# PERFORMANCE EVALUATION AND ENHANCEMENT OF RAP PROTOCOL FOR OFDM-BASED WIRELESS LAN

By

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# Abstract

Because of the scarce transmission capacity of radio channels, an efficient Medium Access Control (MAC) protocol is needed to coordinate the activities of the Mobile Nodes (MNs) that coexist in a wireless Local Area Network (LAN). The design of efficient MAC protocols has become an important research activity.

In this thesis, one specific class of MAC protocol, named as Randomly Addressed Polling (RAP), is investigated. Our purpose is to analyze the performance of RAP protocol at the MAC layer, and to propose and evaluate some protocol enhancements. Considering the limitations to the collision resolution capability of the protocol, we propose a new signaling mechanism based on the signal constellation scheme to increase the number of random addresses. In addition, we propose a simple service differentiation mechanism based on the restriction on accessible random addresses for different priority classes to implement Quality of Service (QoS) guarantees for the protocol. Finally, we propose a new two-dimensional Markovian model to analyze the protocol performance.

Comparisons of our analytical results with those from OPNET software simulations demonstrate that our model is accurate in predicting system throughput, packet delay, and the expected number of active users. Using our model, we evaluate the system performance of the protocol, showing that the new signaling mechanism significantly improves the collision resolution capability of the protocol for both perfect and imperfect channel conditions. Our results also indicate that our service differentiation mechanism can offer effective service differentiation for different priority classes, and can also improve the collision resolution capability of the protocol.

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| | | |
|---|---|---|
| ACK | — | Acknowledgement |
| BPSK | — | Binary Phase Shift Keying |
| BS | — | Base Station |
| CDMA | — | Code Division Multiple Access |
| CSMA | — | Carrier Sense Multiple Access |
| CSMA/CA | — | Carrier Sense Multiple Access with Collision Avoidance |
| CSMA/CD | — | Carrier Sense Multiple Access with Collision Detection |
| CPE | — | Common Phase Error |
| CTS | — | Clear-To-Send |
| DAB | — | Digital Audio Broadcasting |
| DCF | — | Distributed Co-ordinate Function |
| DIFS | — | DCF InterFrame Space |
| DSP | — | Digital Signal Processing |
| DVB-T | — | Digital Video Broadcasting - Terrestrial |
| EIFS | — | Extended InterFrame Space |
| GRAP | — | Group Randomly Addressed Polling |
| GRAPO | — | Optimized Group Randomly Addressed Polling |
| ICI | — | Inter-Carrier Interference |
| IDFT | — | Inverse Discrete Fourier Transform |
| IFFT | — | Inverse Fast Fourier Transform |
| IFS | — | InterFrame Space |
| ISDB-T | — | Terrestrial Integrated Services Digital Broadcasting |
| ISI | — | Inter-Symbol Interference |
| PCF | — | Point Co-ordinate Function |

| | | |
|---|---|---|
| PIFS | — | PCF InterFrame Space |
| PN | — | Pseudo-Noise |
| QoS | — | Quality of Service |
| LAN | — | Local Area Network |
| MAC | — | Medium Access Control |
| MMAC | — | Multimedia Mobile Access Communication systems |
| MN | — | Mobile Node |
| NAV | — | Network Allocation Vector |
| OFDM | — | Orthogonal Frequency Division Multiplexing |
| PSK | — | Phase Shift Keying |
| QPSK | — | Quadrature Phase Shift Keying |
| RAP | — | Randomly Addressed Polling |
| RAP-BPSK | — | Randomly Addressed Polling using multitone BPSK modulation |
| RAP-OFDM | — | Randomly Addressed Polling using OFDM |
| R-GRAP | — | Reserved Group Randomly Addressed Polling |
| R-RAP | — | Reserved Randomly Addressed Polling |
| RTS | — | Request-To-Send |
| SIFS | — | Short InterFrame Space |
| SNR | — | Signal to Noise Ratio |
| TDD | — | Time Division Duplex |
| TDMA | — | Time Division Multiple Access |
| T-RAP | — | TDMA-Based Randomly Addressed Polling |
| WIND-FLEX | — | Wireless INDoor FLEXible high bitrate modem architecture |

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# Chapter 1

# INTRODUCTION

Mobile computing is becoming popular in today's information-driven world, and the Internet and wireless worlds are expected to merge over the next few years. With the emergence of 2.5G and 3G cellular networks, cellular technologies can provide wireless data communications service with data rate up to 2 Mbps. However, these data rates pale in comparison to the data rate of 54 Mbps offered by the wireless LAN technology. Therefore, wireless LAN technology has gained preference in the wireless industry and has expanded exponentially over the past several years. It is one of the fastest growing segments of today's communications industry.

A wireless network consists of a community of wireless devices, referred as mobile nodes (MNs) in this thesis. Each MN usually operates in half-duplex mode, in which transmission and reception are multiplexed in time division duplex (TDD) manner. Wireless LANs have two types of network topologies, namely centralized or infrastructured topology, and distributed or ad-hoc topology. In a centralized topology (Figure 1.1), a MN communicates with a non-mobile device, base station (BS). The BS serves as a bridge or router for the network. On the other hand, a distributed topology (Figure 1.2) has no destined device to serve as a bridge or router. All MNs in the network are connected dynamically in an arbitrary manner. Each MN functions as a router which discovers and maintains routes to other MNs in the network.

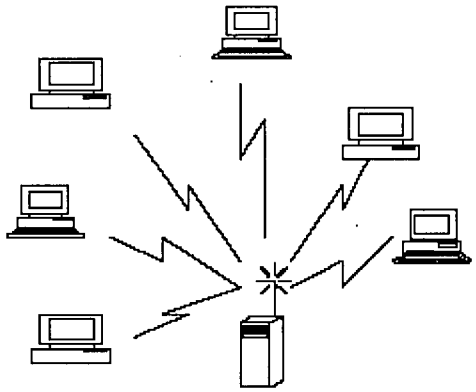


Figure 1.1: Centralized network topology

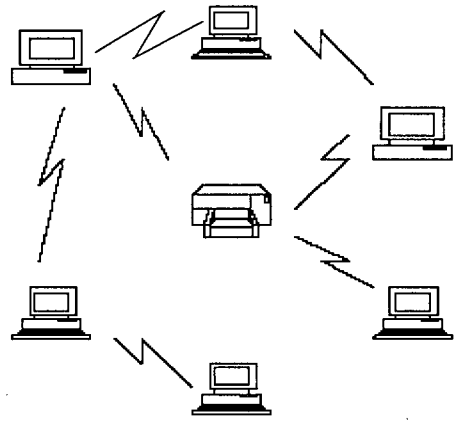


Figure 1.2: Distributed network topology

A wireless LAN is a broadcast network, in which a single wireless channel is shared by a community of BSs and MNs. Data from a MN or BS are broadcast into the channel, and all the other BSs and MNs attached to the channel are required to listen to the transmission. There is potential for transmissions interfering or colliding with one another. Thus, a MAC protocol is employed to co-ordinate the accessibility of the channel in order to avoid or minimize collisions. A MAC protocol plays a crucial role in wireless networks by allowing efficient and fair sharing of the channel.

## 1.1 Motivation for Work

Many MAC protocols have been designed for wireless LANs. Performance of these protocols is typically characterized by metrics such as packet delay, system throughput, fairness, stability, and support for QoS guarantee.

The Randomly Addressed Poll (RAP) was introduced by Chen [23] in 1993 as a possible candidate for the IEEE 802.11 MAC protocol, but it was not selected by the IEEE 802.11 committee. However, the protocol was chosen for the IEEE 802.14 uplink MAC protocol [42].

RAP is a contention-based protocol for centralized networks. A key element of the protocol is the orthogonal random address transmission mechanism, which is a collision resolution mechanism for uplink transmissions. This mechanism enables effective uplink transmission with relatively high system throughput and low packet delay.

Our research focuses on evaluating and improving the performance of the existing RAP protocol. The existing protocol has relatively small number of random addresses, which offers very limited capability for collision resolution; therefore, when the number of active MNs is large compared to the number of random addresses, the number of successful reservations decreases, resulting in decreased system throughput and increased packet delay. In such case, system instability can occur.

RAP is an efficient MAC protocol for uplink transmission, but it has a shortcoming of instability problem. In this thesis, we proposed a modified RAP protocol to offer enhancement in the number of random addresses.

## 1.2 Background

Typical examples of MAC protocols used in wireless LANs include carrier sense multiple access (CSMA) and polling used in IEEE 802.11 standards, and time division multiple access (TDMA) used in HIPERLAN/2 and Bluetooth standards.

### 1.2.1 CSMA with Collision Avoidance (CSMA/CA)

CSMA/CA [1] is derived from the CSMA protocol with collision detection (CSMA/CD) used in Ethernet technologies. CSMA/CA endeavors to avoid collisions by having each MN monitor for channel vacancy and signal for channel access before actually transmitting. The protocol is composed of a four-way handshaking mechanism, illustrated in Figure 1.3.

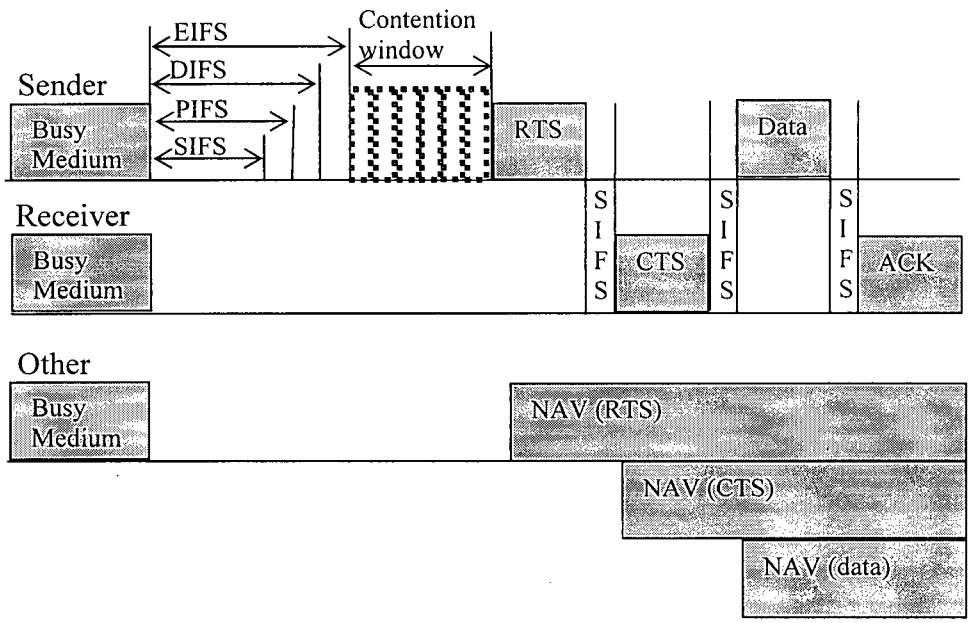



Figure 1.3: Operation of the CSMA/CA

After the end of previous transmission, the active MNs (the MNs which have packet to send), must defer for a certain period called interframe space (IFS). IFS has 4 variations in period length: short IFS (SIFS), PCF IFS (PIFS), DCF IFS (DIFS), and Extended IFS (EIFS). The active MNs with higher priority packets generally choose the IFS with shorter period length to defer. After deferring, the active MNs usually backoff

for a certain number of time slots before initiating the handshake procedure. The number of backoff time slots required depends on the number of retransmission attempts that the MN has tried. If the channel is busy during the deferring or backoff procedures, the MNs normally reschedule the number of backoff slots required and prepare for retrial when the channel is idle again. On the other hand, if the channel remains idle during the procedures, the MN starts the handshake procedure by sending a [request-to-send (RTS)] message to the receiver. Then, the receiver replies to the message with a [clear-to-send (CTS)] message. When the MN receives the [CTS] message, it starts transmitting the data packet to the receiver. Upon successful reception, the receiver responds by sending an [acknowledgement (ACK)] message to the MN. During the handshake procedure, the other MNs adjust their network allocation vectors (NAVs), which are indicators used to mark the duration of current transmission, and wait for the end of the current transmission. Once the transmission is complete, the active MNs will repeat the mechanism described above for channel access.

### 1.2.2 Polling

In polling [1], the BS acts as a central controller and invites the MNs to take turns in accessing the channel. Polling protocol can offer connection-oriented service with QoS guarantee. The operation of the polling protocol is shown in Figure 1.4.

In the polling, the BS polls all MNs in a round-robin manner. The BS uses two types of polling messages in the protocol, namely normal poll and data poll. Normal poll is used if the BS has no downlink packet for the MN, while data poll is used if the BS has

downlink packet. When a MN receives a normal poll, it replies with a [null] message if it has no uplink packet; otherwise, it starts transmitting uplink packet. On the other hand, when a MN receives a data poll, it replies with a [null+ACK] message if it has no uplink packet, or else, it starts transmitting an [ACK] message and uplink packet to the BS. The BS generally responses with an [ACK] message if the uplink transmission is successful.

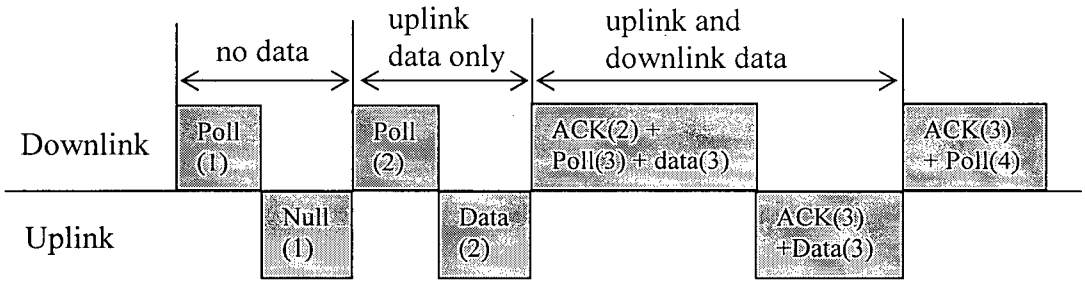



Figure 1.4: Operation of the polling

### 1.2.3 TDMA

TDMA [3] is a demand assignment scheme with contention-based reservations. TDMA operates as shown in Figure 1.5.

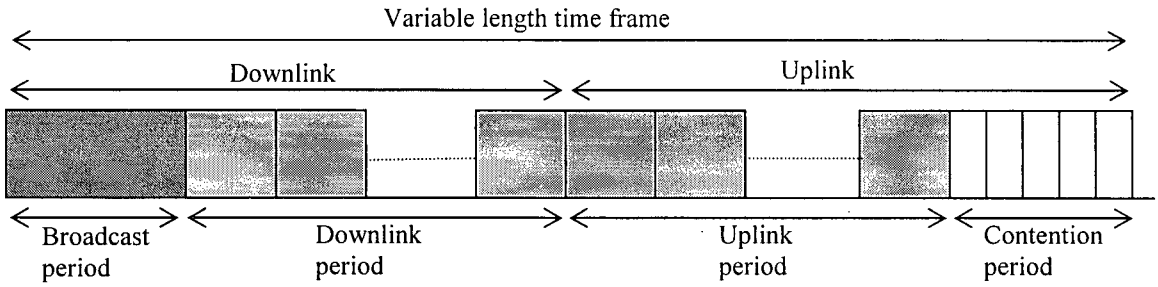



Figure 1.5: Operation of the TDMA

TDMA employs a frame structure, which consists of four periods: broadcast, downlink, uplink, and contention. Each period has a variable length depending on the amount of downlink and uplink traffic scheduled by the BS. The broadcast period is used by the BS to inform all the MNs about the structure of current frame, the schedule for uplink transmission, and the acknowledgement for successful reception of previously sent frames. The downlink period allows the BS to send packets to the MNs, while the uplink period permits the MNs to send packets to the BS, according to the schedule broadcasted. The contention period, composed of many mini-slots, is used by the active MNs to send uplink transmission requests or control information to the BS. During the contention period, the channel is accessed using the slotted Aloha protocol. At the end of the frame, based on the requests received, the BS will schedule the transmissions for the next frame.

## 1.3 Thesis Layout

In this thesis, we propose and evaluate a new random address transmission mechanism to increase the number of random addresses, a simple QoS enhancement to provide service differential mechanism, and a new two-dimensional Markovian model to estimate the performance of RAP protocols.

The thesis is divided into the eight chapters. Our modification of the existing RAP protocol involves the utilization of orthogonal frequency division multiplexing (OFDM) technology. Accordingly, an introduction of OFDM technology is presented in Chapter 2. Chapter 3 describes the operation, existing modifications and features of the RAP protocols. The modification of RAP-OFDM protocol and the QoS enhancement proposed

in this thesis are described in Chapter 4. In order to evaluate the performance of protocols, the two-dimensional Markovian model proposed in this thesis is described in Chapter 5. The performance of both the existing and the modified RAP protocol is evaluated by using our mathematical model and OPNET simulation. Chapter 6 illustrates the scenarios and system parameters employed for the evaluations. Chapter 7 presents the results obtained from the evaluations described in Chapter 6. According to results, the collision resolution capability of the system improves by more than 100% for perfect channel condition, and more than 50% for imperfect channel condition. Furthermore, the results show that the QoS enhancement can provide service differentiation to the protocol, and improve the collision resolution capability of the protocol. A summary of our work, conclusions and suggestion for further work are provided in Chapter 8.

# Chapter 2

# ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING

Orthogonal Frequency Division Multiplexing (OFDM), proposed by Chang [35] in 1966, is a form of digital multi-carrier modulation where the sub-carriers are orthogonal to one another. The orthogonality in OFDM is the result of Digital Signal Processing (DSP) for signal generation. OFDM is gaining its popularity in wireless digital communications due to its ability to make better use of the spectrum bandwidth, and its ability to alleviate impulsive noise and multipath effects. It is employed in the wireless LAN standards (IEEE802.11a, HIPERLAN/2, WIND-FLEX, and MMAC). In addition, it is chosen for the digital audio and video broadcasting standards (DAB, DVB-T and ISDB-T).

## 2.1 Principle of OFDM

The principle of OFDM [5] is to divide a high bit rate input sequence with bit rate $R$ into $M$ lower bit rate sequences each with bit rate $R/M$. The $M$ sequences are carried by $M$ different sub-carriers and are transmitted to the receiver in parallel with one another. The duration of an OFDM symbol is $T$, and the symbol carried by the $k^{th}$ sub-carrier at time interval $iT$ is $d_k(i)$, where $d_k(i)$ is a sequence of complex-valued baseband symbols.

The sub-carriers in OFDM are located at frequency interval of $\frac{1}{T}$ with each other. The $k^{th}$ sub-carrier has central frequency $f_k$ is calculated as follows:

$$f_k = f_o + \frac{k}{T} \qquad k = 0, 1, 2, \ldots, M\text{-}1 \tag{2.1}$$

where $f_o$ is the central frequency of the sub-carrier with the lowest central frequency.

The $d_k(i)$ are packed in the frequency domain according to the central frequency of the $k^{th}$ sub-carrier. Then, the packed $d_k(i)$ are IDFT modulated. Thus, the output symbol carried for each sub-carrier can be written as follows:

$$s_k(t) = \sum_{h=0}^{M-1} \sum_{i=-\infty}^{\infty} d_h(i) e^{j2\pi f_h (t_k - iT)} p(t_k - iT) \tag{2.2}$$

where $p(t)$ represents a rectangular pulse with duration $T$ and amplitude 1.

Because of $p(t)$ , the power spectral density $S_k(f)$ of the $k^{th}$ sub-carrier is a sinc function with central frequency $f_k$. The spectrum of each sub-carrier can be written as follows:

$$S_k(f) = \sum_{k=0}^{M-1} T \operatorname{sinc}^2 (f - f_k) T \tag{2.3}$$

The overlapping of sub-carriers' spectra in the OFDM is shown in Figure 2.1.

Because of IDFT implementation, individual sub-carriers in OFDM are packed orthogonally in the frequency domain. This implementation allows different sub-carriers to overlap one another without causing interference to adjacent sub-carriers; therefore, high spectral efficiency is achieved. This implementation also enables each OFDM

symbol to have a long symbol period that allows OFDM to be more robust to impulse noise and fast channel fading.

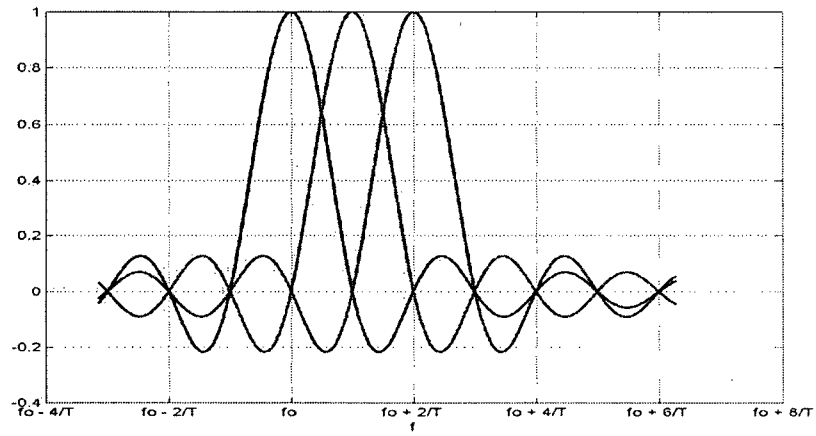



Figure 2.1: Sub-carrier overlapping spectra in OFDM

## 2.2 OFDM Transmitter

The basic building block for an OFDM transmitter [6] contains a serial-to-parallel converter, sub-carrier modulators, an IFFT transformer, a guard time adder, rectangular pulse generators and a parallel-to-serial converter (Figure 2.2).

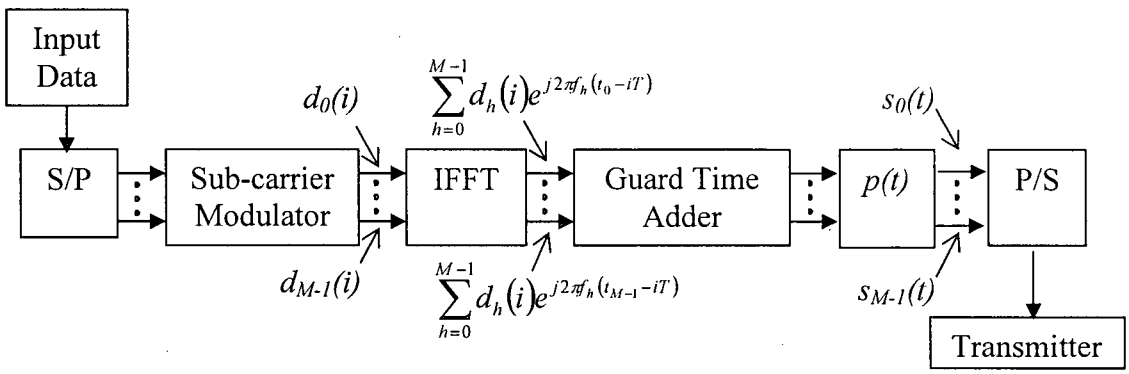



Figure 2.2: Basic building blocks for an OFDM transmitter

In an OFDM transmitter, the input data bits are sent through a serial-to-parallel converter that takes in the serial data bits and outputs the bits in parallel. Data bits output from different output ports of the converter will be carried by different sub-carriers later on. The outputs of the serial-to-parallel converter will be modulated in the sub-carrier modulators using BPSK, QPSK, 16-QAM, or 64-QAM signal constellation scheme. In loading adaptive OFDM, different signal constellation schemes will be used for different serial-to-parallel converter output ports depending on efficient power allocation or effective data rate. Afterwards, the modulated signals will be packed in the frequency domain with fixed sub-carrier central frequency. The signals are sent to an IDFT transformer for IDFT operation. In order to reduce implementation complexity, instead of using IDFT implementation, Inverse Fast Fourier Transform (IFFT) implementation is generally employed in wireless standards. After that, a guard time is added to the time-domain symbols in order to combat intersymbol interference (ISI) between OFDM symbols. Finally, the symbols will go through rectangular pulse generators, a parallel-to-serial converter and a transmitter for transmission.

## 2.3 OFDM Receiver

The basic building block for an OFDM receiver [6] does the reverse of what is done at the transmitter. It includes a serial-to-parallel converter, matched filters, sub-carrier demodulators, a FFT transformer, a guard time remover, and a parallel-to-serial converter (Figure 2.3).

In an OFDM receiver, the received symbols will go through a serial-to-parallel converter and matched filters. Afterwards, the guard time for each parallel symbol sequence will be removed in a guard time remover. Then, the symbol sequence will pass through a FFT transformer to convert the symbols back to the frequency domain signals. After that, the signals will be demodulated into data bits by the sub-carrier demodulators. Finally, the data bits will go through a parallel-to-serial converter and will be sent to the upper layer.

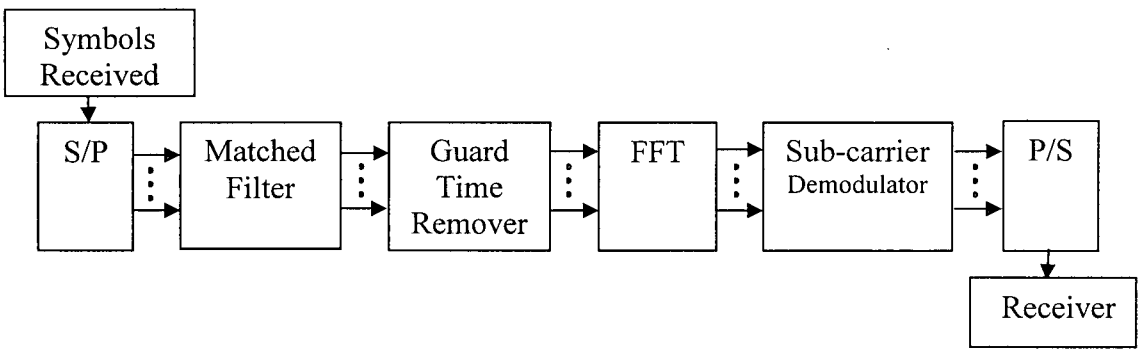



Figure 2.3: Basic building blocks for an OFDM receiver

## 2.4 Distortions in OFDM

OFDM is not entirely immune to the effects of multi-path channel fading. Since each individual sub-carrier is a narrowband signal, the cause of error floor in OFDM is the flat fading on individual sub-carriers. In addition to multi-path channel fading,

hardware imperfections would also affect the quality of OFDM symbols. Distortions, such as, ISI, phase noise, carrier frequency offset and time offset, can cause orthogonality loss, affecting the performance of OFDM system.

### 2.4.1 Intersymbol Interference (ISI)

ISI [6] is caused by either the multi-path delay of the channel or the memory component of the receiver, such as, its filter. ISI corrupts OFDM symbols, making them impossible to be converted back to their original form.

### 2.4.2 Phase Noise

Phase noise [6, 7] is created by the local oscillator when the receiver converts an input frequency to an intermediate frequency before symbol demodulation. Phase noise is modeled as a Wiener process, a continuous path Brownian motion with zero mean and variance of $2\pi BT$, where B is the 3 dB linewidth of Lorentzian power spectrum density for the oscillator. Phase noise causes common phase error (CPE) and inter-carrier interference (ICI), degrading the system performance.

### 2.4.3 Carrier Frequency and Time Offset

Carrier frequency and time offsets [6] are generated by improper synchronization between transmitter and receiver. Carrier frequency offset destroys the orthogonality of the sub-carriers, causing ICI and CPE. Carrier time offset means that the estimation of the starting position of an OFDM symbol is incorrect, resulting in ISI. Both offsets can severely decrease system performance.

## 2.5 Synchronization in OFDM

Different protective measures are designed to reduce the effects of distortions.

### 2.5.1 Guard Time

As mentioned above, one of the protective measures used to eliminate ISI is guard time insertion [6]. Guard time can be inserted by padding trailing zeros or by using cyclic prefix technique. Padding trailing zeros can assure channel-independent retrieval of a transmitted symbol even when channel nulls are located on the sub-carrier. On the other hand, the cyclic prefix technique can make the time-domain symbol appear to be periodic to the channel and it can clear the channel memory at the end of each input. This technique makes the successive transmissions independent. A long guard time can completely eliminate ISI, but the throughput of the system will be reduced.

### 2.5.2 Pilot tone

Another protective measure for channel estimation and correction is to employ sub-carriers to carry reference pilot tones [14, 15]. In the transmitter, the sub-carriers carrying data symbols and the sub-carriers carrying pilot tones are packed together in the frequency domain and are fed into the IFFT transformer. In the receiver, the data symbols and the pilot tones will be extracted from the FFT transformer. The channel effect is then estimated in the frequency domain by comparing the received pilot tones with the locally stored reference pilot tones.

There are two types of pilots in OFDM – scattered and continuous pilots. Scattered pilots occupy different carrier positions on each OFDM symbol, with a periodicity of 4 symbols. They can provide time instants and channel condition for specific sub-carriers. Time interpolation is applied to obtain channel estimation for every time instant and sub-carrier. On the other hand, continuous pilots are inserted in identical fixed positions for every OFDM symbol. They are used to estimate CPE.

### 2.5.3 Training Sequence

The other protective measure incorporates a training sequence [15, 16]. In the transmitter, a pseudo-noise (PN) sequence is inserted at the beginning of an OFDM symbol in the time domain. In the receiver, the channel condition is estimated using cross correlation of the received PN sequence and the locally stored PN sequence.

### 2.5.4 Blind Channel Estimation

An alternative protective measure involves blind channel estimation [17, 18, 19, 20]; this, also known as cyclostationarity, involves the use of the redundancy introduced by the cyclic prefix guard time to estimate the channel condition. Cyclostationarity can be induced at the receiver by oversampling the received waveform. Also, it can be induced at the transmitter by means of an encoder which encodes the OFDM symbols using repetition codes or analysis-synthesis (or precoding) filterbanks. Blind channel estimation saves bandwidth by avoiding the use of training sequence and pilot tones, but requires complex computations for either correlation matching or for use of a blind subspace algorithm to calculate the wireless channel characteristics. In addition, a long time is needed for the estimation results to converge.

## 2.6 Summary

OFDM is a powerful modulation technique that is robust to multipath channel and impulse noise effects. OFDM also increases spectral efficiency. Advances in DSP technology enables OFDM to be efficiently implemented in hardware even for a large number of sub-carriers, thereby simplifying the practical implementation of OFDM. For the next generation of high-speed wireless networks, OFDM is a cornerstone technology.

# Chapter 3

# RANDOMLY ADDRESSED POLLING PROTOCOL

Following development in 1970 of the ALOHA MAC protocol for digital radio communications, numerous MAC protocols for both wired and wireless networks have been proposed and analyzed, to adapt to the growing demands for real-time services. Complex MAC protocols which include scheduling have been developed to provide system resource management for multimedia data and for QoS guarantees. In addition, with the introduction of new wireless technology, MAC protocols are evolved to adapt to the new technology available. The research of this thesis will focus on the Randomly Addressed Polling (RAP) protocol proposed by Chen [23] in 1993.

## 3.1 Operation of the RAP Protocol

RAP is a centralized contention-based random access protocol. It shares the properties of both the TDMA and polling protocols described in Section 1.2.2 and 1.2.3. As in TDMA, uplink reservation is required in the RAP protocol prior to uplink transmission, but reservations in the RAP protocol are made by random address transmission. Channel access in RAP protocol is coordinated by polling. However, unlike the standard polling protocol, the BS in the RAP protocol only polls the active MNs by means of random addressing.

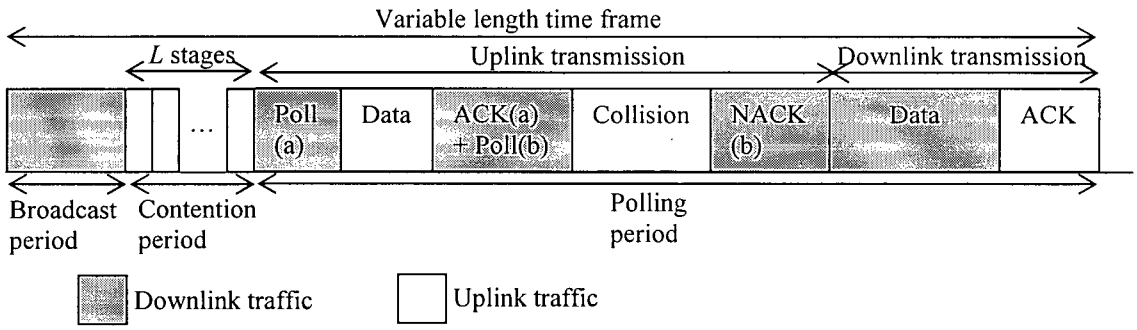



Figure 3.1: Operation of the RAP protocol

The RAP protocol is organized into a time frame structure which can be further divided into 3 periods: broadcast period, contention period, and polling period as shown in Figure 3.1.

For uplink transmission, the 5-way handshaking of basic RAP operates as follow:

1. During the broadcast period, the BS broadcasts network information and [ready to poll] message to all MNs.
2. During the contention period, the active MNs will randomly choose an address from the set of available addresses, and transmit it to the BS. All active MNs will transmit their random addresses to the BS at the same time; thus, all the transmissions will be done orthogonally. All MNs may choose $L$ different addresses and transmit these to the BS in $L$ stages subsequently.
3. The BS listens to all $L$ stages of transmissions from each MN and chooses the stage which contains the most distinct random addresses. Assuming that stage $L'$ is chosen, the BS will then poll each random address received in stage $L'$ subsequently during the polling period.

4. The MN will start uplink data transmission when it is polled by the BS. Collisions may occur if two or more MNs choose the same random address in stage $L'$.
5. The BS will send a [positive ACK] message to the MN if the transmission is received successfully. Otherwise, it will send a [negative ACK] message to the MN. After polling all random addresses received in stage $L'$, the BS will start a new RAP frame by repeating steps 1-5.

Since the downlink transmission is contention-free, the 2-way handshaking for downlink transmission operates as follow:

1. The BS starts downlink transmission when the channel is free.
2. If the MN receives the data successfully, it will reply with a [positive ACK] message.

We will use an example to demonstrate the uplink transmission of the RAP protocol. As shown in Figure 3.2, suppose that we have a RAP system which has an address set {a, b, c}, and works in two stages {1, 2}. For example, there are three MNs {I, II, and III}, in which MN I chooses addresses "a, a" for stage 1 and stage 2 respectively; MN II chooses "a, b"; and MN III chooses "a, b". Then, the BS will receive random address "a" in stage 1, and random addresses "a, b" in stage 2. Since stage 2 contains more distinct random addresses, the BS will poll the MNs using the addresses from stage 2. It will poll address "a", and MN I will start uplink transmission. The BS will reply with [positive ACK] when the transmission finishes. Then, it will poll address "b", and MN II and MN III will transmit at the same time, resulting in a collision. Since a collision occurs, BS will reply with [negative ACK].

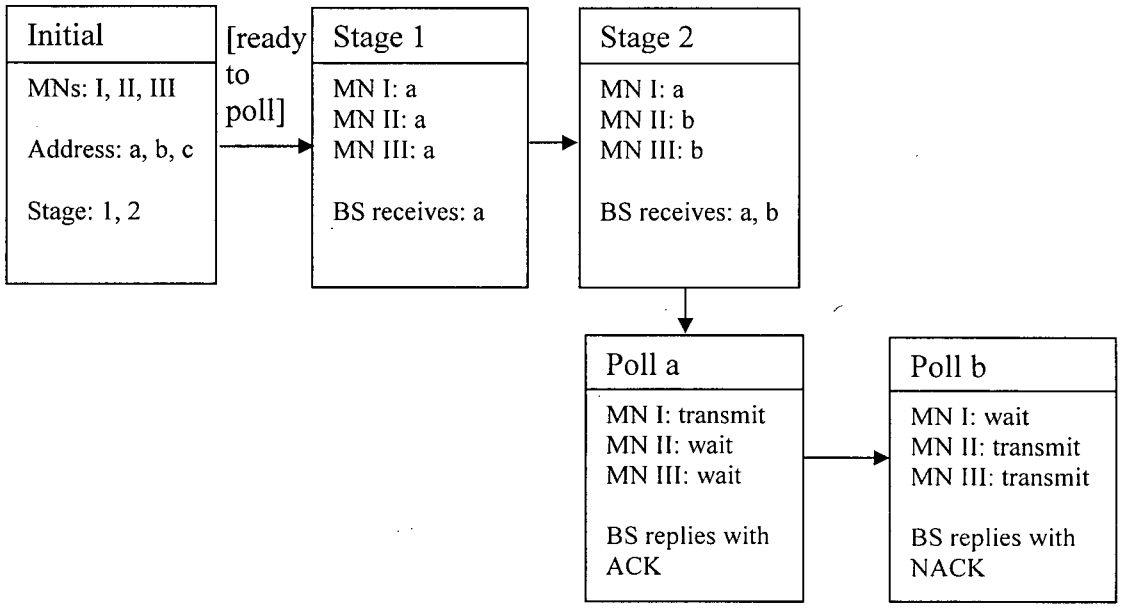



Figure 3.2: Example of RAP operation

## 3.2 Random Address Transmission and Detection

The RAP protocol relies on the orthogonal transmission and detection of random addresses. The orthogonality in random address transmissions is based on the employment of primary prime sequences in code division multiple access (CDMA) modulation technique. According to [23, 40], for a prime sequence with a length of $N$ bits, the number of distinct primary prime sequences can be generated from the sequence is $\sqrt{N}$. For example, with a prime sequence of 25 bits, the 5 distinct primary prime sequences that can be produced are listed as follows.

$C_0 = (10000, 10000, 10000, 10000, 10000)$

$C_1$ = (10000, 01000, 00100, 00010, 00001)

$C_2$ = (10000, 00100, 00001, 01000, 00010)

$C_3$ = (10000, 00010, 01000, 00001, 00100)

$C_4$ = (10000, 00001, 00010, 00100, 01000)

Another approach is to trace the critical frequency components in the following sequences for orthogonal signaling.

$Sequence_1$: 1010101010101010101...

$Sequence_2$: 1001001001001001001...

$Sequence_3$: 1000010000100001000...

$Sequence_4$: 1000000100000010000...

$Sequence_5$: 1111111111111111111...

Since the number of these sequences is very limited, the performance of RAP is restrained.

## 3.3 Strategies Used to Improve the Performance of RAP Protocol

Because of the imperfect performance of RAP protocol, many modifications are proposed to improve its operations.

### 3.3.1 Group Randomly Addressed Polling (GRAP)

A modification of RAP, GRAP, was proposed by Chang and Chen [24] in 1997. GRAP solves the instability problem which occurs in RAP when the traffic load is heavy.

GRAP adapts a super-frame structure which is composed of $M$ RAP frames (see Figure 3.3 where $M = 7$).

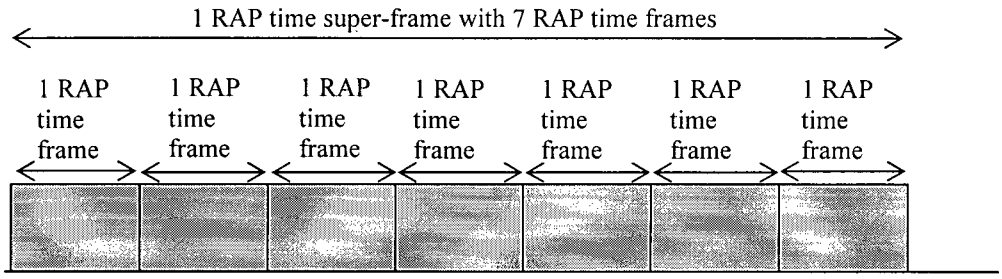



Figure 3.3: Super-frame operation of the GRAP

In GRAP, the [ready to poll] message sent by the BS includes a frame number. Each active MN randomly chooses a frame number and an address. It will transmit its random address to the BS if its frame number matches the frame number of the [ready to poll] message. Then, the BS polls all the random addresses received in current frame. After that, the BS will start the next RAP time frame with next frame number. Eventually, the BS will start a new super-frame when all the time frames in current super-frame are polled.

Since the active nodes are divided into $M$ different groups, the number of collisions in each RAP poll is reduced.

### 3.3.2 Reserved Randomly Addressed Polling (R-RAP)

In order to enable RAP to support real-time services, an alteration of RAP, R-RAP, was published by Lai and Lee [25] in 1998. R-RAP contains the characteristics of the packet reservation multiple access (PRMA) protocol.

In R-RAP, the [ready to poll] message contains the reservation status of all the random addresses. The new active MNs listen to the reservation status and randomly choose an unreserved address from the address set, while each old active MN having a reserved random address will transmit its reserved address to BS. Then, the BS will poll all the random addresses received. In case of successful transmission, the BS will reserve the random address for the MN if the MN requires a QoS service guarantee.

### 3.3.3 Reserved Group Randomly Addressed Polling (R-GRAP)

R-GRAP was published by Chou and Chen [26] in 1995. It is a combination of GRAP and R-RAP described earlier, and it contains all the features of the two versions of RAP.

### 3.3.4 Optimized Group Randomly Addressed Polling (GRAPO)

A modification of R-GRAP, GRAPO, was proposed by Li and Chen [27] in 1994. GRAPO further improves the instability problem in R-GRAP by spreading the number of active MNs evenly among the M frames. Thus, the total number of collisions in the system is further reduced.

### 3.3.5 TDMA-Based Randomly Addressed Polling (T-RAP)

T-RAP was proposed by Nicopolitidis et al. [28] in 2002. T-RAP implements an estimation mechanism to guess the number of active MNs in the network. The operation for uplink transmission of T-RAP is shown in Figure 3.4.

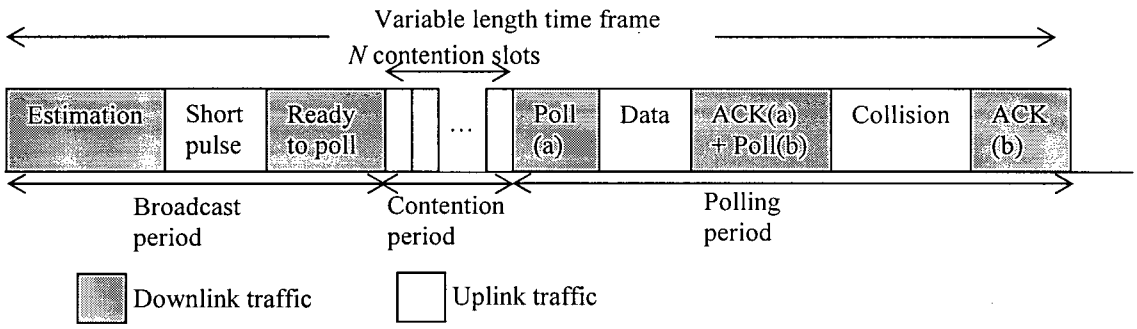



Figure 3.4: Operation of the T-RAP

At the beginning of a RAP cycle, BS sends out an [estimation] message to the MNs, and listens to the replying short pulses from the active MNs. Then, the BS measures the strength of the replying pulses to estimate the number of active MNs, and allocates the appropriate number of contention slots for contention period. Each MN will randomly choose a random address and a contention slot for random address transmission. Therefore, a 7-ways handshaking between BS and MNs is implemented in T-RAP.

### 3.3.6 Randomly Addressed Polling using OFDM (RAP-OFDM)

With the introduction of the new OFDM technology, Chen and Chen [29] proposed a modification on RAP in 2000. Instead of using primary prime sequences, the random address transmission uses the orthogonal sub-carriers in OFDM technology.

The 5-way handshaking in RAP-OFDM is implemented as follow:

1. The BS sends out a [ready to poll] message to all MNs.
2. Each active MN randomly chooses a sub-carrier to transmit a unique tone to the BS.
3. The BS listens to all the sub-carriers and polls the MN identified by its sub-carrier. If two MNs choose the same sub-carrier, a collision occurs and the AP will not poll on that sub-carrier. Collision is detected by measuring the power level of the received sub-carrier.
4. The MN transmits data to BS.
5. The BS will send [positive ACK] message to the MN if the transmission is successful. Otherwise, a [negative ACK] message will be sent. When all sub-carriers with a unique tone are polled, the BS will start another RAP frame by repeating steps 1-5.

There are 48 data sub-carriers and 4 pilot sub-carriers in IEEE802.11a and HIPERLAN/2 standards. Thus, the size of the random address set increases from 5-7 in previous RAP to 48-52 in RAP-OFDM.

## 3.4 Features of RAP protocol

According to [34], RAP can achieve the following performance metrics.

**High Throughput**

According to [23], the uplink throughput of RAP can be as high as 88% without any modification and the downlink throughput is contention-free. If 80% of the traffic is downlink and 20 % of the traffic is uplink, the throughput of the system can be as high as 97%.

**Low Delay**

Since the overhead of the system only includes the [ready to poll] message, the replying random addresses, the polling message and the acknowledgement message, the delay of the system is low.

**Ability to Provide QoS Guarantee**

With the introduction of R-RAP and R-GRAP, the system can offer QoS guarantees to real-time applications by bandwidth reservation.

**Low Power Consumption**

The idle MNs do not need to monitor the BS unless they have data in their buffers and become active. Therefore, power is saved.

**Fairness of Access**

Since the addresses are chosen randomly by MNs from a common list, each MN has a fair chance to access the channel.

**Handoff Ability**

A MN can move to another basic service set by simply answering the [ready to poll] message sent from the new BS and ignoring the [ready to poll] message sent from the old BS. Thus, no hand-off is needed.

## 3.5 Summary

The RAP protocol has been developed over the last decade. Many modifications are published to enable RAP to provide QoS guarantees and to adapt to the new OFDM modulation technology. With the advantage of its features, RAP is introduced to the IEEE 802.11 Working Group and IEEE 802.14 Working Group as a possible candidate for use as a MAC protocol.

# Chapter 4

# MODIFIED RANDOMLY ADDRESSED POLLING PROTOCOL

Due to the restriction of orthogonal transmission, RAP has limited number of random addresses. Therefore, similar to most random access protocols, RAP suffers from the instability problem which occurs under heavy traffic load. When instability arises, the throughput of the system drops rapidly resulting in large packet delay.

Numerous collision resolution algorithms are available to solve the traffic overload problem. One of them is random back-log, recommended in RAP, but this algorithm wastes valuable bandwidth during back-off intervals. Another one is superframing, suggested in GRAP and GRAPO, but the algorithm also wastes bandwidth when idle groups are polled. R-RAP can maintain a steady throughput for reserved traffic, but this algorithm reduces the number of random addresses available for new traffic. Under R-RAP, only reserved traffic can gain access; the unreserved traffic will always be blocked. T-RAP with its estimation mechanism can eliminate the instability problem; however, the 7-ways handshaking mechanism and the contention slots overheads reduce system throughput and increase packet delay. RAP-OFDM with 48-52 random numbers can reduce the effect of the problem, but it is inadequate to handle the busy traffic of a large network with many active MNs.

Since the limited number of random addresses is the main cause for instability, increasing the number of random addresses will resolve the problem. In this thesis, a new address signaling mechanism is proposed to increase the number of addresses.

## 4.1 Proposed Address-Signaling Mechanism

Consider the signaling mechanism of RAP-OFDM depicted in previous chapter. The active MNs mark random addresses by transmitting a tone using one of the sub-carriers in OFDM modulation. An approach is proposed in this thesis to increase the number of addresses by taking the advantage of the orthogonal properties in QPSK signal constellation scheme. Instead of sending the tone using the BPSK signal constellation scheme only, the active MNs can mark the random addresses using either the real part or the imaginary part of the QPSK signal constellation scheme (shown in Figure 4.1). Therefore, the number of random addresses will be doubled if proposed address-signaling mechanism is used.

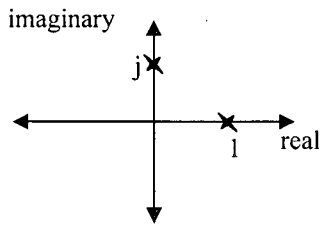



Figure 4.1: Tones used in proposed address signaling scheme

An alternative approach to doubling the number of random addresses is RAP-BPSK [39]. However, the modified RAP-OFDM appears to have implementation advantages over RAP-BPSK. Therefore, we will focus on the modified RAP-OFDM in this thesis. For more details about RAP-BPSK, please refer to the Appendix A.

## 4.2 Implementation of the Modified RAP-OFDM at Physical Layer

The implementation of modified RAP-OFDM involves the addition at the physical layer: a random address selector module on the transmitter side and the random address detector module on the receiver side (see in Figure 4.2).

The random address selector module is composed of a random tone generator which generates one of the two random tones, a zero adder which appends zeros after the random tone to create a 48 or 52 bits block word, and an arithmetic shifter which shifts the location of random tone randomly in the block word. With the operation of the random address selector, a sequence from the set {(1,0,0,...,0), (j,0,0,...,0), (0,1,0,...,0), (0,j,0,...,0),....., (0,0,0,...,1), (0,0,0,...,j)}will be randomly generated.

Because of the linear property of Discrete Fourier Transform, the sequence that the receiver receives is the sum of all the random sequences transmitted by the active MNs, namely, (a+bj,c+dj,...,y+zj) where a, b, c, d, y and z are real numbers. A random address detector is needed to extract the contents of each sub-carrier. The random address detector module is composed of a sub-carrier selector which selects the information from the 48 or 52 sub-carriers, a complex number divider which divides the information into real and imaginary parts, and power detectors which measure the power level of the random tones. After the action of random address detector, the contents from the sub-carriers will be extracted into the sequences{(a,0,...,0), (bj,0,...,0), (0,c,...,0), (0, dj,...,0)....., and ( 0,0,...zj)}. Finally, these results will be sent to the polling scheduler which decides the polling sequence for the RAP cycle.

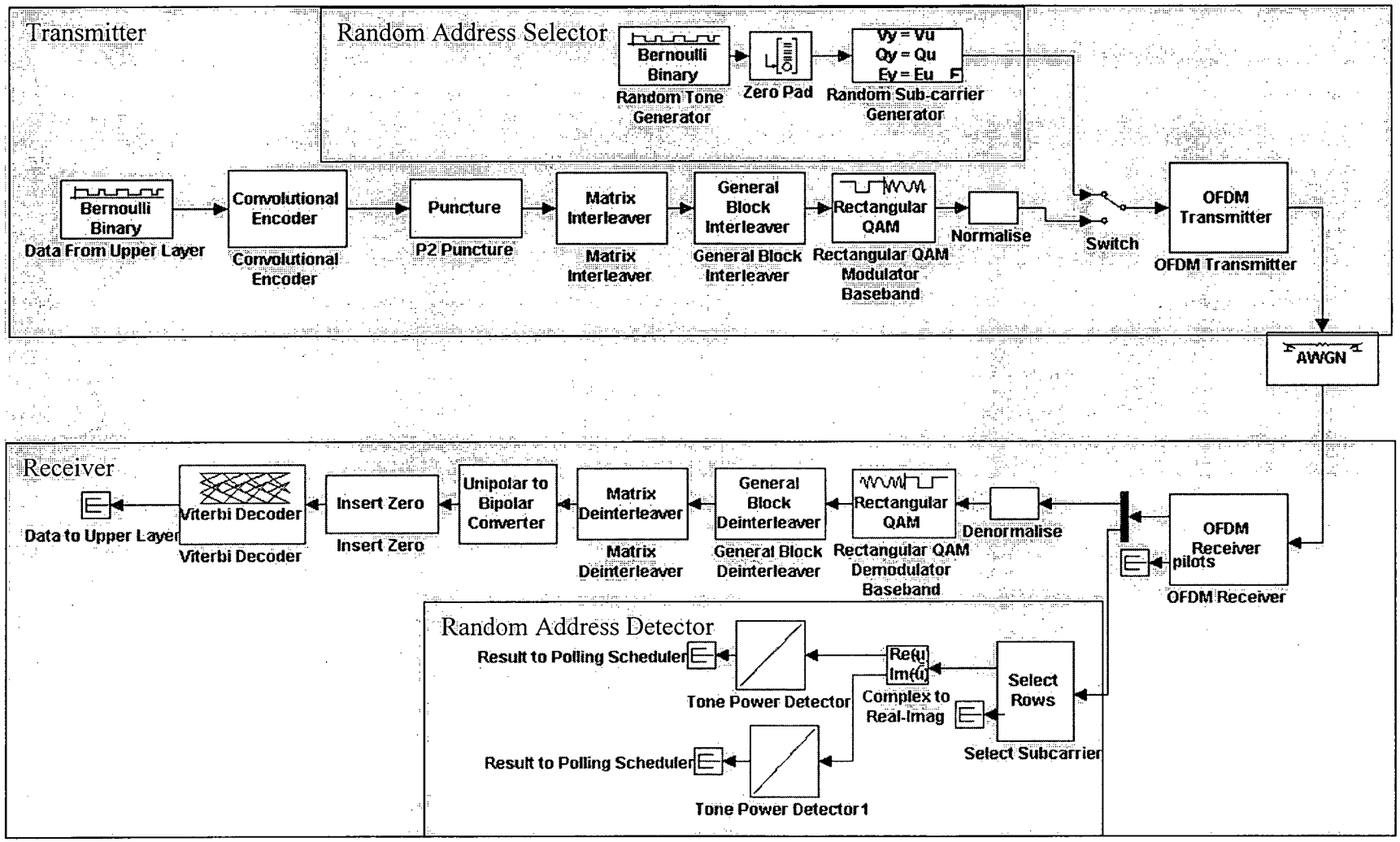



Figure 4.2: Hardware or software implementation of modified RAP-OFDM

## 4.3 Modified RAP-OFDM Protocol

With the modification of address-signaling algorithm, the 5-way handshaking for uplink transmission in the modified RAP-OFDM is implemented as follows:

1. The BS sends out a [ready to poll] message to all MNs.
2. Each active MN selects a random tone, and randomly chooses a sub-carrier for transmission of the tone to the BS. In another words, the MNs will randomly generate one of the sequence from the following set {(1,0,0,…,0), (j,0,0,…,0), (0,1,0,…0), (0,j,0,…,0),……, (0,0,0,…,1), (0,0,0,…,j)} and broadcast it to the BS.
3. The BS listens to all sub-carriers and polls the MN identified by the random tone and the sub-carrier that the MN chooses. If two MNs choose the same combination of random tone and sub-carrier, a collision occurs and the BS will not poll that random tone carried by the sub-carrier. Collision is detected by measuring the power level of the random tone carried sub-carrier.
4. The MN transmits data to the BS.
5. The BS will send a [positive ACK] message to the MN if the transmission is successful. Otherwise, a [negative ACK] message will be sent. If the [positive ACK] or [negative ACK] message is not received by the MN, then the MN will consider the transmission is failed and will re-transmit in the next RAP frame. When all the sub-carriers with a distinctive random tone are polled, the BS will start another RAP frame by repeating 1-5.

## 4.4 QoS Enhancement for the Modified RAP-OFDM Protocol

It is important for a MAC protocol to provide QoS support for real-time services. In this section, we propose a simple modification to enable the protocol to offer service differentiation to different priority classes by access priority.

In the proposed QoS modification, the differentiation mechanism is implemented by limiting the number of random addresses available for lower priority classes in order to ensure that higher priority classes have better chance for successful reservations in most cases. The restriction can be set differently for different classes: the higher the priority classes the more random addresses that are available for random address reservation.

This proposed QoS modification has an advantage of simplicity. It does not require any complex hardware or software implementation.

## 4.5 Key Design Issues, and Solutions

In actual implementation, the quality of OFDM signals suffers from the effects of ISI, phase noise, carrier frequency offset and time offset, resulting in signal strength attenuation and phase error. In this section, the problems encountered while formulating the modified RAP-OFDM protocol are discussed.

### 4.5.1 Signal Strength Attenuation

Both RAP-OFDM and the modified RAP-OFDM protocols rely on the power level of the tones carried by the sub-carriers to determine whether a collision has occurred. The BS will avoid polling MNs which issued the collided tones to improve the chance of successful polling. If the power level is detected incorrectly, the BS will either poll MNs with collided tones if the power level of the tones is similar to that of a non-collided tone, or will ignore these MNs if their power level is similar to that of a MN which produced a collided tone or a null tune. Therefore, the overall throughput will be reduced because of polling MNs associated with collided tones, and the overall delay for uplink traffic will be increased by neglecting non-collided tones. More RAP frames are then required for the successful detection. Signal strength attenuation is produced primarily by ISI and ICI (described in Section 2.4).

### 4.5.2 Phase Error

Phase error does not affect the performance of RAP-OFDM, but it affects that of the modified RAP-OFDM. Since random addresses are determined by signal constellation, if phase error is added to the signals, the wrong random addresses will be detected. This reduces the system throughput for false polling, and increases packet delay for defective detection. CPE is the main cause for phase error (described in Section 2.4).

### 4.5.3 Possible Solutions

One solution for the problem of ISI is to use padding zeros as guard time (described in Section 2.5).

Another solution for the problem of ICI and CPE is to employ transmitters and receivers with better oscillator performance in order to reduce the effects of phase noise, carrier frequency offset and time offset [7].

The other solution for signal strength control is open loop power control [21]. Based on the fact that the channel statistics for uplink and downlink channels are similar in time division duplex when the same frequency band is used, a solution to solve this problem is to employ open loop power control using the [ready to poll] message sent from BS to MNs. The [ready to poll] message will contain information about the transmission power used by the BS. According to the information contained in the message and the power level of the message received, the active MNs adjust the transmission power level for random address signaling. However, this method cannot correct all the signal strength variations and it only works in a slow-fading environment.

One solution to avoid polling MNs whose signals have collided or null random addresses is to employ the efficient polling method suggested in [33]. The operation of the method is shown in Figure 4.3 where the [polling] message contains two addresses: one for data polling and the other for registration polling. The data polled MN will transmit data packet using a strong signal, while the MN polled by the registration polling will send out a jamming tone using a weak signal. Taking the advantage of power capture

effect, the BS will receive the data packet successfully. After receiving the packet, the BS will study the jamming tone and decide whether or not the registering MN has packet to send.

In our case, during the polling period, the [polling] message contains two random addresses instead of actual addresses. The operation is basically same as above, but the registration polling will contain the random address number which will be polled next. The BS will study the power level of the jamming tone to decide whether or not the random address number should be polled for data.

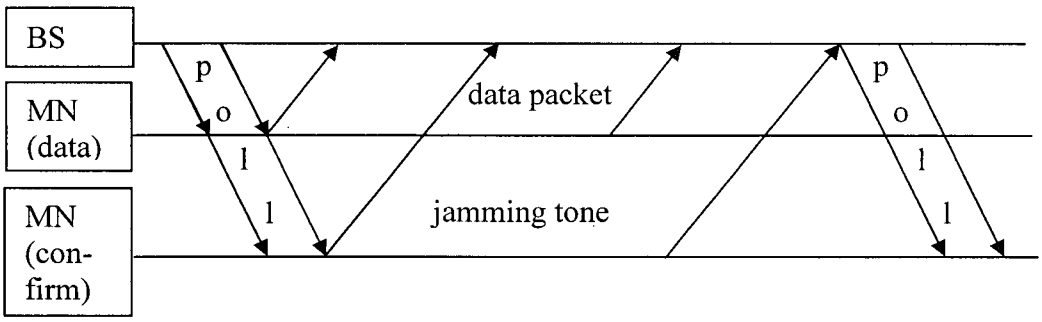



Figure 4.3: Operation of the efficient polling method

## 4.6 Summary

A modified RAP-OFDM protocol is proposed in this chapter. Utilizing the orthogonal properties of the QPSK signal constellation, the modified RAP-OFDM can double the number of random addresses for RAP-OFDM without reducing the system throughput. The modified protocol shares all the features of the original protocol. Although the performance of the modified RAP-OFDM is affected by the wireless

channel impairments, these channel effects can be reduced with the help of channel estimation techniques.

A simple QoS enhancement is also proposed in this chapter. The enhancement can provide a differential access priority mechanism.

# Chapter 5

# PROPOSED MATHEMATICAL MODEL FOR SYSTEM PERFORMACE EVALUATION

In order to compare the system performance of the RAP-OFDM and the modified RAP-OFDM protocols, a mathematical estimation based on a two-dimensional Markovian process is developed. In this chapter, we derive an approximate model for performance analysis.

Since the downlink traffic in RAP is contention-free, we will only focus on the uplink traffic in the analysis. If downlink traffic is also considered, the uplink system throughput will decrease, but both the uplink packet delay and the expected number of active users will increase. However, for the overall system, the system throughput and the expected number of active users will increase, while the packet delay will decrease.

For the purpose of reducing the complexity of the analysis, the following assumptions are made in our model:

1. Fixed sized packets arrive at each MN with Poisson arrivals with mean rate $\lambda$ packets/sec.
2. The RAP frame format, with specific timing requirements, is defined in Figure 5.1.
3. Only one packet is allowed to transmit for each successful reservation.
4. If the packet is lost during transmission, the MN is required to make another successful reservation for retransmission.

The variables used in the models are defined in Table 5.1:

| Symbols used | Description |
|---|---|
| $\lambda$ | Mean packet arrival rate at each MN |
| $T_m$ | Time needed for a BS to send [ready to poll] message to MNs + time needed to receive random addresses from active MNs + time needed for packet overheads |
| $T_p$ | Time needed for a BS to send [polling + ACK] or [polling + NACK] or [polling] message to MN + other polling overheads + time needed for packet overheads |
| $T_d$ | time needed for uplink data transmission $= \frac{(packet\_size)}{(data\_rate)}$ |
| $\tau$ | $T_p + T_d$ |
| $N$ | Total number of MNs in the network |
| $n$ | Number of active MNs in each RAP frame |
| $L$ | Input load of the system $= \frac{\lambda \times (packet\_size) \times N}{(data\_rate)}$ |
| $B$ | Buffer size of a MN |
| $b$ | Total number of random addresses |
| $PER$ | Packet error rate |
| $AER$ | Random address error rate (Probability of incorrect random address detection) |
| $DER$ | Decision error rate (Probability of polling null or collided random addresses because of incorrect detection) |
| $SIFS$ | Short interframe space |
| $slot\_time$ | Time required for a single slot transmission |

Table 5.1: Symbols used in mathematical analysis

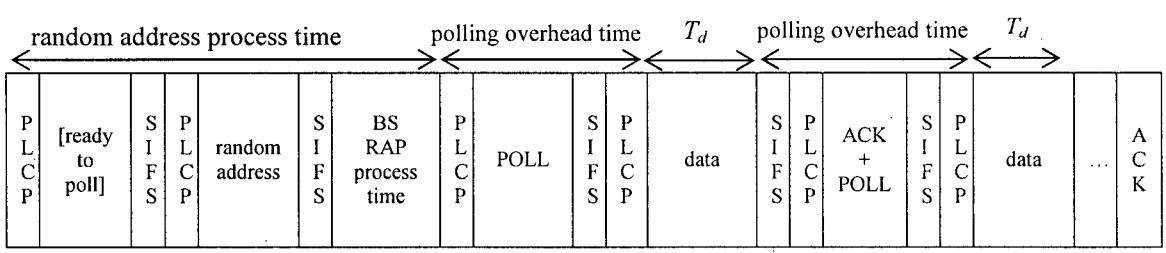



Figure 5.1: A single RAP frame

## 5.1 Basic Markovian Model

The basic Markovian model described in this section is used for performance evaluation under perfect channel conditions.

Since both $\lambda$ and $\tau$ are much less than 1, we approximate that only one packet arrives at a MN in $\tau$ secs. From the Poisson model, the probability ($\gamma$) of packet arriving at a MN in $\tau$ secs is,

$$\gamma = 1 - e^{-\lambda\tau} \tag{5.1}$$

The probability ($P$) for an active MN to succeed in selecting a non-collided random address in a single RAP cycle is,

$$P = \left(1 - \frac{1}{b}\right)^{n-1} \tag{5.2}$$

The expected number ($E[poll]$) of active MNs which will be polled in a single RAP frame, can be deduced as follows:

$$E[poll] = n \times P \tag{5.3}$$

The expected frame period ($E[T_{frame}]$) of a single RAP frame can be represented as,

$$E[T_{frame}] = T_m + E[poll] \times \tau \tag{5.4}$$

The probability ($P_{ready}$) of [ready to poll] message period in a single RAP frame can be shown to be,

$$P_{ready} = \frac{T_m}{E[T_{frame}]} \tag{5.5}$$

The probability ($\alpha$) of a successful packet transmission for a single MN in $\tau$ secs equals the probability of [ready to poll] message period in a single RAP frame × the probability for an active MN to succeed in reserving a random address × the ratio of $\tau$ to $T_m$:

$$\alpha = P_{ready} \times P \times (\frac{\tau}{T_m}) \tag{5.6}$$

Each MN approximates the Markovian model behavior shown in Figure 5.2. The terminal states in the model are classified into E [empty stage], $C_x$ [contention stage with x packets in the buffer of the MN], $R_x$ [transmission stage with x packets in the buffer of the MN], and D [packet drop stage].

The transition matrix ($M$) for the Markovian model of Figure 5.2 is shown in Figure 5.3.

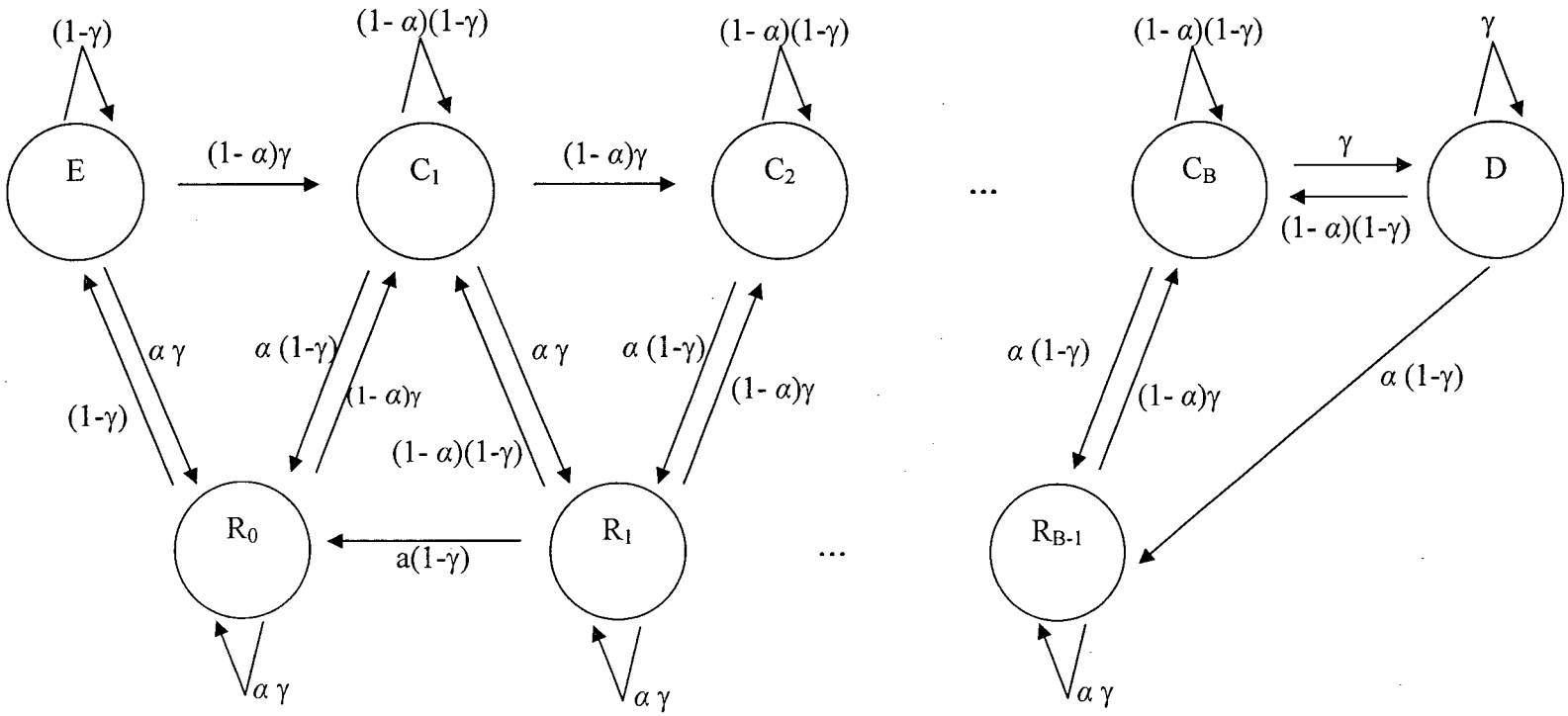



Figure 5.2: Markovian model used for mathematical analysis

$$
M = \begin{array}{c}
\begin{array}{cccccccccccc}
P_E & P_{R_0} & P_{C_1} & P_{R_1} & P_{C_2} & P_{R_2} & \cdots & \cdots & P_{C_{B-1}} & P_{R_{B-1}} & P_{C_B} & P_D
\end{array} \\
\begin{bmatrix}
(1-\gamma) & \alpha\gamma & (1-\alpha)\gamma & 0 & 0 & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & 0 \\
(1-\gamma) & \alpha\gamma & (1-\alpha)\gamma & 0 & 0 & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & 0 \\
0 & \alpha(1-\gamma) & (1-\alpha)(1-\gamma) & \alpha\gamma & (1-\alpha)\gamma & 0 & 0 & \cdots & \cdots & \cdots & \cdots & 0 \\
0 & \alpha(1-\gamma) & (1-\alpha)(1-\gamma) & \alpha\gamma & (1-\alpha)\gamma & 0 & 0 & \cdots & \cdots & \cdots & \cdots & 0 \\
0 & 0 & 0 & \alpha(1-\gamma) & (1-\alpha)(1-\gamma) & \alpha\gamma & (1-\alpha)\gamma & \cdots & \cdots & \cdots & \cdots & 0 \\
\vdots & \vdots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots & \vdots \\
\vdots & \vdots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots & \vdots \\
\vdots & \vdots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots & 0 \\
0 & 0 & \cdots & \cdots & \cdots & \cdots & \cdots & \alpha(1-\gamma) & (1-\alpha)(1-\gamma) & \alpha\gamma & (1-\alpha)\gamma & 0 \\
0 & 0 & \cdots & \cdots & \cdots & \cdots & 0 & 0 & 0 & \alpha(1-\gamma) & (1-\alpha)(1-\gamma)\gamma & \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \alpha(1-\gamma) & (1-\alpha)(1-\gamma)\gamma &
\end{bmatrix}
\end{array}
\begin{array}{c}
P_E \\ P_{R_0} \\ P_{C_1} \\ P_{R_1} \\ P_{C_2} \\ P_{R_2} \\ \vdots \\ \vdots \\ P_{R_{B-1}} \\ P_{C_B} \\ P_D
\end{array}
$$

Figure 5.3: Markovian model transition matrix ($M$)

The method used to obtain the steady state probability for different terminal stages of matrix ($M$) is by solving the Equations (5.7) and (5.8) for limiting probabilities, $\pi_E, \pi_{R_i}, \pi_{C_i}$, and $\pi_D$.

$$\begin{bmatrix} \pi_E \\ \pi_{R_0} \\ \pi_{C_1} \\ \pi_{R_1} \\ \pi_{C_2} \\ \vdots \\ \vdots \\ \vdots \\ \pi_{R_{B-1}} \\ \pi_{C_B} \\ \pi_D \end{bmatrix} = M^T \times \begin{bmatrix} \pi_E \\ \pi_{R_0} \\ \pi_{C_1} \\ \pi_{R_1} \\ \pi_{C_2} \\ \vdots \\ \vdots \\ \vdots \\ \pi_{R_{B-1}} \\ \pi_{C_B} \\ \pi_D \end{bmatrix} \tag{5.7}$$

where $M^T$ is the transpose of matrix $M$.

$$\pi_E + \sum_{i=0}^{B-1} \pi_{R_i} + \sum_{i=1}^{B} \pi_{C_i} + \pi_D = 1 \tag{5.8}$$

For example, assume that $B = 1$. Then, we need to solve Equation (5.9) for limiting probabilities, $\pi_E, \pi_{R_0}, \pi_{C_1}$, and $\pi_D$.

$$\begin{bmatrix} (1-\gamma) & (1-\gamma) & 0 & 0 \\ \alpha\gamma & \alpha\gamma & \alpha(1-\gamma) & \alpha(1-\gamma) \\ 0 & 0 & \gamma & \gamma \\ 1 & 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} \pi_E \\ \pi_{R_0} \\ \pi_{C_1} \\ \pi_D \end{bmatrix} = \begin{bmatrix} \pi_E \\ \pi_{R_0} \\ \pi_D \\ 1 \end{bmatrix} \tag{5.9}$$

After matrix computation, we obtain the following result.

$$\pi_E = \frac{\alpha(1-\gamma)^2}{\alpha - 2\alpha\gamma + \gamma}$$

$$\pi_{R_0} = \frac{\alpha\gamma(1-\gamma)}{\alpha - 2\alpha\gamma + \gamma}$$

$$\pi_{C_1} = \frac{\gamma(1-\gamma)(1-\alpha)}{\alpha - 2\alpha\gamma + \gamma} \qquad (5.10\text{-}5.13)$$

$$\pi_D = \frac{\gamma^2(1-\alpha)}{\alpha - 2\alpha\gamma + \gamma}$$

All terminal stages have positive limiting probabilities, showing that the Markov model has steady state probabilities.

### 5.1.1 Number of Active MNs in a Single RAP Frame

The number ($n$) of active MNs in a single RAP frame equals the probability of a single MN with non-empty buffer × the total number of MNs in the network:

$$n = [(\sum_{i=1}^{B} P_{C_i}) + (\sum_{i=1}^{B-1} P_{R_i}) + P_D] \times N \qquad (5.14)$$

### 5.1.2 System Throughput

The throughput of the system equals the probability of transmission state for a MN × the proportion of useful data transmission × the total number of MNs in the network

$$Throughput = (\sum_{i=0}^{B-1} P_{R_i}) \times (\frac{T_d}{\tau}) \times N \qquad (5.15)$$

### 5.1.3 Packet Delay

The packet delay equals the expected number of packets in a single MN ÷ packet arrival rate of a single MN:

$$Delay = \frac{1}{\lambda}[\,(\sum_{i=1}^{B} iP_{C_i}) + (\sum_{i=1}^{B-1} iP_{R_i}) + (B \times P_D)\,] \tag{5.16}$$

## 5.2 Procedures for Mathematical Analysis

The variables employed in the mathematical model are heavily dependent on one another: $P$ relies on $n$, $E[poll]$ is controlled by $P$, $E[T_{frame}]$ is based on $E[poll]$, and $n$ is affected by $\gamma$ and $E[T_{frame}]$, it is important to determine the value of these variables.

Given that a new estimated $n$ value can be computed using the model, the relationship chain is solved by evaluating the expected value of $n$, $E[n]$. Therefore, the mathematical analysis operation is divided into two stages: the first stage involves the evaluation of $E[n]$, and the second stage includes the evaluation of system throughput and packet delay. The flow chart for the mathematical analysis operation is shown in Figure 5.3.

In the first stage, in order to obtain better analytical result, the evaluation is done by a feedback operation which terminates when the system reaches steady state. Since a new estimated $n$ can be computed using the model, $n$ is chosen as an indicator to test if the system reaches steady state. At the beginning, $n$ is initially set to a specific value. Then, all the variables are calculated using this value of $n$. Next, the variables are substituted into the mathematical model, $M$, for terminal stages' probabilities calculation.

After that, a new value of $n$ is computed using the terminal states' probabilities. Then, the new estimated $n$ is compared with the previous presumed $n$. If the differences of the two $n$ values are beyond a certain error ($\varepsilon$), the system is in transient state, and more iteration is required. On the other hand, if the differences of the two $n$ values are within a certain error ($\varepsilon$), this means that the system has reached steady state. Afterwards, the new estimated $n$, together with the other new estimated $n$ values obtained by selecting new initial $n$ values will be used for calculating $E[n]$.

In the second stage, $E[n]$ will be used for the calculation of all the other variables. After that, the variables are substituted into the mathematical model, $M$. Eventually, the throughput and the packet delay of the system can be calculated with the help of the terminal states' probabilities obtained from $M$.

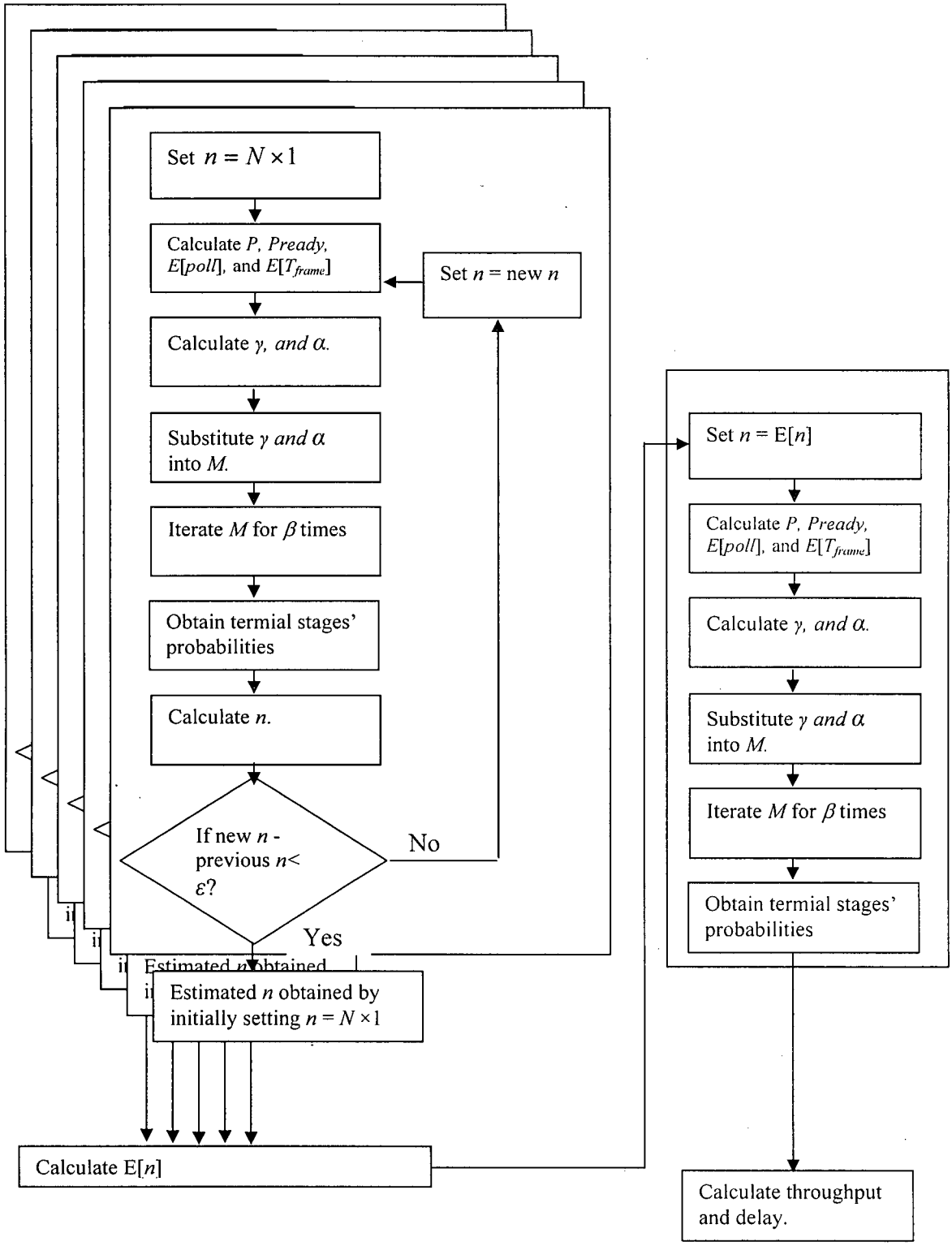



Figure 5.4: Flow chart for mathematical analysis procedures

## 5.3 Enhancements for Imperfect Channel Conditions

In order to use the basic model to perform evaluations for imperfect channel conditions, some enhancements are required to the basic model.

The probability ($P_{success}$) of a successful packet transmission for a single MN in a single RAP frame can be represented as follows:

$$P_{success} = P \times (1 - AER) \times (1 - PER) \tag{5.17}$$

The expected number ($E[poll]$) of active MNs can be deduced as,

$$E[poll] = \min\{ n \times [P \times (1 - AER) + DER \times AER] \ , \ b\} \tag{5.18}$$

The probability ($\alpha$) of a successful packet transmission for a single MN in $\tau$ secs becomes,

$$\alpha = P_{ready} \times P_{success} \times (\frac{\tau}{T_m}) \tag{5.19}$$

The calculations of the other variables, the structure of the Mavkovian model and the evaluation procedures are the same as those for the basic model.

## 5.4 Modifications for the Performance Evaluation of the QoS Enhancement

Some modification to the basic model is needed to enable the performance evaluation of the QoS enhancement to be achieved. For simplicity, we use only two priority classes with class 1 having a higher priority than class 2.

The additional variables used in the modifications are defined in Table 5.2:

| Symbols used | Description |
|---|---|
| $N_1$ | Total number of class 1 MNs in the network |
| $N_2$ | Total number of class 2 MNs in the network |
| $n_1$ | Number of active class 1 MNs in each RAP frame |
| $n_2$ | Number of active class 2 MNs in each RAP frame |
| $b_1$ | Total number of random addresses available for class 1 MNs |
| $b_2$ | Total number of random addresses available for class 2 MNs |
| *address_ratio* | Ratio of number of the addresses between the two protocol $= \frac{b_1}{b_2}$ |

Table 5.2: Addition symbols used in the QoS enhancement analysis

The probability ($P_1$) for an active class 1 MN to succeed in selecting a non-collided random address in a single RAP cycle can be expressed as,

$$P_1 = address\_ratio \times \left(1 - \frac{1}{b_1}\right)^{n_1 - 1} \left(1 - \frac{1}{b_2}\right)^{n_2} + \left(1 - address\_ratio\right) \times \left(1 - \frac{1}{b_1}\right)^{n_1 - 1} \tag{5.20}$$

The probability ($P_2$) for an active class 2 MN to succeed in selecting a non-collided random address in a single RAP cycle is,

$$P_2 = \left(1 - \frac{1}{b_1}\right)^{n_1} \left(1 - \frac{1}{b_2}\right)^{n_2 - 1} \tag{5.21}$$

The expected number ($E[poll]$) of active MNs which will be polled in a single RAP frame, can be deduced as,

$$E[poll] = n_1 \times P_1 + n_2 \times P_2 \tag{5.22}$$

The probability ($\alpha_1$) of a successful packet transmission for an active class 1 MN in $\tau$ secs becomes

$$\alpha_1 = P_{ready} \times P_1 \times (\frac{\tau}{T_m}) \tag{5.23}$$

The probability ($\alpha_2$) of a successful packet transmission for an active class 2 MN in $\tau$ secs becomes

$$\alpha_2 = P_{ready} \times P_2 \times (\frac{\tau}{T_m}) \tag{5.24}$$

The calculations of the other variables and the structure of the Mavkovian model are similar to those in the basic model. However, there is a slight difference in the evaluation procedures. We need to evaluate all combinations of initial $n_1$ and $n_2$ values in order to estimate $E[n_1]$ and $E[n_2]$ accurately.

## 5.5 Summary

The proposed two-dimensional Markovian model is a useful tool to evaluate the system performance of the RAP-OFDM and the modified RAP-OFDM protocols. It can be used for both perfect and imperfect channel conditions. In addition, it can be used for the evaluation of the QoS enhancement.

# Chapter 6

# IMPLEMENTATION OF ANALYSIS AND SIMULATION

In order to study the system performance of the RAP-OFDM and the modified RAP-OFDM protocols, three evaluation scenarios are described in this chapter. Furthermore, the systems have been simulated using OPNET software, allowing us to compare the precision of the mathematical models.

## 6.1 OPNET Simulation Model Implementation

We have created the BS and MN simulation models that allow OPNET software to run RAP protocols. The operations of the models are as shown in Figure 6.1.

In the BS simulation model, a polling list is implemented to store the random addresses successfully received in the current RAP frame. When all the random addresses in the list are polled and all packets in the buffer are emptied, the BS will send out a [ready to poll] message to the MNs. Next, the BS will collect the random addresses transmitted by the active MNs and update its polling list. After that, the BS will start polling the random addresses in the list. If the uplink data is received successfully, the BS will reply with a [positive ACK] message. Otherwise, the BS will reply with a [negative ACK] for collision or time-out. After polling all the random addresses, the BS will start downlink transmission by sending downlink packets. If the BS receives a [positive ACK]

message from the MN, it will remove the packet from its buffer. Otherwise, it will retransmit the packet.

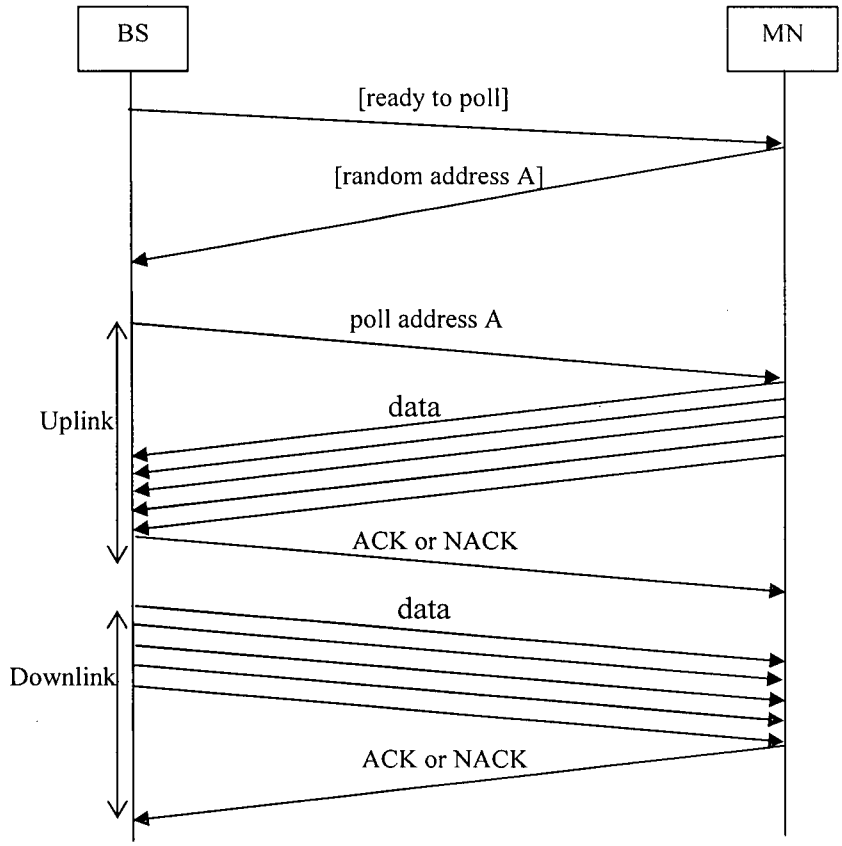



Figure 6.1 Operations of BS and MN process models

In the MN simulation model, all actions are triggered by the message from the BS. When a [ready to poll] message is received, the active MNs will send out their random addresses, while the non-active MNs will remain idle. The active MNs will then listen to the [polling] messages from the BS. When the random address in the [polling] message matches the random address the MN transmitted earlier, the MN will start uplink data transmission. After that, if a [positive ACK] message is received, the MN will

remove the packet from its buffer. Otherwise, the MN will keep the packet and wait for the next RAP frame to retransmit. When a MN receives a downlink packet, in which the destination address matches its address, it will transmit a [positive ACK] to the BS if the data is received successfully.

## 6.2 Perfect Channel Condition Scenario

We first analyze the performance of the two protocols under perfect channel conditions with *packet_size* = 512 and 1024 bytes. Furthermore, we study the precision of the mathematical model, using the OPNET simulation model.

The system parameters used in the numerical model and software simulations are shown below:

| Parameters | Value |
|---|---|
| *data_rate* | 2 Mbits/sec |
| *packet_size* | 512, 1024 bytes |
| *load (L)* | 75% for *packet_size* = 512 bytes<br>85% for *packet_size* = 1024 bytes |
| $\lambda$ | $\frac{(load)\times(data\_rate)}{(packet\_size)\times N}$ |
| *slot_time* | 10 $\mu s$ |
| *SIFS_time* | 20 $\mu s$ |
| *PLCP_overhead_time* | 192 $\mu s$ |
| *Ready_to_poll* | $\frac{CTS\_frame\_size}{data\_rate} = 56\ \mu s$ |
| *Random_address* | $\frac{CTS\_frame\_size}{data\_rate} = 56\ \mu s$ |

| | |
|---|---|
| *Data_overhead* | $\frac{Data\_frame\_overhead\_size}{data\_rate} = 136\ \mu s$ |
| *Poll* or *Poll+ACK* | $\frac{Data\_frame\_overhead\_size}{data\_rate} = 136\ \mu s$ |
| *ACK* | $\frac{ACK\_frame\_size}{data\_rate} = 56\ \mu s$ |
| *BS_RAP_process* | $250\ \mu s$ |
| $T_m$ | $(Ready\_to\_poll) + (Random\_address) + (ACK) + 3 \times (PLCP\_overhead\_time) + 3 \times (SIFS) + (BS\_RAP\_process\_time)$ |
| $T_p$ | $(Poll + ACK) + (Data\_overhead) + 2 \times (PLCP\_overhead\_time + 2 \times (SIFS\_time)$ |
| $T_d$ | $\frac{packet\_size}{data\_rate}$ |
| *PER* | 0 |
| *AER* | 0 |
| *DER* | 0 |

Table 6.1: System parameters used in mathematical analysis and simulation

In the simulation, the *data_rate, load* and *packet_size* are chosen arbitrary, but heavy traffic load is preferred in order to demonstrate the instability effect. The value of $\lambda$ used depends on the *data_rate*, *load*, *packet_size* and the number of network users. The timing requirements of *slot_time*, *SIFS_time*, *PLCP_overhead_time*, *poll*, *poll+ACK*, *ACK* and *Data_overhead* are adjusted according to the specifications of 802.11 standards [1]. The timing requirements of *Ready_ to_ poll* and *Random_address* are set equal to that of a CTS frame in 802.11 standards. The *BS_RAP_ process* time is required for the system to run properly in OPNET simulation. The values of $T_m$, $T_p$ and $T_d$ are calculated according to the timing requirements mentioned above.

## 6.3 Imperfect Channel Condition Scenario

In this section, we investigate the performance of the two protocols over an AWGN channel in the presence of phase noise. Under the phase noise conditions, the random address transmission of the RAP-OFDM is assumed to have the same error probability as BPSK modulation, while the random address transmission of the modified RAP-OFDM is approximated to have similar error probability as QPSK modulation. The phase noise has different effects on the two protocols' AER values. In this simulation, we employ the results from [33] for the values of *AER*. Since the mathematical model provides accurate estimates, the results presented in this section will be obtained from the mathematical model only.

The system parameters used in the numerical model for imperfect channel conditions are same as those for perfect channel conditions, except the following:

| | | |
|---|---|---|
| *PER* | $10^{-2}$ | |
| *DER* | $5 \times 10^{-2}$ | |
| *AER* | RAP-OFDM: (BPSK) | |
| | $10^{-2}$ | for SNR = 5 dB |
| | $3 \times 10^{-7}$ | for SNR = 20 dB |
| | Modified RAP-OFDM: (QPSK) | |
| | $2.5 \times 10^{-2}$ | for SNR = 5 dB |
| | $3 \times 10^{-3}$ | for SNR = 20 dB |

Table 6.2: System parameters used in imperfect channel conditions

The values of PER and DER are assumed to be $10^{-2}$ and $5 \times 10^{-2}$, respectively, for imperfect channel conditions. The value of AER is obtained from the results of [33], in

which the bit error rates of OFDM system running under both BPSK and QPSK modulation are estimated.

## 6.4 QoS Enhancement Scenario

In this section, we study the performance of the QoS enhancement, in which the MNs are divided into two classes: class 1 with high priority and class 2 with low priority.

The system parameters used in the numerical model for the evaluation are same as those for perfect channel condition. The following additional parameters are used in the evaluation:

| | |
|---|---|
| $N_1$ | 25%, 50%, 75% of $N$ |
| $N_2$ | 25%, 50%, 75% of $N$ |
| $b_1$ | 48 |
| $B_2$ | 96 |
| *address_ratio* | Ratio of number of the addresses between the two protocol $= \frac{b_1}{b_2} = 50\%$ |

Table 6.3: Addition system parameters used in the QoS enhancement's evaluation

In this section, the number of class 1 and class 2 MNs are divided according to the total number of MNs in the following proportional respectively: 25%/75%, 50%/50% and 75%/25%. Class 2 MNs are limited to 48 possible random addresses only, while class 1 MNs can select all the 96 random addresses.

## 6.5 Summary

With the help of the two-dimensional Markovian model and the OPNET simulation software, we can evaluate the system performance of the RAP-OFDM and the modified RAP-OFDM protocols. The analytical and simulation results will be shown in the following chapter.

Chapter 7

# ANALYSIS AND SIMULATION RESULTS

Based on the Markovian model and OPNET simulation introduced in previous chapter, the performance of the RAP-OFDM and the modified RAP-OFDM are evaluated in this chapter. The two protocols are compared with each other, according to the length of stability region, recalling that the "stability" here means that the system can maintain the same throughput as the input load.

## 7.1 Perfect Channel Conditions

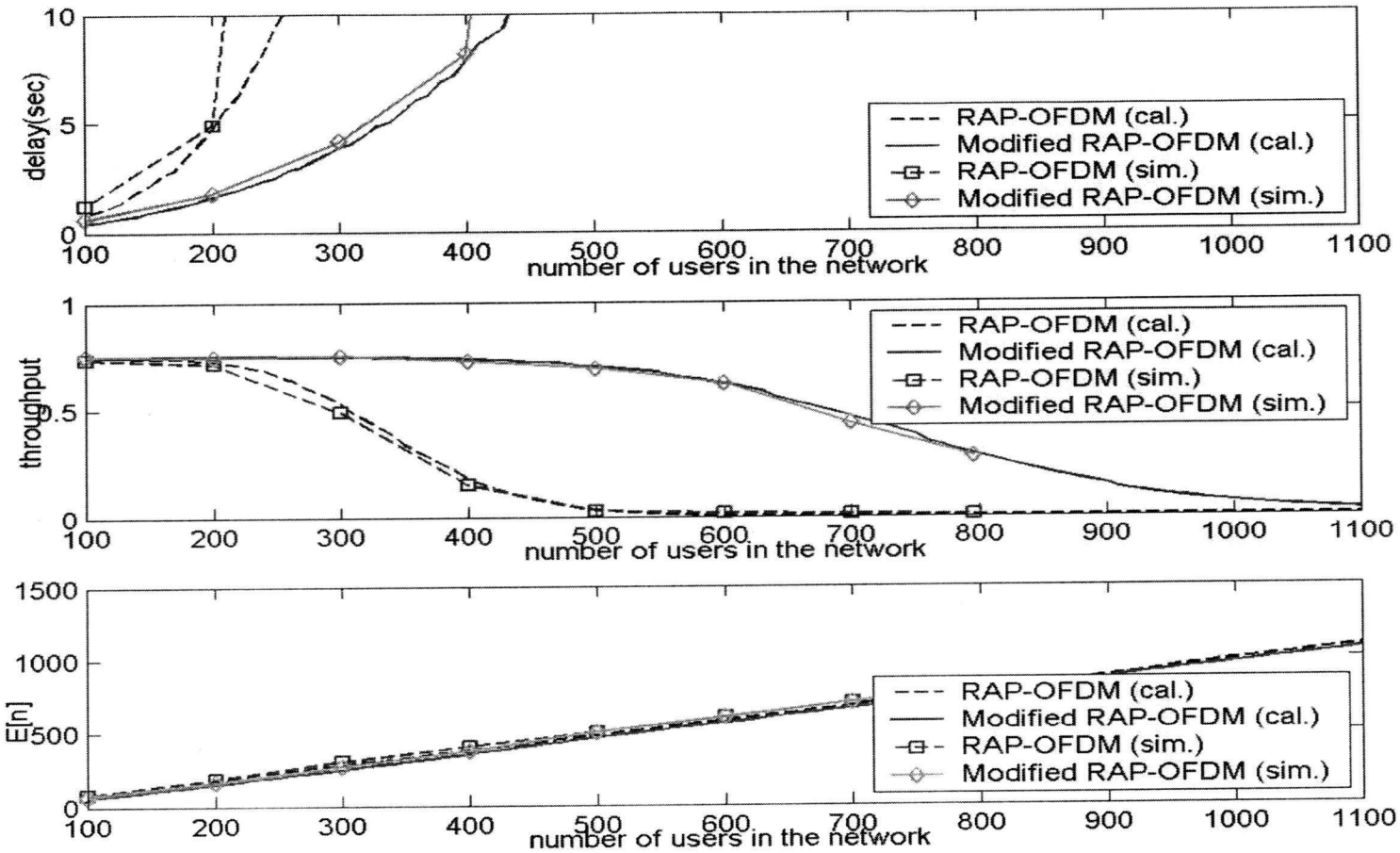
In this section, we examine the performance of the two RAP-OFDM protocols under perfect channel conditions with *packet_size* = 512 and 1024 bytes. The system throughput results are shown in Figures 7.2 and 7.5, those for the packet delay are presented in Figures 7.1 and 7.4, and those for the $E[n]$ are shown in Figures 7.3 and 7.6. In the figures, the solid lines correspond to the modified RAP-OFDM, and the dashed lines correspond to the RAP-OFDM. The graphical symbols represent the results obtained from the OPNET simulation.

As observed from the figures, results from the Markov Chain model provide an excellent match to the simulation results. The mathematical model provides accurate performance estimates for the protocols: it can estimate the gradual changes in system performance when *packet_size* = 512 bytes; and the rapid changes, when *packet_size* =

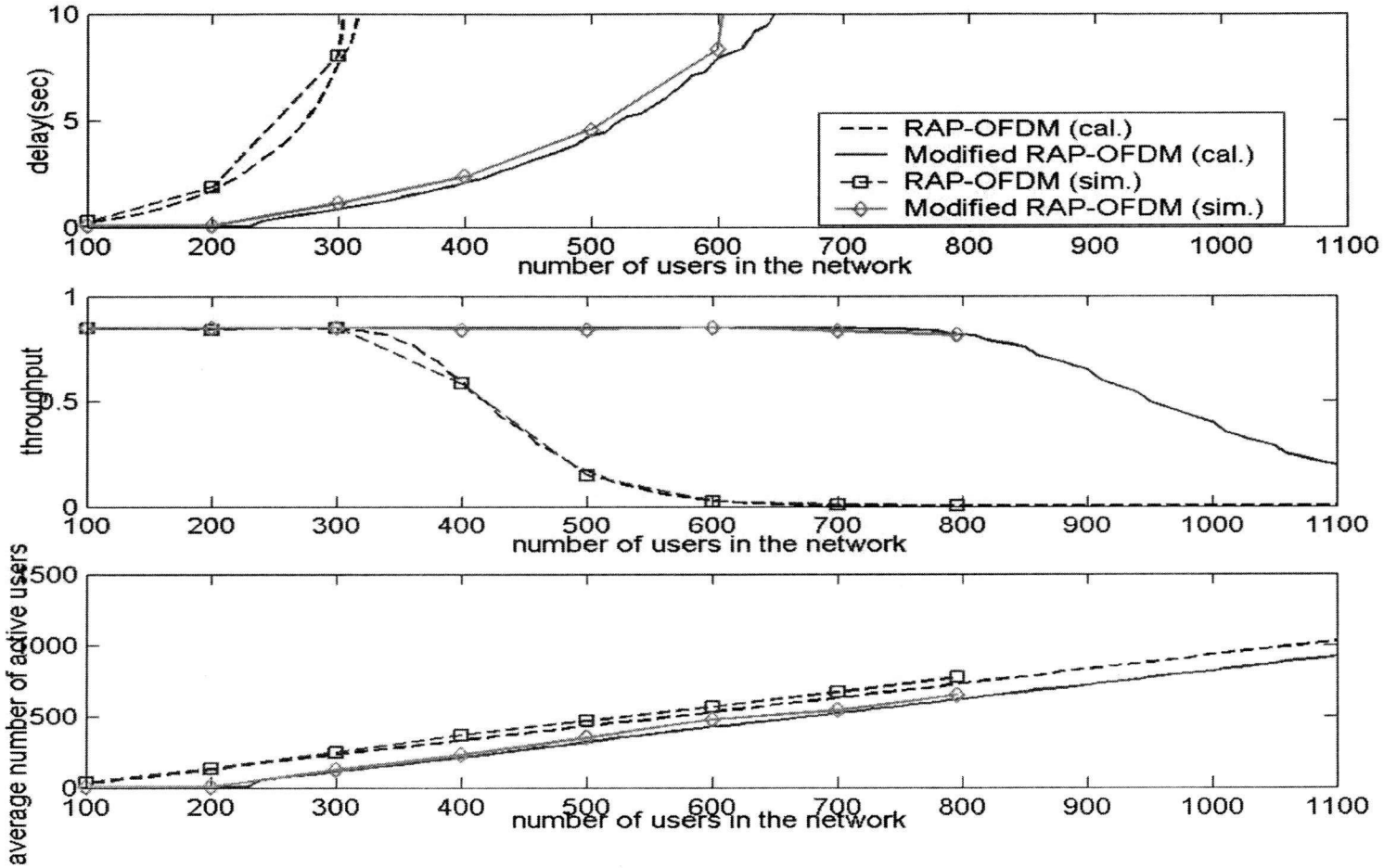
1024 bytes. The difference between the analytical and the simulation results is within 0.02 for system throughput estimation, within 0.4 secs for packet delay estimation, and within 50 users for $E[n]$ estimation.

As indicated in Figures 7.1, 7.2 and 7.3, for *packet_size* = 512 bytes and *load* = 75%, the performance of the two protocols is identical when there are fewer than 100 users in the network. However, the performance of the two protocols differs dramatically when the number of users is between 200 and 400. The RAP-OFDM performance degrades rapidly as the number of users increases beyond 200 users. According to Figure 7.2, the stability region of the RAP-OFDM is 0-200 users, while that of the modified RAP-OFDM is 0-400 users.

As shown in Figures 7.4, 7.5 and 7.6, for *packet_size* =1024 bytes and *load* = 85%, the performance of the two protocols improves as *packet_size* increases. This can be explained by the fact that when *packet_size* increases, the ratio of payload to overhead also increases, improving the efficiency of useful data successfully transmitted. In addition, increased *packet_size* allows more data to be sent in a single reservation, thereby reducing the number of reservations required. However, this will cause the system to degrade more rapidly when the number of active users exceeds the collision resolution capability of the protocols. According to Figure 7.4, the performance of the two protocols is alike when there are less than 100 users. The stability region of the RAP-OFDM becomes 0-300 users, while that of the modified RAP-OFDM becomes 0-800 users.




(Top) Figure 7.1: Delay vs. number of users in the network for *packet_size* = 512 bytes and *load* = 75%
(Middle) Figure 7.2: Throughput vs. number of users in the network for *packet_size* = 512 bytes and *load* = 75%
(Bottom) Figure 7.3: $E[n]$ vs. number of users in the network for *packet_size* = 512 bytes and *load* = 75%




(Top) Figure 7.4: Delay vs. number of users in the network for *packet_size* = 1024 bytes and *load* = 85%
(Middle) Figure 7.5: Throughput vs. number of users in the network for *packet_size* = 1024 bytes and *load* = 85%
(Bottom) Figure 7.6: $E[n]$ vs. number of users in the network for *packet_size* = 1024 bytes and *load* = 85%

## 7.2 Imperfect Channel Conditions

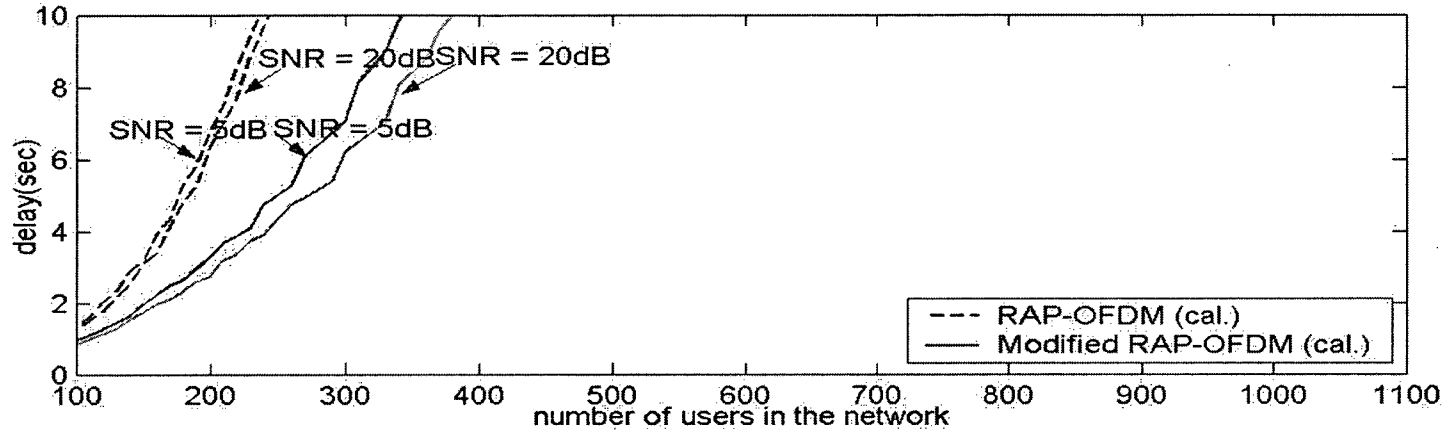
In this section, we investigate the performance of the two protocols operating on an AWGN channel in the presence of phase noise. The results are shown in Figures 7.7, 7.8, 7.9 and 7.10. In the figures, the dashed and solid lines correspond, respectively, to the RAP-OFDM and the modified RAP-OFDM.

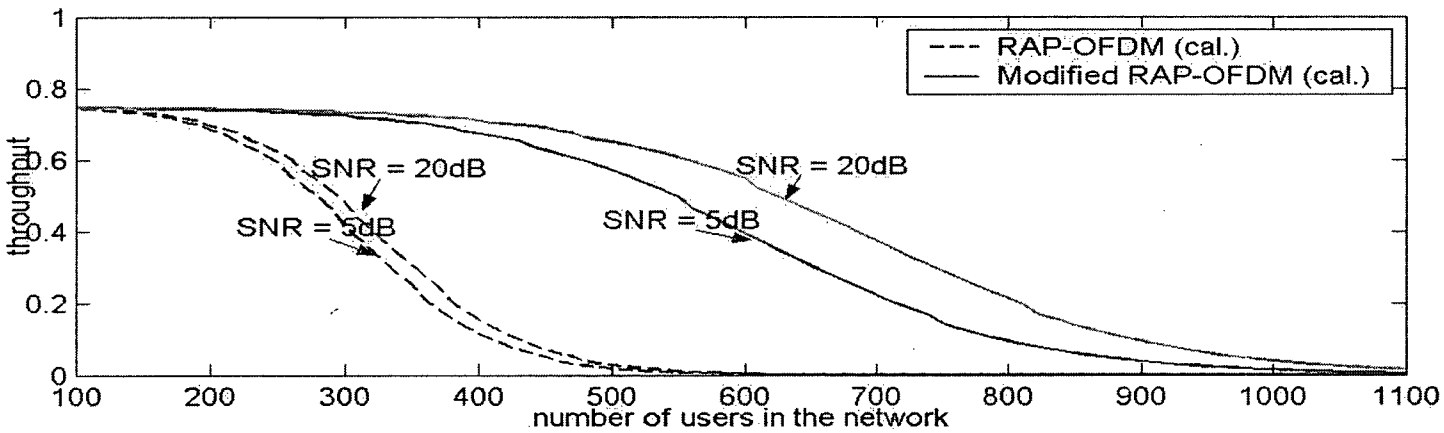
As observed from the figures, the performance of the modified RAP-OFDM degrades more rapidly than does that of the RAP-OFDM as SNR decreases from 20 dB to 5 dB. Since QPSK modulation is more susceptible to phase noise than is BPSK modulation, the modified RAP-OFDM is also more vulnerable to phase noise than is RAP-OFDM.

As Figures 7.7 and 7.8 show, for *packet_size* = 512 bytes and *load* = 75%, the stability region of the modified RAP-OFDM reduces considerably from 0-300 to 0-230 users, whereas that of the RAP-OFDM reduces slightly from 0-150 to 0-135 users. Furthermore, as shown in Figures 7.9 and 7.10, for *packet_size* = 1024 bytes and *load* = 85%, the stability region of the modified RAP-OFDM reduces substantially, by 140 users from 490 users, while that of the RAP-OFDM reduces slightly by 20 users from 250 users,

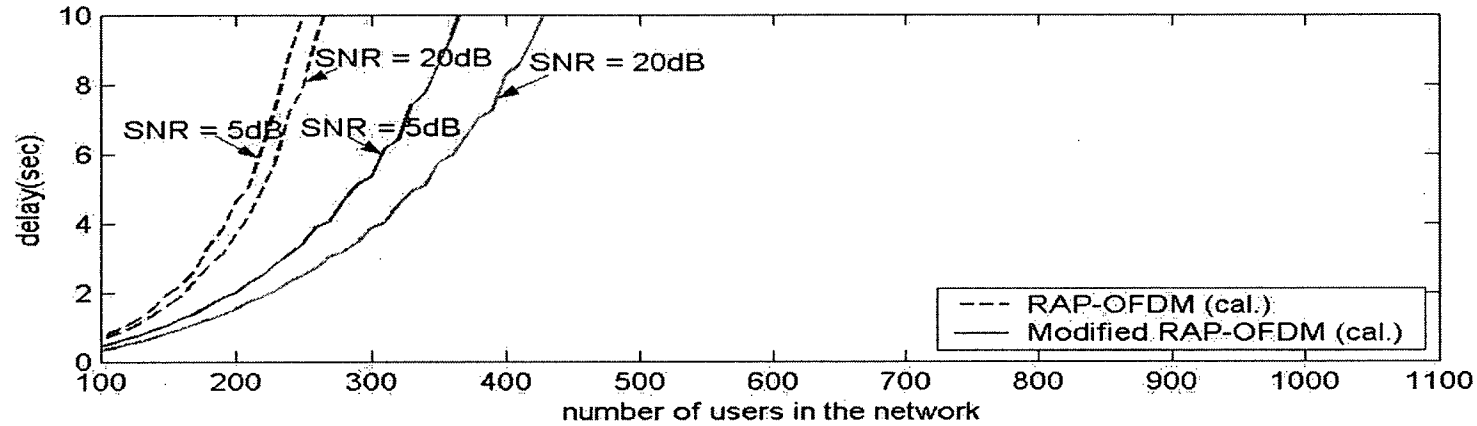
At SNR = 5dB, the stability region of the modified RAP-OFDM remains larger than that of the RAP-OFDM by 90 users for *packet_size* = 512 bytes, and by 110 users for *packet_size* = 1024 bytes. Since the performance of the modified RAP-OFDM degrades much faster than does that of the RAP-OFDM, it is tempting to believe that the stability region of the RAP-OFDM would go beyond that of the modified RAP-OFDM if

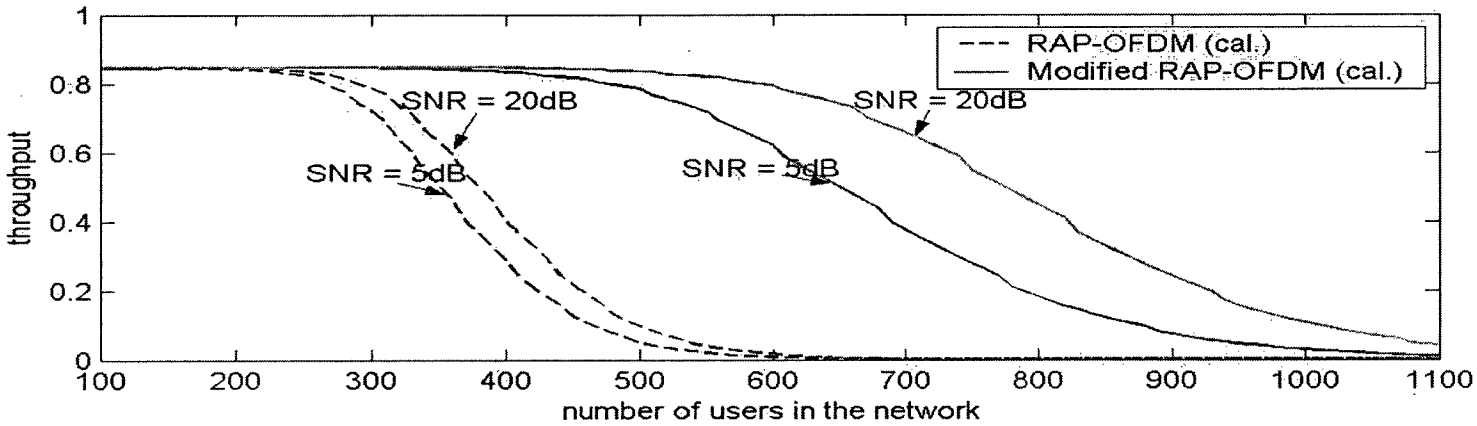
SNR continues to decrease. However, as SNR decreases, the AER values for the two protocols become identical, resulting in similar collision resolution capability for the two protocols, or more specificly, slightly better for the modified RAP-OFDM than for the RAP-OFDM.




(Top) Figure 7.7: Delay vs. number of users in the network for *packet_size* = 512 bytes and *load* = 75% at SNR = 5 dB & 20 dB
(Bottom) Figure 7.8: Throughput vs. number of users in the network for *packet_size* = 512 bytes and *load* = 75% at SNR = 5 dB & 20dB




(Top) Figure 7.9: Delay vs. number of users in the network for *packet_size* = 1024 bytes and *load* = 85% at SNR = 5 dB & 20 dB

(Bottom) Figure 7.10: Throughput vs. number of users in the network for *packet_size* = 1024 bytes and *load* = 85% at SNR = 5 dB & 20 dB

## 7.3 Evaluation of QoS Enhancement

In this section, we describe the service differentiation performance of the QoS enhancement. The results for perfect channel conditions are shown in Figures 7.11, 7.12, 7.13 and 7.14, and those for imperfect channel conditions with SNR = 5d B are shown in Figures 7.15, 7.16, 7.17 and 7.18. The solid lines correspond to the class 1 MNs, and the dashed lines correspond to the class 2 MNs.

The figures show a clear separation between the plots of each class for both perfect and imperfect channel conditions. Class 1 MNs have lower packet delay and longer stability region than class 2 MNs for all proportion of populations. As expected, class 1 MNs always have better reservation capability.

It is seen from the figures that the stability regions of both classes of MNs enhance as their population proportions decrease. For perfect channel conditions with *packet_size* = 512 bytes and *load* = 75%, the throughput of class 1 MNs decays rapidly at 1500 users with 75% of the total population, at 2600 users with 50% of the total population and at 6100 users with 25% of the total population. Class 2 MNs performance degrades at 200 users with 75% of the total population, at 400 users with 50% of the total population and at 700 users with 25% of the total population.

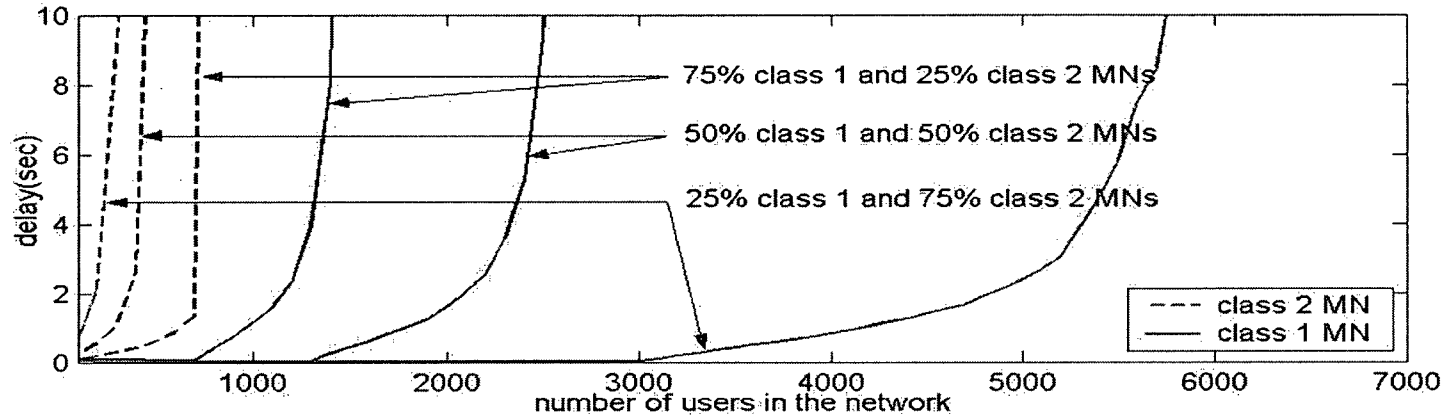
For imperfect channel conditions with SNR = 5 dB, *packet_size* = 512 bytes and *load* = 75%, the stability regions of both classes are reduced by about 30%.

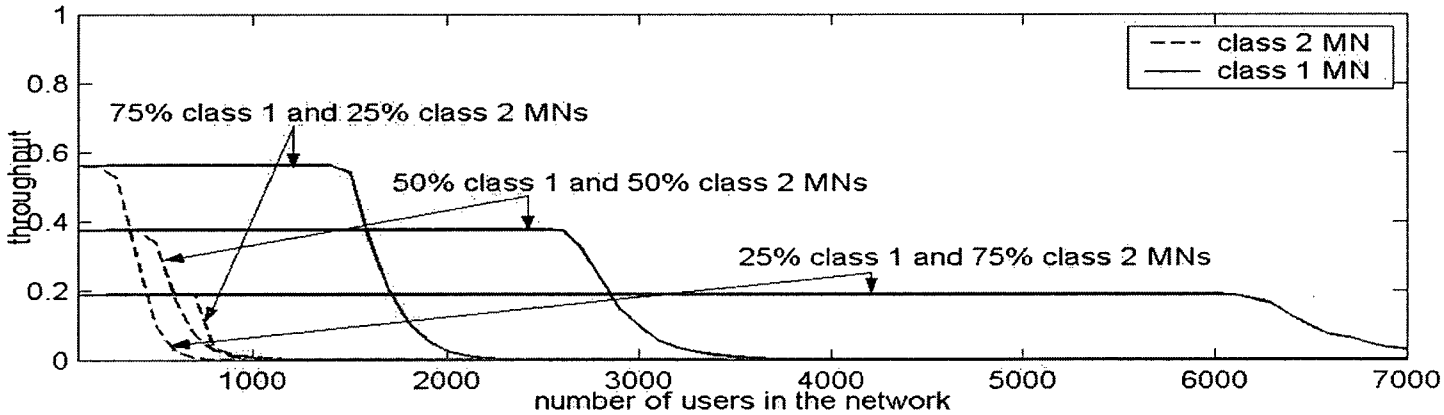
For perfect channel conditions with *packet_size* = 1024 bytes and *load* = 85%, the throughput of class 1 MNs decays with 1600 users at 75%, with 2800 users at 50% and with 6600 users at 25% of the total population; while that of class 2 MNs degrades with

200 users at 75%, with 400 users at 50% and with 800 users at 25% of the total population.

For imperfect channel conditions with SNR = 5 dB, *packet_size* = 1024 bytes and *load* = 85%, the stability regions of both classes are reduced by about 33%.

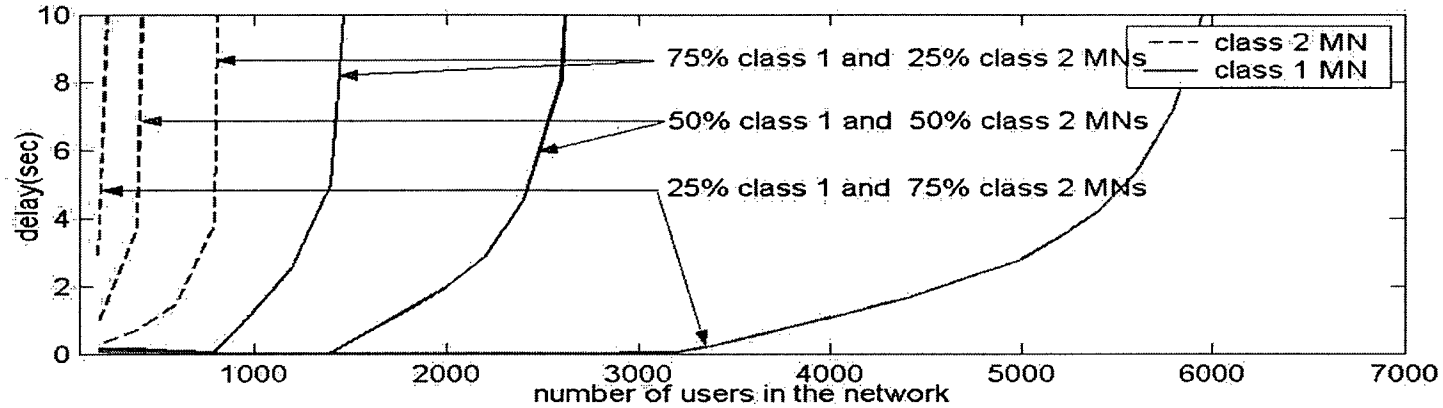
One interesting observation from the figures is that the overall performance of the modified RAP-OFDM with QoS support is better than that without QoS support. This can be explained by the fact that the bottleneck of system performance is determined by the collision resolution capability of the system. Therefore, with the help of service differentiation, which allows class 1 MNs to have advantages in random address reservation, the contention experienced by users is reduced, and the performance of the system is improved as accordingly.

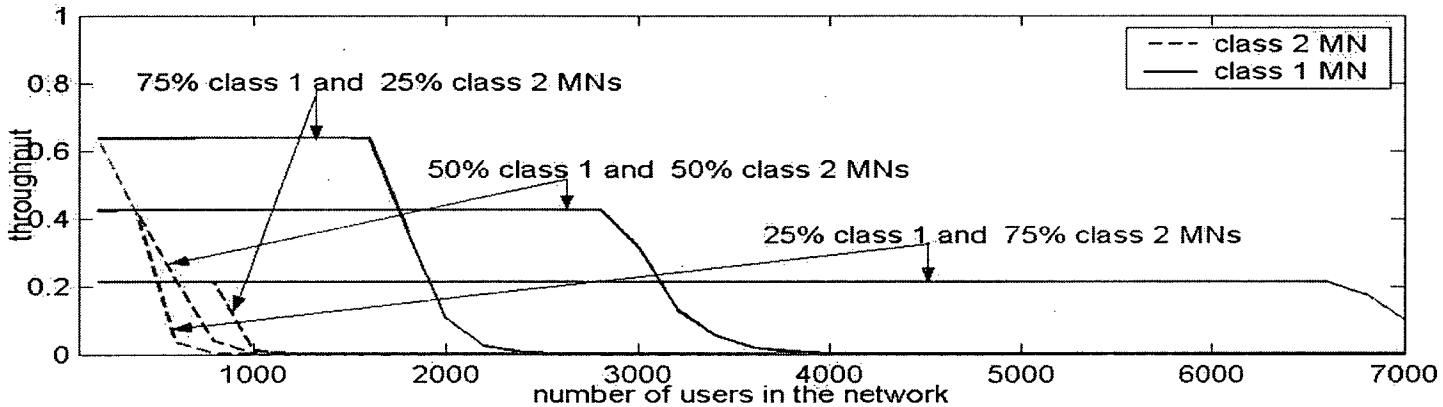



(Top) Figure 7.11: Delay vs. number of users in the network for *packet_size* = 512 bytes and *load* = 75% for different population proportions

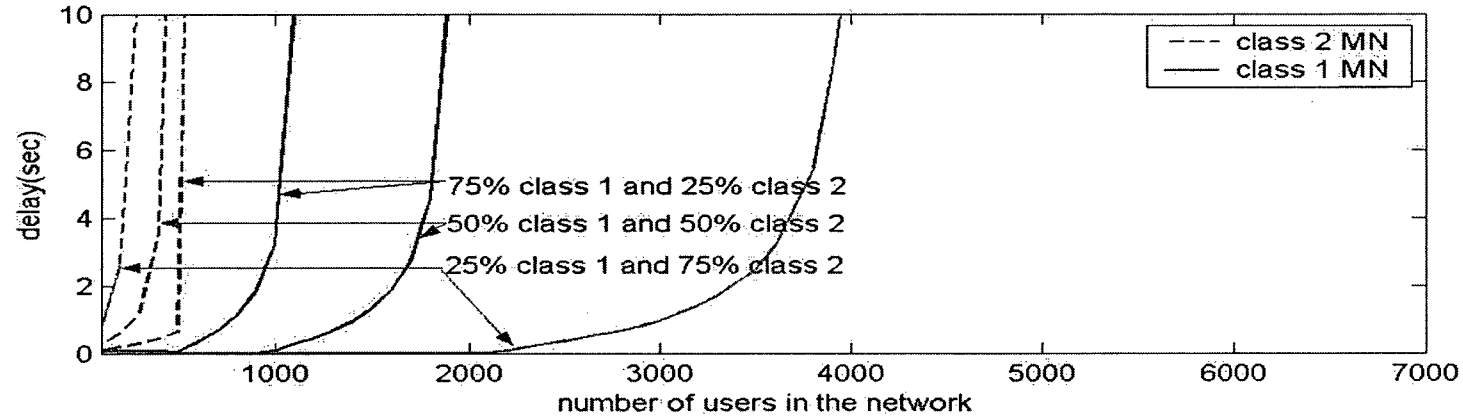
(Bottom) Figure 7.12: Throughput vs. number of users in the network for *packet_size* = 512 bytes and *load* = 75% for different population proportions

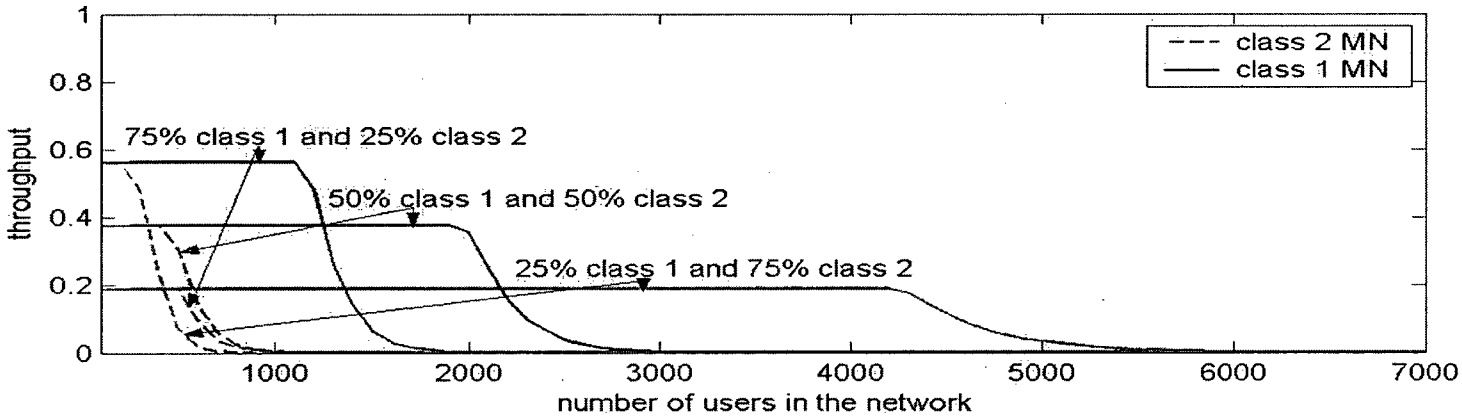



(Top) Figure 7.13: Delay vs. number of users in the network for *packet_size* = 1024 bytes and *load* = 85% for different population proportions

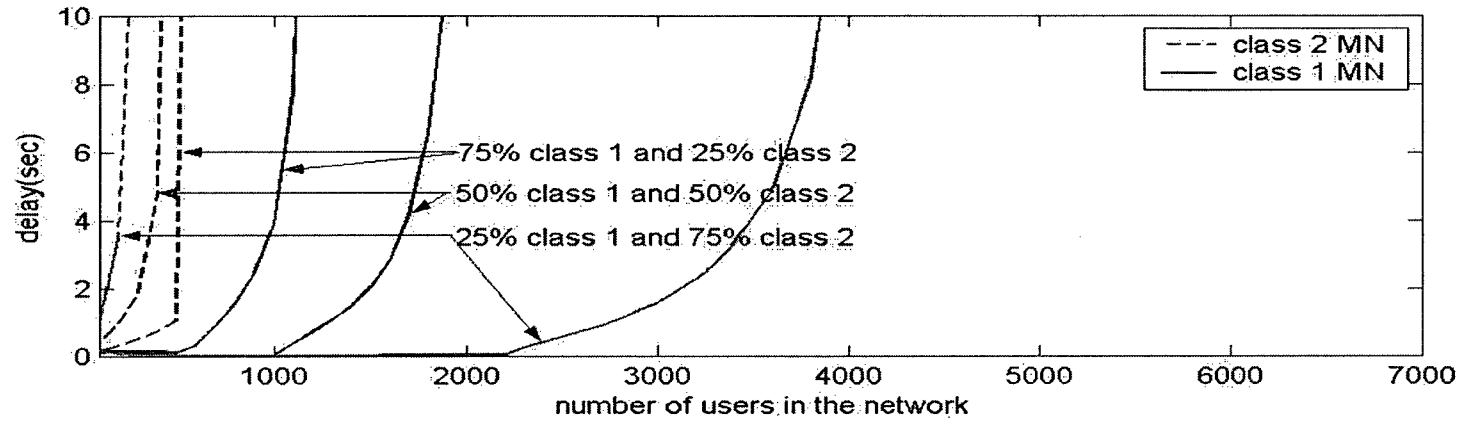
(Bottom) Figure 7.14: Throughput vs. number of users in the network for *packet_size* = 1024 bytes and *load* = 85% for different population proportions

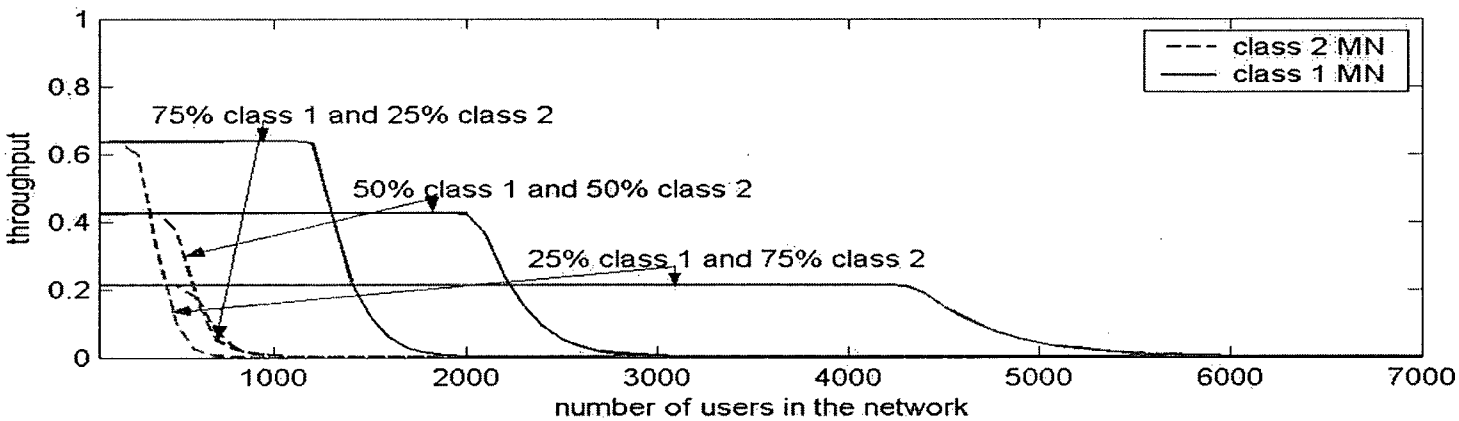



(Top) Figure 7.15: Delay vs. number of users in the network for *packet_size* = 512 bytes and *load* = 75% for different population proportions at SNR = 5 dB

(Bottom) Figure 7.16: Throughput vs. number of users in the network for *packet_size* = 512 bytes and *load* = 75% for different population proportions at SNR = 5 dB




(Top) Figure 7.17: Delay vs. number of users in the network for *packet_size* = 1024 bytes and *load* = 85% for different population proportions at SNR = 5 dB

(Bottom) Figure 7.18: Throughput vs. number of users in the network for *packet_size* = 1024 bytes and *load* = 85% for different population proportions at SNR = 5 dB

## 7.4 Summary

Our analytical and simulation results lead to the following conclusions:

1. The analytical results agree well with the simulation results, proving that the mathematical model is a promising tool for performance analysis.
2. For perfect channel conditions, the use of the modified RAP-OFDM extends the stability region of the RAP-OFDM by 100% and 167% for *packet_size* = 512 bytes and 1024 bytes respectively.
3. For imperfect channel conditions, with the help of the modified RAP-OFDM, the stability region is extended by 100% and 96% for *packet_size* = 512 bytes and 1024 bytes, respectively, at SNR = 20 dB, and by 70% and 60% for *packet_size* = 512bytes and 1024 bytes, respectively, at SNR = 5 dB.
4. The QoS enhancement can provide not only service differentiation to the protocol, but also improves the collision resolution capability of the protocol.

All of these conclusions support the use of modified RAP-OFDM to improve delay and throughput performance.

# Chapter 8

# SUMMARY, CONCLUSIONS AND POSSIBLE FOLLOW-ON WORK

In this thesis, we propose a new random address transmission mechanism and a QoS enhancement to the existing RAP-OFDM protocol. As well, we present a new two-dimensional Markovian model to estimate the performance of RAP protocols.

According to the studies provided in Chapter 3, the collision resolution capability of the RAP protocols is restrained by the limited number of random addresses. Therefore, in order to improve the performance, we propose a modification to double the number of random addresses by use of the QPSK signal constellation scheme. Our modified RAP-OFDM can preserve all the functionalities and features of the RAP-OFDM.

Although the modified protocol requires a moderately more complex hardware implementation, the performance of the modified protocol surpasses the original protocol considerably. As observed from our simulation results in Chapter 6, the modified protocol has a much larger stability region (in terms of number of users supported) than does the original protocol under both perfect and imperfect channel conditions. Notwithstanding that the modified protocol experiences more rapid degradation than does the original protocol when the SNR decreases, it still surpasses considerably the original protocol in performance.

In Chapter 3, we propose a service differentiation mechanism for the protocol by limiting the number of random addresses accessible for two priority classes. From the

simulation results in Chapter 6, one sees that the high priority class has considerable advantages in random address reservation over the low priority class. In addition, the results show that the QoS enhancement can also reduce the competition for random addresses, and eventually, upgrade the collision resolution capability of the protocol.

In Chapter 5, with the intention of overcoming the problem of very time consuming software simulations, a two-dimensional Markovian model is introduced to facilitate analytical evaluation for the performance of the RAP protocols. The results in Chapter 6 show very good argument between the analytical and simulation results. Both results match well with each other in determining throughput, delay and number of active users. Therefore, the mathematical model may be used in place of software simulation.

## 8.1 Future Work

For future work, we would like to examine the actual behavior of the protocols more thoroughly. In particular, we would like to take following details into consideration:

### 8.1.1 Impact of OFDM Signal Distortion

As mentioned in Chapter 4, a concern regarding the modified protocol is that it relies heavily on the quality of OFDM signals. Phase noise and signal strength attenuation can affects the BS's capability in detecting random addresses. Since the analysis of system performance in this thesis is focused on the MAC layer only, several aspects of the physical layer are assumed ideal. Therefore, the full impact of signal

distortion is still unknown, and a more detail model is required to simulate the behavior at the physical layer.

Some solutions are proposed in Chapter 4 to minimize the effects of signal distortion. Further investigation is needed to determine and study the performance improvements which might result from implementing these solutions.

### 8.1.2 Performance of Real-time Traffic

Many different traffic models, including, for example, bursty as well as constant bit rate traffic models are of practical interest. Such models represent many different traffic types, including speech, video, graphics, images, and data.

For simplicity, the analysis in this thesis is done using the Poisson packet arrival model with fixed-length data packets only. Further research to evaluate the actual performance of real-time traffic would be useful.

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# APPENDIX A

# ALTERNATIVE IMPLEMENTATION OF ADDRESS SPACE DOUBLING USING MULTITONE BPSK MODULATION

In this appendix, we will describe an alternative means to double the number of random addresses. In this alternative implementation, orthogonality of the sub-carriers is achieved by multitone BPSK modulation, in which sub-carriers are separated by frequency $\frac{1}{2T}$ Hz (where $T$ is the symbol period). This approach was suggested during the late stages of this thesis work [39].

## A.1 Basis Multitone Functions of BPSK Modulation

Conventional multitone BPSK modulation includes the following basis functions:

$$\psi_h(t) = \sqrt{\frac{2}{T}}\cos\left(2\pi f_h t\right) \qquad h = 0, 1, 2, \ldots, M\text{-}1 \quad [0, T] \qquad \text{(A.1)}$$

where $\sqrt{\frac{2}{T}}$ is the scaling factor for the basis functions [41].

## A.2 Orthogonality of Basis BPSK Functions

In order to maintain orthogonality among the sub-carriers, the central frequency separation $f_a$ - $f_b$ for the basis functions $\psi_a(t)$ and $\psi_b(t)$ is determined as shown below.

Orthogonality of $\psi_a(t)$ and $\psi_b(t)$ requires that

$$\int_0^T \psi_a(t)\psi_b(t)dt = 0 \tag{A.2}$$

$$\Rightarrow \frac{2}{T}\int_0^T \cos(2\pi f_a t)\cos(2\pi f_b t)dt = 0$$

$$\Rightarrow \frac{\sin(2\pi(f_a - f_b)T)}{(2\pi(f_a - f_b)T)} = 0$$

Equation (A.2) shows that if and only if $(2\pi(f_a - f_b)T) = \pi n$, where $n$ is an integer, then $\psi_a(t)$ and $\psi_b(t)$ are orthogonal. Therefore, the multitone frequency separation required is $\frac{n}{2T}$ Hz; the minimum separation is $\frac{1}{2T}$ Hz.

## A.3 Random Addressed Polling Using Multitone BPSK Modulation (RAP-BPSK)

As an alternative to OFDM modulation as proposed in this thesis, multitone BPSK modulation is potentially possible.

The implementation of the transmitter for RAP-BPSK is shown in Figure A.1.

In this implementation, the random address selector will randomly select a BPSK sub-carrier to carry a unique tone to the BS. Since the sub-carriers are separated by $\frac{n}{2T}$ Hz (as shown in Section A.2), and those of OFDM are separated by $\frac{n}{T}$ Hz (as shown in Appendix B), BPSK modulation has twice as many sub-carriers as does OFDM.

Therefore, replacing the OFDM with multitione BPSK modulation can double the number of random addresses offered by RAP-OFDM.

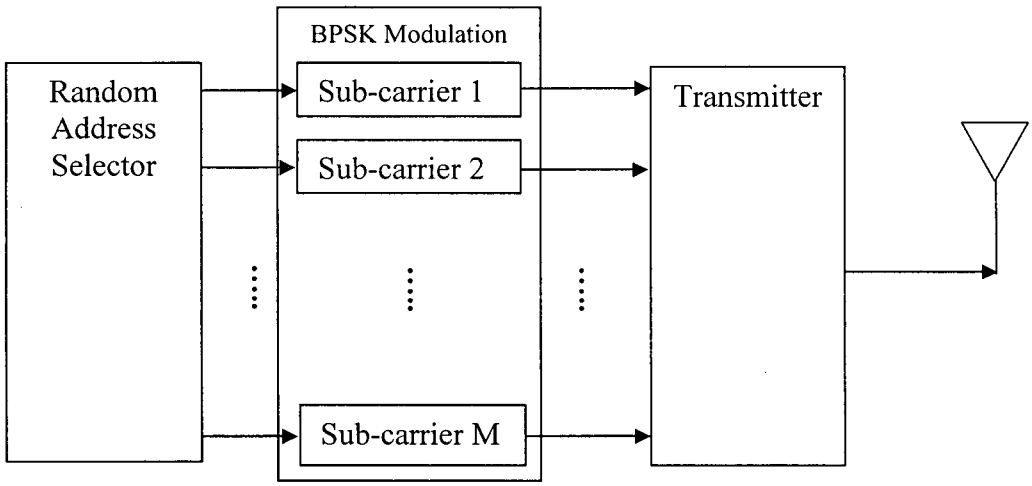


Figure A.1: Hardware or software implementation of RAP-BPSK

## A.4 Comparisons between RAP-BPSK and the Modified RAP-OFDM

Both RAP-BPSK and the modified RAP-OFDM offer the same number of random addresses. BPSK modulation, which requires simple hardware implementation, is an alternative to OFDM. However, implementing RAP-BPSK requires oscillators and matched filters for each sub-carrier, while implementing the modified RAP-OFDM only requires a FFT and an IFFT signal processors. Furthermore, implementing RAP-BPSK would require less frequency error in both the transmitter and the receiver, in which complex equalizers are needed for each sub-carrier. Therefore, the modified RAP-OFDM is likely easier to implement.

## A.5 Summary

RAP-BPSK provides an alternative means to double the number of random addresses offered by RAP-OFDM. However, the modified RAP-OFDM appears to have implementation advantages over RAP-BPSK. Further study would be needed to arrive at a definitive comparison of implementation costs and benefits of the two schemes.

# APPENDIX B

# ORTHOGONALITY OF OFDM

In this appendix, we consider the minimum frequency separation required for OFDM implementation using the IDFT signal processing algorithm.

## B.1 Basis Functions of IDFT

As shown in Chapter 2, the output signals of the IDFT operation for the $k^{th}$ sub-carrier are:

$$u_k(t) = \sum_{h=0}^{M-1} d_h(i) e^{j2\pi f_h (t-iT)} \tag{B.1}$$

Then, the basis functions, contained in $u_k$, are shown as follows:

$$\Phi_h(t) = \frac{1}{\sqrt{T}} e^{j2\pi f_h (t-iT)} \qquad h = 0, 1, 2, \ldots, M\text{-}1 \quad [0, T] \tag{B.2}$$

where $\frac{1}{\sqrt{T}}$ is the scaling factor for the basis functions.

## B.2 Orthogonality of IDFT Basis Functions

The inner product for the basis functions $\Phi_a$ and $\Phi_b$ with sub-carrier's central frequency separation = $\frac{n}{T}$ Hz is:

$$\int_0^T \Phi_a(t)\hat{\Phi}_b(t)dt = \frac{1}{T}\int_0^T e^{j2\pi f_a(t-iT)} e^{-j2\pi f_b(t-iT)} dt \tag{B.4}$$

$$= \frac{1}{T}\int_0^T e^{\frac{j2\pi(t-iT)n}{T}} dt$$

$$= \frac{1}{T} e^{-j2\pi in}\left[\frac{\left(e^{j2\pi n}-1\right)T}{j2\pi n}\right] \qquad \text{for } i = \text{integers}$$

In order to ensure that $\Phi_a$ and $\Phi_b$ are mutually orthogonal, $\left(e^{j2\pi n}-1\right)$ must equal to 0. Therefore, the two basis functions are orthogonal if and only if the sub-carrier's central frequency is separated from the others by $\frac{n}{T}$ Hz, where $n$ is an integer. Such orthogonality is required for OFDM [41].

## B.3 Summary

This appendix shows that in order to ensure orthogonality among the sub-curriers in OFDM implementation using IDFT, the frequency separation between the adjacent sub-carriers is required to be $\frac{n}{T}$ Hz where $n$ is an integer. Thus, the minimum frequency separation of OFDM sub-carriers is $\frac{1}{T}$ Hz, where $T$ is the symbol period.