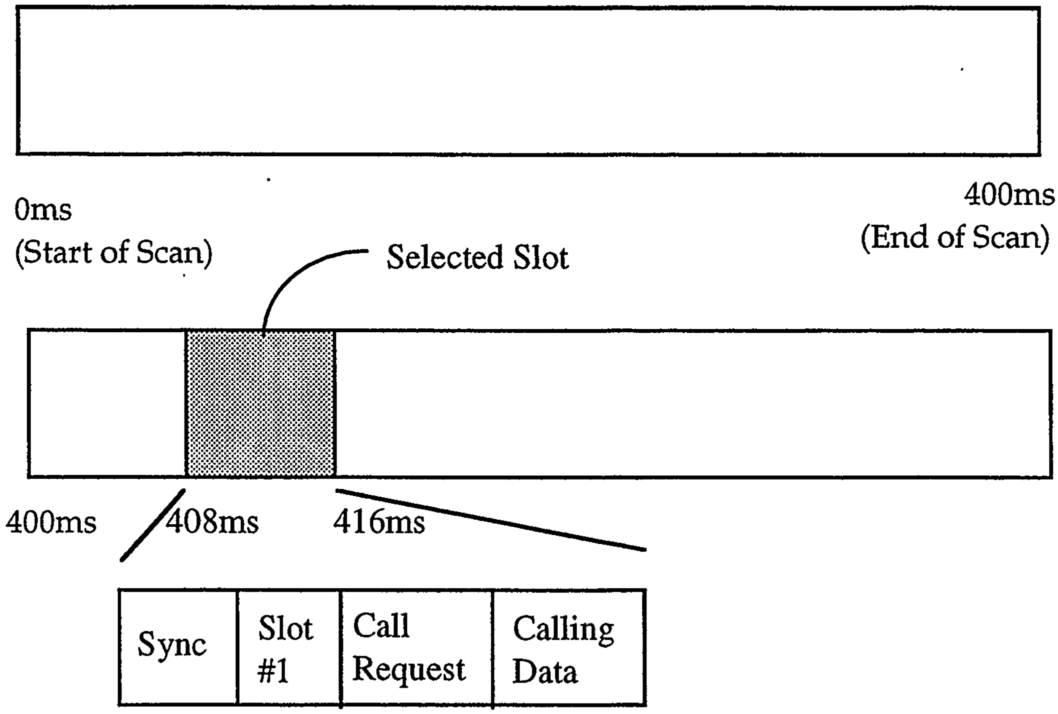

Figure 4.7 *Selected slot for empty Call Request channel*

4.5.1.2 Non-Empty Call Request channel

If the Call Request channel has one or more used slots, the terminal must find an empty slot (with 8ms idle time) right adjacent to the first busy slot. If no empty slot exists, the terminal must move to the next busy slot until an idle slot right adjacent to the busy slot is found. Two possible cases follow.

<u>Protocol #1 Case I -- More than 8ms idle time between the end of the busy slot and the end of the scan</u>

The terminal must transmit right adjacent to the busy slot as shown in Fig. 4.8.

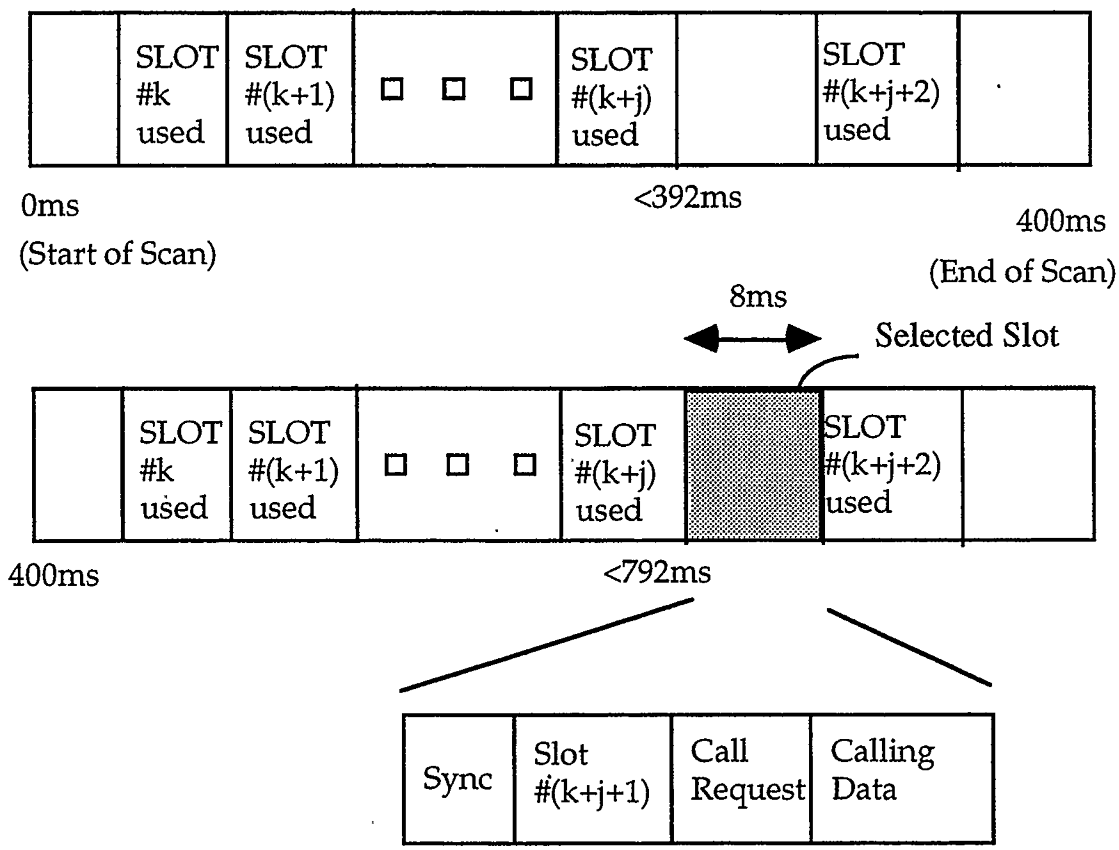

Figure 4.8 *Selected slot for non-empty Call Request channel (Protocol #1 Case I)*

Protocol #1 Case II -- Less than 8ms idle time between the end of the busy slot and the end of the scan

The terminal must transmit left adjacent to the busy slot as shown in Fig. 4.9. This assumes an idle slot exists between the start of the scan and the start of the first busy slot. Otherwise, no slot can be used in the Call Request channel.

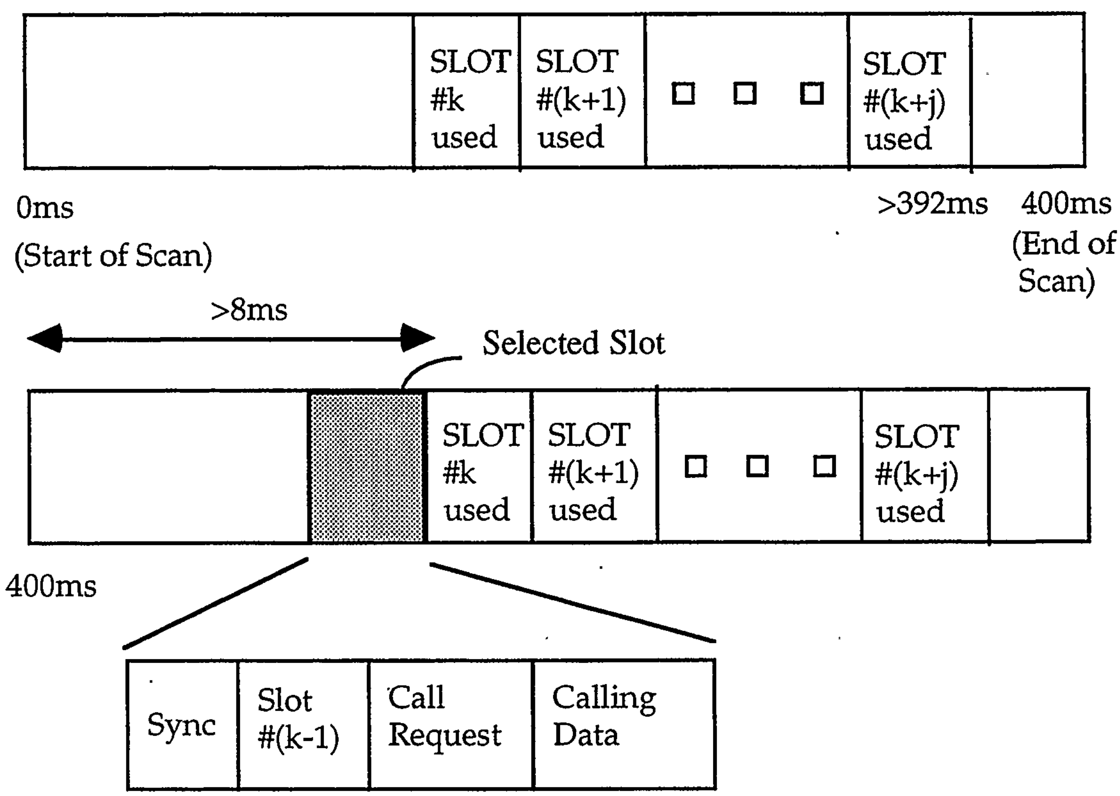

Figure 4.9 *Selected slot for non-empty Call Request channel (Protocol #1 Case II)*

4.5.2 MAC Protocol #2

This protocol is a slight variation of protocol #1. Again, after the user goes off-hook, the terminal must:

(1) tune to the Call Request channel and scan for 400 ms (1 period), and

(2) determine which slots contain the call_request or call_busy packets by decoding all the used slots ID.

Two different situations occur on the Call Request channel.

4.5.2.1 Empty Call Request channel

The same rule applies as in the protocol #1 (section 4.5.1.1). The selected slot starts at 408 ms.

4.5.2.2 Non-Empty Call Request channel

The terminal must determine the duration between the start of the scan and the start of the first busy slot. Again, two different cases occur for the non-empty Call Request channel.

Protocol #2 Case I -- Less than 8ms idle time between the start of the scan and the start of the first busy slot

The terminal must transmit at the right adjacent idle slot as shown in Fig. 4.10.

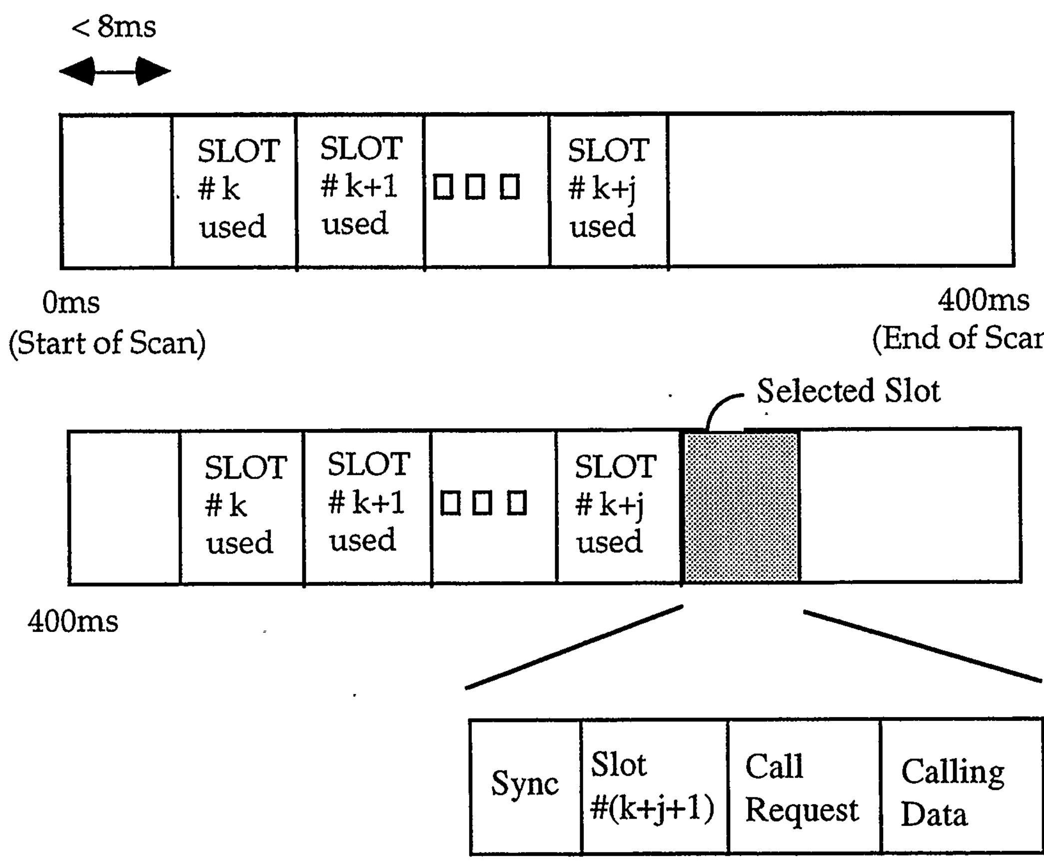

Figure 4.10 *Selected slot for non-empty Call Request channel (Protocol #2 Case I)*

<u>Protocol #2 Case II -- More than 8ms idle time between the start of the scan and the start of the first busy slot</u>

The terminal must compute the start of the transmission time (= $t - 8 * \left\lfloor \frac{t}{8} \right\rfloor$ +400 ms where $\lfloor x \rfloor$ = largest integer value smaller than or equal to x), and use slot id #j, where j = k - $\left\lfloor \frac{t}{8} \right\rfloor$, as shown in Fig. 4.11.

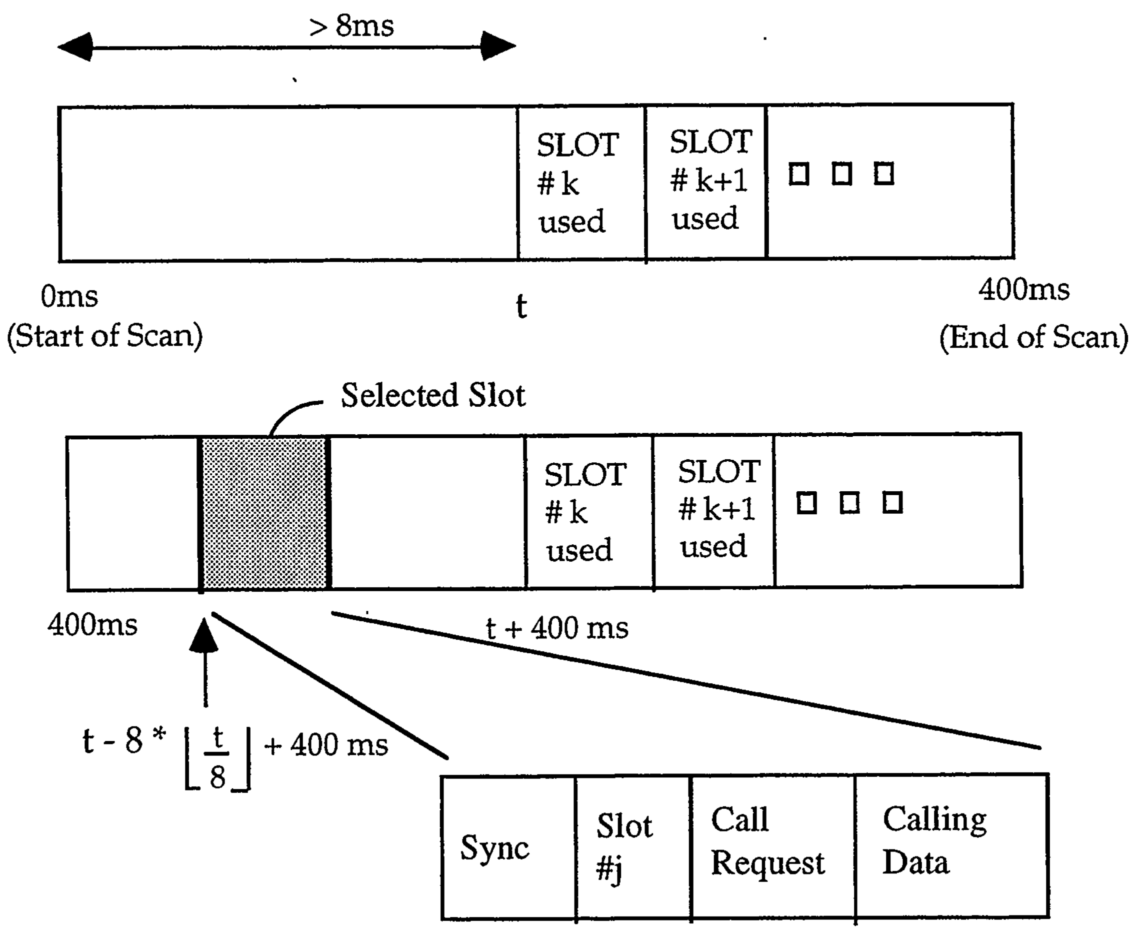

Figure 4.11 *Selected slot for non-empty Call Request channel (Protocol #2 Case II)*

Since the MAC protocols are used for the call set up, they can affect the system blocking probability during the busy hour period. High blocking probability decreases the system capacity. Therefore, the MAC protocol performance needs to be examined in the next chapter.

4.6 Message Channels

The message channels are a pool of hopping patterns allowing multiple user-pairs to exchange information. Once a user-pair accesses a time slot on the Call Request channel, they synchronize and exchange information on the assigned hopping pattern using the time-division duplex (TDD) scheme shown in Fig. 4.12. The calling party must transmit the synchronization information to the called party on the Call Request channel.

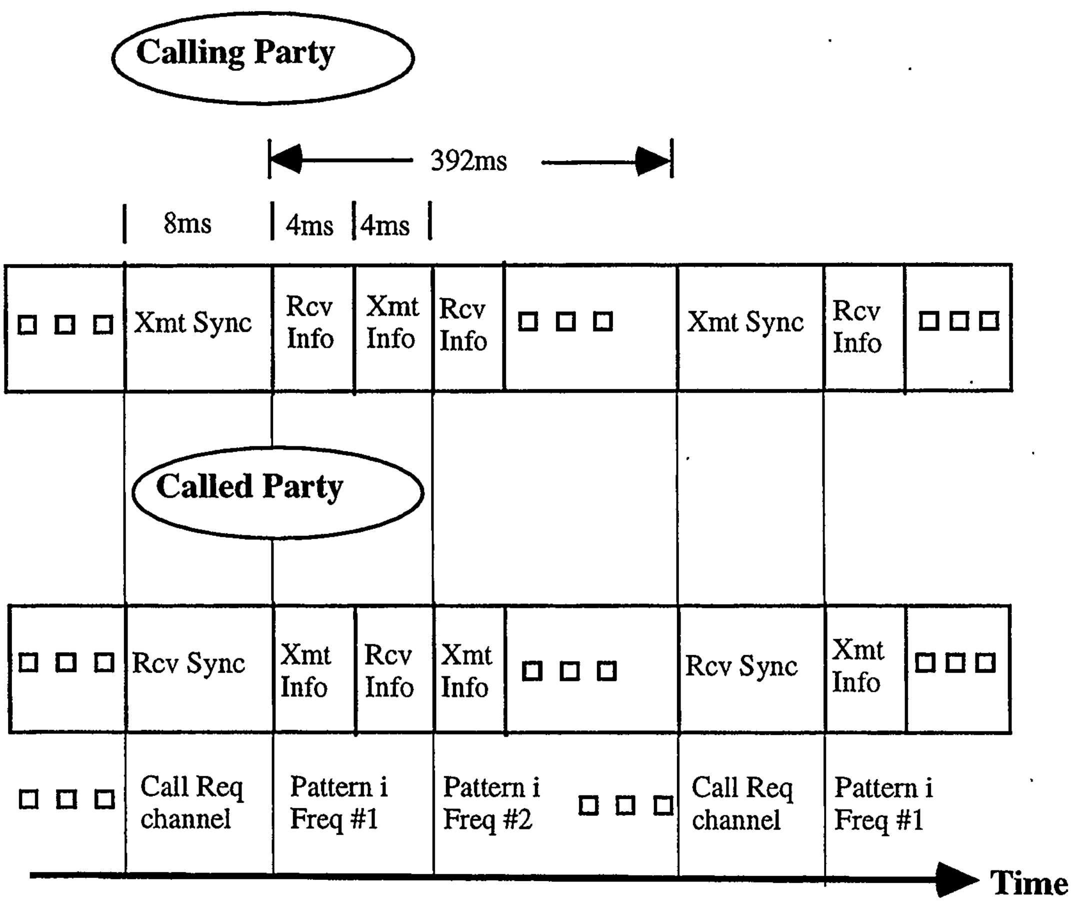

Figure 4.12 *Two terminals hop and synchronize using TDD*

This completes the discussion of the channel access scheme. The hopping patterns are examined as part of the physical layer communications in the next section.

4.7 Physical Layer Communications

The physical layer communications allows the user information to be encoded and transmitted over the wireless channel. Fig. 4.13 lists the components of the physical layer communications.

Physical Layer Communications
-- Voice coding & Transmission Rate -- Hopping Patterns -- Modulation, Channel Bandwidth, and Carrier Spacing -- Synchronization

Figure 4.13 *Physical Layer Communications components*

These components will be discussed in sections 4.8 to 4.11.

4.8 Voice Coding and Transmission Rate

Since toll-quality voice and group 3 fax transmissions are required, the chosen voice coding scheme is the 32 kbps Adaptive Differential Pulse Code

Modulation (ADPCM). ADPCM allows fax transmission at 9600 bps and the bit rate is half of the conventional Pulse Code Modulation (PCM). Therefore, the data transmission rate of each terminal is determined by assuming that:

-- the 32 kbps Adaptive Differential Pulse Code Modulation (ADPCM) is used to provide toll-quality voice coding without using any forward error correction or error detection scheme, and
-- the transmit and receive slots duration is 4 ms with a guard time of 0.25 ms allocated between the slots in the time-division duplex (TDD) scheme as shown in Fig. 4.14.

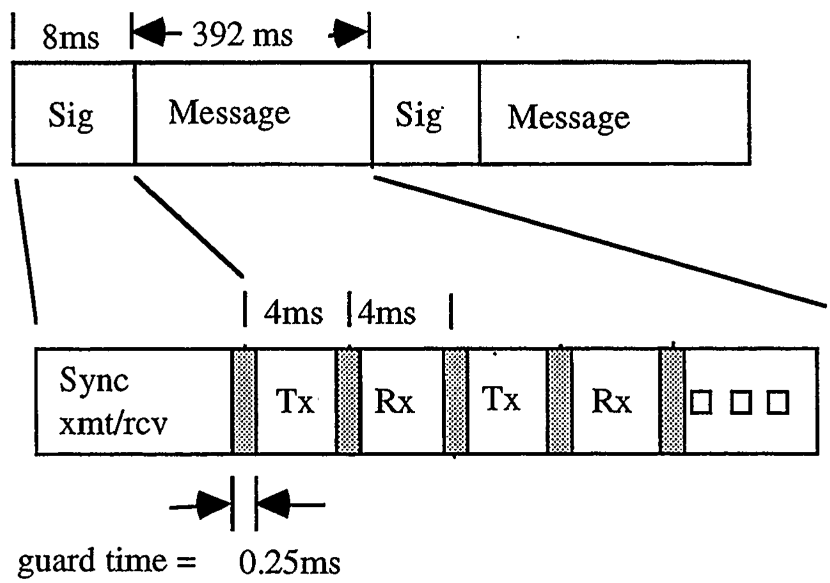

Figure 4.14 *Time Division Duplex with guard time of 0.25 ms*

Total guard time per frame (in 400 ms) = 392 / 4 * 0.25 = 24.5 ms.

The required transmission rate = 32 kbps * 400 * 2 / (392-24.5)

= 69.66 kbps.

The transmission rates for other guard times are listed in table 4.1.

Guard Time (ms)	Transmission Rate (kbps)
0.25	69.7
0.50	74.7
0.75	80.4
1.00	87.1
1.25	95.0

Table 4.1 *Transmission rates for different guard times*

In a TDD scheme, the information transmission is not continuous. The delay between successive packets must be small to enable voice transmission. In our system's TDD scheme, the duration between two consecutive transmit or receive slots is chosen to be 4 ms in the message channel as shown in Fig. 4.14. During transmitter-receiver synchronization, the duration between two consecutive transmit or receive slots is 12 ms in every 400ms. The duration is smaller than the Digital European Cordless Telecommunication (DECT) standard most of the time in which the duration is 9.583 ms [14] as shown in Fig. 4.15. Since the DECT standard also uses the same 32 kbps ADPCM voice coding, the TDD structure in the peer-to-peer wireless system can handle voice transmission.

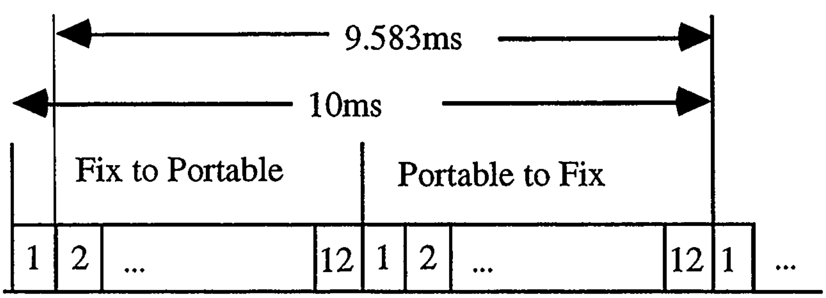

Figure 4.15 *DECT Time Division Duplex structure*

4.9 Hopping Patterns

The system uses 50 hopping patterns each with 50 different hopping frequencies. To minimize the performance degradation when all the message channels are in use, these hopping patterns are chosen with no co-channel interference (frequency hits). One solution is to assign the hopping patterns as shown in Fig. 4.16 where each hopping pattern is simply a right one-step cyclic shift of the previous one. We then replace the frequencies with the signaling channel diagonally as denoted by {S} in Fig. 4.16.

Sequence #1:	[1 {S}	2	3	4...	48	49	50]
Sequence #2:	[2	3 {S}	4	5...	49	50	1]
Sequence #3:	[3	4	5 {S}	6...	50	1	2]
.							
.							
.							
Sequence #50:	[50	1	2	3...	47	48	49 {S}]

Figure 4.16 *A possible set of hopping patterns*

Although co-channel interference does not exist, two adjacent sequences have adjacent channel interference all the time. Also, in the peer-to-peer wireless system environment, the adjacent channel interference can be further increased due to the possible "near-far problem".

Fig. 4.17 illustrates this near-far problem. When user A communicates to user B on a particular hopping pattern, if A's neighbours C and D are also communicating on the adjacent hopping pattern, the amount of adjacent channel interference will be increased by the

$$\text{Near-Far end ratio} = 10\log\left(\frac{d_1}{d_2}\right)^2 \text{ dB}$$

where $d_1 > d_2$

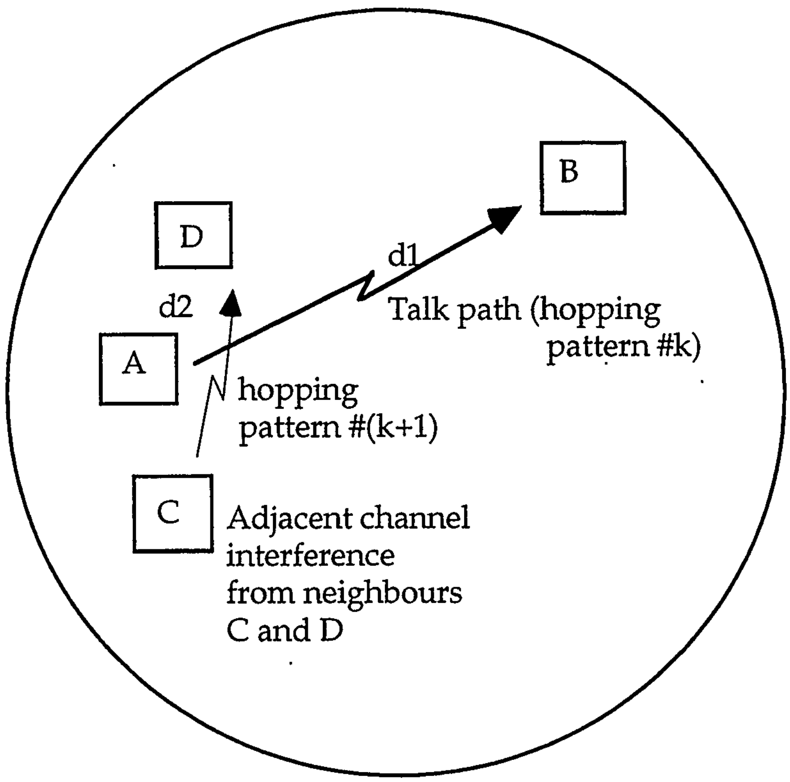

Figure 4.17 *Near-Far problem in the Peer-to-Peer Wireless System*

If d1=10 km, and d2 = 100m (worst case scenario), then the adjacent channel interference is increased by 40 dB. Therefore, an additional requirement of the set of 50 hopping patterns is to minimize the adjacent channel interference. This will be investigated in the next chapter.

4.10 Modulation, Channel Bandwidth, and Carrier Spacing

Since the channel bandwidth can be as wide as 500 kHz in the 902-928 MHz band, binary frequency shift keying (BFSK) is chosen. It is the simplest but least bandwidth efficient modulation scheme. Using a transmission rate of 70 kbps (symbol period T = 0.01429 ms), the power spectral density (one-sided) of continuous phase BFSK with modulation index h of about 1 is shown in Fig. 4.18 [10].

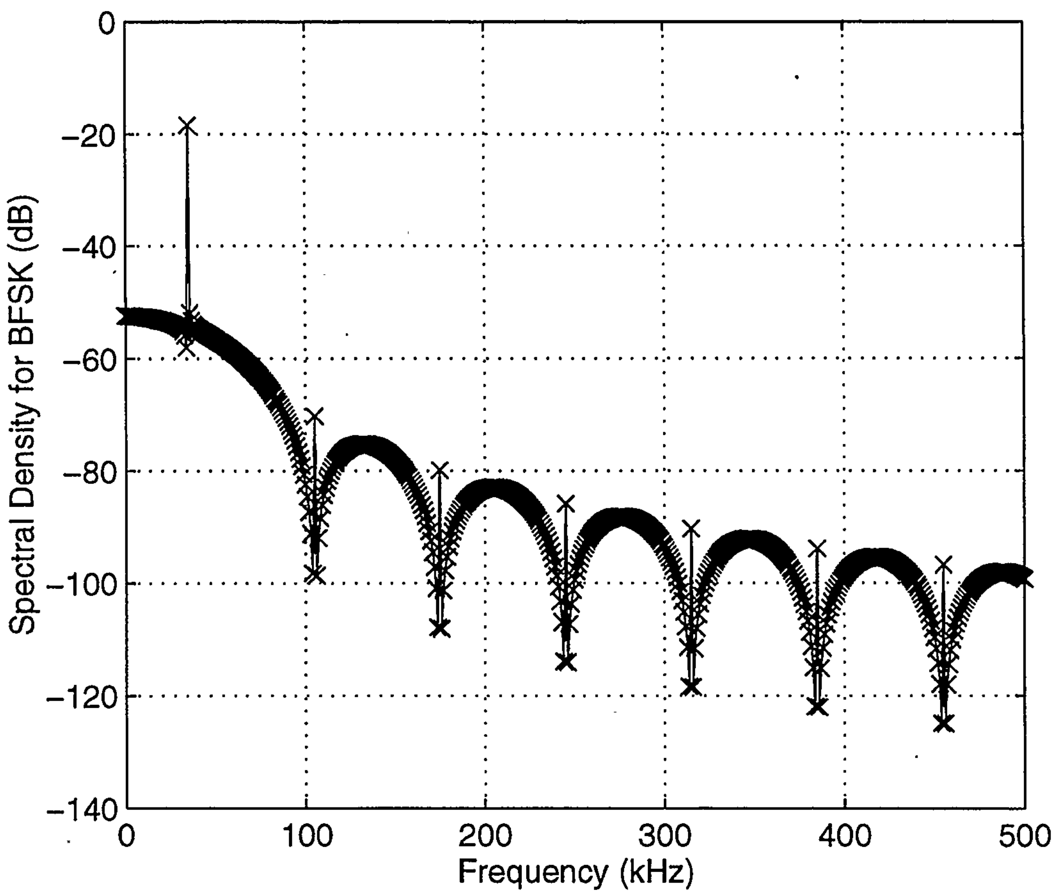

Figure 4.18 *Power Spectral Density of Binary Frequency Shift Keying with h=1.01 and T=0.01429 ms (The space/mark tone occurs at 35kHz)*

By integrating the power spectral density curve, the percentages of power bandwidth are determined and listed in table 4.2.

Percentage of Total Power (%)	Bandwidth (kHz)
85	74
90	88
93	100
95	110
97	124
98	137
99	150

Table 4.2 *Percentage of Power Bandwidths of BFSK modulated signal*

From table 4.2, the required channel bandwidth is less than 150 kHz. However, we also want to choose the channel bandwidth to ensure a flat fading channel. Otherwise, the channel suffers frequency selective fading which causes intersymbol interference (ISI). The use of equalizer becomes necessary to reduce the ISI but this increases the terminal complexity. Since the delay spread for the outdoor residential areas is about 2.5μs [11], the coherence bandwidth is about 400 kHz. The channel bandwidth is therefore chosen to be 100 kHz to ensure a flat fading channel. This channel bandwidth is also used in the CT2+ public cordless phone standard in Canada [12].

Since the system requires only 50 channels plus the signaling channel in the 902-928 MHz band, we want to increase the carrier spacing to reduce the adjacent channel interference. Assuming a 2.5 MHz guard band is allocated at each end of the ISM band, the carrier spacing between the adjacent channels is chosen to be 400 kHz. The total bandwidth used is less than 21 MHz.

4.11 Synchronization

Two areas of synchronization are examined including the synchronization of a user-pair (transmitter-receiver pair) and the synchronization among the user-pairs.

4.11.1 Synchronization of a user-pair

The calling party must provide the master clock for the called party to ensure that they both hop synchronously. The calling party transmits the call_busy packet containing the synchronization information on the Call Request channel every 400 ms as discussed in section 4.6.

4.11.2 Synchronization among the user-pairs

The Call Request channel consists of used time slots with either the call_request or call_busy packets transmitted by all the calling parties. Since each calling party (terminal) uses its own internal clock, the transmitted bursts (packets) will drift over time. If the drift is serious, interference of the time slots on the Call Request channel results. Therefore, synchronization among the user-pairs (i.e. the transmitted time slots on the Call Request channel) is required. Two methods are proposed.

4.11.2.1 Method 1 -- Use a Stable Internal Clock

Since a transmitted packet (call_busy) only lasts for as long as the call duration, each terminal needs a stable internal clock that will not drift too much over the maximum call duration. Assume the guard time between adjacent time slots on the Call Request channel is 2 ms as shown in Fig. 4.19, and the maximum call duration is 5 hours.

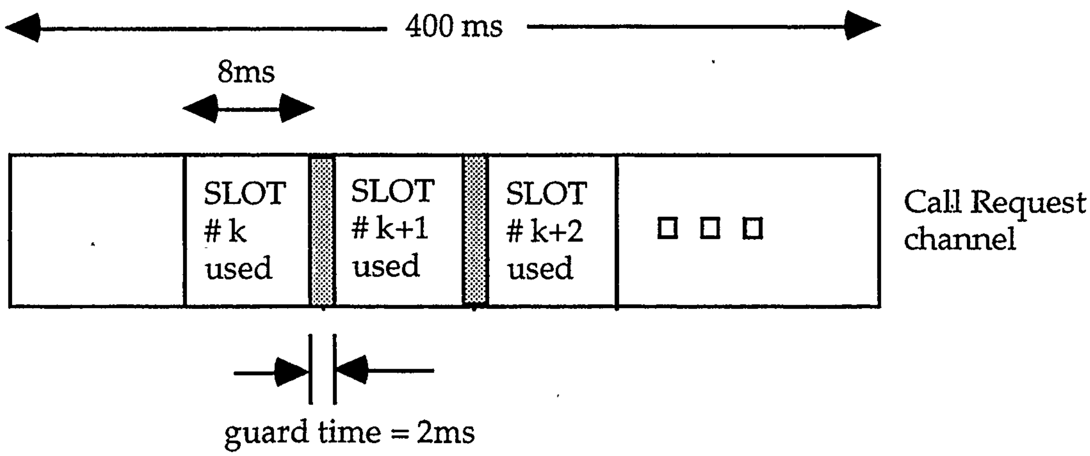

Figure 4.19 *Guard time between adjacent used slots on the Call Request channel*

The required frequency offset of the clock $= \frac{2x10^{-3}}{5x60x60} = 1.11 \times 10^{-7}$. The current crystal clock in the cellular handset can only achieve a frequency offset of 10^{-6}. A more expensive clock is required to achieve such a stability.

4.11.2.2 Method 2 -- Synchronize with the Adjacent Slots

Another proposed method is to have each used slot synchronized with the adjacent used slot. For example, in Fig. 4.19, the wireless terminal which transmits in slot #(k+1) must first listen for 8ms (i.e. "robbing" a TDD slot on the message channel) to obtain the synchronization information in slot #k. The wireless terminal then adjusts its own clock for transmitting in slot #(k+1) to ensure sufficient guard time with slot #k. If slot #k is empty, the wireless terminal uses its own internal clock. In this way, every transmitted slot tracks and synchronizes with the adjacent used slot.

This completes the discussion of the physical layer communications. Before investigating the two-hop system, we examine the radio terminal functions to implement the single-hop system.

4.12 Radio Terminal Functions

The interactions among the user states, the wireless terminal functions, and the radio channels are shown in Fig. 4.20. The wireless terminal has three modes: (1) scan, (2) search, and (3) hop & synchronize modes.

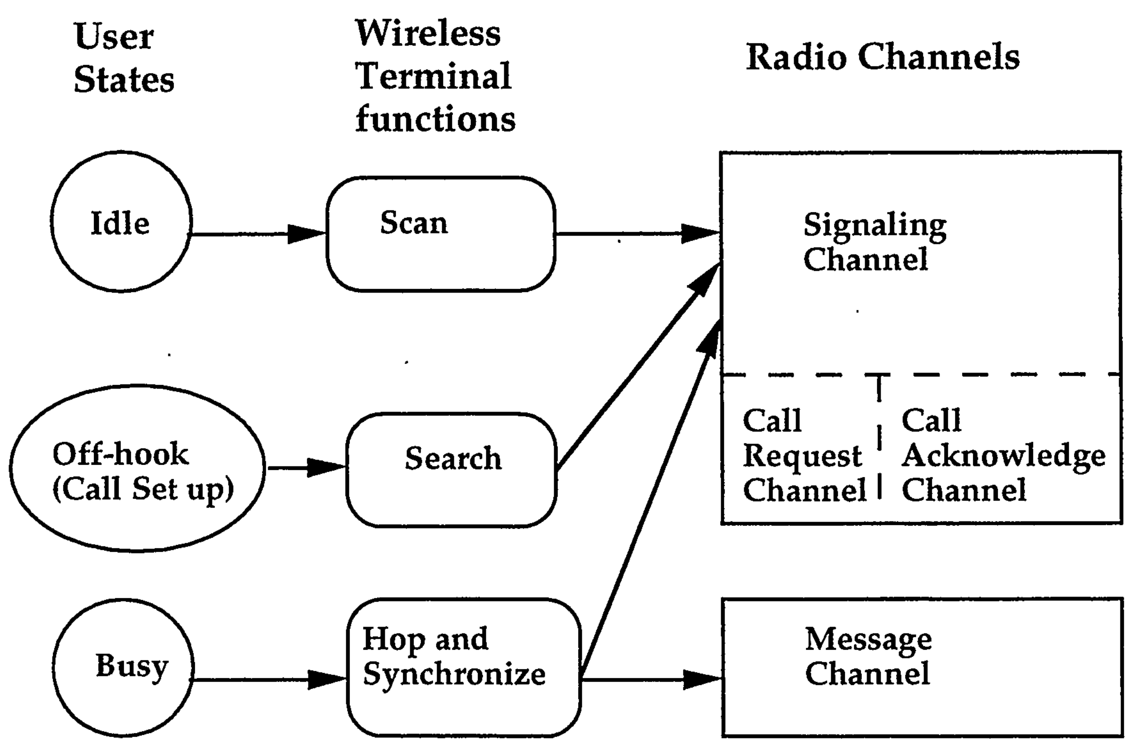

Figure 4.20 *Interactions among the User, the Wireless terminal, and the Radio channels*

4.12.1 Scan mode

When the user is in the idle state, the terminal continuously scans the Call Request channel and decodes every call_request packet to detect incoming calls. If "sleep" mode is implemented, the scanning only occurs periodically (every few seconds) but this increases the call set up delay.

4.12.2. Search Mode

When the user goes off-hook, the wireless terminal enters the search mode for the call set up. The terminal searches for an idle time slot on the Call Request channel using a media access control (MAC) protocol described in section 4.5. Once a time slot is found, the terminal transmits the call_request packet for 8ms every 400ms and wait for the call_ack packet from the call acknowledge channel.

4.12.3. Hop and Synchronize Mode

When the call set up procedure is completed, two terminals (a user-pair) must synchronize using the time slot on the Call Request channel. The calling party must transmit the call_busy packet every 400 ms for synchronizing with the called party. Information exchange between the two terminals on the assigned hopping pattern (message channel) uses the time-division duplex (TDD) scheme discussed in section 4.6. A typical call procedure is shown in Fig. 4.21 when user A initiates a call to user B. The assigned time slot on the Call Request channel is used for the entire call duration while the Call Acknowledge channel is only used for acknowledgment during the call set up.

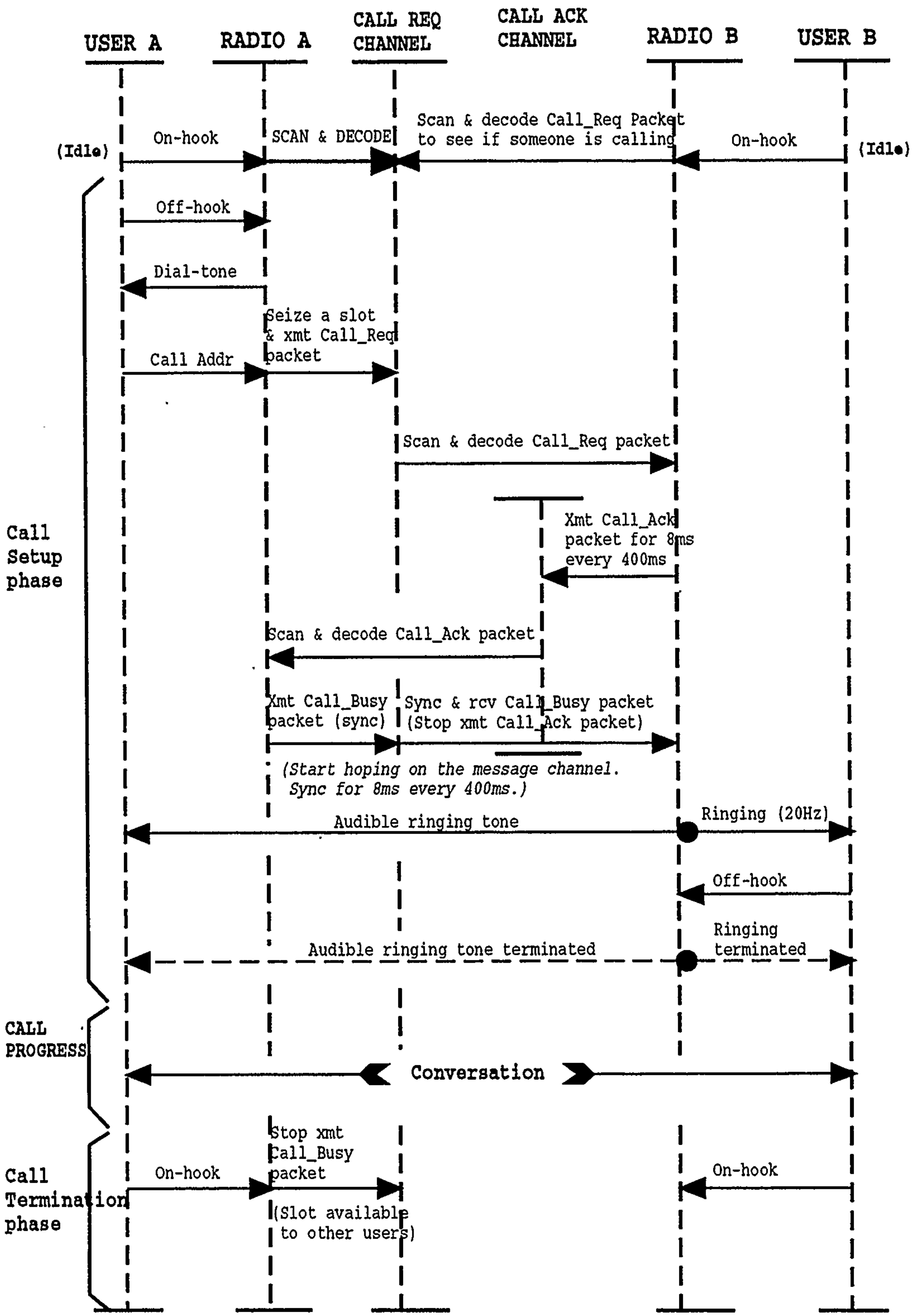

Figure 4.21 *A Typical Call Procedure*

4.13 Two-hop Connection using Repeaters

The previous sections on the network organization and channel access scheme provide the background information for the single-hop system. If two-hop or multi-hop connection is desired, the use of one or more intermediate nodes as repeaters is required. This section will discuss the use of a single repeater for the two-hop connection.

Since each terminal (node) is identical in the peer-to-peer wireless system, it is "unfair" to assign only certain terminals as repeaters. We propose to use idle terminals in the system as possible repeaters for the two-hop links. The advantage of this approach is to utilize all the possible resources (terminals) in the system for the transmission of information. However, the problem occurs when the repeater is in use, and the user wants to access that terminal. To avoid this problem, there are three possible solutions:

(1) the user is denied access to the terminal until it is idle again.

(2) a new connection using another repeater must be established, or

(3) each terminal can be both a terminal and a repeater at the same time.

The first solution may annoy the terminal user (owner). The second solution is similar to a "handoff" procedure and increases the system complexity. Also, it can possibly create drop calls. The third solution increases the cost of the terminal because of the extra transceiver required. However, the service quality and the system simplicity are maintained. Hence, it is considered the best solution.

4.13.1 Use of Repeaters

One advantage of using repeaters in the system is to increase the radio transmission range between the originating and destination terminals. This translates to increase in the radio coverage area. The other advantage is to resolve the problem of hidden terminals in the system. Two possible schemes are examined: the polling and the paging schemes.

4.13.2 Polling Scheme

This scheme assumes that each terminal knows its 1-hop neighbours. When a terminal initiates a call, it first checks its list of 1-hop neighbours. If the destination terminal is not on the list, then it first finds an idle slot on the Call Request channel, and starts polling one of its neighbours to ask for a connection to the destination terminal. If no acknowledgment is received from a neighbour, it will poll the next neighbour and repeat the process until all neighbours are polled or the user delay limit expires. This is illustrated in Fig 4.22 when user B wants to reach user C by polling users R1 to R5. Although this scheme is simple, each terminal must maintain a list of its neighbours.

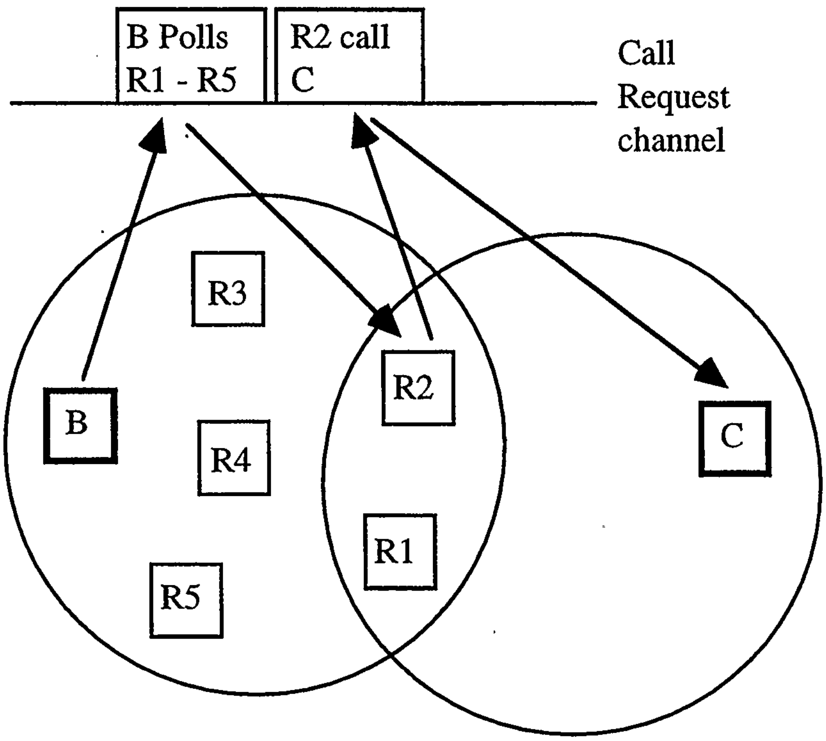

Figure 4.22 *Polling scheme example -- B calls C by polling R1 to R5*

4.13.3 Paging Scheme

A simple paging scheme is proposed here and is described in both the media access control (MAC) and physical layers. The performance results are described in the next chapter.

4.13.3.1 Media Access Control Layer

This paging scheme allows a terminal randomly activating some idle neighbours as repeaters to connect to the destination terminal when a direct link cannot be established. In this scheme, each terminal does not need to know its neighbours. This is illustrated in Fig. 4.23 when user B wants to reach user C by randomly activating several neighbours including R1, R2, and R4. User B is not concerned about which neighbours are activated. It simply sends out a repeater_request packet to activate several of its 1-hop neighbours as repeaters to page user C, and hopefully user C can 'hear' from one of the repeaters and responds accordingly. In this case, R2 and R4's packets collide and the connection is established through R1.

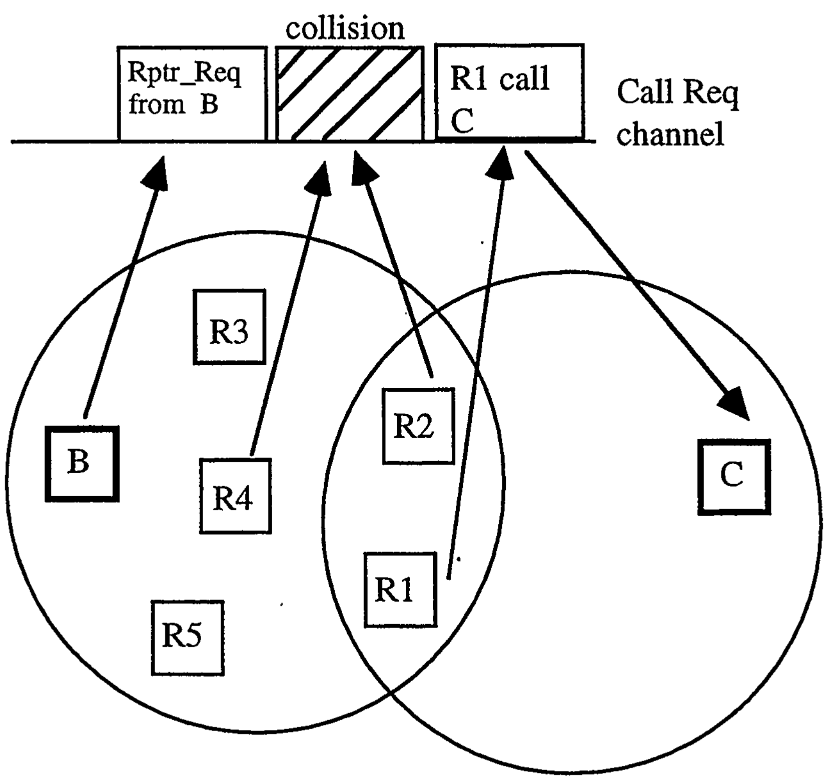

Figure 4.23 *Paging scheme example -- B calls C by activating idle neighbours*

Using the example of user B trying to establish a link to user C. The following protocol applies:

(1) 'B' sends a call_request packet on the Call Request channel and wait for the acknowledgment from 'C'.

(2) If no acknowledgment is received, 'B' will send a repeater_request packet on the Call Request channel. The format of the repeater_request packet is shown in Fig. 4.24. The user delay limit indicates the maximum duration in which 'B' waits for acknowledgment from the repeaters.

SYNC	SLOT ID	RPTR REQUEST	USER DELAY LIMIT	CALLED ADDR	CALLING ADDR

Figure 4.24 *Repeater_Request Packet*

Any idle terminals which can decode this message will do the following:

(2.1) The terminal randomly selects a discrete backoff time (b x 800 ms where b = integer). If the selected backoff time is greater than the user delay limit d (a user-specified or system default value), then it must go back to the idle state. If the selected backoff time is less than the user delay limit, then after the backoff time expires, the terminal starts searching for an idle slot on the Call Request channel. Once the idle slot is seized, the terminal transmits the repeater_call_request packet and waits for the call_ack packet from 'C'. The format of the repeater_call_request is shown in Fig. 4.25.

SYNC	SLOT ID	RPTR CALL REQUEST	CALLED ADDR	CALLING ADDR	RPTR ADDR

Figure 4.25 *Repeater_Call_Request Packet*

In the example, R1, R2, and R4 transmit the packets. R2 and R4's packets collide. R1's packet is successfully transmitted.

(2.2) When 'C' sends a call_ack packet to repeater 'R1', 'R1' will send a repeater_call_ack packet to 'B'. The format of the repeater_call_ack packet is shown in Fig. 4.26.

SYNC	CALLED ADDR	CALLING ADDR	RPTR ADDR

Figure 4.26 *Repeater_Call_Ack Packet*

(2.3) When 'B' receives a repeater_call_ack packet, it must stop transmitting the repeater_request packet and start transmitting the call_busy packet. Both 'B' and 'R1' then start hopping synchronously.

(2.4) 'R1' then stops transmitting the repeater_call_request and starts transmitting the repeater_call_busy packet. 'C' will stop transmitting the call_ack packet. Both 'R1' and 'C' then start hopping synchronously. The format of the repeater_call_busy packet is shown in Fig. 4.27.

SYNC	SLOT ID	RPTR CALL BUSY	CALLED ADDR	CALLING ADDR	RPTR ADDR

Figure 4.27 *Repeater_Call_Busy Packet*

Procedure (1) follows the MAC protocol developed for the single-hop system. Procedure (2) is added to the existing protocol to accommodate the use of a single repeater. Fig. 4.28 displays the event diagram of procedure (2).

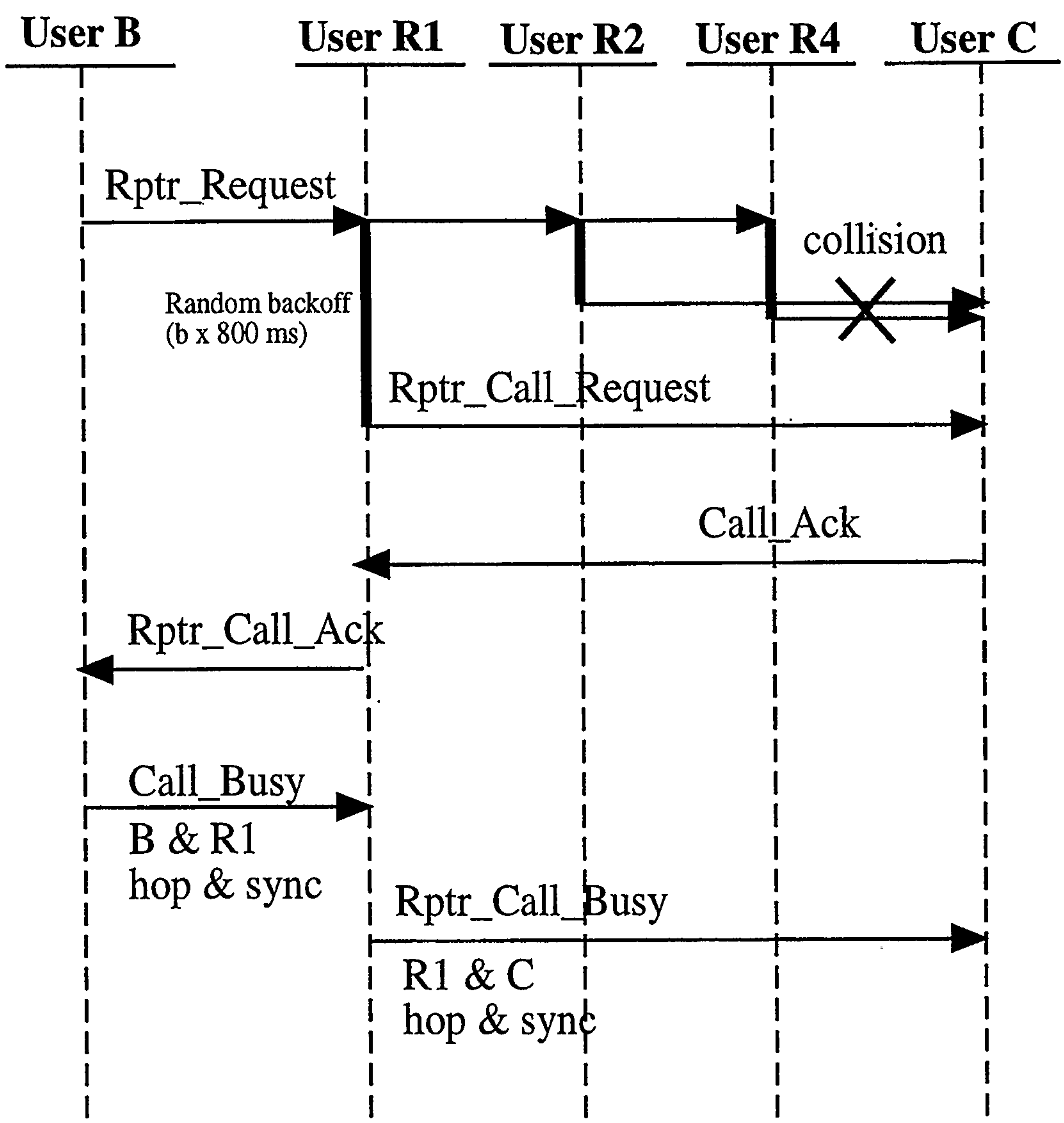

Figure 4.28 *Event diagram -- User B connecting to C through Repeater R1*

4.13.3.2 Physical Layer

For full duplex operation, using a repeater with two different hopping patterns is sufficient, as shown in Fig. 4.29.

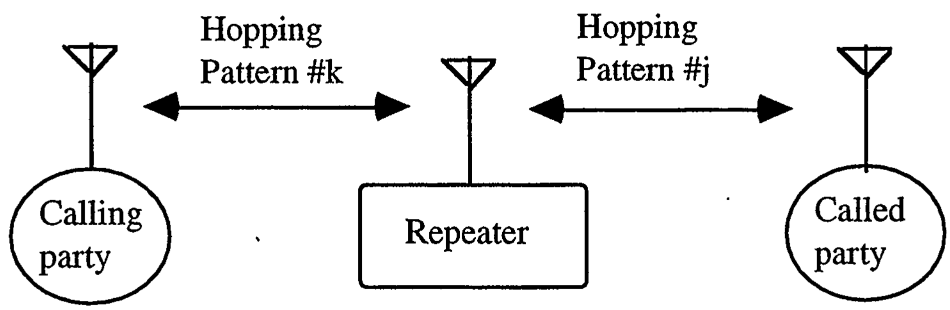

Figure 4.29 *Use of Repeater for full duplex operation*

Each repeater transmits at half rate in TDD mode as shown in Fig. 4.30.

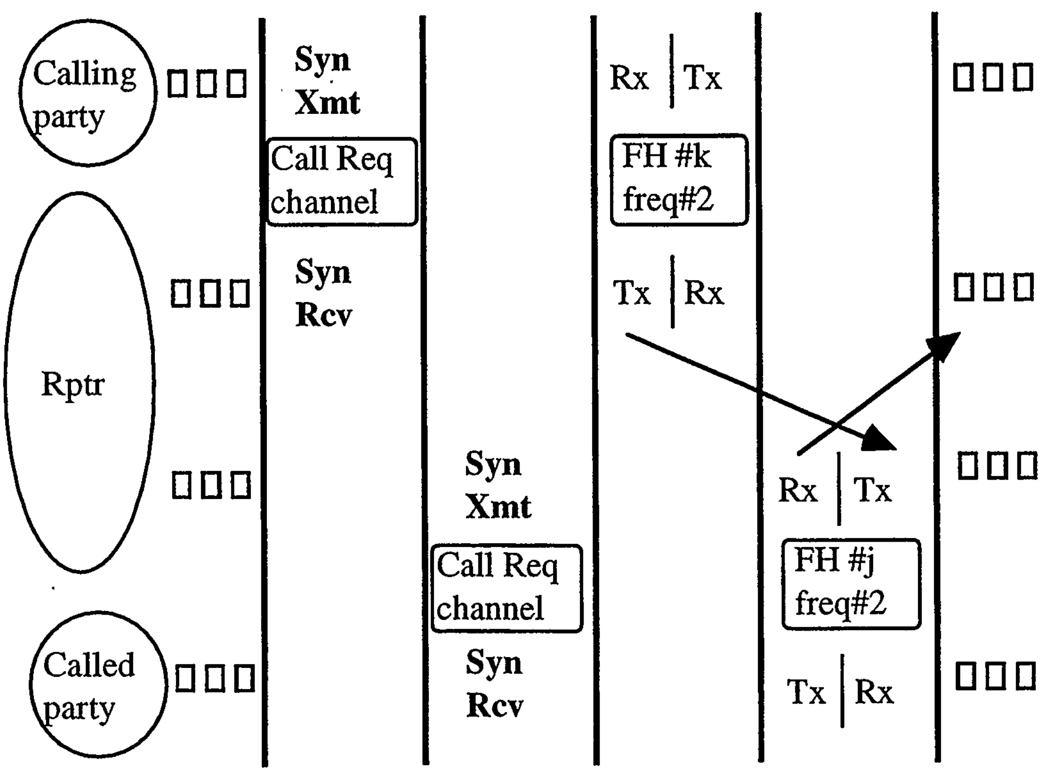

Figure 4.30 *Use of Repeater in full duplex operation with TDD*

4.13.4 Comparison between the Polling and Paging Schemes

If each terminal knows its neighbours, then a polling scheme can be implemented. The polling scheme can also be considered as a contentionless scheme. However, the polling scheme requires periodic network initialization to enable each terminal updating its neighbours. This increases the system and terminal complexity. To avoid each terminal keeping record of its neighbours, the paging scheme can be used. The paging scheme is considered as a contention scheme because more than one neighbour can be activated at the same time to page the destination terminal. Some neighbours' transmitted packets may collide. The paging scheme needs to be designed carefully to minimize the collisions among the neighbours' transmitted packets and the delay experienced by the terminal to connect to the destination terminal. The analysis of the paging scheme is discussed in the next chapter. Table 4.3 compares the requirements and limitations of the polling and paging schemes.

Requirements / Limitations	Polling (contentionless scheme)	Paging (contention scheme)
Initialize network periodically with each user predetermines its 1-hop neighbours	Yes	No
Chance of finding a repeater to connect to the destination terminal	High	Depending on the number of repeaters activated to page the destination terminal
Chance of Collisions on the Signaling Channel	Nil	Exist but depending on the number of repeaters activated and the length of backoff time

Table 4.3 *Comparison between the Polling and Paging schemes*

4.14 Summary

In this chapter, we have described the three components of the peer-to-peer wireless system including the network organization, channel access scheme, and physical layer communications. In the network organization, a single-hop system is the simplest and is desired for the rural area application. In the channel access scheme, two media access control protocols have been proposed. In the physical layer communications, the voice coding, transmission rate, modulation, channel bandwidth, carrier spacing, and synchronization scheme have been specified. The desired hopping patterns remain to be determined. We have also described the radio terminal functions for the single-hop system. The two-hop system using a repeater paging scheme is proposed. We summarize the specifications for the single-hop system in table 4.4.

Network Organization	No system initialization
Channel Access Scheme	Access a time slot on the signaling channel and obtain a corresponding message channel (hopping pattern)
Operating Frequency Band	902-928 MHz
Number of message channels	50
Number of signaling channel	At least 1
Spread Spectrum Technique	Frequency Hopping with 125 hops/second hopping rate and 50 different channels per hopping pattern
Transmission Scheme	Time-division duplex with 4ms transmit/receive duration
Voice Coding	32 kbps ADPCM
Transmission Rate	70 kbps
Maximum Transmit Power	1 W
Modulation	BFSK (continuous phase with modulation index: h =1)
Channel Bandwidth	100 kHz
Carrier Spacing	400 kHz

Table 4.4 *System Specifications*

After specifying the system, we can proceed to the next chapter to examine the system performance.

CHAPTER 5

SYSTEM PERFORMANCE

5.1 Overview

Chapter 4 has provided detailed descriptions of the peer-to-peer wireless system. This chapter examines the performance of various areas of the system and determines if the specified parameters meet the service requirements. In particular, we examine the areas of each wireless system component in the order as shown in Fig. 5.1.

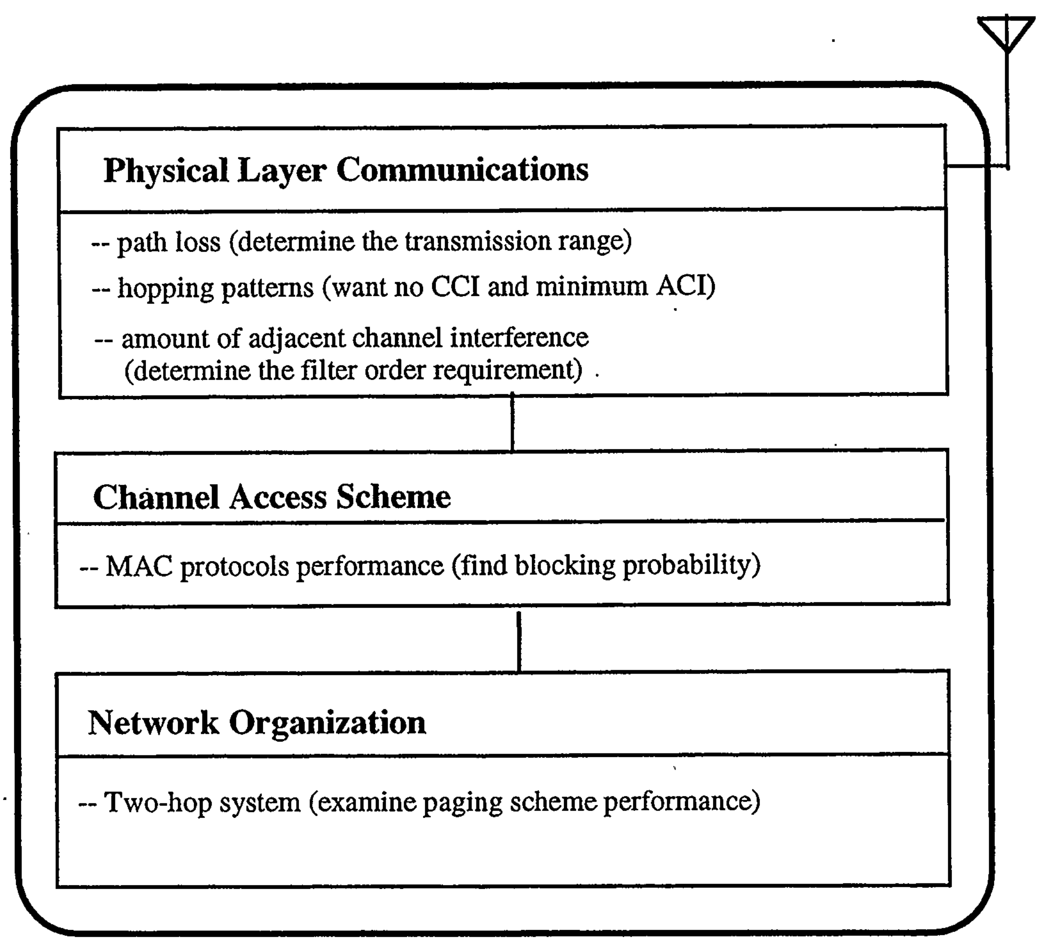

Figure 5.1 *Performance of the areas of the System to be examined*

5.2 Path Loss

To calculate the path loss between two terminals, we assume the terminals are used in the rural area local communications, and are therefore fixed. We further assume that the terminals have line-of-sight with each other. Hence, we will employ the point-to-point microwave radio path loss calculation to determine the fade margin [13]. We use the following data:

Operating Frequency:	915	MHz (ISM band)
Bit Rate:	70	kbps
Gaseous absorption:	0.2	dB
Receive Antenna gain:	0	dB
Receive Waveguide loss:	0.5	dB
Transmit EIRP:	0	dBW (Maximum power)
Noise Figure:	10	dB
Distance:	10	km (Desired range)

The free space loss (FSL) is determined as follow:

$$FSL_{dB} = 32.45 + 20\log D_{km} + 20\log F_{MHz} \tag{5.1}$$

$$= 32.45 + 20\log(10) + 20\log(915)$$

$$= 111.68 \text{ dB}$$

where

Dkm = Distance from transmitter to receiver (km)

$FMHz$ = Operating frequency (MHz)

The unfaded receive signal level (RSL) is determined by:

$$RSL_{dBW} = EIRP_{xmt} + FSL + L_g + G_2 + L_r \tag{5.2}$$

$$= 0 - 111.68 - 0.2 - 0 - 0.5$$

= -112.38 dBW

where

$EIRP_{xmt}$ = Transmit output power x Antenna Gain

FSL = Free Space Loss

L_g = Gaseous absorption

G_2 = Receive antenna gain

L_r = Receive waveguide loss

The received bit energy (E_b) to noise density (N_o) ratio is expressed in terms of received signal level power RSL by:

$$\frac{E_b}{N_o} = \frac{RSL}{N_o(BR)} \tag{5.3}$$

or in dB

$$\frac{E_b}{N_o} = RSL_{dBW} - 10\log(BR) - N_o \tag{5.4}$$

where BR = System bit rate (bps)

The noise density for the receiver operating at room temperature (20 °C) can be expressed by:

$$N_o = -204dBW + NF_{dB} \tag{5.5}$$

where NF_{dB} = Receiver noise figure

204 dBW = Receiver thermal noise power at 20 °C

By combining (5.4) and (5.5), we obtain:

$$\frac{E_b}{N_o} = RSL_{dBW} + 204dBW - 10\log(BR) - NF_{dB} \tag{5.6}$$

Substituting the parameters, we get:

$$\frac{E_b}{N_o} = -112.38 + 204 - 10\log(70000) - 10$$

= 33.17 dB

Assuming the non-coherent binary frequency shift keying (BFSK) is used at the receiver, the required ideal bit energy to achieve a bit error rate (BER) of 10^{-5} is 12.6 dB. With an implementation loss of 2 dB, the fade margin = 33.17 - 12.6 - 2 = 18.57dB. For paths over land with unobstructed line-of-sight, the link availability and the required fade margins are listed in table 5.1 [13]:

Link Availability (%)	Fade Margin (dB)
90	8
99	18
99.9	28
99.99	38
99.999	48

Table 5.1 *Link Availability for various Fade Margins*

With a fade margin above 18 dB, the link availability between any two wireless terminals is better than 99%.

The path loss calculation shows that a 10 km transmission range between two fixed wireless terminals can be achieved with a bit-error rate of 10^{-5} and a link availability of 99% using non-coherent BFSK. Hence, the single-hop system is capable of covering the entire rural community.

5.3 Optimum Set of Hopping Patterns

Section 4.9 identifies the problem of constant adjacent channel interference between two adjacent sequences. Therefore, we attempt to find a set of frequency hopping sequences that has minimum adjacent channel interference as well as no co-channel interference.

5.3.1 Hopping Patterns Search Procedures

The procedure to search for a set of frequency hopping sequences with no co-channel and minimum adjacent channel interference is listed below.

(1) Create a sequence file with an arbitrary sequence
For example, use the sequence {1 2 3 4 .... n-1 n}.

(2) Search for the next sequence such that:

(2.1) it is not the same as any sequence in the sequence file,

(2.2) it does not have the same channel number at the same time with any sequence in the sequence file,

(2.3) the 'true" adjacent channel occurrences at the same time with any sequence in the sequence file is minimum, and

(2.4) the 'true' adjacent channel occurrences should be as evenly distributed as possible among the 'interfering' sequences.

(3) Once the search is done, append the new sequence in the sequence file and goto (2) until n sequences are obtained.

5.3.2 Results

The desired set of hopping patterns of length n=50 with no co-channel and minimum adjacent channel interference is listed in Fig. A4.2 of Appendix A. Here, we use the set of hopping patterns of length n = 6 to illustrate its properties. The optimum set of sequences with length n=6 is listed in Fig. 5.2.

	n = 6
sequence #1	[1 2 3 4 5 6]
sequence #2	[3 4 5 6 1 2]
sequence #3	[5 6 1 2 3 4]
sequence #4	[2 3 6 1 4 5]
sequence #5	[4 5 2 3 6 1]
sequence #6	[6 1 4 5 2 3]

Figure 5.2 *Optimum hopping patterns for length n=6*

In addition to no co-channel interference, the optimum sequence set with minimum adjacent channel interference has the following properties:

(1) the first half of the set sequences has no 'true' adjacent channel interference among themselves,

(2) the second half of the set sequences also has no 'true' adjacent channel interference among themselves, and

(3) the 'true' adjacent channel interference of any particular sequence of the first half of the sequences is evenly distributed among the second half, and vice versa.

Fig. 5.3 illustrates property (3) for sequence length n=6. In Fig. 5.3a, the adjacent channels of the first sequence are evenly distributed among the second half of the sequences (#4 - #6). In Fig. 5.3b, the adjacent channels of the forth sequence are evenly distributed among the first half of the sequences (#1 - #3).

sequence #1	-> [1 2 3 4 5 6]	
sequence #2	[3 4 5 6 1 2]	(0)
sequence #3	[5 6 1 2 3 4]	(0)
sequence #4	[2* 3* 6 1 4* 5*]	(4)
sequence #5	[4 5 2* 3* 6* 1]	(3)
sequence #6	[6 1* 4* 5* 2 3]	(3)

(a)

sequence #1	[1* 2* 3 4 5* 6*]	(4)
sequence #2	[3* 4* 5* 6 1 2]	(3)
sequence #3	[5 6 1 2* 3* 4*]	(3)
sequence #4	-> [2 3 6 1 4 5]	
sequence #5	[4 5 2 3 6 1]	(0)
sequence #6	[6 1 4 5 2 3]	(0)

(b)

* denotes the 'true' adjacent channel of the sequence marked by '->', and the numbers of adjacent channels from other sequences are displayed in brackets.

Figure 5.3 *The set of hopping sequences no co-channel and minimum adjacent channel interference for sequence length of 6*

The proof of the optimality of such a hopping sequence set with the above three properties is listed in Appendix A. The optimum hopping sequence set can be generated without searching for every optimum sequence from all the possible sequence permutations. The sequence set generation procedure is listed in Appendix B. Although the optimum sequence set does not appear to be 'pseudo-random', this problem can be resolved by randomly swapping the columns of the sequence set without affecting the properties of the hopping patterns.

5.3.3 Evaluation of the Optimum Hopping Patterns

Each hopping pattern represents a message channel. The first half of the sequences (channels) has no interference from the 'true' adjacent channels among themselves. Therefore, the adjacent channel interference is small during low traffic periods (i.e. no more than half of the channels are used). This is also true when the system traffic load never exceeds half of the maximum available channels.

When more than half of the channels are used, the adjacent channel interference will gracefully increase rather than having two sequences constantly interfering with each other. This achieves the adjacent channel interference minimization objective.

5.4 Adjacent Channel Interference

Although the hopping patterns minimize the adjacent channel interference when no more than half of the channels are used, adjacent channel interference exists during the peak traffic period. This interference is further increased due to the near-far problem identified in section 4.9. Here, we first examine the amount of adjacent channel interference due to the adjacent channel separation alone. Then we determine the additional amount of interference due to the near-far end problem. After obtaining the total amount of adjacent channel interference in the system, we determine the receiver filter order requirement in each terminal.

5.4.1 Adjacent Channel Separation

Current analog cellular standard requires that the adjacent channel power must be less than 60 dB [14]. Therefore, the adjacent channel interfering power must satisfy:

$$10\log\int_a^b 2s(f)df = -60dB \qquad (5.7)$$

where

s(f) = adjacent channel power spectral density

The factor of 2 in equation (5.4) is due to two adjacent channels interfering with the desired channel. For the channel bandwidth of 100 kHz and carrier spacing of 400 kHz, a and b are equal to 350 and 450 kHz respectively as shown in Fig. 5.4.

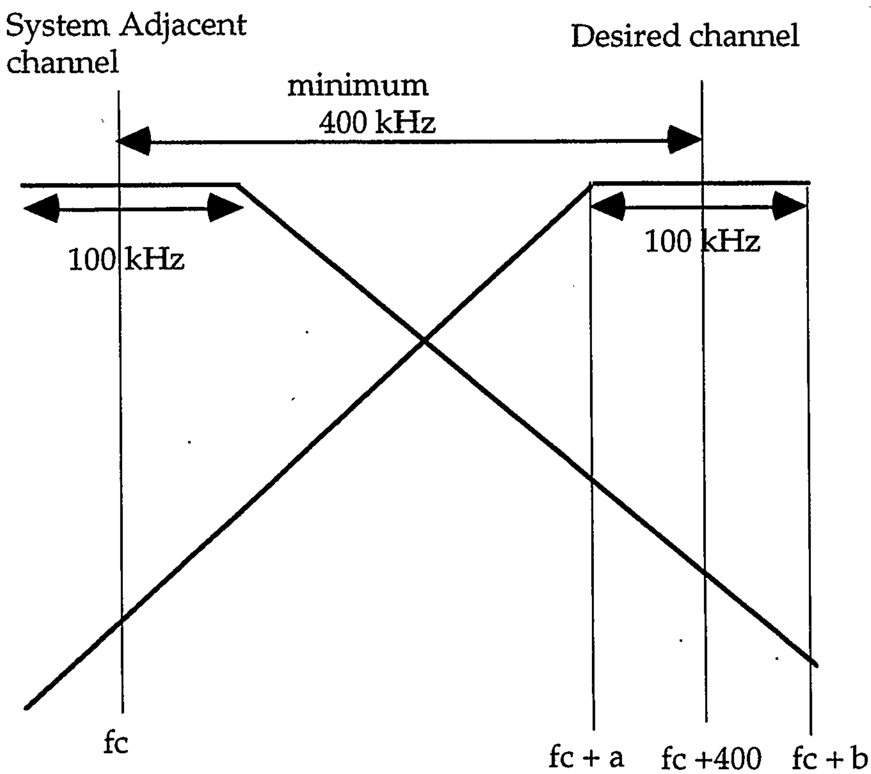

Figure 5.4 *Frequency separation between the desired and system-adjacent channels in the Peer-To-Peer Wireless System*

Assuming s(f) is the power spectral density of the binary frequency shift keying shown in Fig. 4.18 (section 4.10), the adjacent channel interfering power would be - 41.1 dB. Therefore, a channel filter of out-of-band attenuation of 19 dB will satisfy the adjacent channel interference requirement before considering the near-far problem.

5.4.2 Near-Far Problem

As mentioned in section 4.9, the adjacent channel interference is increased by the near-far end ratio. The worst case near-far end ratio is 40 dB. However, such an extreme situation does not often occur. We want to determine the average near-far end ratio with various numbers of users in different network topologies.

5.4.2.1 Near-Far Problem Simulation

A simulation study is done to determine the average near-far end ratios with the following assumptions:

(a) the coverage area (100 km^2) is divided into a maximum of 1000 x 1000 blocks. Each block represents a 10m x 10m area.

(b) an arbitrary number of fixed users resides in the coverage area.

These assumptions are illustrated in Fig. 5.5.

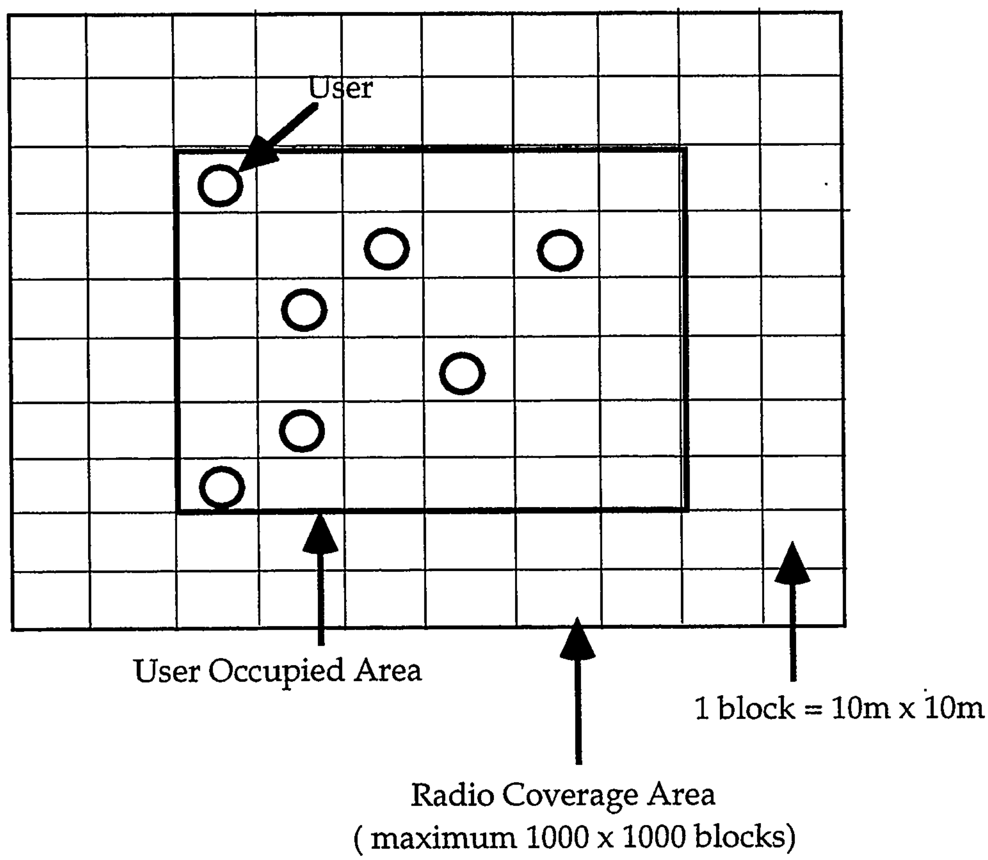

Figure 5.5 *Simulation to determine the Average Near-Far End Ratio*

The procedure to compute the near-far end ratios is as follows:

(1) Create a coverage area with a certain size.

(2) Randomly distribute a given number of users in the area.

(3) Select 1 user as the caller.

(4) Select 1 user as the called party.

(5) Compute the call_distance from the caller to the called party.

(6) Select all the other users (neighbours) such that the distance (interfering distance) from the caller to each of the other users is less

than the current call_distance. Take the average of the total interfering distances.

(7) Goto (4), select the next user as the called party until done.

(8) Goto (3), select the next user as the caller until done.

(9) For each user, extract the mean and the 90th percentile of the average near-far end ratios.

(10) Goto (1) using different coverage areas and number of users.

5.4.2.2 Simulation Results

The mean and the 90th percentile of the average near-far end ratios for various numbers of users and occupied areas are listed in table 5.2.

Occupied Area (km^2)	# of Users	Mean of the Average Near-Far End ratios (dB)	90th percentile Average Near-Far End ratios (dB)
100 (10 x 10)	50	7.2	11
	100	7.0	10
	150	7.3	12
	200	6.9	11
25 (5 x 5)	50	7.2	11
	100	7.0	10
	150	7.3	11
	200	7.7	12
1 (1 x 1)	50	6.5	9
	100	7.3	11
	150	7.9	14
	200	6.9	10
	Average	**7.2**	**11**

Table 5.2 *Mean and 90th percentile of the average Near-Far End ratios*

The simulation results indicate that the average near-far end ratios are from 9 to 14 dB occurring 90% of the time under different number of users and occupied areas. The 90th percentile average near-far end ratio is approximately equal to 11 dB.

5.4.3 Receiver Filter Order Requirement

Combining the results in sections 5.4.1 and 5.4.2, the total adjacent channel interference power is -30 dB on average and -1 dB under the worst condition. Therefore, the minimum out-of-band attenuation required are 30 dB on average, and about 60 dB in the worst case. The receiver selectivity mask is shown in Fig. 5.6.

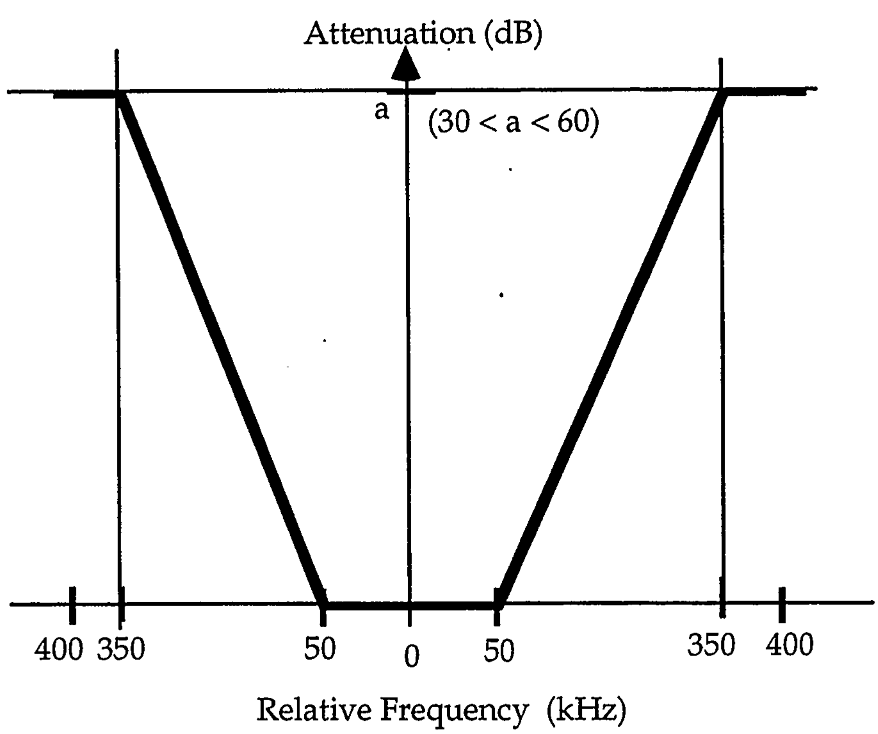

Figure 5.6 *Receiver Selectivity mask*

To determine the filter order requirement, we assume the following:

(a) the desired passband radian frequency is w_p, below which the attenuation has to be less than a specified maximum value of $\alpha_{\max}$;

(b) beyond a stopband radian frequency of w_s, the attenuation has to exceed the value $\alpha_{\min}$; and

(c) the Butterworth low-pass configuration is required.

For the Butterworth low-pass configuration, the attenuation α (dB), is given by

$$\alpha = 10\log_{10}\left[1+w^{2n}\right] \tag{5.8}$$

where w = desired cutoff frequency (rad/s)

n = filter order

Equation (5.8) can be arranged and we get

$$w = \left(10^{\frac{\alpha}{10}} - 1\right)^{\frac{1}{2n}} \tag{5.9}$$

After applying equation (5.9) to the passband and stopband and taking the ratio of the two, we get

$$\frac{w_s}{w_p} = \left(\frac{10^{\frac{\alpha_{\min}}{10}} - 1}{10^{\frac{\alpha_{\max}}{10}} - 1}\right)^{\frac{1}{2n}} \tag{5.10}$$

or

$$n = \frac{\log_{10}\left[\left(\frac{10^{\frac{\alpha_{\min}}{10}} - 1}{10^{\frac{\alpha_{\max}}{10}} - 1}\right)\right]}{2\log_{10}\left(\frac{w_s}{w_p}\right)} \tag{5.11}$$

The low-pass equivalent model for the adjacent channels can be represented in Fig. 5.7.

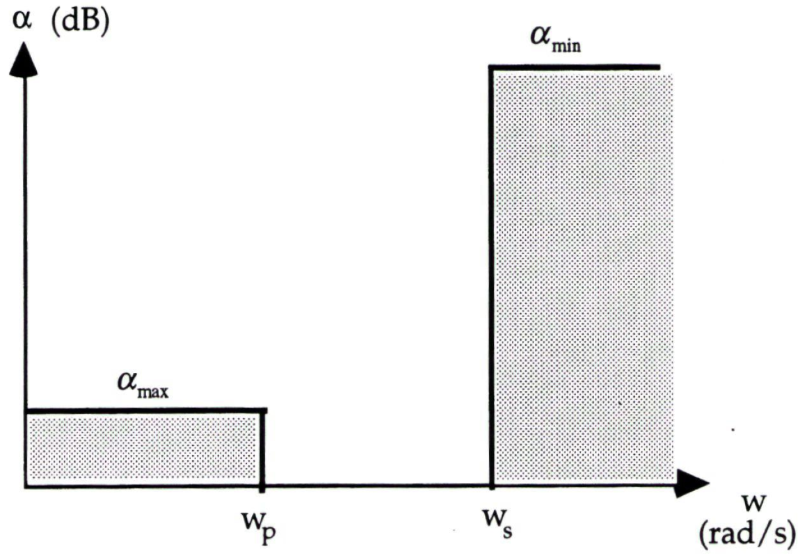

Figure 5.7 *Low-pass equivalent model for the adjacent channels*

From the receiver selectivity mask in Fig. 5.6, we obtain the following parameters:

$$w_S = 2\pi \times 350 \times 10^3 \text{ rad/s}$$

$$w_P = 2\pi \times 50 \times 10^3 \text{ rad/s}$$

Also α_{max} = 0.5 dB is assumed, and α_{min} = 30 dB on average and 60 dB under the worst condition. Substituting the parameters into equation (5.8), we get n = 3 and 4 for the average and worst case respectively. Hence, the peer-to-peer wireless terminal receiver requires a fourth-order Butterworth or equivalent filter to suppress the adjacent channel interference.

5.5 Media Access Control Protocol Performance

The media access control (MAC) protocol is designed for the wireless terminals to access a time slot on a common signaling (Call Request) channel during the call set up. Two protocols were proposed in section 4.5. The performance of the MAC protocols is measured by the call_request packet collision percentages as the system offered traffic load (or channel utilization) increases. Since there is no retransmission of the call_request packet after the collision occurs, the packet collision percentage represents the blocking probability during call set up. For a given probability of blocking, the maximum offered traffic load indicates the number of users that can be supported by the system. Also, the channel fading conditions may require the use of diversity on the signaling channel. The probability of unsuccessful call attempt due to fading conditions is used to measure the performance gain of the channel diversity.

5.5.1 Analysis of the MAC Protocols

To determine which MAC protocol has a lower probability of collisions, we first need to examine the collision window of each protocol. We assume that the Call Request channel has some used time slots, and are divided into unused and used time-slot pairs (a_1,b_1), (a_2,b_2),... ,(a_n,b_n) with a_1, a_2,... ,a_n and b_1, b_2,...,$b_n \geq 8$ms as shown in Fig. 5.8.

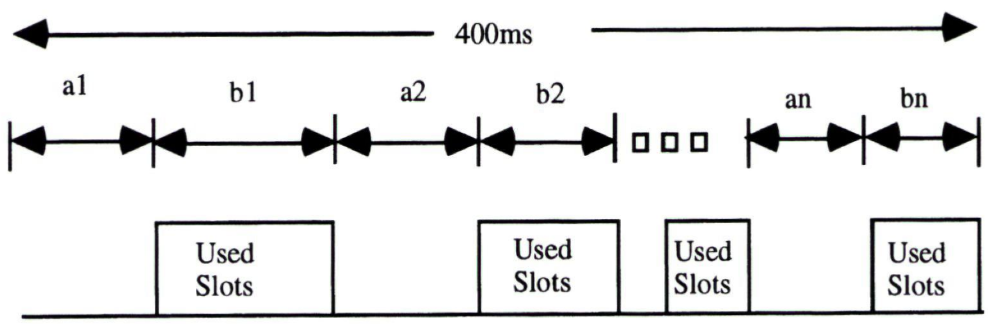

Figure 5.8 *Call Request channel unused and used time-slot pairs*

5.5.1.1 MAC protocol #1

Using the MAC protocol #1 described in section 4.5.1, any terminal which starts searching within a time-slot pair (a_k,b_k) must use the first idle slot in a_{k+1} as shown in Fig. 5.9.

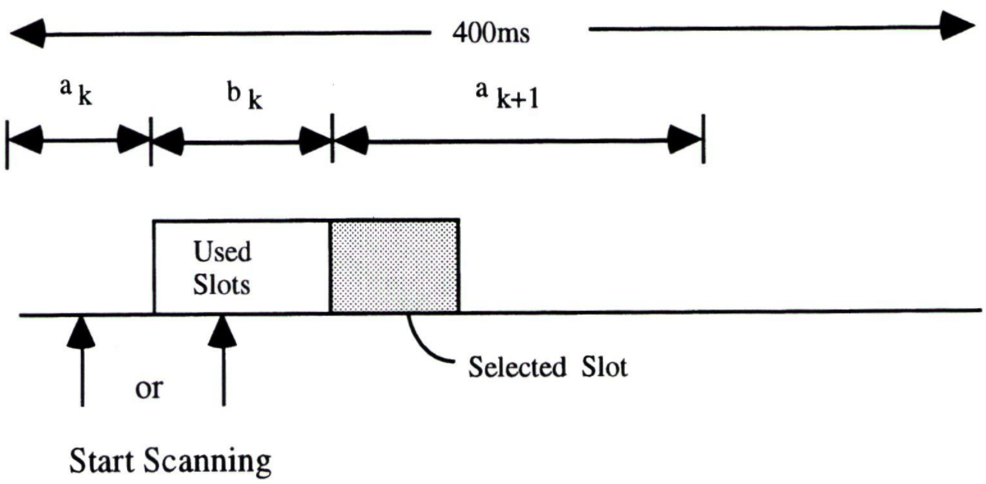

Figure 5.9 *Selected Slot using MAC Protocol #1*

If more than one terminal start searching within the same time-slot pair, collision occurs. Therefore, the collision window depends on the length of each time-slot pair (a_k,b_k). The maximum collision window = Max $[a_k + b_k]$ where k = 1,2,3,... ,n.

5.5.1.2 MAC protocol #2

Using the MAC protocol #2 described in section 4.5.2, any terminal which starts searching within an unused time block a_k will use an idle slot in a_k, and within a used time block b_k will use the first idle slot on a_{k+1} as shown in Fig. 5.10.

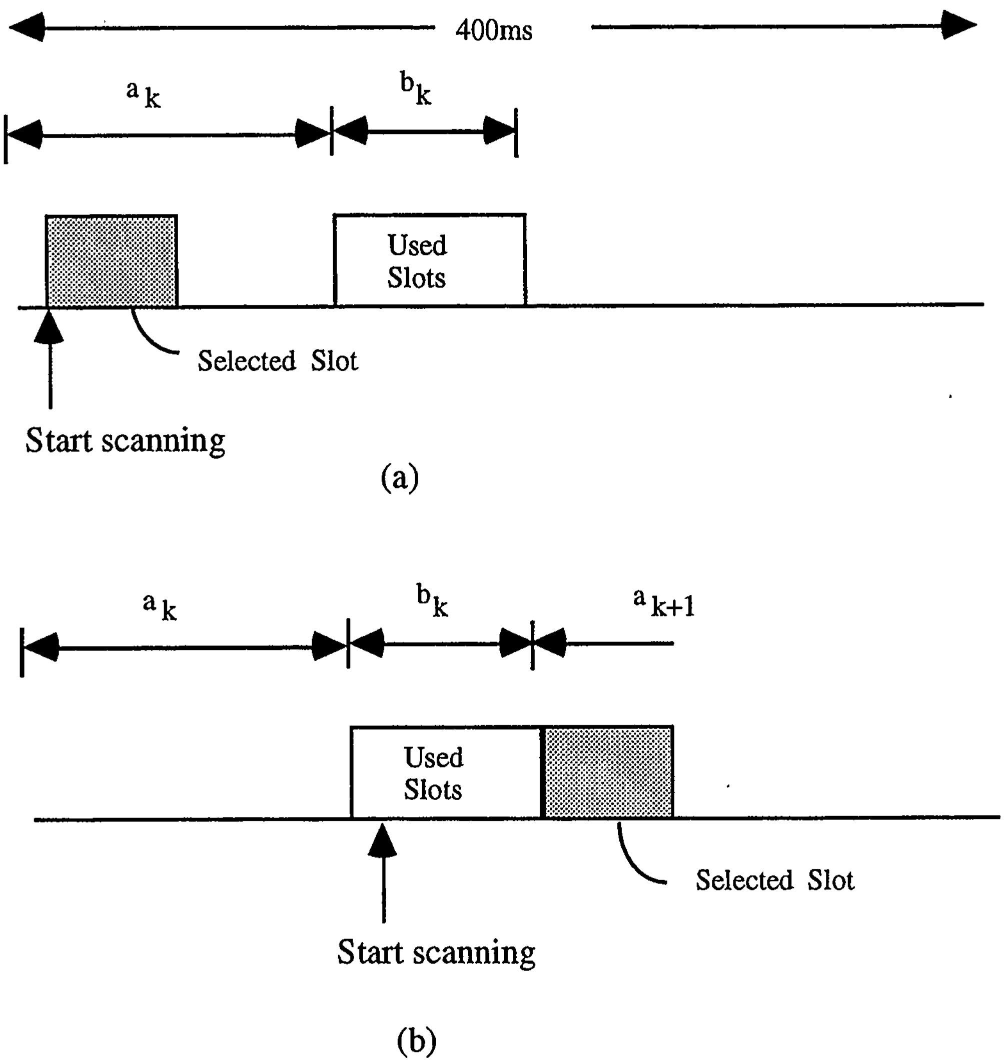

Figure 5.10 *Selected Slot using MAC protocol #2 when start scanning (a) within a_k and (b) within b_k*

If more than one terminal start searching within the same used or unused time block, collision occurs. Therefore, the collision window depends on the length of each unused and used time blocks duration. The maximum collision window = Max [a_k , b_k] where k = 1,2,3,...,n.

5.5.1.3 Simulation Results of the MAC protocols

Simulation of the MAC protocols uses the Network II.5 software. The simulated system consists of 10 channels with 20 users (10 time slots on the Call Request channel). Poisson call arrival with 5 minutes call duration is assumed. As the call arrival rate increases, both the collision (blocking) probability and the Call Request channel utilization representing the amount of carried traffic increase. The collision probability is plotted against the channel utilization as shown in Fig. 5.11.

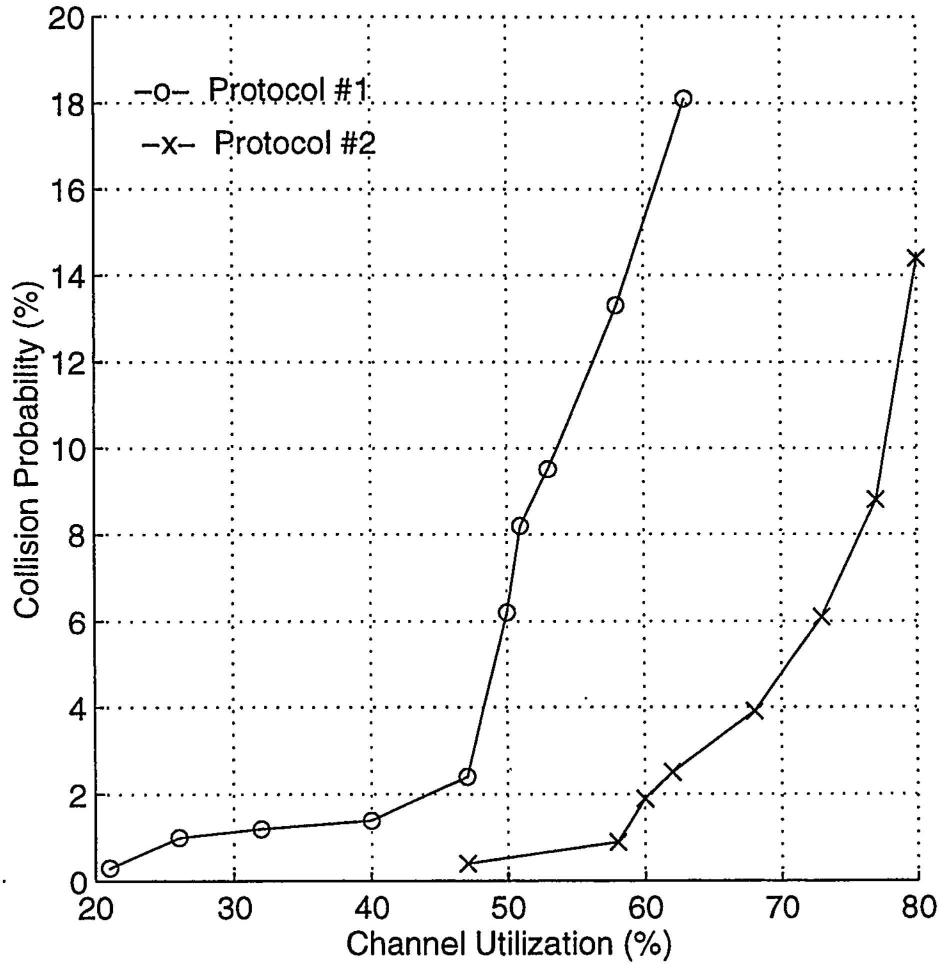

Figure 5.11 *Collision Probability for Protocols #1 and #2*

The graph of the MAC protocol #1 indicates that as the channel utilization increases beyond 47%, the collision percentage increases almost linearly. On the other hand, the MAC protocol #2 shows a smaller collision percentage at a higher channel utilization. This agrees with the analysis in the previous section because the maximum collision window of protocol #1 is always greater than protocol #2. This is because Max $[a_k + b_k] \geq$ Max $[a_k, b_k]$ where k = 1,2,3,... ,n.

As mentioned in section 3.4, providing telephone service in rural areas requires a probability of blocking during the busy hour ≤ 1% with 0.05 - 0.09 erlang per line. Here, we assume traffic per line is 0.1 erlang. For the 1% blocking objective, the maximum channel utilizations are 40% and 57% for protocols #1 and #2 respectively. By linear interpolating the result for 50 channels, this translates to 20 and 28.5 erlangs of offered traffic load respectively. Therefore, the maximum numbers of users supported by the system are 200 and 285 using protocols #1 and #2 respectively. Linear interpolation of the result from 10 to 50 channels is a conservative estimate since 50 channels can carry more traffic than 5 times 10 channels.

5.5.1.4 Comparison of the MAC protocols

The MAC protocol #1 always uses idle slots adjacent to the busy slots. It tries to keep all the used slots in a contiguous block. This has two advantages from the system viewpoint.

(1) Since all the used slots are in a single block, protocol #1 always tries to use up the first half of the channels. By using the optimum hopping patterns described in section 5.3, the adjacent channel interference will always be minimum during the low traffic period.

(2) If each terminal cannot have a stable internal clock, synchronization with adjacent slots can be implemented. This is because each used slot will often have a used adjacent slot.

The MAC protocol #2 sometimes uses idle slots adjacent to the busy slots. Therefore, the used slots may not be in a contiguous block. However, it also decreases the collision window and can carry more traffic.

In the rural area local communications, using the MAC protocol #1 is recommended because:

(a) it meets the objective of supporting up to 200 users,

(b) it can take advantage of the optimum hopping patterns, and

(c) it allows the synchronization with the adjacent slots.

5.5.2 Use of Diversity on the Signaling channel

Since the signaling channel uses time-division multiple access and is also used for the call set up and synchronization, the system can suffer serious degradation if fading occurs on the signaling channel. Here, we want to determine the improvement of using diversity on the signaling channel. The MAC protocol #1 is used under the flat fading channel condition. Fig. 5.12 displays the probability of unsuccessful call attempt due to fading for various channel availability percentages using one and two signaling channels.

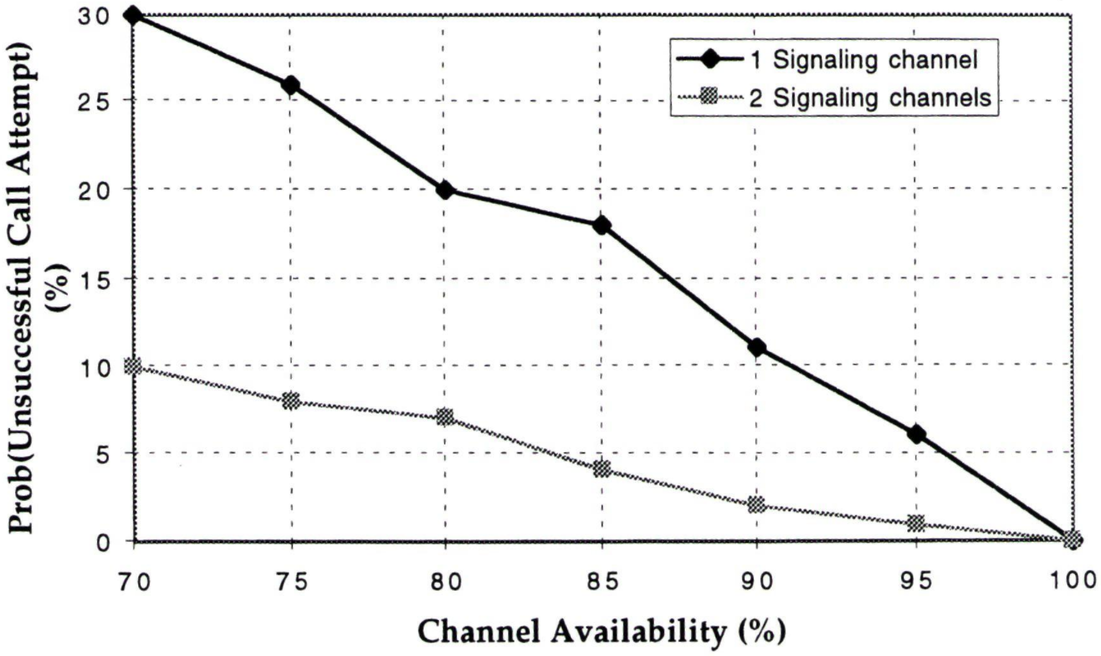

Figure 5.12 *Prob(Unsuccessful Call Attempt) for one and two signaling channels*

By using two signaling channels, the reduction in the unsuccessful call attempt probability is more than half even in good channel conditions (i.e. > 90% channel availability). Therefore, using diversity on the signaling channel is recommended. If two signaling channels are used in the system, then two Call Request channels and two Call Acknowledge channels are required. The time slot duration in each channel is reduced by half from 8ms to 4ms as shown in Fig. 5.13.

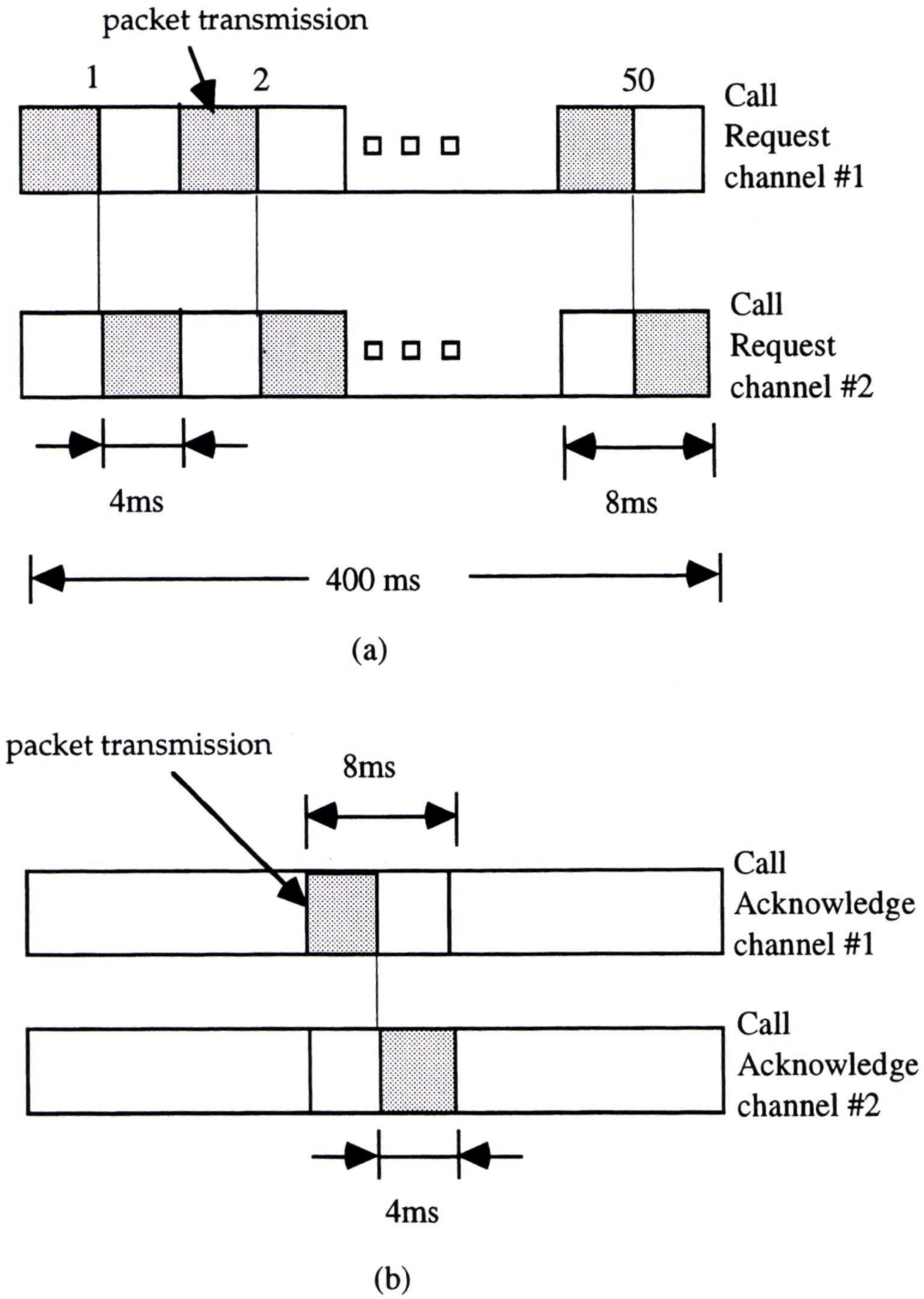

Figure 5.13 *Use of Two Signaling channels: (a) Call Request channels and (b) Call Acknowledge channels*

5.6 Single Repeater Paging Scheme Performance

This section presents the analysis and simulation results of the proposed single repeater paging scheme. This paging scheme has been described in section 4.13 in the media access control (MAC) and physical layers. Here, we focus on the analysis and results of the MAC layer.

5.6.1 Analysis of the Paging Scheme

The number of repeaters that can connect to the destination terminal is determined by the network configuration such as the number of users and the user occupied areas. Since no terminal knows which repeaters can connect to the destination terminal, the number of 1-hop neighbours (potential repeaters) activated should be as many as possible to maximize the chance of finding the destination terminal. However, two problems arise. First, the 1-hop neighbours need to be activated in an orderly fashion. Otherwise, if more than one neighbour are activated at the same time, packet collisions result on the Call Request channel. Second, activating more 1-hop neighbours results in longer call set up delay. Hence, an optimum backoff time needs to be determined that will minimize the number of collisions while maintaining low delay to reach the destination terminal.

Once the optimum backoff time is obtained, we can measure the performance of the paging scheme by estimating the average probability of connecting to the destination terminal.

5.6.2 Optimum Backoff Time of the Paging Scheme

The procedure to determine the optimum backoff time of the paging scheme is as follows.

(1) Assume a fixed call set up delay limit.

(2) Given a number of idle terminals (potential repeaters) and a set of discrete backoff times for each terminal to randomly choose from, determine the number of repeaters successfully activated.

(3) Vary the set of discrete backoff times from 1 to 200 and the number of idle terminals from 1 to 100 and repeat step (2).

(4) Repeat steps (2) and (3) over 100 iterations to determine the average number of repeaters successfully activated.

Fig. 5.14 shows the number of repeaters activated for different number of idle 1-hop neighbours and various sets of backoff times with the call set up delay = 30 seconds. Fig. 5.15 shows the number of repeater collisions for different number of idle 1-hop neighbours and various sets of backoff times with the call set up delay = 30 seconds. When the set of backoff times = 100, nearly the maximum number of idle terminals (repeaters) are activated, and the number of collisions is small. Therefore, the optimum set of backoff times is chosen to be 100. We also assume a collision window = 400 ms (worst case). Therefore, each backoff time unit represents 2 x 400 ms = 800 ms so that terminals choosing different backoff times in the set will never collide.

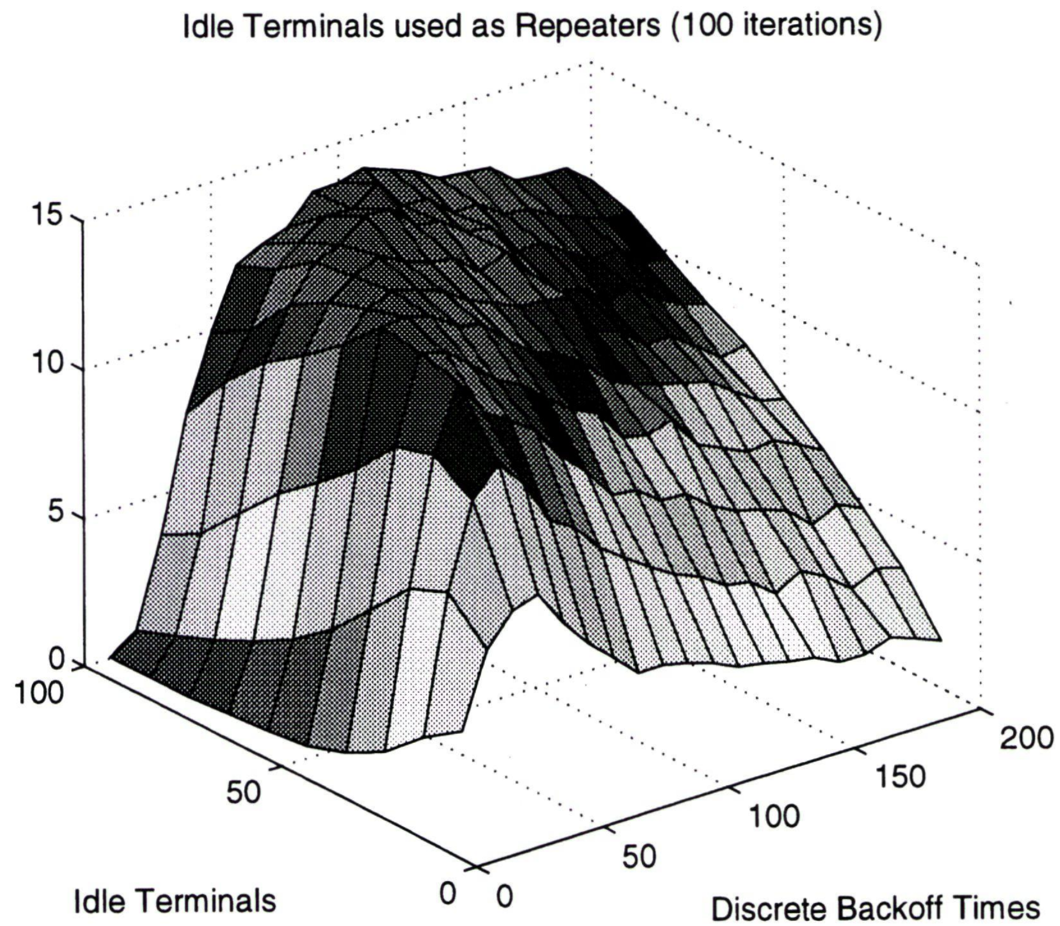

Figure 5.14 *Number of Repeaters activated (call set up delay = 30 seconds)*

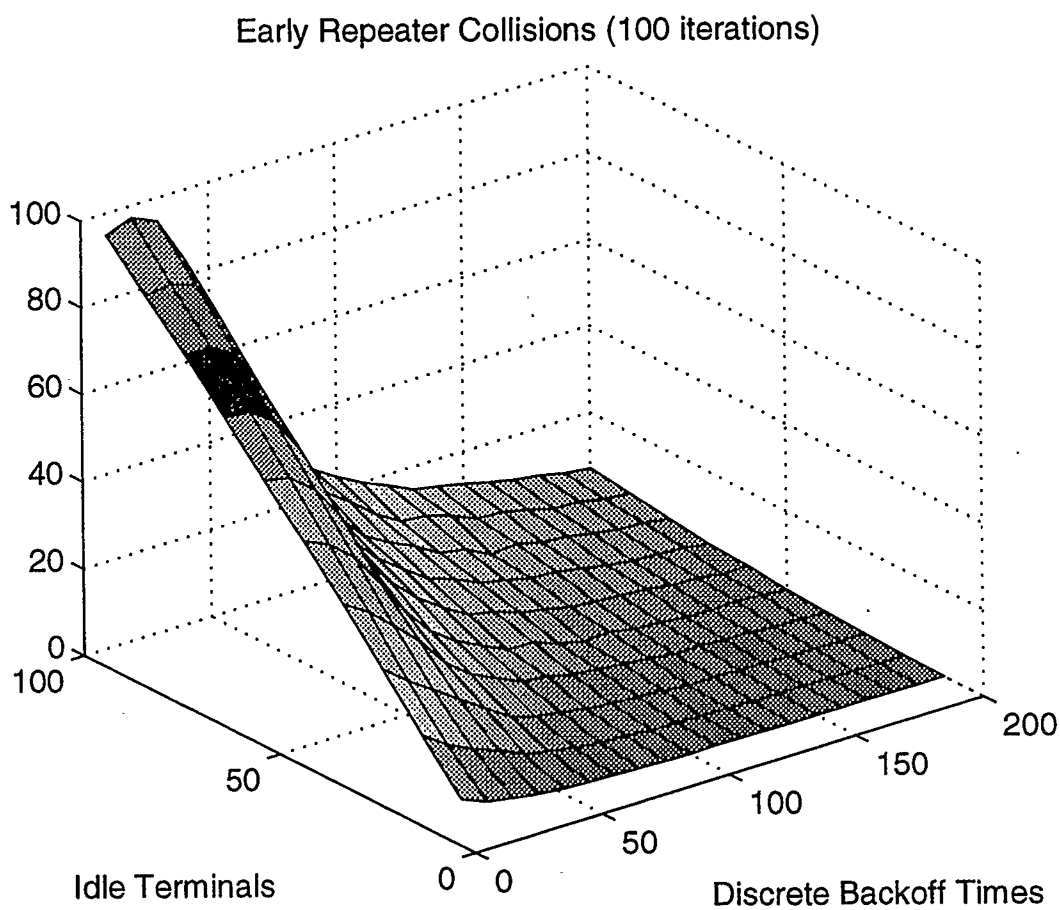

Figure 5.15 *Number of Repeater collisions (call set up delay = 30 seconds)*

5.6.3 Network Simulation of the Paging Scheme

Once we have determined the optimum set of backoff times (=100) from the previous section, we can use network simulation to obtain the average probability of connection to the destination user for various numbers of users and occupied areas. The procedure is as follows.

(1) Fix the number of users.

(2) Fix the user occupied area.

(3) Randomly scatter the users in the area specified in (2).

(4) Choose a terminal as the originating terminal.

(5) For each call from the originating terminal to another terminal, determine:

(a) the number of 1-hop neighbours (within 10 km) of the originating terminal, and

(b) the number of 1-hop neighbours that can reach the destination terminal.

(6) Choose another terminal as the originating terminal and repeat step (5) until all terminals are selected. Obtain the average results of (5).

(7) Goto step (3) to repeat for 100 different configurations.

(8) Goto step (2) and change the size of the user occupied area from 100 to 800 km^2.

(9) Goto step (1) and change the number of users from 10 to 100.

5.6.4 Average Probability of Successful Connections

After obtaining the average number of 1-hop neighbours for each node and the average number of 1-hop neighbours that can reach the destination terminal from section 5.6.3, we can calculate the average probability of a successful connection from a terminal to another terminal using a repeater. An example is given as follows:

Given an area of 400 km^2, the number of users = 30 randomly scattered in the area, and the user delay limit = 30 seconds, we obtain:

(1) the average number of 1-hop neighbours for each terminal = 12 (from the network simulation in section 5.6.3),

(2) the average number of 1-hop neighbours that can reach the destination terminal = 3 (from the network simulation in section 5.6.3),

(3) the average number of 1-hop neighbours activated = 4 for the number of backoff scan time = 100 (from section 5.6.2).

The probability of a successful connection from one terminal to another terminal using a repeater = 1 - Prob(no connection made)

$$= 1 - \frac{9}{12} \times \frac{8}{11} \times \frac{7}{10} \times \frac{6}{9}$$

$$= 74.5\%.$$

This probability is calculated over 100 different configurations, and the average probability obtained = 78%. By varying the given area from 100 to 800 km^2, and the number of users from 10 to 100, we obtain the average connection probabilities as shown in table 5.3.

No of Users	Area (km²)							
	100	200	300	400	500	600	700	800
10	100%	83%	56%	38%	26%	18%	9%	7%
20	100%	97%	81%	66%	55%	41%	33%	27%
30	100%	100%	93%	78%	63%	50%	43%	38%
40	100%	100%	97%	89%	74%	64%	47%	40%
50	100%	100%	98%	94%	84%	71%	62%	53%
60	100%	100%	99%	95%	88%	80%	67%	59%
70	100%	100%	99%	96%	90%	83%	74%	64%
80	100%	100%	100%	97%	91%	84%	77%	69%
90	100%	100%	100%	98%	93%	86%	80%	73%
100	100%	100%	100%	98%	95%	89%	82%	76%

Table 5.3 *Average Probability of Connection between two terminals with call set up delay = 30 seconds (Shaded area indicates the average probabilities ≥ 95%)*

If the user delay is increased further, the average probability of connection between two terminals will increase. Tables 5.4, 5.5, and 5.6 display the connection probabilities for the user delay of 40, 50, and 60 seconds respectively.

No of Users	Area (km^2)							
	100	200	300	400	500	600	700	800
10	100%	89%	68%	55%	41%	30%	17%	14%
20	100%	99%	91%	77%	65%	48%	40%	33%
30	100%	100%	98%	87%	74%	65%	55%	45%
40	100%	100%	99%	96%	85%	75%	62%	54%
50	100%	100%	100%	98%	93%	84%	74%	64%
60	100%	100%	100%	99%	95%	89%	80%	74%
70	100%	100%	100%	99%	96%	92%	84%	77%
80	100%	100%	100%	99%	97%	93%	87%	80%
90	100%	100%	100%	100%	98%	94%	90%	84%
100	100%	100%	100%	100%	98%	95%	92%	87%

Table 5.4 *Average Probability of Connection between two terminals with call set up delay = 40 seconds (Shaded area indicates the average probabilities ≥ 95%)*

No of Users	Area (km^2)							
	100	200	300	400	500	600	700	800
10	100%	95%	76%	59%	43%	31%	17%	14%
20	100%	100%	97%	87%	78%	62%	54%	44%
30	100%	100%	99%	95%	85%	78%	67%	58%
40	100%	100%	100%	98%	92%	87%	75%	68%
50	100%	100%	100%	99%	97%	91%	85%	78%
60	100%	100%	100%	100%	98%	95%	88%	83%
70	100%	100%	100%	100%	99%	96%	91%	85%
80	100%	100%	100%	100%	99%	97%	93%	88%
90	100%	100%	100%	100%	99%	98%	95%	91%
100	100%	100%	100%	100%	100%	98%	96%	93%

Table 5.5 *Average Probability of Connection between two terminals with call set up delay = 50 seconds (Shaded area indicates the average probabilities ≥ 95%)*

No of Users	Area (km^2)							
	100	200	300	400	500	600	700	800
10	100%	98%	86%	70%	51%	35%	19%	15%
20	100%	100%	99%	93%	85%	70%	63%	57%
30	100%	100%	100%	98%	92%	86%	77%	69%
40	100%	100%	100%	99%	96%	93%	82%	76%
50	100%	100%	100%	100%	99%	96%	91%	86%
60	100%	100%	100%	100%	99%	98%	94%	90%
70	100%	100%	100%	100%	100%	99%	96%	92%
80	100%	100%	100%	100%	100%	99%	97%	94%
90	100%	100%	100%	100%	100%	99%	98%	96%
100	100%	100%	100%	100%	100%	100%	99%	97%

Table 5.6 *Average Probability of Connection between two terminals with call set up delay = 60 seconds (Shaded area indicates the average probabilities ≥ 95%)*

Although the probabilities shown in the tables are only averages, they provide a good approximation of the repeater scheme performance for various network configurations. This information is useful in planning a two-hop peer-to-peer wireless system in a given area serving a given number of users.

5.6.5 Performance relative to the Polling Scheme

The performance of the paging scheme relative to the polling scheme is examined in two areas including the number of repeaters activated, and the number of time slots used on the Call Request channel.

5.6.5.1 Number of Repeaters Activated

As mentioned in section 4.13.4, the polling scheme provides a high probability of connection. This is because the polling scheme can activate more repeaters than the paging scheme. Assume polling each terminal requires 1.2 seconds (3 frames on the Call Request channel). Fig. 5.16 shows the number of activated repeaters using the paging and polling schemes for various possible repeaters within the call set up delay of 30 seconds.

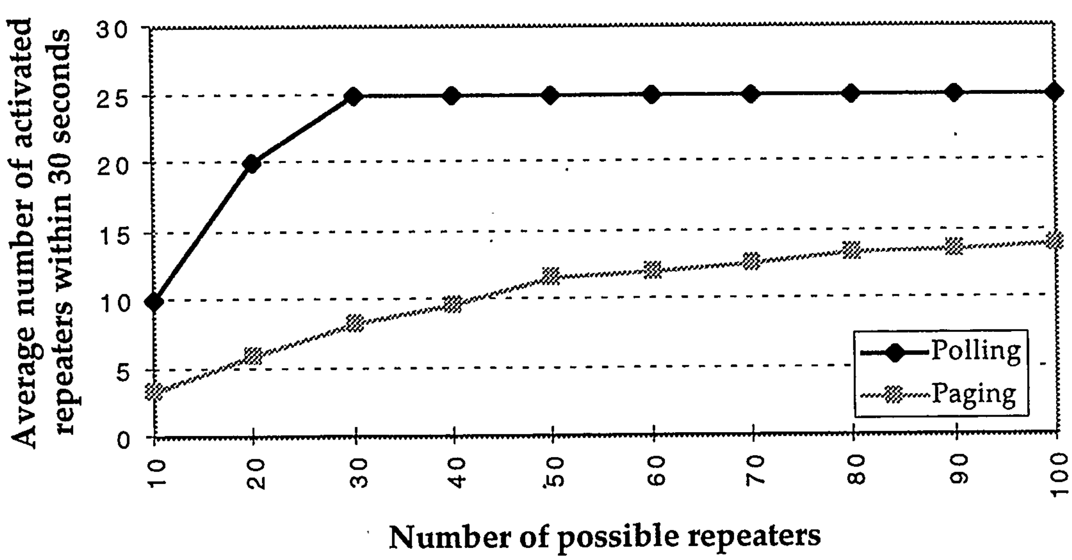

Figure 5.16 *Number of activated repeaters in the Paging and Polling schemes within the call set up delay of 30 seconds*

Activating more repeaters increases the chance of finding the destination terminal. The increases in the average probability of connection for various network configurations are shown in table 5.7. The polling scheme is more effective than the paging scheme for small number of users or for large user occupied area.

No of Users	Area (km^2)							
	100	200	300	400	500	600	700	800
10	0%	17%	40%	53%	45%	34%	23%	18%
20	0%	3%	19%	34%	45%	55%	67%	54%
30	0%	0%	7%	22%	37%	50%	57%	62%
40	0%	0%	3%	11%	26%	36%	53%	60%
50	0%	0%	2%	6%	16%	29%	38%	47%
60	0%	0%	1%	5%	12%	20%	33%	41%
70	0%	0%	1%	4%	10%	17%	26%	36%
80	0%	0%	0%	3%	9%	16%	23%	31%
90	0%	0%	0%	2%	7%	14%	20%	27%
100	0%	0%	0%	2%	5%	11%	18%	24%

Table 5.7 *Increases in the Average Probability of Connection over the Paging scheme with call set up delay of 30 seconds*

5.6.5.2 Number of Time Slots used on the Call Request channel

Another difference is the number of time slots used on the Call Request channel. In the polling scheme, only one time slot is used to poll each neighbour at a time. In the paging scheme, if each repeater, after the b x 0.8 seconds backoff where b = integer and b x 0.8 ≤ user delay limit, transmits a call_request packet for L seconds and waits for acknowledgment from the destination terminal, then L/0.8 time slots are used on the Call Request channel at a time. If L = 1.6 seconds, then the paging scheme uses twice as many time slots on the Call Request channel as the polling scheme.

Although the polling scheme performs better than the paging scheme, the paging scheme does not require any network initialization. Each terminal does not need to know its neighbours. Hence, the paging scheme is considered as a simple and effective method to increase the system coverage area.

5.7 System Specifications and Performance check

In the final stage of our system design, we want to determine if the system specifications and performance meet the requirements. We map the service and the operating frequency band requirements against the system specifications and performance as shown in table 5.8. We find that all the requirements are met by the single-hop system.

		System Specifications / Performance
Service Requirements in Rural areas	Voice telephony & Group 3 fax	32 kbps ADPCM voice coding
	Coverage area of 4 km diameter	Single-hop system with 10 km diameter and 99% link availability
	Prob(blocking) ≤ 1%	MAC protocol with 1% call set up blocking probability during busy hour
	Maximum Capacity of 150 to 200 users	Maximum capacity of 200 users with 1% blocking
Operating Frequency Band Requirements (902-928 MHz)	Minimum number of hopping frequencies = 50	50 different hopping frequencies per hopping pattern
	0.4 seconds dwell time within 20 second period at any frequency	same as requirement
	Maximum output power = 1W	1W transmit output power
	Maximum 20 dB channel bandwidth = 500 kHz	100 kHz channel bandwidth
	Minimum channel spacing is 25 kHz or 20 dB bandwidth	400 kHz channel spacing

Table 5.8 *Mapping System Specifications and Performance with the Requirements*

5.8 Summary

We have examined the performance in different areas of the physical layer communications, channel access scheme, and network organization. In the physical layer communications, we have determined from the path loss calculation that a single-hop system can serve the entire rural community. The set of hopping patterns with no co-channel and minimum adjacent channel interference is found. Since the system does not have any co-channel interference, we focus on determining the amount of adjacent channel interference and the filter order requirement. In the channel access scheme, we have examined and compared the two protocols. Although both protocols can support 200 users, one of them can take advantage of the minimum adjacent channel interference of the hopping patterns and allow synchronization with the adjacent slot. In the network organization, the two-hop system using the repeater paging scheme has been investigated.

CHAPTER 6

CONCLUSIONS

6.1 Concluding Remarks

The conventional method to provide telephone service in rural areas is expensive. This is because the telephone company must install and maintain the local switching and transmission facilities. The use of the peer-to-peer wireless system in conjunction with a mobile satellite system presents a low cost alternative of serving the rural areas. A simple single-hop peer-to-peer wireless system has been proposed and examined in this thesis. The system specifications and performance meet all the requirements of the basic telephone service in rural areas. A simple single repeater paging scheme is proposed to allow increased coverage of the system.

6.2 Future Work

Several areas can be further investigated.

(1) The extension of the system into a multi-hop system can be examined.

(2) Since the system is designed for rural area application, the terminals are assumed to be fixed but movable. If the terminal mobility is required, further analysis of the system is necessary such as path loss, interference, and power consumption.

(3) System design is required for developing other applications such as wireless local loop and cordless extension of cellular.

(4) Integration of the peer-to-peer wireless terminal with the cellular or the mobile satellite terminal can be examined.

Finally, the prototype of the proposed single-hop system with four terminals is currently under construction. The results should be available in the near future.

REFERENCES

[1] G. Calhoun. ,"*Wireless Access and the Local Telephone Network*". Artech House, Norwood, MA, 1992.

[2] U.S. Congress. ,"*The Changing Telephone Industry: Access Charges, Universal Service, and Local Rates*". U.S. Government Printing Office, Washington, DC, June 1984.

[3] A. Ephremides, J.E. Wieselthier, and D.J. Baker. ,"A Design Concept for Reliable Mobile Radio Networks with Frequency Hopping Signaling". *Proc. IEEE,* 75(1), pp. 56-73, 1987.

[4] C.R. Lin and M. Gerla. ,"A Distributed Control Scheme in Multi-hop Packet Radio Networks for Voice/Data Traffic Support". *Proc. of ICC '95*, pp. 1238-1242, 1995.

[5] D.S. Sharp. ,"Integrated Rural Subscriber Access Systems". *Proc of ICUPC,* pp. 591-594, 1994.

[6] C.M. Rush. ,"How WARC '92 Will Affect Mobile Services". *IEEE Communications Magazine,* 30(10), pp. 90-961, 1992.

[7] Industry and Science Canada. ,"*Low Power Radiocommunication Devices*". RSS-210 Issue 1, 1993.

[8] D.F. Bantz and F.J. Bauchot. ,"Wireless LAN Design Alternatives". *IEEE Network,* 8(2), pp. 43-53, 1994.

[9] R. Kohno, R. Meidan, and L.B. Milstein. ,"Spread Spectrum Access Methods for Wireless Communications". *IEEE Communications Magazine,* 33(1), pp. 58-67, 1995.

[10] J.G. Proakis., *"Digital Communications"*. McGraw-Hill Book Company, New York, 1989.

[11] The Joint Technical Committee of T1P1.4. , *"Draft Final Report on RF Channel Characterization"*. JTC(AIR) 238R2, 1993.

[12] J.E. Padgett, C.G. Gunther, and T. Hattori. ,"Overview of Wireless Personal Communications". *IEEE Communications Magazine*, 33(1), pp. 28-41, 1995.

[13] R.L. Freeman. ,*"Radio System Design For Telecommunications"*. John Wiley & Sons, New York, 1987.

[14] A.Mehrotra., *"Cellular Radio Performance Engineering"*. Artech House, Norwood, MA, 1994.

Appendix A

PROOF OF THE OPTIMALITY OF THE SET OF HOPPING SEQUENCES FOR THE PEER-TO-PEER WIRELESS SYSTEM

A1. Objective:

Given n distinct frequencies {1,2,3,... ,n}, generate n hopping sequences of length n with:

(a) each frequency in every hopping sequence occurring no more than once,

(b) no co-channel interference, and

(c) minimum adjacent channel interference.

These n hopping sequences can be represented by an n x n sequence matrix as shown in Fig. A1.1 with each row corresponding to a hopping sequence and each column corresponding to the frequencies of all the sequences at a particular time instance.

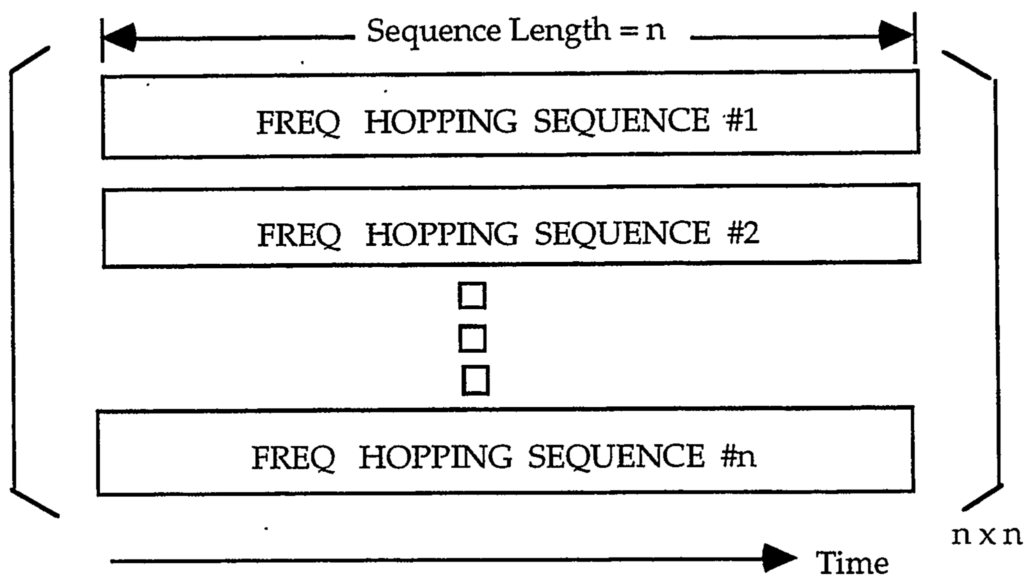

Figure A1.1 *An n x n Sequence Matrix*

A2. Implications of the Constraints on the Sequence Matrix

The requirements of the hopping sequences stated in section A1 are translated to the following three constraints on the sequence matrix:

(A2.1) Each frequency in any hopping sequence occurring no more than once

This implies that each row of the sequence matrix is the sequence {1 2 3... n} arranged in any order.

(A2.2) No Co-channel Interference

To generate n hopping sequences of length n with no co-channel interference, no identical frequencies should occur at any particular time instance. That means each column of the sequence matrix is also the sequence {1 2 3... n} arranged in any order.

(A2.3) Minimum Adjacent Channel Interference

A 'true' adjacent channel is defined as either one of the two next adjacent frequencies. For example, frequency '4' will have the two adjacent frequencies '3' and '5'; frequency '1' will only have adjacent frequency '2'.

Minimizing the adjacent channel interference implies that:

(a) the occurrence of 'true' adjacent channels of a particular hopping sequence from the other hopping sequences is ideally nil.

(b) when the adjacent channel interference of a particular hopping sequence is unavoidable from the other hopping sequences, it should be evenly spread among the interfering hopping sequences.

Condition (a) takes precedent over condition (b). In other words, when start searching for the hopping sequences, the first goal is to ensure no adjacent channel interference among the hopping sequences until it is unavoidable. Condition (b) implies that the 'true' adjacent channels of a particular hopping sequence should be as evenly distributed as possible among the interfering hopping sequences. For example, if the number of true adjacent channels of a particular hopping sequence = A and the number of interfering hopping sequences = N, then each one of interfering hopping sequences should contain $\left\lfloor \frac{A}{N} \right\rfloor$ or $\left\lfloor \frac{A}{N} \right\rfloor+1$ (where $\lfloor x \rfloor$= largest integer value smaller than or equal to x) true adjacent channels of the particular hopping sequence.

A3. Optimum Sequence Matrix

A sequence matrix is considered optimum if it meets the requirements (A2.1) to (A2.3). The following theorem defines an optimum sequence matrix.

Theorem A3.1

A sequence matrix (n x n, where n is even) with the following properties is optimum:

(a) the first half of the sequence matrix (n/2 x n) has no adjacent channel interference (ACI) among themselves while satisfying the constraints (A2.1) and (A2.2),

(b) the second half of the sequence matrix (n/2 x n) has no ACI among themselves while satisfying the constraints (A2.1) and (A2.2), and

(c) the ACI of every sequence in the first half of the sequence matrix is evenly distributed among the sequences in the second half of the sequence matrix, and vice versa.

To prove theorem A3.1, we first state and prove theorems A3.2, A3.3, and A3.4.

Theorem A3.2

For a given sequence {1 2 3... n} of any arranged order, where n is even, a sequence set of n/2 sequences can be generated by rotating 2 positions from the previous sequence. Such a sequence set will satisfy the constraints (A2.1) and (A2.2) with no adjacent channel interference.

Proof of Theorem A3.2

Given a sequence [1 2 3 4 5 6... n-3 n-2 n-1 n],

the next sequence can be generated by rotating this sequence by 2 positions and becomes:

[3 4 5 6... n-3 n-2 n-1 n 1 2]

Similarly, the following sequence can be generated by rotating this sequence again by 2 positions and becomes:

[5 6... n-3 n-2 n-1 n 1 2 3 4]

The sequence set then = [1 2 3 4 5 6... n-3 n-2 n-1 n]

[3 4 5 6 ... n-1 n 1 2]

[5 6... 1 2 3 4]

. . .

. . .

. . .

[n/2 n/2+1... n-5 n-4 n-3 n-2]

Each column of the sequence set is made up of either even or odd numbers. Hence, it has no 'true' adjacent channel interference between any sequences while satisfying the constraints (A2.1) and (A2.2). If the first sequence is randomly generated. The sequence set can also be generated by changing the columns of the above sequence set accordingly. Hence, for every sequence, there is always a sequence set of n/2 sequences that satisfy constraints (A2.1) and (A2.2) with no adjacent channel interference among themselves. Every other sequence set generated is a result of the re-arrangement of the columns of the above sequence set. The number of columns of even numbers {2 4 6... n-2 n} and the number of columns of odd numbers {1 3 5... n-3 n-1} in the sequence set are identical and equal to n/2. This completes the proof.

Theorem A3.3

The maximum number of sequences of length n that satisfies (A2.1) and (A2.2) with no ACI among themselves = n/2.

Proof of Theorem A3.3

From (A2.2), each column is the sequence {1 2 3... n} arranged in any order. To select the largest set of numbers from each column with no ACI is simply done by selecting the odd or even numbers of the sequence. Thus, each column will contain a maximum of n/2 numbers (either even or odd numbers). By using theorem A3.2, any n/2 sequences of length n with no ACI can be generated. Therefore, the maximum number of sequences of length n that satisfies (A2.1) and (A2.2) with no ACI among themselves = n/2. This completes the proof.

Theorem A3.4

The total number of 'true' ACI of any sequence from other sequences in the sequence matrix that satisfies (A2.1) and (A2.2) is a constant and is equal to (n-1)*2.

Proof of Theorem A3.4

From (A2.2), since each column of the sequence matrix is {1 2 3... n} arranged in any order, 'true' adjacent channel interference must exist. For any column (member) of a particular sequence, if the sequence has channels '1' or 'n', then the number of adjacent channels is equal to 1 (i.e. 1 'true' adjacent channel interference from all other sequences at the same time); otherwise it is equal to 2.

Also, from (A2.1), since each row of the sequence matrix is {1 2 3... n} arranged in any order, each sequence must contain channels '1' and 'n' with the number of adjacent channels equal to 1 and (n-2) channels with the number of adjacent channels equal to 2.

Hence, for any sequence in the sequence matrix that satisfies (A2.1) and (A2.2), the total number of adjacent channels from all the other sequences equals 2 + (n-2)*2 = (n-1)*2. This completes the proof of theorem A3.4.

We can now make use of theorems A3.2, A3.3, and A3.4 to validate theorem A3.1.

Proof of Theorem A3.1 Part (a)

Since from (A2.3), condition (a) takes precedent over condition (b), the maximum number of sequences of length n that satisfies (A2.1) and (A2.2) with no ACI will always be found first. From theorem A3.3, the maximum number of sequences found will be n/2. This completes the proof of part (a) of theorem A3.1.

Proof of Theorem A3.1 Part(b)

From theorem A3.2, each column of the first (n/2 x n) sequence set is either even or odd numbers but not both. Also from (A2.2), each column of the sequence matrix (n x n) must be the sequence {1 2 3... n} arranged in any order. Therefore, if a particular column of the first sequence set is even numbers, the same column of the second (n/2 x n) sequence set must be odd numbers to form a complete set {1 2 3... n}. Similarly, if a particular column of the first sequence set is odd numbers, the same column of the second (n/2 x n) sequence set must be even numbers to form a complete set {1 2 3... n}. Therefore, the second (n/2 x n) sequence set is also made up of either even or odd numbers in each column. Since each column is either even or odd numbers but not both, there is no ACI among the sequences of the second (n/2 x n) sequence set. From the proof of theorem A3.2, for any given sequence of {1 2 3... n}, there is always a set of n/2 sequences that satisfies the constraints (A2.1) and (A2.2) with no ACI. Hence, given the second (n/2 x n) sequence set satisfying the constraint (A2.2) with no

ACI, we can always arrange the elements in each column such that the constraint (A2.1) is also satisfied. This completes the proof of part (b) of theorem A3.1.

Proof of Theorem A3.1 Part (c)

From theorem 3.4, the number of ACI of any sequence from other sequences in the sequence matrix that satisfies (A2.1) and (A2.2) = (n-1)*2. Since we have eliminated the ACI among the first n/2 sequences by using the theorem A3.2 to generate the sequence set, the ACI of every sequence in the first (n/2 x n) sequence set can only come from the second sequence set. Similarly, since the second (n/2 x n) sequence set has no ACI among themselves, the ACI of every sequence in the second sequence set can only come from the first sequence set.

Hence, to minimize the ACI of any sequence of the first sequence set from the sequences of the second set is to evenly distribute the 'true' adjacent channels among the n/2 sequences in the second set, and vice versa. This will allow graceful degradation of system due to ACI as more sequences (channels) are being used at the same time. This completes the proof of theorem A3.1 part (c).

A4. Optimum Sequence Matrix

The optimum n x n sequence matrix is displayed in Fig. A4.1. Any combination of the columns of the optimum sequence matrix still preserves its properties. An optimum sequence matrix of 50 x 50 representing 50 hopping patterns is displayed in Fig. A4.2. Such a sequence matrix will be used in the peer-to-peer wireless system.

column	#1	#2	#3	#4	#5	#6	#7	#8..	#(N-3)	#(N-2)	#(N-1)	N
pattern #1	[1	2	3	4	5	6...			N-3	N-2	N-1	N]
pattern #2	[3	4	5	6	7	8...			N-1	N	1	2]
pattern #3	[5	6	7	8	9	10...			1	2	3	4]
			.	.	.							
			.	.	.							
			.	.	.							
pattern #N/2	[N-1	N	1	2	3	4...			N-5	N-4	N-3	N-2]
pattern #(N/2+1)	[2	3	N	1	N-2	N-1	N-4	N-3...			4	5]
pattern #(N/2+2)	[4	5	2	3	N	1	N-2	N-1...			6	7]
pattern #(N/2+3)	[6	7	4	5	2	3	N	1...			8	9]
			.	.	.							
			.	.	.							
			.	.	.							
pattern #N	[N	1	N-2	N-1	N-4	N-3	N-6	N-5...			2	.3]

Figure A4.1 *Optimum n x n Sequence Matrix*

->1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	
3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	1	2	(0)
5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	1	2	3	4	(0)
7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	1	2	3	4	5	6	(0)
9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	1	2	3	4	5	6	7	8	(0)
11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	1	2	3	4	5	6	7	8	9	10	(0)
13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	1	2	3	4	5	6	7	8	9	10	11	12	(0)
15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	1	2	3	4	5	6	7	8	9	10	11	12	13	14	(0)
17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	(0)
19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	(0)
21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	(0)
23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	(0)
25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	(0)
27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	(0)
29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	(0)
31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	(0)
33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	(0)
35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	(0)
37	38	39	40	41	42	43	44	45	46	47	48	49	50	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	(0)
39	40	41	42	43	44	45	46	47	48	49	50	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	(0)
41	42	43	44	45	46	47	48	49	50	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	(0)
43	44	45	46	47	48	49	50	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	(0)
45	46	47	48	49	50	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	(0)
47	48	49	50	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	(0)
49	50	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	(0)
2*	3*	50	1	48	49	46	47	44	45	42	43	40	41	38	39	36	37	34	35	32	33	30	31	28	29	26*	27*	24	25	22	23	20	21	18	19	16	17	14	15	12	13	10	11	8	9	6	7	4	5	(4)
4	5	2*	3*	50	1	48	49	46	47	44	45	42	43	40	41	38	39	36	37	34	35	32	33	30	31	28*	29*	26	27	24	25	22	23	20	21	18	19	16	17	14	15	12	13	10	11	8	9	6	7	(4)
6	7	4*	5*	2	3	50	1	48	49	46	47	44	45	42	43	40	41	38	39	36	37	34	35	32	33	30	31	28*	29*	26	27	24	25	22	23	20	21	18	19	16	17	14	15	12	13	10	11	8	9	(4)
8	9	6	7	4*	5*	2	3	50	1	48	49	46	47	44	45	42	43	40	41	38	39	36	37	34	35	32	33	30*	31*	28	29	26	27	24	25	22	23	20	21	18	19	16	17	14	15	12	13	10	11	(4)
10	11	8	9	6*	7*	4	5	2	3	50	1	48	49	46	47	44	45	42	43	40	41	38	39	36	37	34	35	32	33	30*	31*	28	29	26	27	24	25	22	23	20	21	18	19	16	17	14	15	12	13	(4)
12	13	10	11	8	9	6*	7*	4	5	2	3	50	1	48	49	46	47	44	45	42	43	40	41	38	39	36	37	34	35	32*	33*	30	31	28	29	26	27	24	25	22	23	20	21	18	19	16	17	14	15	(4)
14	15	12	13	10	11	8*	9*	6	7	4	5	2	3	50	1	48	49	46	47	44	45	42	43	40	41	38	39	36	37	34	35	32*	33*	30	31	28	29	26	27	24	25	22	23	20	21	18	19	16	17	(4)
16	17	14	15	12	13	10	11	8*	9*	6	7	4	5	2	3	50	1	48	49	46	47	44	45	42	43	40	41	38	39	36	37	34*	35*	32	33	30	31	28	29	26	27	24	25	22	23	20	21	18	19	(4)
18	19	16	17	14	15	12	13	10*	11*	8	9	6	7	4	5	2	3	50	1	48	49	46	47	44	45	42	43	40	41	38	39	36	37	34*	35*	32	33	30	31	28	29	26	27	24	25	22	23	20	21	(4)
20	21	18	19	16	17	14	15	12	13	10*	11*	8	9	6	7	4	5	2	3	50	1	48	49	46	47	44	45	42	43	40	41	38	39	36*	37*	34	35	32	33	30	31	28	29	26	27	24	25	22	23	(4)
22	23	20	21	18	19	16	17	14	15	12*	13*	10	11	8	9	6	7	4	5	2	3	50	1	48	49	46	47	44	45	42	43	40	41	38	39	36*	37*	34	35	32	33	30	31	28	29	26	27	24	25	(4)
24	25	22	23	20	21	18	19	16	17	14	15	12*	13*	10	11	8	9	6	7	4	5	2	3	50	1	48	49	46	47	44	45	42	43	40	41	38*	39*	36	37	34	35	32	33	30	31	28	29	26	27	(4)
26	27	24	25	22	23	20	21	18	19	16	17	14*	15*	12	13	10	11	8	9	6	7	4	5	2	3	50	1	48	49	46	47	44	45	42	43	40	41	38*	39*	36	37	34	35	32	33	30	31	28	29	(4)
28	29	26	27	24	25	22	23	20	21	18	19	16	17	14*	15*	12	13	10	11	8	9	6	7	4	5	2	3	50	1	48	49	46	47	44	45	42	43	40*	41*	38	39	36	37	34	35	32	33	30	31	(4)
30	31	28	29	26	27	24	25	22	23	20	21	18	19	16*	17*	14	15	12	13	10	11	8	9	6	7	4	5	2	3	50	1	48	49	46	47	44	45	42	43	40*	41*	38	39	36	37	34	35	32	33	(4)
32	33	30	31	28	29	26	27	24	25	22	23	20	21	18	19	16*	17*	14	15	12	13	10	11	8	9	6	7	4	5	2	3	50	1	48	49	46	47	44	45	42*	43*	40	41	38	39	36	37	34	35	(4)
34	35	32	33	30	31	28	29	26	27	24	25	22	23	20	21	18*	19*	16	17	14	15	12	13	10	11	8	9	6	7	4	5	2	3	50	1	48	49	46	47	44	45	42*	43*	40	41	38	39	36	37	(4)
36	37	34	35	32	33	30	31	28	29	26	27	24	25	22	23	20	21	18*	19*	16	17	14	15	12	13	10	11	8	9	6	7	4	5	2	3	50	1	48	49	46	47	44*	45*	42	43	40	41	38	39	(4)
38	39	36	37	34	35	32	33	30	31	28	29	26	27	24	25	22	23	20*	21*	18	19	16	17	14	15	12	13	10	11	8	9	6	7	4	5	2	3	50	1	48	49	46	47	44*	45*	42	43	40	41	(4)
40	41	38	39	36	37	34	35	32	33	30	31	28	29	26	27	24	25	22	23	20*	21*	18	19	16	17	14	15	12	13	10	11	8	9	6	7	4	5	2	3	50	1	48	49	46*	47*	44	45	42	43	(4)
42	43	40	41	38	39	36	37	34	35	32	33	30	31	28	29	26	27	24	25	22*	23*	20	21	18	19	16	17	14	15	12	13	10	11	8	9	6	7	4	5	2	3	50	1	48	49	46*	47*	44	45	(4)
44	45	42	43	40	41	38	39	36	37	34	35	32	33	30	31	28	29	26	27	24	25	22*	23*	20	21	18	19	16	17	14	15	12	13	10	11	8	9	6	7	4	5	2	3	50	1	48*	49*	46	47	(4)
46	47	44	45	42	43	40	41	38	39	36	37	34	35	32	33	30	31	28	29	26	27	24*	25*	22	23	20	21	18	19	16	17	14	15	12	13	10	11	8	9	6	7	4	5	2	3	50	1	48*	49*	(4)
48	49	46	47	44	45	42	43	40	41	38	39	36	37	34	35	32	33	30	31	28	29	26	27	24*	25*	22	23	20	21	18	19	16	17	14	15	12	13	10	11	8	9	6	7	4	5	2	3	50*	1	(3)
50	1*	48	49	46	47	44	45	42	43	40	41	38	39	36	37	34	35	32	33	30	31	28	29	26*	27*	24	25	22	23	20	21	18	19	16	17	14	15	12	13	10	11	8	9	6	7	4	5	2	3	(3)

The adjacent channels of the first sequence are marked by * and the total number of adjacent channels contained in each sequence is shown in bracket at the right most column.

Figure A4.2 *Optimum 50 x 50 Sequence Matrix*

Appendix B

GENERATION OF THE OPTIMUM HOPPING SEQUENCES FOR THE PEER-TO-PEER WIRELESS SYSTEM

B1. Objective

Given n distinct frequencies {1,2,3,... ,n}, generate n hopping sequences of length n with:

(a) each frequency in every hopping sequence occurring no more than once,

(b) no co-channel interference, and

(c) minimum adjacent channel interference.

B2. Optimum Sequence matrix

These n hopping sequences can be represented by an n x n sequence matrix with each row corresponding to a hopping sequence and each column corresponding to the frequencies of all the sequences at a particular time instance.

From theorem A3.1 in Appendix A, the optimum sequence matrix (nxn) has the following properties:

(a) the first half of the sequence matrix (n/2 x n) has no ACI among themselves while satisfying the constraints (A2.1) and (A2.2),

(b) the second half of the sequence matrix (n/2 x n) has no ACI among themselves while satisfying the constraints (A2.1) and (A2.2),

(c) The ACI of every sequence in the first half of the sequence matrix is evenly distributed among the sequences in the second half of the sequence matrix, and vice versa.

B3. Generating the Optimum Sequence Matrix

A procedure to generate the optimum sequence matrix is as follows.

(1) Use theorem A3.2 from Appendix A to generate the first n/2 sequence set as follows:

'For a given sequence {1 2 3... n} of any arranged order, where n is even, a set of n/2 sequences can be generated by rotating 2 positions from the previous sequence.'

(2) Generate the second n/2 sequence set using the method in (1) while minimizing the adjacent channel interference of the sequences of 1 set from those of the other set.

(3) Combine the 2 sets of n/2 sequences of length n to form the n x n sequence matrix.

(B3.1) Generating the First n/2 Sequence Set

The first n/2 sequence set can be generated by taking an arbitrary sequence of {1 2 3... n} of any arranged order and using the method stated in theorem A3.2.

(B3.2) Generating the Second n/2 Sequence Set

While the first n/2 sequence set can be generated very easily, the second n/2 sequence set requires the additional constraint that the adjacent channel interference of any sequence from the first set being minimized.

From theorem A3.4 in Appendix A, the total number of 'true' adjacent channels of any sequence from the other sequences in the matrix = (n-1)*2. Therefore, the objective of minimizing the adjacent channel interference becomes distributing the (n-1)*2 adjacent channels of each sequence in the first n/2 sequence set as evenly as possible among the sequences in the second n/2 sequence set, and vice versa. This implies that each of the n/2 sequences will have $\frac{(n-1)*2}{n/2} = \left\lfloor 4-\frac{4}{n} \right\rfloor$ or $\left\lfloor 4-\frac{4}{n} \right\rfloor$ +1 adjacent channels of the particular hopping sequence where $\lfloor x \rfloor$ = the largest integer value smaller than or equal to x. For n=50, each sequence in the second n/2 sequence set will mostly have 4's but not greater than 4 and some 3's but not smaller than 3 adjacent channels of any sequence in the first n/2 sequence set.

One method of generating the second n/2 sequence set that satisfies theorem A3.1 in Appendix A is as follows.

> For any particular sequence in the first n/2 sequence set, select the adjacent channels of that sequence and place them diagonally on the second n/2 sequence set such that there are no more than 4 adjacent channels in any row.

For example, when n = 14 and the first sequence in the first n/2 sequence set = [1 2 3 4 5 6 7 8 9 10 11 12 13 14], then the first n/2 sequence set is:

[1	2	3	4	5	6	7	8	9	10	11	12	13	14]
[3	4	5	6	7	8	9	10	11	12	13	14	1	2]
[5	6	7	8	9	10	11	12	13	14	1	2	3	4]
[7	8	9	10	11	12	13	14	1	2	3	4	5	6]
[9	10	11	12	13	14	1	2	3	4	5	6	7	8]
[11	12	13	14	1	2	3	4	5	6	7	8	9	10]
[13	14	1	2	3	4	5	6	7	8	9	10	11	12]

The second n/2 sequence set is first constructed using the adjacent channels of the first sequence:

[2	3							8	9				]
[		2	3					10	11				]
[		4	5							10	11		]
[				4	5					12	13		]
[				6	7							12	13]
[						6	7					14	1*]
[14*	1					8	9						]

* not adjacent channel but treated as 'wrap-around' adjacent channels

There are no more than 4 adjacent channels in any row while satisfying the constraints (A2.1) and (A2.2). Then adding the adjacent channels of the second sequence:

[2	3					**10**	**11**						]
[**4**	**5**							10	11				]
[		4	5					**12**	**13**				]
[		**6**	**7**							12	13		]
[				6	7					**14**	**1**		]
[				**8**	**9**							14	1]
[						8	9					**2**	**3**]

* Bold numbers indicate new entries in the sequence set.

Again, there are no more than 4 adjacent channels in any row. This process is repeated until all entries in the sequence set have been filled.

B4. Conclusion

Generating n optimum hopping sequences of length n can be achieved by generating and combining two n/2 sequence sets. The first n/2 sequence set can be generated by using theorem A3.1 of Appendix A. The second n/2 sequence set can be generated by evenly spreading the 'true' adjacent channels of the sequences of the first n/2 sequence set. The resulting sequence matrix eliminates the co-channel and minimizes the adjacent channel interference among the hopping sequences.