ABSTRACT

MEDIUM ACCESS CONTROL DESIGN FOR ALL-IP AND AD HOC WIRELESS NETWORK

by
Zaihan Jiang

Medium Access Control (MAC) protocol in a wireless network controls the access of wireless medium by mobile terminals, in order to achieve its fair and efficient sharing. It plays an important role in resource management and QoS support for applications. All-IP wireless WAN is fully IP protocol-based and it is a strong candidate beyond 3G (Third Generation Wireless Network). Ad hoc wireless network has recently been the topic of extensive research due to its ability to work properly without fixed infrastructure.

This dissertation is composed of two main parts. The first part pursues a Prioritized Parallel Transmission MAC (PPTM) design for All-IP Wireless WAN. Two stages are used and each packet is with a priority level in PPTM. In stage 1, a pre-transmission probability is calculated according to the continuous observation of the channel load for a certain period of time. In stage 2, a packet is prioritized and transmitted accordingly. It is modeled and analyzed as a nonpreemptive Head-Of-the-Line prioritized queueing system with Poisson arrival traffic pattern. Its performance is analyzed under three other traffic patterns, which are Constant Bit Rate, Exponential On/Off, and Pareto On/Off, by using a NS-2 simulator, and compared with that of Modified Channel Load Sensing Protocol. PPTM supports dynamic spread code allocation mechanism. A mobile terminal can apply for a spreading code according to the current channel condition.

To use the idea of dynamic bandwidth allocation in PPTM for adhoc wireless network, a Dynamic-Rate-with-Collision-Avoidance (DRCA) MAC protocol is proposed in the second part of the dissertation. DRCA is based on spread spectrum technology. In DRCA, a terminal sets the spreading factor for a packet according to the activity level of neighboring nodes. If the total number of usable spreading codes with this spreading factor is less than the total number of mobile terminals in the network, to avoid collision, the spreading code id is broadcast such that other terminals can avoid using it when the packet is being transmitted. The performance of DRCA is theoretically analyzed in a slotted, single-hop, multi-user environment. To evaluate DRCA's performance in an environment closed to a real one, a simulator that supports multi-hop, random mobility pattern is created with OPNET. Both theoretical and simulation results show that DRCA outperforms MACA/CT (Multiple Access with Collision Avoidance with Common Transmitter-based) in case if there are more than one communication pair and the ratio of inactive mobile terminals to active ones is high.

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To my wife: Zhi Fu
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my sons: Peter and Alan
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LIST OF ABBREVIATIONS

2G	Second Generation
3G	Third Generation
ACK	Acknowledgement
AP	Access Point
AODV	Ad-hoc On-demand Distance Vector
ATM	Asynchronous Transfer Mode
BE	Best Effort
BER	Bit Error Rate
BS	Base Station
BTMA	Busy Tone Multiple Access
CBR	Constant Bit Rate
CDMA	Code Division Multiple Access
CLSP	Channel Load Sensing Protocol
CSMA	Carrier Sense Multiple Access
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CSMA/CP	Carrier Sense Multiple Access with Collision Prevention
C-T	Common-Transmitter-based
CTS	Clear-To-Send
DBTMA	Dual Busy Tone Multiple Access
DCA	Dynamic Channel Assignment
DCF	Distributed Coordination Function
DPS	Distributed Priority Scheduling
DRCA	Dynamic-Rate-with-Collision-Avoidance

DSSS	Direct Sequence Spread Spectrum
ertPS	extended real time Polling Service
FAMA	Floor Acquisition Multiple Access
FAMA-NTR	FAMA Non-persistent Transmit Request
FDD	Frequency Division Duplexing
FDMA	Frequency Division Multiple Access
FEC	Forward Error Correction
FFT	Fast Fourier Transfer
FHSS	Frequency Hopping Spread Spectrum
FIFO	First-In-First-Out
FTP	File Transfer Protocol
GRAP	Group Random Access Polling
HOL	Head-Of-the-Line
IAP	Internet Access Point
ICLSP	Improved Channel Load Sensing Protocol
IMT	Internet Mobile Terminal
IP	Internet Protocol
LAN	Local Area Network
MAC	Medium Access Control
MACA	Multiple Access with Collision Avoidance
MACA-BI	MACA By Invitation
MACA/CT	Multiple Access with Collision Avoidance/ Common-Transmitter-based
MACA/RT	Multiple Access with Collision Avoidance/ Common-Receiver-based
MACAW	MACA-Wireless

MAI	Multi-Access Interference
MAN	Metropolitan Area Network
MANET	Mobile Ad hoc NETwork
MARCH	Multiple Access with ReduCed Handshake
MCLSP	Modified Channel Load Sensing Protocol
MMAC	Multi-channel MAC
MPEG	Moving Picture Experts Group
MS	Mobile Station
MSS	Mobile Subscriber Station
MT	Mobile Terminal
nrtPS	non real time Polling Service
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	OFDM Multiple Access
PCF	Point Coordination Function
PN	Pseudo Random Number
PS-DCF	Priority Scheme-Distributed Coordination Function
PTMP	Parallel Transmission MAC Protocol
PPTM	Prioritized Parallel Transmission MAC
QoS	Quality of Service
RAP	Random Access Polling
R-T	Receiver-Transmitter-Based
RTMAC	Real Time MAC
rtPS	Real-time Polling Services
RTS	Request-To-Send
RTR	Ready to Receive

SM	Short Message
SNDR	Sequenced Neighbor Double Reservation
SNIR	Signal to Interference and Noise Ratio
SNR	Signal to Noise Ratio
SS	Spread Spectrum
STMP	Serial Transmission MAC Protocol
TDD	Time Division Duplexing
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
THSS	Time Hopping Spread Spectrum
TTD	Transmission Time Delay
UGS	Unsolicited Grant Services
VBR	Variable Bit Rate
VoIP	Voice over IP
WAN	Wide Area Network
WLAN	Wireless LAN

CHAPTER 1

INTRODUCTION

1.1 Objectives

This research intends to propose proper Medium Access Control (MAC) designs for All-IP wireless WAN (Wide Area Network) and ad hoc wireless network, and analyze the performance of these designs. The specific objects are:

1) To investigate the MAC requirements for All-IP wireless WAN and then to propose a MAC design that works properly in an All-IP wireless WAN;
2) To analyze the performance of this MAC design in an All-IP wireless WAN and compare it with that of Modified Channel Load Sensing Protocol (MCLSP);
3) To investigate the new challenges brought by ad hoc wireless network and then to propose a MAC design that uses bandwidth efficiently in an ad hoc wireless network; and,
4) To analyze the performance of this MAC protocol in an ad hoc wireless network; compare it with that of MACA/CT (Multiple Access with Collision Avoidance/ Common Transmitter-based).

1.2 Statement of Problems

MAC protocols in a wireless network are created to control mobile terminals (MTs) to access the physical medium. They play an important role in resource allocation, Quality of Service (QoS) support and security management. They intend to keep balance among three objects: efficiency, QoS and fairness. Design a proper MAC protocol is critical for the operation of a wireless network.

All-IP wireless WAN deploys IP technology as common service platform for different types of service and the unified transport platform. It is a strong candidate beyond 3G cellular networks. MAC design for an All-IP wireless WAN faces some new challenges, e.g., how to support different QoS requirements from applications, how to achieve high throughput, how to use spectrum efficiently, and how to work properly in a high mobility and wide area coverage environment? A good MAC design should resolve these problems properly.

Ad hoc wireless networks attract many research interests in recent years due to its capacity to work properly without any infrastructure network. It becomes extremely useful in some scenarios that infrastructure network is too expensive or impossible to be built, like military operations, emergency relief, and wireless sensor networks. However, controlling mobile terminals to access the physical medium is more difficult than that in infrastructure-depend networks. The support of real-time applications and resolution of hidden and exposed terminal issues are other two major challenges.

Spread Spectrum (SS) technology has been used successfully in cellular networks. It has some advantages like high capacity, robust performance with interference and jamming. However, four related issues, which are spread code allocation, collision avoidance, bandwidth efficiency and high peak rate achievement, prevent SS technology from being widely accepted in ad hoc wireless networks. An SS-based MAC design should resolve these issues and all other challenges brought by the distributed, self-organized nature of ad hoc wireless networks.

1.3 Motivation

All-IP wireless WAN is a strong candidate beyond 3G cellular network. A MAC design for All-IP wireless WAN should work properly in a WAN environment and support services range from voice, streaming video, web browser, email, ftp, etc, with different QoS requirement. The existing MAC protocols are either improper or need some significant modifications to be used for an All-IP wireless WAN.

Carrier Sensing Multiple Access (CSMA) based MAC protocols are mainly used in a Local Area Network (LAN). Even combined with other mechanisms like handshaking, token passing and polling, a CSMA-based protocol is hard to work properly in a wireless WAN due to two reasons. First, the high mobility of MTs in WAN brings a severe fading channel condition. Carrier sensing may be inaccurate in it. Second, CSMA-based protocol cannot apply its measurement in time because of the long propagation time delay caused by the wide area coverage. Serious consequence can be brought because of that. On the other hand, the polling-based protocols lack the flexibility and efficiency required by All-IP wireless WAN MAC design.

Channel Load Sensing Protocol (CLSP) is very sensitive to propagation time delay caused by the big coverage radius. Thus, it is not a good candidate for WAN. Modified CLSP (MCLSP) achieves robust performance in the case of long propagation time delay. However, MCLSP does not distinguish packets according to their importance and QoS requirement. A more important packet is transmitted with the same opportunity as a less important one. MCLSP is proposed mainly for usage in a voice service wireless network, in which the difference of importance levels and QoS requirements is insignificant among packets. But situations become completely different in an All-IP wireless network that has to support many types of service, e.g., voice, video, database access, email, and web browser. The importance levels and QoS requirements can be much different among packets. Obviously, a more important packet or a time-delay sensitive packet should be transmitted faster than a less important packet or a time-delay non-sensitive packet.

Ad hoc wireless networks have recently been the topic of extensive research due to their ability to work properly without any fixed infrastructure. It becomes extremely useful in scenarios where such infrastructure is infeasible or expensive to be built. On the other hand, without the help of a centralized controller like a base station, it is hard for an ad hoc wireless network terminal to obtain the network-wide states of queues and channels at any given time instant. It is one of the fundamental challenges impacting various design issues in ad hoc wireless networks. Controlling terminals to access the medium in an efficient and effective way then becomes a difficult task.

Due to its superior characteristics, Spread Spectrum [44] is used as one of the basic access technologies in cellular systems, including 2G, e.g., IS-95 [51] and recently deployed 3G systems, e.g. CDMA2000 [52] and WCDMA [53]. It is natural to consider SS-based MAC for ad hoc wireless networks to achieve higher capacity, more flexibility and robust resistance to interference. However, four pending issues, i.e., code assignment, collision avoidance, bandwidth efficiency and high peak rate, limit the popularity of SS-based MAC protocols. An SS-based MAC protocol for ad hoc wireless network should solve these issues properly.

1.4 Background

1.4.1 Medium Access Control Protocols

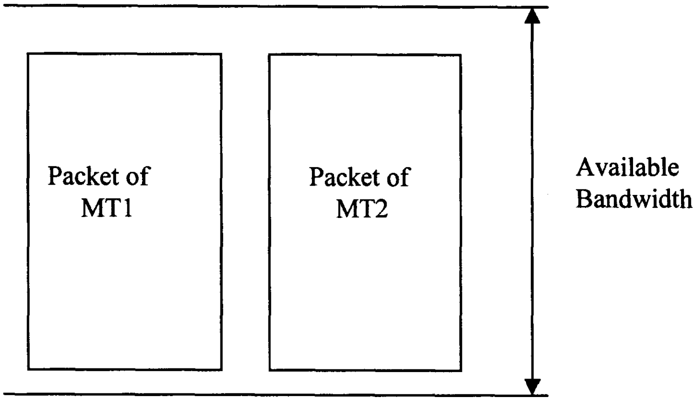
Wireless medium is different from wired medium in the following aspects:

1) the channel condition is unstable;
2) the channel as a resource is often shared among many users; and,
3) the available radio spectrum is very limited.

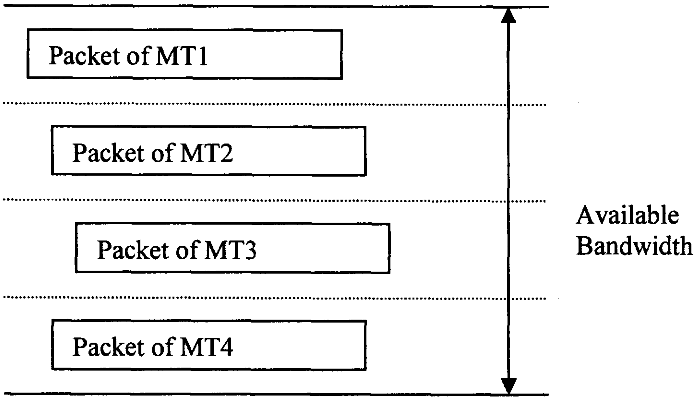
MAC protocols, which control MTs to access medium, play an important role in resource allocation, QoS support and security management in a wireless network.

Because of the limited radio spectrum in a wireless network, the bandwidth available for communication is also limited. Access to the shared medium should be controlled in such a manner that all nodes in the network receive a fair share of the available bandwidth and the bandwidth is efficiently utilized. Due to the fact that wireless medium is different from wired medium, a different set of protocols is required for controlling access to the shared medium in wireless networks.

The existing MAC protocols for wireless networks are classified into two categories: Serial Transmission MAC Protocol (STMP) and Parallel Transmission MAC Protocol (PTMP) [2]. STMP statistically multiplexes traffic over a single channel and at any time point the channel can transmit a packet of one MT. It is called a Single Channel MAC protocol, too. PTMP divides available bandwidth into several parts and data can be transmitted on each one in parallel. It is also termed as Multi-Channel MAC protocol. Figure 1.1 illustrates the difference between PTMP and STMP.



PTMP transmit a packet through the whole available bandwidth; it can only transmit one packet of a Mobile Terminal at any time point



STMP divides available bandwidth into several parts and transmits packets in parallel

Figure 1.1 STMP vs. PTMP.

MAC protocols based on CSMA or Polling belong to STMP. Because of the popularity of Ethernet, a CSMA-based MAC protocol is attractive to many researchers and manufactures. A CSMA-based MAC protocol uses a carrier sense mechanism to determine when an MT transmits a packet. One typical example is IEEE 802.11 MAC Distributed Coordination Function (DCF) [1], which uses CSMA/CA (CSMA with

Collision-Avoidance). It is a distributed MAC protocol, too. A CSMA based MAC protocol works properly in a Wireless Local Area Network (WLAN) environment and is usually efficient and flexible. To fight against the hidden and exposed terminal issues, a RTS-CTS dialogue is introduced in IEEE 802.11 DCF and many other CSMA-based MAC designs, which can cause considerable signaling overhead [58]. Besides, carrier-sensing should be accurate in a CSMA-based MAC. Otherwise, serious consequence may be brought. In a WAN environment, due to the severe fading caused by high mobility and long propagation time delay caused by large coverage area radius, the accuracy of carrier-sensing degrades drastically. Accordingly, it is not recommended to use a CSMA-based MAC protocol for wireless WAN.

On the other hand, MAC protocols based on polling are usually centralized MAC protocols. Polling means that a central station polls all mobile terminals and finds out which one is ready to transmit a packet. It is one kind of coordinated-packet transmission methods. The simplest polling scheme is that an access point polls every mobile terminal in sequence and checks if it has a packet to transmit. It leads to very low efficiency when just a few mobile terminals among many have packets to transmit. RAP (random access polling) [7] and GRAP (group random access polling) [7] are two typical examples of polling MAC designs. In RAP, every active MT within an access point's coverage area produces and transmits a random number and the access point polls these terminals according to the number. Hence, only active MTs' information is needed. System capacity increase is achieved by dividing active MTs into different groups in GRAP. The advantages of polling are two folds. First, it can achieve high reliability. Second, some benefits can be gained in the physical layer. For example, it allows antenna elements to direct toward the transmitting MT to overcome fading and interference problems. The biggest disadvantage of such polling MAC protocols is their low efficiency.

Typical examples of PTMP include Channel Load Sensing Protocol (CLSP) [8, 70, 71, 72, 9, 73], Improved Channel Load Sensing Protocol (ICLSP) [15], and modified one (MCLSP) [10, 74, 75].

CLSP is proposed for CDMA-ALOHA systems since it can improve system throughput. It is a centrally-controlled access protocol in which the access point sets a channel load threshold and controls the admission of a packet. If it senses the channel load above the threshold, it denies further packet access until it detects below-the-threshold channel load. The scheme of CLSP is exemplified in Figure 1.2.

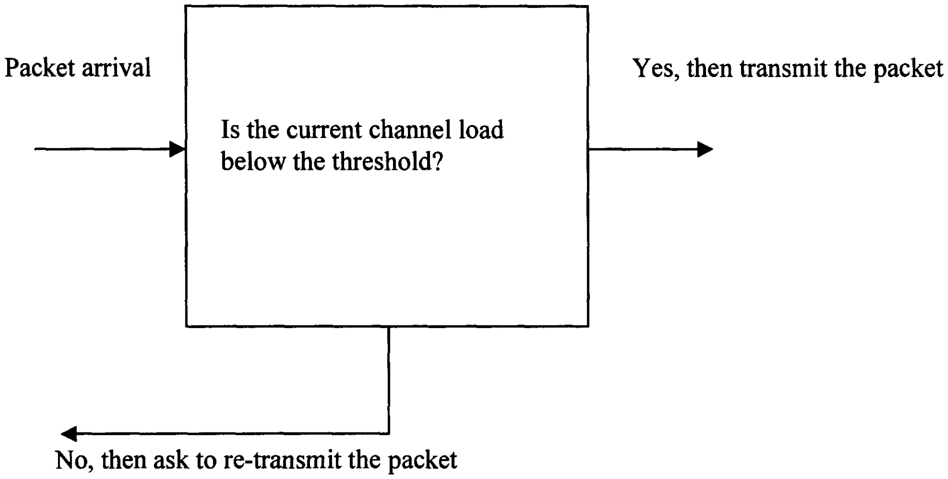


Figure 1.2 Scheme of CLSP.

CLSP requires immediate channel load information, which is hard to achieve in a real situation. It is found that as the propagation time delay increases, the offered load increases and throughput performance decreases significantly [9]. For small delay, CLSP can be expected to maintain the throughput performance well. But for large delay, the throughput degrades even with small offered load. Figure 1.3 gives the performance of CLSP in a CDMA ALOHA system with different access time delays τ_0 [10], which is defined as the sum of propagation time delay and process time delay. From the figure it is found that the maximum throughput of CDMA ALOHA system with CLSP can reach almost 1.5 times of the maximum throughput of a conventional CDMA ALOHA system, if there is no access timing delay. However, when the access timing delay is no longer negligible, the performance degrades. As shown in the figure, even with the case of small access timing delay, say τ_0 = 0.2 time units, the performance degrades. Such performance degrading is especially severe in the large offered load. For the case of τ_0 = 5.0 time units, it is seen that its performance is worse than that of CDMA ALOHA without employing CLSP.

To mitigate the effect of long propagation time delay, MCLSP is proposed by controlling packet access based on estimated average offered load [10]. The access point first keeps observing the channel load for a certain period of time. It then calculates and broadcasts a probability P_{tr} with which each MT transmits a packet based on the observation. An MT that has a packet to transmit sends it with probability P_{tr} and does not send it with $1-P_{tr}$. MCLSP is an experiential CLSP and its performance is stable. It assumes that the mobile transmission is a smooth random process. Figure 1.4 shows a wireless network with MCLSP.

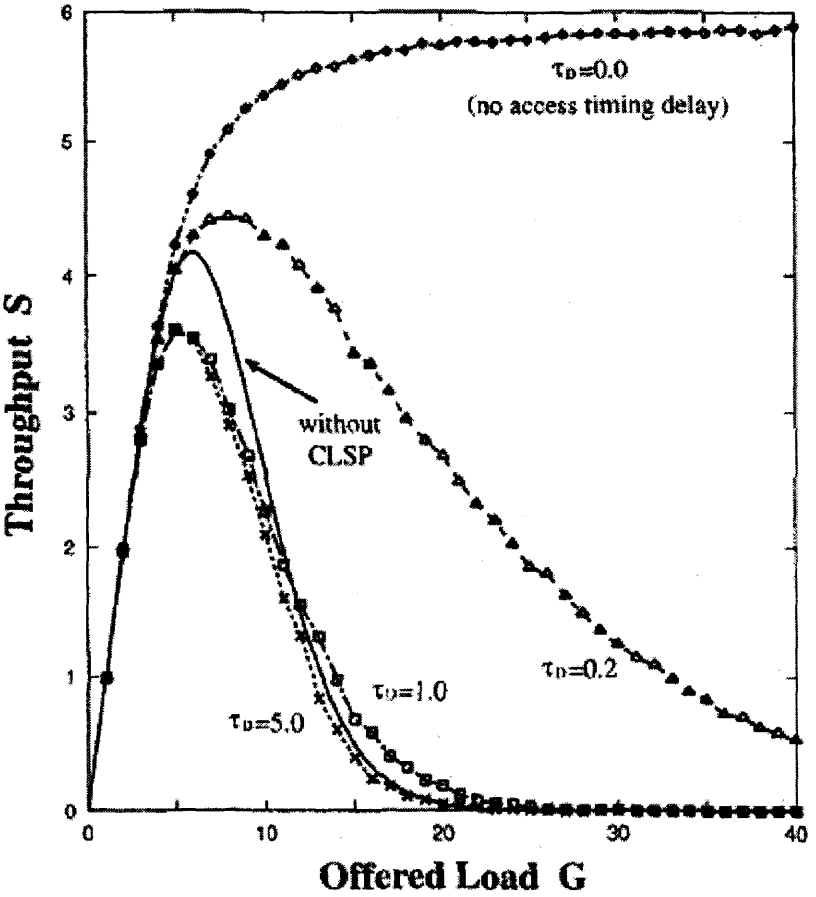


Figure 1.3 CLSP performance with different access time delay [10].

ICLSP [47] controls channel access on both ongoing transmission and average channel load. The central controller calculates a pre-transmission probability with the channel load and makes access decision according to the number of ongoing transmissions and a certain threshold. It has been shown that ICLSP performs a little bit better than MCLSP in case of small propagation time delay. However, it is found that its performance is worse than that of MCLSP when propagation time delay becomes large. It is because ICLSP uses ongoing transmissions as one criterion to control physical medium access and this information is usually inaccurate with an environment of long propagation time delay.

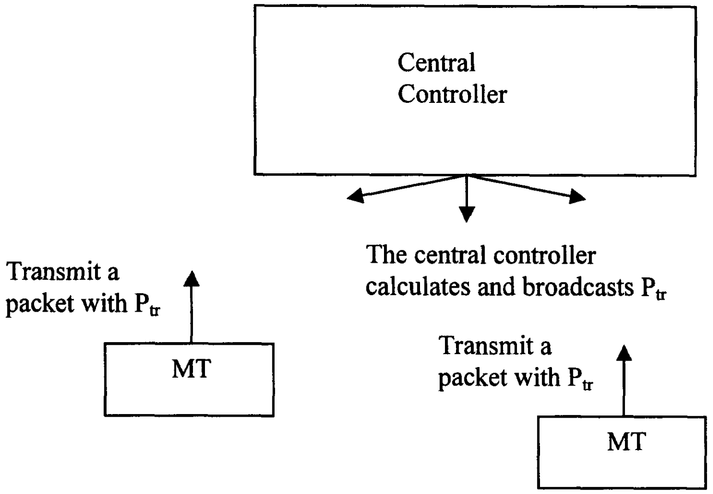


Figure 1.4 A Network using MCLSP.

Compared with an STMP MAC protocol, PTMP MAC has several advantages. Although the bandwidth of a channel is not increased, the capacity of the network improves because simultaneous communications can take place on different channels in the same space. The utilization of multiple channels is one approach for reducing the probability of collision since the multi-channel protocols may mitigate the problems caused by intruders [13] and normalized propagation time per channel can be decreased [19, 20]. QoS support is easier by using multiple channels than a single-channel in MAC protocols. Finally, the network becomes more flexible since a node can switch from one channel to another dynamically.

Despite the advantages of a PTMP MAC, much of the current work on MAC still focuses on STMP MAC protocols. One reason is the easy implementation of STMP MAC. For example, IEEE 802.11 DCF is CSMA-based and it is an STMP. It is easier to be realized in a distributed system like WLAN than a centrally-controlled MAC. Another reason is that an STMP MAC protocol can easily support high peak rate while a multiple channel protocol is hard to do so unless dynamical channel allocation mechanism is deployed. In many PTMP protocols, bandwidth is divided statically and cannot be changed per node's request. Regarding the whole bandwidth as a big "pipe", multiple channel protocols create many thinner pipes. If the size of each thinner pipe is fixed, a special user cannot achieve high peak bit rate as that in an STMP protocol.

MAC protocols can also be classified as centralized MAC and distributed one. The central controller in a centralized MAC plays a key role in determining which mobile terminal to access physical resource. Mobile terminals can either be polled or compete for resource allocation and the central controller makes the final decision. For example, in a cellular network, a Base Station (BS) decides which mobile terminal to use a channel. It avoids signaling overhead like RTS (Request-To-Send)-CTS (Clear-To-Send) dialog in IEEE 802.11 DCF. However, a mobile terminal does not play any important role in resource allocation. It can ask for more bandwidth. However, it is the central controller who makes the decision, based on a few factors. Comparing with a centralized MAC, there is no central controller in a distributed one. Usually, each mobile terminal competes for physical medium access. It is flexible to re-allocate resource according to the status of each mobile terminal. On the other hand, signal overhead like RTS-CTS sometimes takes a considerable percentage of available bandwidth. One typical example of distributed MAC protocol is IEEE 802.11 DCF for both WLAN and ad hoc wireless network.

MAC can be also divided as contention-based MAC and non-contention-based one. In contention-based MAC, mobile stations compete for medium access. This kind of method is often deployed in a distributed system. For example, the IEEE 802.11 DCF is used in WLAN or ad hoc wireless systems. A system with a central controller can use contention-based MAC, too. For example, the contention mechanism is used for Non-real-time Polling Services (nrtPS) in IEEE 802.16e. However, these kinds of MAC usually do not give QoS support for real-time applications. In a non-contention-based MAC, a mobile terminal accesses medium either by being polled or using reserved time slot/bandwidth such that there is no competition among terminals. It is usually deployed in a centrally-controlled system. One typical example is IEEE 802.11 PCF. Compared with contention-based MAC, non-contention-based one can usually support real-time applications.

In summary, MAC protocols are classified into STMP and PTMP. MAC protocols can also been classified as centralized MAC and distributed one. They can be divided as contention-based MAC and non-contention-based one.

1.4.2 All-IP Wireless WAN

Internet Protocol (IP) provides a universal network-layer protocol for wireline packet networks, and it is an attractive candidate to play the same role in wireless systems. IP provides a globally successful open infrastructure for creating and providing services and applications. An All-IP wireless network could be more robust, scalable, and cost effective by deploying IP technology [100]. It will also enable the abundant applications and software technologies developed for wired IP networks to be used over wireless networks. Today's many different wireless systems are not compatible with each other, making it difficult for a user to roam from one wireless system to another. With IP as the common network layer protocol, an IP-based mobile device could roam among different wireless systems.

With the explosive growth of the Internet subscriber population, it is a trend to support Internet service, for example, Voice over IP (VoIP). Some Non-All-IP mobile networks, like GSM, use VoIP signaling protocols to support this kind of service. Switch or Gateway are often deployed to connect a Non-All-IP mobile networks with IP network, as exemplified in Figure 1.5 [101].

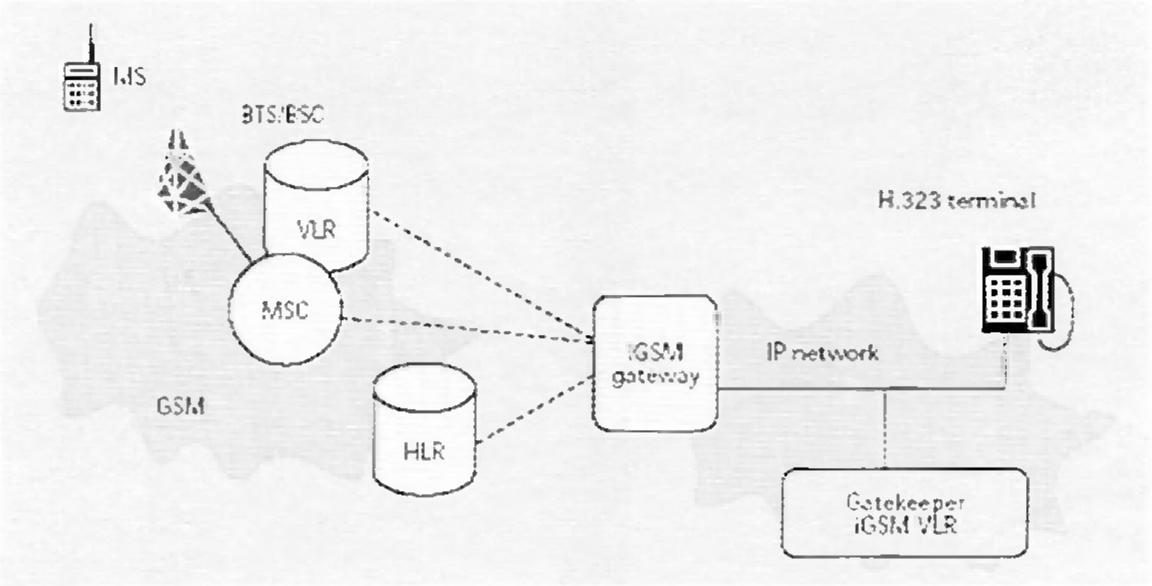


Figure 1.5 A GSM architecture that supports VoIP.

To integrate IP and wireless technologies, UMTS all-IP architecture is proposed by the 3GPP [101, 104, 105]. There are two options for a UMTS all-IP network. Option 1 architecture supports Packet-Switch domain multimedia and data services. However, the Circuit-Switch domain still supports voice application. Option 2 architecture supports all kinds of services over a packet-switched core network. The two architectures are exemplified in Figures 1.6 and 1.7.

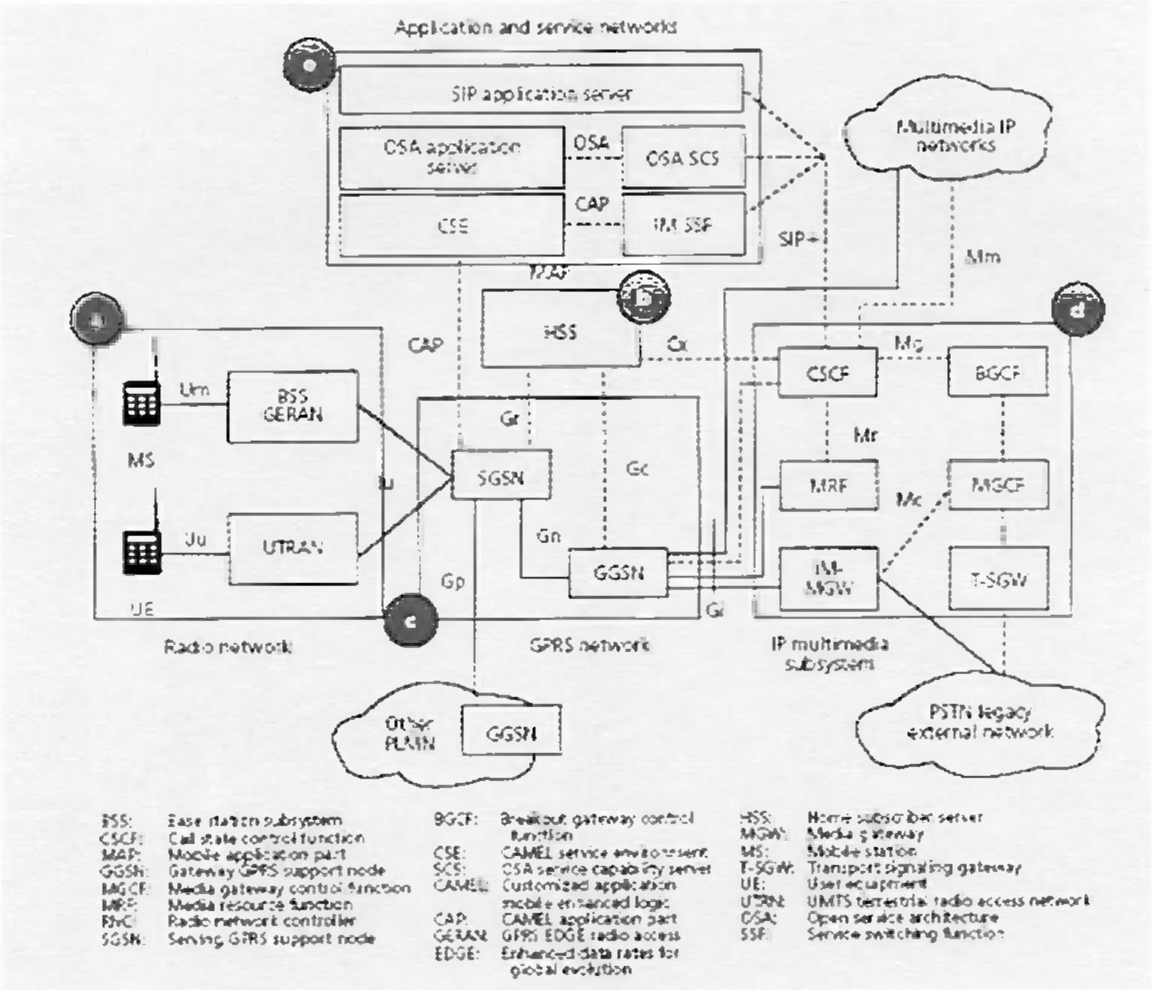


Figure 1.6 Option 1: UMTS All-IP network architecture..

It is clear that the next generation wireless network beyond 3G must support very high throughput, low access time delay, seamless transmission, and applications with different QoS requirements. Meanwhile, low cost for the infrastructure is required. The present trend is to use Internet Protocol [11, 12, 13, 14]. All-IP wireless WAN, which deploys IP technology as common service platform for different types of service and the unified transport platform, is a strong candidate beyond 3G.

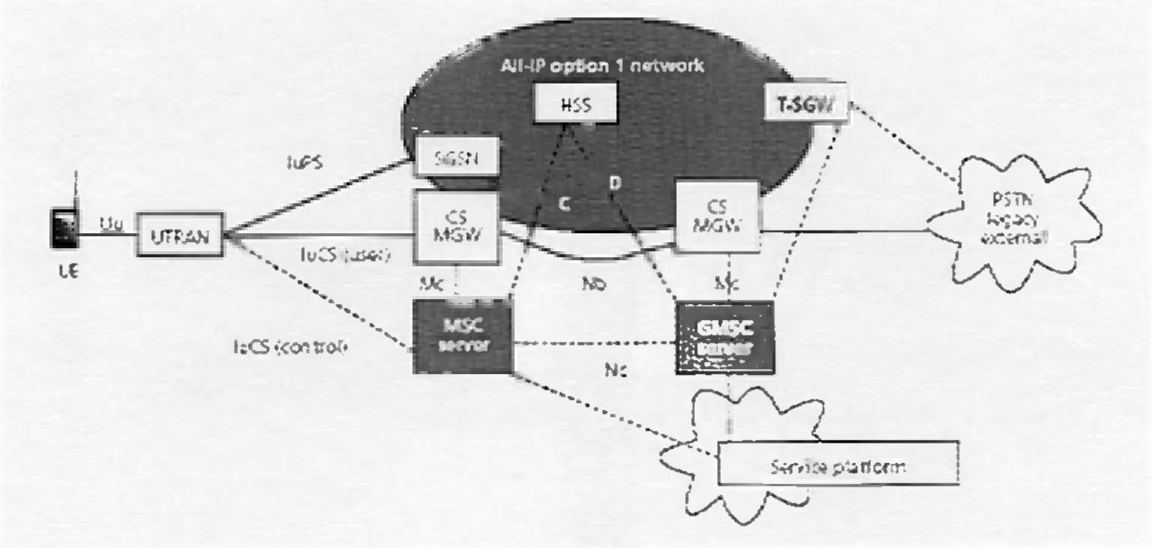


Figure 1.7 Option 2: UMTS All-IP network architecture.

This dissertation defines All-IP wireless WAN as a fully IP protocol-based wireless network with wide-area-coverage and high-mobility support. The architecture of an All-IP wireless WAN is described in Figure 1.8 and used in this dissertation. The backbone is IP-based as well. Internet Access Point (IAP) connects the backbone with Internet Mobile Terminals (IMT).

The architecture of this All-IP wireless WAN is simple and easy to be implemented. It has only three kinds of component: Internet Backbone, IAP and IMT. Since all of them support IP, transformation components like gateway and switch centers, become unnecessary. The existing Internet backbone can be re-used so that the infrastructure cost can be drastically reduced. This architecture is defined mainly for academic research purpose. It requires much more detail to be commercially viable.

The selection of a MAC protocol is a critical issue for an All-IP wireless WAN. MAC protocol in a wireless network controls the access of the medium by mobile terminals, in order to achieve fair and efficient share of a physical resource. The requirements of MAC for All-IP wireless WAN are as follows:

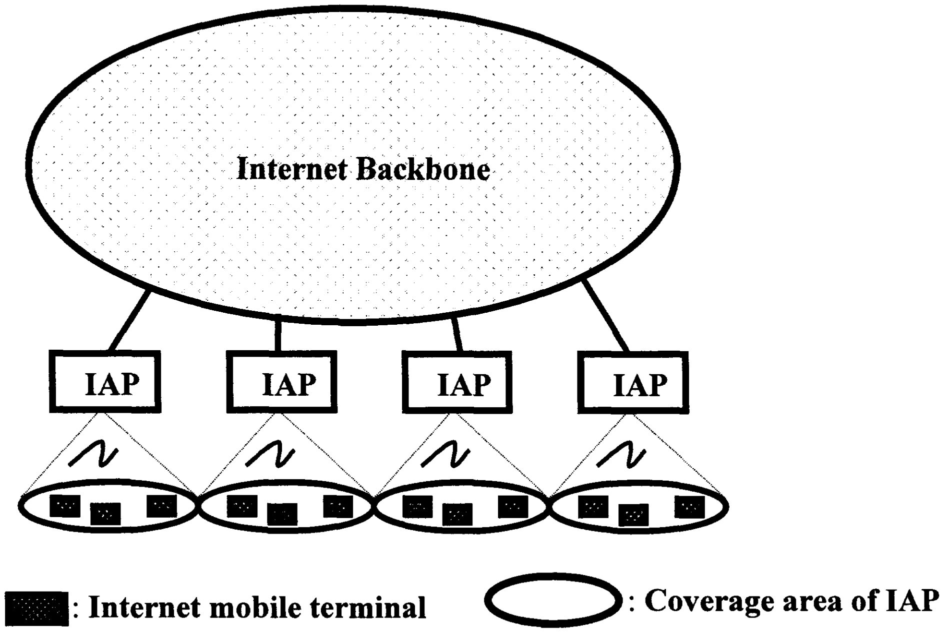


Figure 1.8 Architecture of an All-IP wireless WAN.

First, it is flexible and highly efficient. There are two meanings of flexibility. The first one is that not only an IAP, but also an IMT, plays a role in the resource allocation decision. An IAP knows more of the system level information; an IMT knows more of itself and its surrounding environment. Both should play their roles in the MAC. The second meaning is that a physical resource is allocated according to the importance and QoS requirements of the applications and the current channel load condition. It can be easily re-allocated if the condition changes. Efficiency means that the physical bandwidth is utilized as efficiently as possible. To be efficient, the signaling overhead should be kept small and the bandwidth waste should be avoided. Flexibility and efficiency are closely related. A MAC design that lacks flexibility to re-allocate bandwidth is usually inefficient.

Second, it achieves high throughput; "Throughput" is defined as data that are successfully transmitted and received per time unit within the system. The unit is bit per second.

Third, it supports high mobility and works properly with long propagation time delay. In a WAN environment, due to the large radius of the coverage area, it takes longer time for a transmitting signal to be received or sensed than that in a LAN. High mobility can cause severe fading in wireless medium. A MAC design should handle both fading and long propagation time delay.

Forth, it transmits certain packets with low time delay, especially for packets of real time applications, e.g., voice call, video call and control information. At last, it gives varying level QoS support for varying priority level services. QoS offered to applications is described in terms of loss, delay, and reliability. This dissertation focuses on their delay characteristics.

Since most applications in IP network are packet-based, a packet switch-based MAC protocol is definitely needed for an All-IP wireless WAN. Obviously, the traditional circuit switch-based access control protocol, which has been used mainly for voice service, cannot satisfy the above criteria.

It seems that a MAC protocol must also be a compromise between centralized and distributed protocols to enjoy the advantages of both protocols without suffering from their primary disadvantages. That is, the signaling overhead is kept low as a centralized MAC protocol does; meanwhile it has some kinds of flexibility as a distributed one does.

Additionally, high mobility and long propagation time delay become two issues that need to be resolved in a WAN environment. It is expected that a mobile terminal can move at very high speed, for example, 100 mile/hour. Such speed can cause severe fading. The radius of a coverage area is much bigger than a WLAN environment, e.g., 2 kilometers, which can cause considerable propagation time delay. A MAC protocol for All-IP wireless WAN should work properly with the fading and longer propagation time delay situations.

In summary, All-IP wireless WAN is a strong candidate beyond a 3G cellular network. Its architectures are given in this section. The requirements of MAC design for the All-IP wireless WAN is analyzed. A MAC design for All-IP wireless WAN should adjust to the new challenges brought by the All-IP wireless WAN.

1.4.3 Ad Hoc Wireless Networks

Within the last few years, there has been a surge of interest in mobile ad hoc networks. Ad hoc wireless network is defined as one that uses multi-hop radio relaying for message transmission and is capable of operation without the support of any fixed infrastructure or centralized administration. An ad hoc network is shown in Figure 1.9. The current cellular wireless network is classified as the infrastructure dependent networks. Its example is given in Figure 1.10.

Due to the distributed nature of ad hoc wireless network, MAC design is different from that of the traditional cellular network. Without the help from a central controller like base stations in a cellular network, it is hard for a node in ad hoc network to know

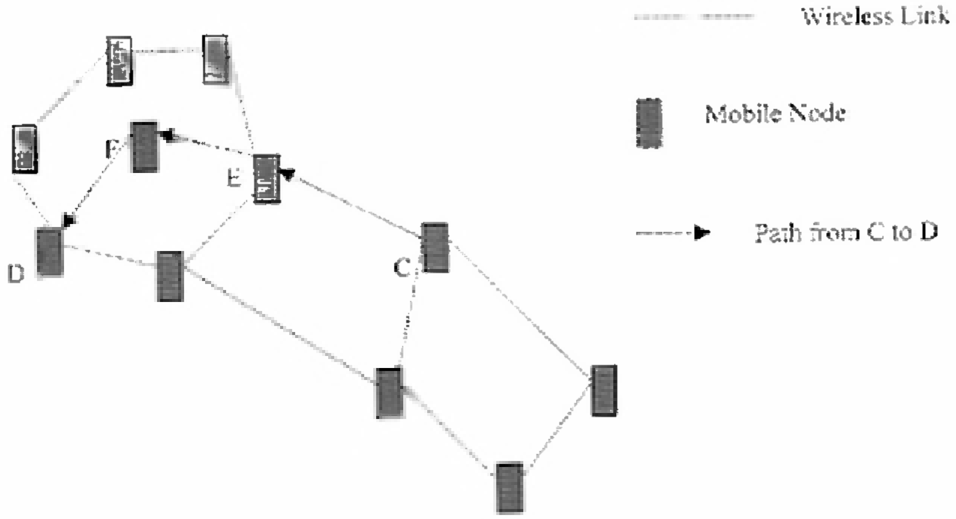


Figure 1.9 An ad hoc wireless network.

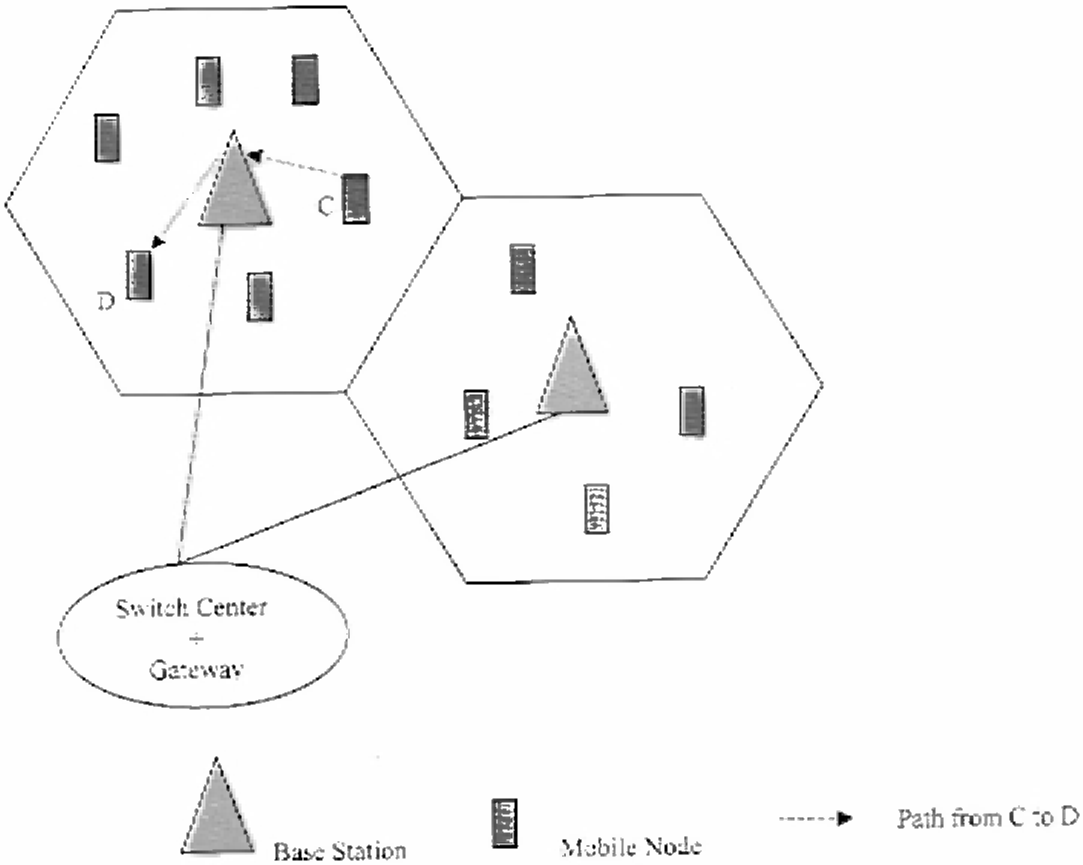


Figure 1.10 A traditional cellular network.

network-wide information. Arranging nodes to access the medium in an efficient and effective way is a great challenge.

An ad hoc wireless network often uses multi-hops to deliever packets from source to destination because of the limitation of each node's transmission range. Power efficiency is important for a node. Hidden and exposed terminal problems are common in an ad hoc wireless network [28]. As shown in Figure 1.11, a node "H" is a hidden node to "S" since it is far away from the sending node "S" but close to a sink node "D". It does not detect "S". Collision may happen if "H" sends a packet to "D" when "S" is transmitting. Node "E" is an exposed node to "S". Its transmission to "R" is blocked by the transmission from "S" to "D" since it is close to "S" and believes that it should not interfere with the on-going transmission.

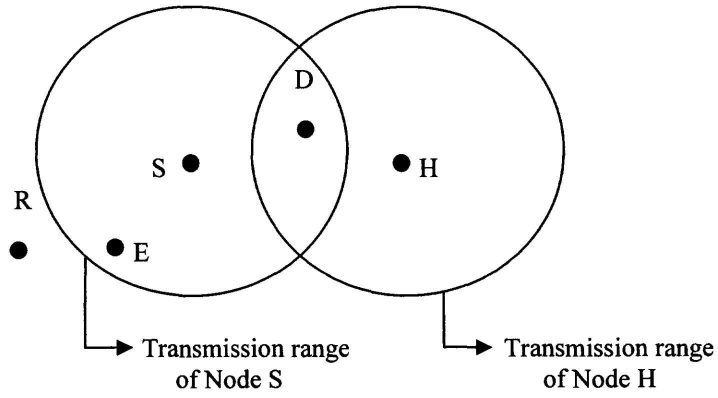


Figure 1.11 Hidden and exposed terminals.

Real-time applications, like voice and video, are often required in ad hoc network. On the other hand, QoS support and guarantee for delay sensitive traffic become extremely challenging in ad hoc wireless networks with a contention-based distributed

MAC layer [29]. The fundamental reason is that without a central controller, it is hard to obtain a network-wide distribution of the state of queues and the channels at a node at any given instant. Beside, random back-off techniques are usually implemented in many of those contention-based MAC protocols, e.g., IEEE 802.11 Distributed Coordination Function (DCF), and MACA (Multiple Access with Collision Avoidance) [15]. The random back-off techniques prevent them from providing deterministic upper bounds on channel access delays [21].

Based on the above analyses, it is concluded that the requirements for ad hoc wireless network MAC are:

- It must be capable of giving each user equal access to physical medium with the minimum amount of interference and collision in the absence of a central coordinator;
- It should make the efficient usage of bandwidth and achieve high throughput;
- It must solve the hidden and exposed terminal problems; and
- It can give QoS support for delay-sensitive traffic in real-time applications.

1.4.4 MAC Designs for ad hoc wireless network

Because of its distributed nature, and the absence of any central controller, MAC design for an ad hoc wireless network is different from that of the traditional cellular network. The existing MAC protocols for ad hoc wireless network can also be classified into two categories: single and multi-channel MAC.

Single channel MAC uses all the available bandwidth as one channel and the channel is shared by a number of communication nodes located in close proximity [17]. Typical examples include 802.11 DCF, MACA (Medium Access/Collision Avoidance), MACAW (MACA-Wireless) [15], MARCH (Multiple Access with ReduCed Handshake)

[16], FAMA (Floor Acquisition Multiple Access) [18] and MACA-BI (MACA By Invitation) [19]. Due to the increasing contention and collision, their performance decreases quickly with the number of mobile hosts.

MACA uses a sequence of three messages: RTS, CTS and DATA. Binary exponential backoff algorithm is used to resolve collisions. It is found that the throughput is not high under imperfect channel condition. MACAW is proposed to improve MACA [15]. The RTS-CTS dialogue is the same as that of MACA. But the data part is different. First, the data is preceded by a short Data Send message to inform neighboring terminals about the immediate transmission of the packet. The neighboring terminals will then refrain from transmission to avoid collision. An ACK message is sent by the receiver to ensure reliability.

MARCH is proposed for a multi-hop ad hoc wireless network [16]. A RTS-CTS dialogue is used only by the first hop of a route to forward data packets while for the rest it utilizes a new CTS-only message. Since fewer control packets are transmitted, the probability of packet collision is reduced and therefore channel throughput is increased.

FAMA is a family of MAC protocols with both carrier sensing and a collision – avoidance dialogue between a source and the intended receiver [18]. It is required that a station that has a data packet to send to acquire the control of the channel (Floor Acquisition) before sending it and to ensure that no data packet collides with any other packet. MACA and MACAW belong to this category if RTS and CTS last long enough. FAMA-NTR (Non-persistent Transmit Request) works as follows [18]: when a station has one or multiple packets to deliver, it first listens to the channel. In case of a busy channel, the station goes to backoff and tries to re-transmit later. If the channel is clear, it sends an RTS message. The sender listens to the channel for one round-trip time plus the time needed for the receiver to send a CTS message. If the CTS message is corrupted or not received, the sender goes into backoff and re-tries later. Otherwise, it begins to transmit data message. The time is limited to the transmission time of a maximum number of data packets. The sending station must release the channel after the transmission or when the time limitation is reached.

MACA-BI is a simplified version of MACA [19]. It is proposed to reduce the overhead caused by the RTS-CTS dialogue. It has only two-way handshake. A station ready to transmit, instead of "acquiring" the floor, waits for an invitation of the receiver with a control message called RTR (Ready to Receive). However, it needs accurate predication of traffic. It performs well in steady-traffic environments, e.g., ATM (Asynchronous Transfer Mode) VBR (Variable Bit Rate) and CBR (Constant Bit Rate). Its performance degrades if traffic pattern becomes hard to predicate.

CSMA/CP (CSMA with collision prevention) has been proposed to decrease collision [20]. Its innovation is to employ the binary countdown mechanism to achieve 100% collision-free transmissions. In such protocols, the collision of data packets is usually caused by failed negotiation/announcements in the control channel. Hence, the central idea for CSMA/CP to achieve 100% collision-free operation is to prevent collision in the control channel.

Multi-channel MAC divides bandwidth into several parts and can transmit data on each one simultaneously. For example, BTMA (Busy Tone Multiple Access) [21], DBTMA (Dual BTMA) [17], and MMAC (Multi-channel MAC) [22] belong to this category. In MMAC, there is no dedicated control channel. It uses multiple channels for data transmission. N channels that have enough spectral separation between each other are available for data transmission. Channels are classified into three types according to their usage status. It needs only one transceiver and can achieve higher throughput than IEEE 802.11 DCF does when the network load is high. But it needs synchronization among all nodes in the network, which is hard to achieve.

In Multichannel CSMA MAC Protocol [34], total available bandwidth is divided into N non-overlapping channels. A node with a packet to be transmitted selects an idle channel randomly from the idle channel list. A node prefers to choose the channel used in its last successful transmission. When N is sufficiently large, each node tends to reserve a channel for itself. By doing so, collision can be reduced greatly. But this protocol has high hardware cost and does not attempt to resolve the hidden-terminal problem due to lack of the RTS/CTS-like mechanism.

SNDR (Sequenced Neighbor Double Reservation) uses a neighbor-sequenced method to avoid contention and a double reservation method to improve total throughput [35]. But the transmission delay is high because of its large frame size. Besides, the throughput is reduced due to the waiting time of senders.

DCA (Dynamic Channel Assignment) [5] does not need global synchronization among mobile nodes. It dynamically assigns channels to mobile hosts in an "on-demand" manner. Whenever a host needs a channel, it goes through an RTS/CTS/RES (REServation) dialogue to grab a channel. Once it completes its transmission, the channel is released. The number of channels given to the network is fixed and is independent of the network size, topology, and degree. However, each channel should be allocated beforehand and the bandwidth of each channel cannot be changed.

To incorporate explicit support for real-time applications, such mechanisms as prioritized transmission, scheduling and reservation are often used. Prioritized transmission protocols like PS-DCF (Priority Scheme-DCF) [3] have been proposed for real-time applications. In PS-DCF, a forward backup algorithm is used in which packet priority plays a key role. Reservation is another mechanism. Nodes with real-time applications have higher priority to reserve bandwidth over those transmitting non-real-time applications. In some reservation protocols [30, 31, 32], global time synchronization among all nodes is required. Asynchronous protocols such as RTMAC (Real Time MAC) [33] do not need global synchronization. In scheduling-based protocols, packets are scheduled at nodes and nodes are scheduled to access the channel. For example, in DPS (Distributed based Priority Scheduling scheme) [29], a node's priority tag is piggybacked on the control and data packets. By retrieving information from such packets, a node builds a scheduling table. It then knows its rank to access medium from the table. These protocols can provide QoS support for real-time applications.

1.4.5 Issues of Using Spread Spectrum Technology in Ad Hoc Wireless Networks

Spread Spectrum (SS) [44] has been used as one of the basic access technologies in cellular systems, including 2G, e.g., IS-95 [51], and recently deployed 3G systems, e.g., CDMA2000 [52] and WCDMA [53] due to its superior characteristics. There are basically three types of SS technology, which includes Direct Sequence Spread Spectrum (DSSS), Frequency Hopping Spread Spectrum (FHSS) and Time Hopping Spread Spectrum (THSS) [54]. Since the first one has more desirable properties than the other two technologies, it has been used more often in the recent wireless standards. It is thus the focus of this dissertation. In the remainder of the dissertation, until explicitly indicated, the term “spread spectrum” is used to indicate DSSS only.

The major advantages of SS technology can be concluded as follows:

First of all, SS technology can achieve concurrent transmissions in one channel without either accurate time scheduling like Time Division Multiple Access (TDMA) or individual allocation to specified frequency bands as in Frequency Division Multiple Access (FDMA). By contrast, conventional radio signals from uncoordinated sources cannot co-exist in the same frequency channel. SS has been shown to provide up to six times the capacity compared with TDMA and FDMA in cellular systems [55] and is flexible to switch from signal to signal for a transmitter or receiver. Second, SS signals are very effective against jamming, multipath interference and generally, any interference that appears deterministic [44].

It is natural to consider SS-based MAC for ad hoc wireless networks to achieve higher capacity, more flexibility and robust resistance to interference. However, most proposed MAC protocols for ad hoc wireless network are not SS-based [28]. The difficult issues, related to code assignment, collision avoidance, bandwidth efficiency and high peak rate, have limited the popularity of SS-based MAC protocols.

Code assignment means allocating spreading codes to network terminals in the system. The purposes of code assignment are to avoid packet collisions as much as possible such that high system throughput is achieved; and to react dynamically to the network topology changes. A code assignment strategy is needed to avoid primary collision by guaranteeing that all neighbors of a terminal have different PN codes. It is trivial when the number of mobile terminals in the network is small. However, when the number grows, it becomes inefficient to assign a unique code to each mobile terminal, especially for a large network in which the available PN codes are less than the number of total mobile terminals and spatial PN code reusing is necessary. Several code assignment protocols have been proposed [63, 64, 65]. In [64], a distributed algorithm is given for assigning codes in a dynamic, multi-hop wireless radio network. It does not need any form of synchronization and no collision occurs after the convergence of the algorithm. In [9], a two-phase algorithm is proposed to assign codes to transmitters, receivers and to pairs of stations in a large dynamic Packet Radio Network (PRN). How to assign orthogonal codes to mobile stations to eliminate hidden terminal interference is investigated in [63].

A spreading-code protocol is also needed to decide which codes to transmit a packet and to monitor the channel in anticipation of a packet reception [46]. Spread-code protocols can be classified into four categories:

1) Common-code: a single spreading code is used by all terminals to transmit some types of signal. DRCA protocol to be proposed in this chapter uses common code to transmit control signals like RTS, CTS and ACK message.

2) Receiver-based: A transmitter spreads its data packets using the code of its receiver and all idle terminals keep monitoring the channel by its own code. It simplifies the receiver's circuitry since each receiver just needs to monitor only one code. The essential drawback is the un-avoidance of primary collision at the receiver if two or more terminals are trying to send signal to the same receiver. Another disadvantage is the difficulty to broadcast since each receiver has different codes

3) Transmitter-based: A transmitter spreads a packet with its own code and its receiver de-spreads the packet with the transmitter's code. Primary-collision is avoided completely since transmitting signals are with distinct codes and will not collide with each others. Broadcast is easy now due to the fact that all receivers just need to turn to the transmitting code to receive it. However, each receiver could be very complex since it should be able to de-spread any of the transmitters' codes and needs to monitor all of them.

4) Hybrid: Various combinations of the above three mechanisms. For example, in the common-transmitter-based protocol and receiver-transmitter-based protocol proposed in [46] by E. Sousa and J. Silverster, the packet header that contains the source and destination addresses are spread by either common code or receiver's code and the message part is spread by the transmitter's code. An idle terminal monitors the channel by either common code or its own receiving code, respectively. In [79], a combination of transmitter-based code, TDMA and reservation schemes is used.

Collisions often happen and collision-avoidance is one of the most important research topics in an SS system. Collision can be further classified into two categories: primary collision and secondary one. Primary collision is caused by two or more signals with the same spread code being received at the same receiver. Primary collision can completely destroy a transmitting message and it should be avoided in a good SS MAC protocol. Secondary collision is defined as the collision between two or more transmissions that use different spread codes. It is caused by multi-access interference induced by the nonzero cross-correlations between different spreading codes [66]. It becomes un-avoidable in time-asynchronous systems like ad hoc wireless networks and the system throughput is reduced due to its existence.

The efficient usage of bandwidth is important for SS. Sometimes the goal is in conflict with the goal of code assignment and collision-avoidance. To make code assignment and collision-avoidance easy to implement and maintain, a static code assignment strategy is widely accepted and used. Each terminal has a district spread code and a terminal knows other terminal's code so that collision can be easily avoided. Unfortunately, much of available bandwidth is wasted if a certain percentage of terminals are inactive in the network. Consider the following scenario in Figure 1.12. There are four terminals T1-4 in the network. Each terminal is allocated with a unique PN code as C1-4 respectively to transmit with the same spreading factor, say 100, which means 1 percentage of the chip rate. During the operation, T3 and T4 become idle. T1 and T2 could not increase their transmission rate during the time of operation due to the restriction of the static code assignment method. Half of the usable bandwidth is therefore wasted.

The high peak rate for a terminal can be achieved in such contention-based MAC protocols as IEEE 802.11 DCF if this terminal is given higher priority than others. However, with a static PN code assignment SS MAC protocol, it is hard to predict which terminal may need more bandwidth before the operation. Hence, it is not easy to allocate a proper rate to a terminal. Even worse is that a terminal could not ask to increase its transmitting rate since the PN code allocated to it cannot be changed. Accordingly, it is hard for a terminal to achieve as high peak rate as that in a CSMA-based MAC protocol.

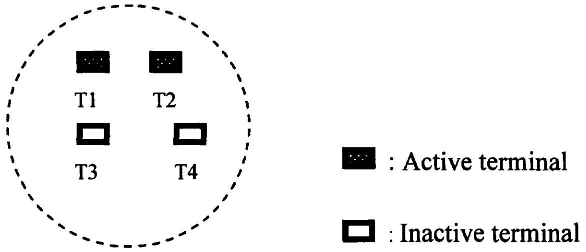


Figure 1.12 An example of bandwidth waste in static code allocation case.

There is much research to address those four issues. Some fundamental concepts are discussed and two hybrid spread code protocols, Common-Transmitter (CT) and Receiver-Transmitter (RT), are proposed in [46]. Their performance is analyzed and two limiting throughput results are given. To address the hidden and exposed terminal problems, the combinations of Multiple Access with Collision Avoidance (MACA) [67] with CT (MACA/CT) and MACA with RT (MACA/RT) are proposed and their throughput is analyzed [24]. In [68], a CDMA-based power controlled MAC design is proposed to address the secondary-collision issue. All the above protocols use static code allocation mechanism and hence, the transmission rate of each terminal cannot be changed during the operation. A rate-adaptive MAC design is given for low-power ultra-wide band ad hoc network [69]. However, it can change only channel coding rate but not spread code. This means only raw data rate but not the transmission rate can be changed. It does not consider collision-avoidance issue either.

1.4.6 MAC Designs in 802.11 and 802.16 Standards

802.11 MAC is the de facto MAC protocol for Wireless LAN (WLAN) and ad hoc wireless network. There are mainly two accessing methods in 802.11 standards. The first is Distributed Coordination Function (DCF). It is a contention-based method and it is similar to IEEE 802.3 Ethernet. It uses CSMA/CA as the basic medium access mechanism. By default, all 802.11-complaint stations operate using the DCF. It suffices in most cases.

Point Coordination Function (PDF) is the second method. It is contention-free access protocol usable on infrastructure network configurations containing a controller called a point coordinator with the access points. The point coordinator uses the polling mechanism to choose a station for transferring a packet. It is priority-based and used for processing time-critical information transfers. Both DCF and PCF can operate concurrently with the same Basic Service Set (BSS) to provide alternating contention and contention-free periods [61].

CSMA/CA is the basic medium access method in 802.11. Combination of OFDM (Orthogonal Frequency Division Multiplexing) [62] and CSMA/CA is used in IEEE 802.11e.

IEEE standard 802.16 defines the air interface specification for wireless Metropolitan Area Network (MAN) [59]. It is designed primarily for broadband wireless access industry, which provides high-rate network connections to stationary or slow-moving sites. The MAC protocol of 802.16 addresses the need for very high bit rates, at both uplink and downlink. It provides a wide range of service types, including voice and data, IP connectivity and packetized voice over IP (VoIP). These services expect to be assigned QoS in keeping with the traffic types [60]. While extensive bandwidth allocation and QoS mechanisms are provided, the details of scheduling and reservation management are left un-standardized and thus allow vendors to differentiate their equipments.

In general, the 802.16 MAC is designed to support a point-to-multipoint architecture with a central BS handling multiple independent sectors simultaneously. On the downlink, data to subscribers are multiplexed in Time Division Multiplexing (TDM) fashion. The uplink is shared between subscribers in TDMA fashion.

IEEE 802.16 MAC is connection-oriented. This means every service must have a connection associated with it. All services are mapped to a connection and the connection requests bandwidth and associates QoS and traffic parameters.

There are five types of QoS requirements are supported in IEEE 802.16, which are [60]:

1. Unsolicited Grant Services (UGS). It is for CBR or CBR-like service flows.
2. Real-time Polling Services (rtPS). It is for VBR-like service such as MPEG (Moving Picture Experts Group) video.
3. Extended rtPS (ertPS): This service class combines UGS and rtPS classes, can be used for variable rate with delay dependent application.
4. Non-real-time Polling Services (nrtPS). It is for non-real-time with better than best effort service such as bandwidth-intensive file transfer.
5. Best Effort (BE). It is for best-effort traffic.

IEEE 802.16 MAC uses both Time Division Duplexing (TDD) and Frequency Division Duplexing (FDD) to divide uplink and downlink. Time Division Multiple Access (TDMA), Frequency Division Multiple Access (FDMA) and Orthogonal Frequency Division Multiple Access (OFDMA) are deployed to access the physical medium. Combinations of OFDM-TDMA and OFDMA-OFDM with a form of FDMA are used.

IEEE 802.16 MAC is also a centralized MAC design. A base station allocates resource for both uplink and downlink. Both polling and contention mechanisms are implemented to allocate bandwidth. The way to allocate bandwidth differs from one service class to another. Table 1.1 gives the bandwidth allocation methods for each service classes.

IEEE 802.16 MAC is designed primarily for point-to-multipoint architecture. However, it has been extended to support mesh network architectures. Both centralized and distributed scheduling mechanisms are proposed to support this mesh architecture [83].

Table 1.1 Bandwidth Allocation for Service Classes in 802.16

Service Class	Bandwidth Allocation Methods
UGS	1. Periodic fixed bandwidth allocation to meet real time constraints; 2. Polling if requested by MSS (Mobile Subscriber Station)
rtPS	1. Periodic bandwidth allocation (polling) to send bandwidth requests; 2. No Contention based bandwidth requests.
ertPS	1. Periodic variable bandwidth allocation to meet real time constraints; 2. MSS may request change in bandwidth.
nrtPS	1. Bandwidth allocation (polling) to send bandwidth requests; 2. Contention based bandwidth requests.
Best Effort	Contention based bandwidth requests only

1.5 Technique Approach

Based on the requirement analysis and literature review, PPTM is proposed for All-IP wireless WAN in the first part of the research. Its performance is analyzed by both theoretical and simulation methods. PPTM is modeled as a nonpreemptive Head-Of-the-Line prioritized queueing system. Three important variables: transmission time delay (TTD), throughput and average number of packets in the queue are derived with this model. To evaluate its performance in an All-IP wireless WAN, a simulator is created with NS-2. Its performance is evaluated and compared with that of the benchmark MCLSP under four different traffic patterns, which are Poisson arrival, CBR, Exponential On/Off, and Pareto On/Off.

The second part of the research proposes a MAC design named DRCA based on the requirement analysis and literature review of exciting MAC designs of ad hoc wireless network. It is modeled as a Markov chain and its throughput is derived in a slotted, single-hop environment. To evaluate its performance in an environment that is close to real network, a simulator that supports multi-hops and random mobility pattern is created with OPNET. The throughput of DRCA in a multi-hops, multi-users environment with mobility is derived by simulation and compared with that of the benchmark MACA/CT.

1.6 Significance

PPTM is proposed for All-IP wireless WAN in the first part of the research. It always gives higher priority packets more chance to be transmitted. Consequently, time-sensitive packets reach their destination faster and time non-sensitive packets suffer from longer time delay compared with MCLSP. From the QoS point of view, it performs much better than MCLSP does.

PPTM is modeled as a nonpreemptive HOL prioritized queueing system with Poisson arrival traffic pattern. Transmission-Time-Delay and number of packets in the queue are derived under this model and verified by simulation. Its performance is compared with MCLSP under four different traffic patterns, which are Poisson arrival, CBR, Exponential On/Off, and Pareto On/Off. The simulation results verify that the prioritized transmission is important to support different QoS requirements.

The second part of the research proposes a MAC protocol named DRCA for small and medium scale ad hoc wireless networks. In DRCA, a terminal sets the spreading factor for a packet according to the activity level of neighboring nodes. If the total number of usable spreading codes with this spreading factor is less than the total number of mobile terminals in the network, to avoid collision, the spread code id is broadcast such that other terminals avoid using it when the packet is being transmitted. DRCA uses bandwidth more efficiently and thus achieves higher throughput compared with MACA/CT.

DRCA is modeled as a Markov chain and the number of communication pairs is used as the state in a slotted, single-hop environment. To evaluate its performance and compared it with that of benchmark MACA/CT, a simulator is created with OPNET. The simulation results verify that DRCA achieves higher throughput when there are inactive mobile terminals. However, the throughput difference between DRCA and MACA/CT is insignificant if most of the mobile terminals are active.

1.7 Organization

Chapter 1 gives of objectives, motivations, background, literature review and significance of this research. Chapter 2 proposes Prioritized Parallel Transmission MAC protocol for All-IP wireless WAN. Chapter 3 analyzes its performance. Chapter 4 proposes Dynamic-Rate-with-Collision-Avoidance MAC protocol for ad hoc wireless networks. Chapter 5 presents its performance analysis results. Both analytical and simulation results are included in this chapter. Finally, Chapter 6 concludes this dissertation by presenting its contributions, the limitations of the present work, and future research directions.

CHAPTER 2

PRIORITIZED PARALLEL TRANSMISSION MAC PROTOCOL FOR ALL-IP WIRELESS WAN

PPTM (Prioritized Parallel Transmission MAC) belongs to the category of PTMP (Parallel Transmission MAC Protocol). It uses a two-stage scheme, which includes pre-transmission decision and prioritized transmission stages. A pre-transmission probability is set according to the observation of the channel load for a certain period of time and a packet is passed to the next stage with this probability in stage 1. In the prioritized transmission stage, a packet is transmitted according to its priority level. PPTM is derived from CLSP (Channel Load Sensing Protocol) and MCLSP (Modified CLSP). However, CLSP performance degrades in wide area network due to the long propagation time delay. Compared with it, MCLSP performs robustly in case of large time delay. Thus, MCLSP is chosen as the benchmark protocol to compare with the proposed PPTM.

2.1 System Model

All-IP wireless WAN is fully IP protocol-based, which means not only the IP layer but also the layers below and above the IP layer should meet the requirements of IP network [20]. An All-IP wireless WAN architecture is defined in Figure 1.8, Chapter 1 in this dissertation. In this figure, an Internet Access Point (IAP) is connected with Internet Backbone and its coverage area, which has radius up to 2000 meters. This value is set according to the UMTS cell radius, which ranges from 0 to 2000 meters [99]. Within an IAP's coverage area there can be many Internet Mobile Terminals (IMTs), each of which can move with a speed up to 180km/h. The architecture looks similar to that of wireless

LAN at the first look. However, it supports high mobility services and offers wide area coverage. Compared with it, a WLAN supports stationary or low speed moving terminals and local area coverage with a much smaller coverage area radius.

The selection of a MAC protocol is a critical issue for an All-IP wireless WAN. Chapter 1 concludes the MAC design requirements for All-IP wireless WAN as follows:

- It is flexible and highly efficient;
- It achieves high throughput;
- It supports high mobility and works properly with long propagation time delay;
- It transmits packets with low time delay, especially for real time application packets;
- Control overhead is low; and,
- It gives Qualify of Service (QoS) support for different priority level services.

Prioritized Parallel Transmission MAC can meet all these requirements. It can thus become a proper MAC design for an All-IP wireless WAN.

2.2 Prioritized Parallel Transmission MAC

There are two ideas behind PPTM protocol. This first one is channel load sensing and the second one is prioritized transmission. Direct Sequence CDMA technology [44] is used and each IMT is assigned with a distinct spread code to spread its data packets. It is composed of two stages. In stage 1, probability P_{pt} is set by IAP according to its continuous observation of the channel load condition. A packet proceeds to stage 2 with this probability and is denied with probability $1-P_{pt}$. In stage 2, packets are transmitted to physical medium according to their priority level. The procedure of access control is as follows and illustrated in Figure 2.1.

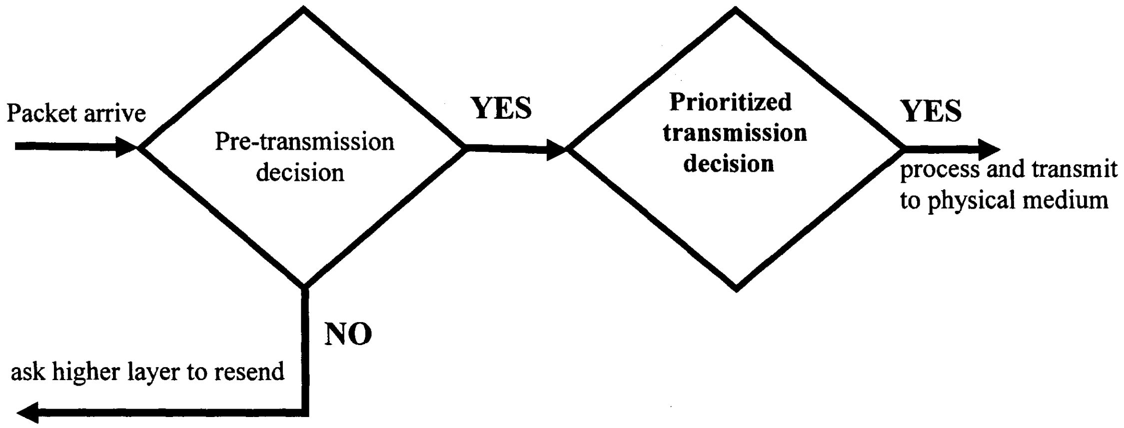


Figure 2.1 Prioritized Parallel Transmission MAC Scheme.

- The Internal Access Point (IAP) calculates and broadcasts a pre-transmission probability P_{pt} according to its continuous observation of the channel;
- An Internet Mobile Terminal (IMT) that has a packet to transmit passes it to the next stage with probability P_{pt} as the pre-transmission decision;
- Each packet is connected with a priority index. The index indicates its priority level. All the packets are thus prioritized and transmitted to medium accordingly. The index can be an x-bit width, representing one of the up to 2^x priority levels.

Additionally, the flexible allocation of bandwidth mechanism is used in PPTM. That is, the processing gain of each IMT can change in PPTM. For example, an IMT's previous processing gain is 32 and its bit rate is 500kbps. If the IMP needs to increase its transmission rate to 1Mbps, it can apply for a new processing gain, e.g., 16. If IAP approves it, the IMP changes its processing gain to 16. This mechanism is important for the efficient usage of bandwidth.

In this dissertation, the rules of prioritized transmission are defined as follows:

1. A packet that is being transmitted cannot be interrupted;
2. A higher priority packet is always transmitted before a lower priority packet if it has not been transmitted yet; and,
3. Packets with the same priority level are transmitted according to FIFO (First In First Outcome).

The advantages of PPTM are as follows:

- A more important packet is always digitized with a higher priority level and is transmitted with more chances. By doing so, the overall system performance is improved since higher priority packets carry more important information and should be transmitted first;
- The processing gain of each IMP can change so that bandwidth is used more efficiently compared with CLSP and MCLSP and the high peak rate can be achieved by an IMP;
- The advantages of both centralized and distributed MAC designs are taken with simple communications between IAP and IMTs. The central controller in IAP calculates and broadcasts a pre-transmission P_{tr} and approves processing gain change applications form IMTs. On the other hand, an IMT transmits its packets according to the packet priority.

Additionally, PPTM works properly in high mobility and long propagation time delay scenarios, which are common in wireless WAN environment. PPTM uses Spread Spectrum technology that is very effective against fading caused by high speed movement. An IMT uses the time-average channel load information to set the pre-transmission probability in stage 1. Even if the propagation delay is large, it does not affect much of the accuracy of the channel load information it observes. Therefore, the performance of PPTM does not degrade much. Besides, PPTM is easy to be implemented in hardware and the computations is simple.

PPTM satisfies the requirements of All-IP wireless WAN. It is flexible because of its distributed nature. In other words, an IMT makes prioritized transmission decisions. It is efficient, since it does not require complex signaling between an IAP and IMTs and therefore, the signaling overhead is small. It is fair because it allows a packet to access to the medium according to its priority while packets with the same priority level are transmitted via FIFO.

PPTM controls packet transmission more effectively and reasonably because of two mechanisms: flexible allocation of bandwidth and prioritized transmission. First, it can support the flexible allocation of bandwidth for each IMT dynamically, according to the request from IMTs and the system load condition [9]. Second, it supports prioritized transmission. Each packet is connected with a priority index and is thus transmitted accordingly.

2.3 Comparison among PPTM, CLSP and MCLSP

PPTM is based on the idea of channel load sensing. CLSP and MCLSP are two predecessors of PPTM. However, two special characters distinguish PPTM from CLSP and MCLSP. The first is service differentiation. Each packet carries a priority index, which is set according to the importance and QoS requirement of the application. PPTM transmits each packet according to its priority. Neither CLSP nor MCLSP can do so. Both of them are used for voice-dominant application and service differentiation is not required. Another advantage of PPTM is that bandwidth can be allocated dynamically according to an IMP's request to achieve the maximum utilization of the available physical resource. Table 2.1 gives the difference among PPTM, CLSP and MCLSP.

Table 2.1 Differences between PPTM, CLSP and MCLSP

	CLSP	MCLSP	PPTM
Time delay sensitivity	Need immediate channel load information. Highly sensitive to time delay	Robust performance; insensitive to time delay.	Robust performance; insensitive to time delay.
Resource allocation	Centralized control	Centralized control	Centralized-based. But allowing each IMT compete for more resource.
Applications	Voice service only	Voice service only	Voice, streaming video, email, ftp, web browser, etc.
Multiple access method	CDMA with fixed code assignment	CDMA with fixed code assignment	CDMA with fixed code; but allowing dynamic code assignment
Signaling overhead	Low	Low	Low

In conclusion, PPTM is proposed for All-IP wireless WAN and it can work as a proper MAC design in an All-IP WAN environment. In another words, it is designed to support different service classes with different QoS requirements. It functions properly with fading caused by IMT movement and long propagation time delay caused by large coverage. It has some advantages that both CLSP and MCLSP do not have for an All-IP WAN.

2.4 Potential Applications of PPTM in Industry and Standards

PPTM is proposed for All-IP wireless WAN, which is a strong candidate beyond 3G wireless networks. PPTM can also be deployed in any CDMA-based wireless network with slight modifications. Some of its superior characteristics, like capacity improvement, flexible bandwidth allocation, differentiated services, support for high mobility, and wide area coverage, are attractive and competitive. It has some good opportunity to be chosen by industry for a wireless WAN or similar environment that needs to support applications with different QoS requirements. Compared with benchmark MCLSP, the hardware cost is slightly higher since there are two stages of operation in PPTM and MCLSP just needs one. It is hard to know the real cost of the hardware before it is implemented. However, it will show in Chapter 3 that the performance of PPTM is significantly increased compared with that of MCSLP from the QoS point of view.

IEEE 802.16 standard was proposed for wireless Metropolitan Area Network (MAN) [59, 60]. It is primarily designed for broadband wireless access industry, which provides high-rate network connections to stationary or slow-moving sites. However, IEEE 802.16 is recently extended to support fast-moving subscribers. The physical layer is OFDM-based.

IEEE 802.16 chooses OFDM as the physical layer technology based on two main reasons. First, it is robust to frequency-selective fading. Second, the implementation is not complex, i.e., it does not require an equalizer and the complexity is determined by the FFT (Fast Fourier Transfer). However, it is found that OFDM has some disadvantages such as difficulty in subcarrier synchronization and sensitivity to frequency offset and nonlinear amplification, which result from the fact that it is composed of many subcarriers with their overlapping power spectra and exhibits a non-constant nature in its envelope. Compared with it, CDMA technology is quite robust to frequency offsets and nonlinear distortion. Beside, CDMA has advantages in interference average and soft handover [62].

There are a great deal of research and discussions to deploy CDMA or Multi-Carrier CDMA (the combination of CDMA scheme with OFDM signaling) [86, 87, 88] to a broadband MAN system [62]. If IEEE 802.16 decides to choose CDMA-based technology as an option for its physical layer, PPTM then has the potential to be accepted by the extension of the standard. There are many similarities between the principles of MAC in IEEE 802.16 and PPTM, e.g., differentiated service, and combination of central-control and distributed MAC characteristics. PPTM can become a strong candidate as a proper MAC design to work in a high mobility MAN environment if CDMA-based technology is accepted in the future IEEE standards.

CHAPTER 3

PERFORMANCE ANALYSIS OF PPTM

Chapter 2 proposes PPTM for All-IP wireless WAN. This chapter gives mathematical model of PPTM and analyzes its performance in the context of Poisson arrival traffic. Numerical results are presented with four different traffic patterns, which are Poisson arrival, CBR, Exponential On/Off, and Pareto On/Off, respectively. MCLSP is the benchmark to compare with PPTM. It is chosen because PPTM is derived from MCLSP and MCLSP works properly in an environment with high mobility and long propagation time delay.

3.1 Mathematical Model of PPTM

3.1.1 Poisson Arrival Traffic

Assuming that a packet arrival process follows a Poisson process, PPTM can be depicted with the mathematical model as shown in Figure 3.1 [45],

The following assumptions are made for this system:

- Packet arrival is a Poisson process with rate λ_A.
- There are K priority levels for those packets, with 1 being the highest priority level, K the lowest priority level. Within priority level i, packet size is arbitrarily distributed with mean value n_i, $1 \leq i \leq K$.
- For simplicity, it is assumed that the only relationship between stages 1 and 2 is that the output of stage 1 is the input to stage 2. Hence, stage 2 is driven by a Poisson process, too. The input rate to stage 2 is λ, with $\lambda = P_{pt}\lambda_A$.
- Since the processing time spent in stage 1 is much less than that in stage 2,

it is omitted for simplicity; and,

- Each IMP has unlimited space to save packets.

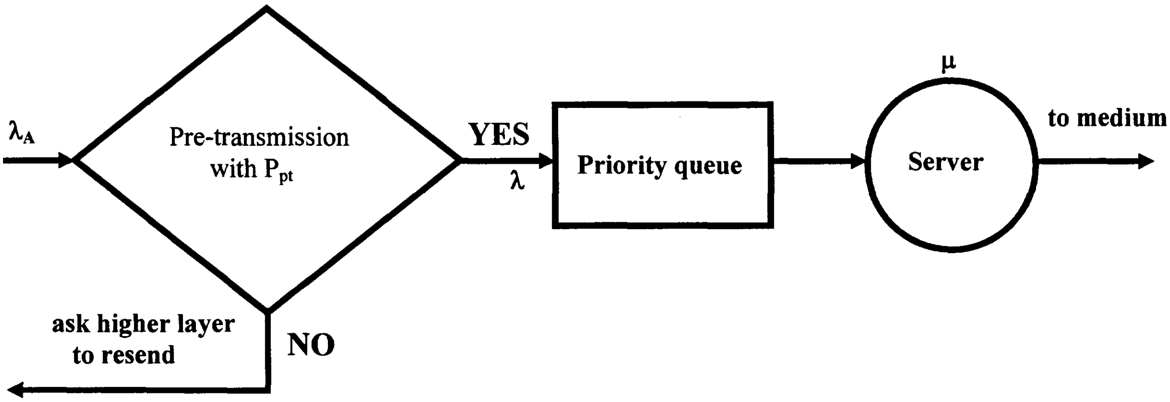


Figure 3.1 Mathematical mode of PPTM in Poisson arrival traffic pattern.

Thus PPTM can be decomposed stage by stage and each stage can be analyzed independently according to the above assumptions. Since the packet arrival rate is λ_A in stage 1, P_{pt} is given by [37]:

$$P_{pt} = \begin{cases} 1 & : \quad G \le G_{\max} \\ \frac{G\max}{G} & : \quad G > G_{\max} \end{cases} \tag{3.1}$$

in which, G_{max} is the channel load threshold set beforehand. G is the average channel load that IAP has observed for a certain period of time.

Based on the model and the way of prioritized transmission, stage 2 can be modeled as an $M/G/1/\infty$ nonpreemptive Head-Of-the-Line (HOL) priority queueing system [38]. Obviously, it becomes an $M/G/1/\infty$ queueing system with FIFO if there is no priority difference among packets.

3.1.2 Other Traffic Patterns

Compared with 2G cellular network, 3G and beyond 3G networks need to support not only voice service, but also high speed packet data. Correspondingly, the traffic arrival pattern can be much different from a Poisson distribution. It is important to know the accurate characteristics of the heterogeneous traffic such that the physical medium and network resource can be shared among users efficiently.

It is shown in [91, 92] that packet data traffic burst can be represented well by Pareto distribution. [93] models traffic as an On-Off source using the Pareto distribution. The work of [90] by Sunary, Tekinay and Ozer uses a similar traffic model to represent the traffic pattern of a CDMA based wireless packet data system. Based on study of the impact of the burstiness of the packet data traffic on the conventional circuit and packet switching techniques, it proposes an alternative burst switching techniques. In this technique, it allocates radio resource to users for the duration of data bursts rather than an entire session or a single packet and releases them at the end of the burst. It is shown that it is an efficient radio resource allocation scheme for a CDMA based 3G system that provides high speed packet data services.

If the packet arrival pattern is different from a Poisson process, which is common in real situation, the system becomes a $G/G/1/\infty$ HOL priority queueing system. For simplification, it is assumed that the packet size is exponentially distributed. Hence, it can be expressed as a $G/M/1/\infty$ HOL priority queueing system. An example system will be simulated under three different traffic patterns: Constant Bit Rate (CBR), Exponential On/Off, and Pareto On/Off. By investigating the performance of PPTM under these traffic patterns and comparing with that of the MCLSP, this work shows the superiority of PPTM over MCLSP under real network conditions.

3.2 Performance Analysis of PPTM in Poisson Arrival Case

To simplify the analysis, it is assumed that packet size is exponentially distributed with identical average length. The system becomes an $M/M/1/\infty$ nonpreemptive HOL queueing system in the Poisson arrival case. This section analyzes three important variables: transmission time delay (TTD), throughput and average number of packets in the queue.

3.2.1 Transmission Time Delay

Transmission time delay is defined as the time period from the moment when MAC layer receives a packet from the higher layer to when the packet reaches the physical medium. According to the assumptions made in Section 3.1, the processing time in stage 1 is too small to count. Hence, it is just needed to analyze the transmission time delay in stage 2.

Stage 2 can be represented by a nonpreemptive HOL priority queueing system with packet arrival rate $\lambda = P_{pt}\lambda_A$. It is assumed that the average service rate of stage 2 is μ. The unit of both arrival rate and service rate is packet/s. Assume that there are K different priority groups. The input rate of group r is λ_r, and the service rate is μ_r. $\mu_r = \mu$ if the service time is linear to the packet size. The utilization factor of group r is $\rho_r = \lambda_r/\mu_r$. If the input rate of group r to stage 1 is λ_{Ar}, then $\rho_r = P_{pt}\lambda_{Ar}/\mu_r$, where P_{pt} is given by Equation (3.1).

For a packet with priority level r, the waiting time W_r is determined by three factors.

1. Waiting time T_0, to finish the service that is already in the server;
2. Waiting time T_m, with $1 \leq m \leq r$, to finish the service of packets that already in the queue when packet r arrives; and
3. Waiting time T_n, with $1 \leq n < r$, to service packets with priority level less than r during T_r.

Therefore,

$$W_r = T_0 + \sum_{m=1}^{r} T_m + \sum_{n=1}^{r-1} T_n \tag{3.2}$$

Similar to that in [38], the expected value of W_r is obtained as follows:

$$E(W_r) = \frac{E(T_0)}{(1 - \sum_{l=1}^{r} \rho_l)(1 - \sum_{l=1}^{r-1} \rho_l)} \tag{3.3}$$

Hence, T_r, the average transmission time delay of a packet with priority level r is given by:

$$\begin{aligned} E(T_r) &= E(W_r) + \frac{1}{\mu_r} \\ &= \frac{E(T_0)}{(1 - \sum_{l=1}^{r} \rho_l)(1 - \sum_{l=1}^{r-1} \rho_l)} + \frac{1}{\mu_r} \end{aligned} \tag{3.4}$$

Here, $E(T_0)$ is the average time to finish transmitting a packet that is already in service when the packet we are interested in arrives. It can be expressed as:

$$E(T_0) = \frac{\lambda E(\tau^2)}{2} = \frac{P_{pt} \lambda_A E(\tau^2)}{2} \tag{3.5}$$

where $E(\tau^2)$ is the second moment of the service time distribution and is given by:

$$E(\tau^2) \ = \ \sigma^2 + 1/\mu^2 \tag{3.6}$$

where σ^2 is the variance of the service-time distribution. Finally, traffic intensity ρ is defined as:

$$\rho = \frac{\lambda}{\mu} = \frac{P_{pt}\lambda_A}{\mu} = \sum_{l=1}^{K} \frac{P_{pt}\lambda_l}{\mu_l} \tag{3.7}$$

ρ can be greater than 1. Equations (3.3) and (3.4) hold if $1 - \sum_{l=1}^{r} \rho_l \quad > 0$.

3.2.2 Throughput of PPTM

The throughput in this chapter is defined as the number of packets per second transmitted without error. For an $M/M/1/\infty$ queueing system, the blocking probability P_B is zero. Hence, the throughput S of an IMT with PPTM can be expressed as:

$$S = \lambda_A P_{pt} P_s \tag{3.8}$$

where P_s is the mean rate of successful transmission of the IMT when the packet arrival rate is λ_A, and pre-transmission rate is P_{pt}. P_s is determined by Signal to Interference and Noise Ratio (SNIR) of the physical channel during the transmission time. Since the packet size is exponentially distributed with the same average value and the same average transmission power is used to transmit packets among all priority groups, P_s has the same value with or without prioritized transmission. That is, the throughput of PPTM S is the same as the one of MCLSP.

3.2.3 Number of Packets in the Queue

From Little's Formula [41], the average number of packets in the queue from priority group l is:

$$\overline{N}_l = \lambda_l E(W_l) \tag{3.9}$$

Hence, the average number of packets in the queue from all groups can be expressed as:

$$\overline{N} = \sum_{l=1}^{K} \lambda_l E(W_l) \tag{3.10}$$

3.3 Numerical Results under Four Traffic Patterns

The performance of PPTM is evaluated in a simplified All-IP wireless WAN based on the architecture presented in Chapter 1. Network simulation tool NS2 [42] is used in the evaluation. The system details are shown in Table 3.1. Transmission time delay is the main concern in the simulation, since the real difference between PPTM and MCLSP is that the first one divides packets into different priority classes and transmits them accordingly, while the second one give packets the equal chance to be transmitted. There are six priority levels and each packet belongs to one of them. Packet Priority Level 1 corresponds to the highest priority index, and 6 corresponds to the lowest one. PPTM is proposed as a potential candidate that could be accepted into IEEE 802.16 standard. There are five different services in IEEE 802.16. The simulation uses six priority levels to represent the priority of control signal and the five services in the standard.

Table 3.1 Simulation Parameters

Parameter	Value
IAP Number	2
IMT Number	20
IMT Speed (m/s)	0-50
Wired Node Number	2
Coverage Radius (m)	1600
Packet Priority Level	1 2 3 4 5 6

Without the loss of generality, the evaluation focuses on the performance of one IMT. The queue size is set to be 100000 packets in simulation so it is large enough. Packet size is exponentially distributed in simulation. For simplification, packet arrival rate and average packet size are set the same for each priority. The default value of $P_{pt} = 1$. If IAP finds that the average number of packets is more than 1000 (G_{max}) in the channel during 10ms time period, it will broadcast P_{pt} according to Equation (3.1). The delay requirement of each priority class is set in Table 3.2 [103]. The numerical results are shown in Figures 3.2 – 3.7.

Table 3.2 Delay Requirement for Each Priority Class

Priority level	1	2	3	4	5	6
Delay requirement	50ms	100ms	150ms	200 ms	400ms	800ms

3.3.1 Simulation Results with Poisson Arrival Traffic Pattern

Figure 3.2 shows the average packet TTD for each priority level. From Figure 3.2, it is found that the simulation result matches with Equation (3.4) closely with average offset less than 5%. The offset can be caused by some simplifications in analysis, e.g., the assumption that time delay in stage 1 is too small to count and processing time is linear with the packet size.

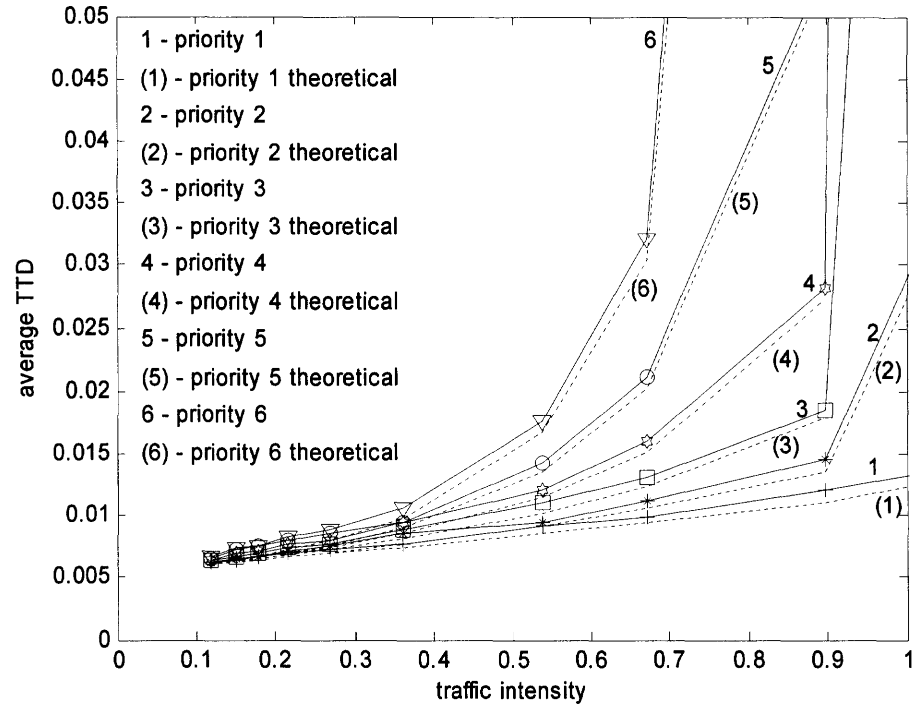


Figure 3.2 PPTM performance with Poisson arrival traffic pattern.

Figure 3.3 represents the number of packets in the queue with PPTM versus the traffic intensity. This figure shows that the number of packets in the queue increases with ρ, the traffic intensity. Most of these are lower priority packets. Higher priority packets are transmitted with much less TTD than lower priority packets. Therefore, there are fewer high priority packets in the queue than low priority packets.

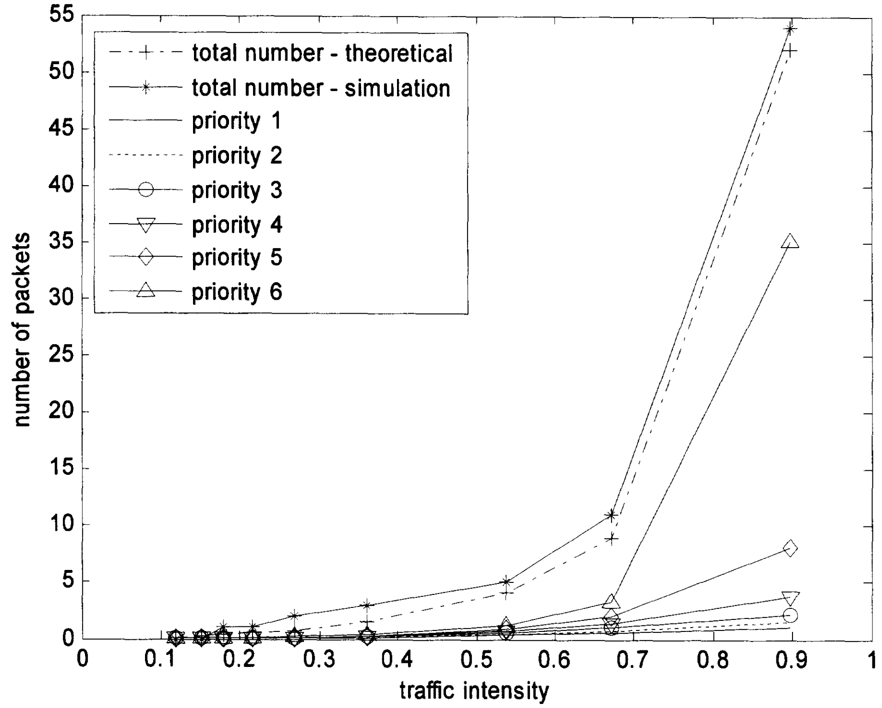


Figure 3.3 Number of packets in queue with Poisson arrival traffic pattern.

Figure 3.4 depicts the TTD results under PPTM vs. MCLSP. From Figure 3.4, it is seen that as traffic intensity ρ increases (meaning that packet arrival rate increases) from 0.1 to 5.5, average TTD of priority level 1 and 2 packets increases slightly and is kept at very low level, i.e., under 0.3 and 0.7, respectively. TTD of priority levels 3 and 4 packets does not change much when ρ is less than 1. Average TTD of priority levels 5 and 6 packets increases to large values when ρ is close to 0.8. Compared with PPTM, average packet TTD in MCLSP becomes large when ρ is close to 0.8, almost the same as priority levels 5 and 6 packets do in PPTM.

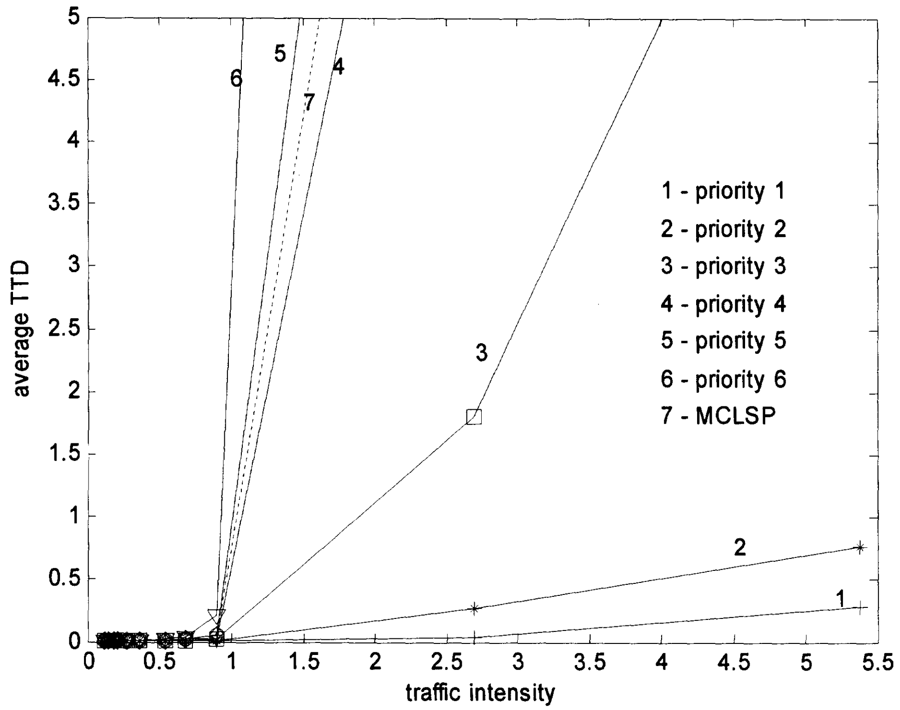


Figure 3.4 PPTM vs. MCLSP with Poisson arrival traffic pattern.

After the delay requirement is checked for each priority class, it is found that PTTM performs much better than MCLSP. In PPTM, packets can all meet their delay requirements when ρ is less than 1. Packets belonging to priority level 1 can even meet the requirement when ρ is as big as 2.6. Priority 2 packets meet their requirement when ρ is as big as 2.0. Compared with that, in MCLSP, when $\rho > 0.9$, priority level 1 packets could not meet the delay requirement. All packets miss their requirements when $\rho > 1$. From the QoS point of view, it is easy to conclude that the performance of PPTM is significantly improved from that of MCLSP.

Table 3.3 gives the average, maximum and minimum TTD difference between PPTM and MCLSP when $0.1 < \rho < 0.9$. The difference is calculated based on MCLSP.

Positive value means the improvement of PPTM from MCLSP. Negative value means the degradation of PPTM from MCSLP. The table shows that for priority levels 1,2,3 and 4 packets, TTD in PPTM is less than that in MCLSP, especially for priority levels 1,2, and 3 packets. TTD for priority levels 5 and 6 in PPTM is slightly longer than that in MCLSP. Hence, it is concluded that PPTM can guarantee that higher priority packets be transmitted in significantly shorter time; meanwhile, lower priority packets suffer from longer TTD compared with that in MCLSP.

Table 3.3 TTD Difference between PPTM and MCLSP in Poisson Arrival Case

Priority index	Average TTD difference	Maximum TTD difference	Minimum TTD difference
1	36.28%	79.17%	4.62%
2	30.86%	74.87%	4.62%
3	23.30%	68.16%	1.54%
4	13.19%	51.64%	0%
5	-5.50%	-15.93%	6.71%
6	-70.49%	-271.94%	-1.54%

It is found that the theoretical results match the simulation results for the Poisson arrival case. The simulation results validate the suitability of the proposed theoretical model under the Poisson traffic conditions.

3.3.3 Simulation with other Traffic Patterns

It has been shown that traffic burst represents packet data traffic more accurately [91, 92, 93]. Pareto distribution is often used to describe such traffic. To illustrate the superiority of PPTM to MCLSP, three other different traffic patterns are used in the simulation, although there is no close form of TTD under these traffic patterns. The first one is CBR traffic pattern [42]. The second one is Exponential On/Off traffic pattern [42], in which, burst time is 30ms, idle time is 30ms too, and average rate during burst time is changed from 400 to 1800 packet/s. The last one is Pareto On/Off traffic pattern [43]. Burst time and idle time are both 30ms and average rate during burst time varies from 400 to 1800 packet/s.

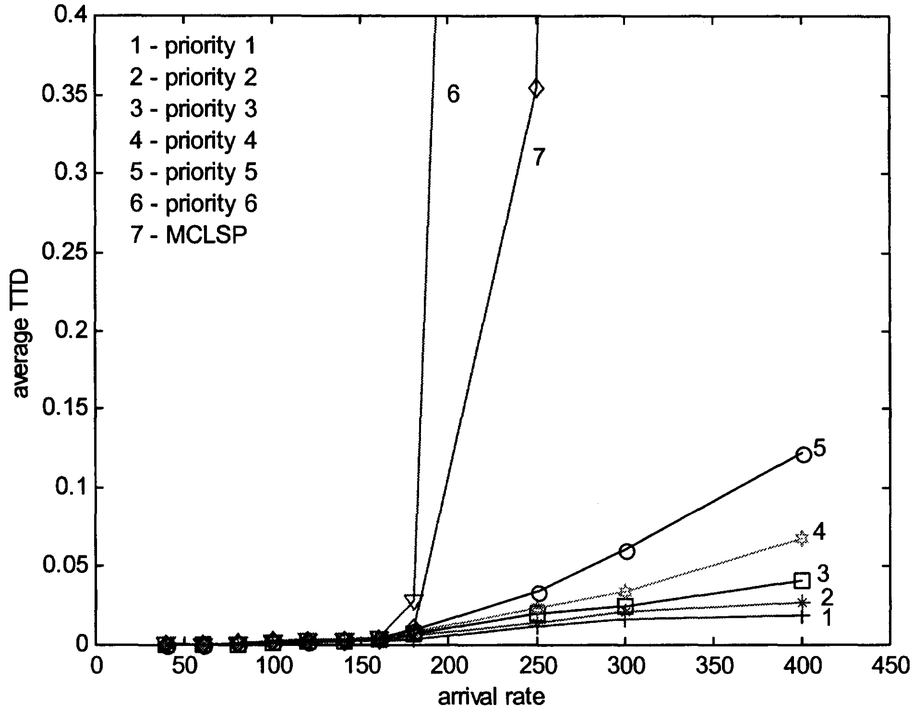


Figure 3.5 PPTM vs. MCLSP with CBR traffic pattern.

From Figures 3.5 to 3.7, the simulation result shows that in PPTM, average TTD of higher priority packets (priority 1, 2, 3) is always low even when packet arrival rate is pretty high. Lowest priority packet has very high average TTD (more than 2) when input rate is above 200 in CBR traffic pattern, or above 600 in Exponential On/Off traffic pattern, or above 600 in Pareto On/Off traffic pattern. Meanwhile, with MCLSP, packet average TTD becomes very high when input rate is more than 300 in CBR, or more than 700 in Exponential On/Off case, or more than 800 in Pareto On/Off case.

After the delay requirement is checked, with Pareto On/Off traffic pattern, packets belonging to priority levels 1, 2, and 3 meet their requirement when packet arrive rate is less or equal to 1800 packet/s. Priority level 4 packets miss it only when arrival rate equals to or bigger than 1800 packet/s. Priority level 5 packets miss it if arrival rate is equal to or above 1400 packet/s. Priority level 6 packets miss it when arrival rate is above 600 packet/s. Compared with PPTM, MCLSP performs much worse. All packets miss their delay requirements when packet arrival rate become equal to or bigger than 800 packet/s. Table 3.4 gives the performance difference between PPTM and MCLSP with Pareto On/Off traffic pattern. "Y" stands for "meet" and "N" means "miss" the delay requirement; "P" stands for PPTM and "M" stands for MCLSP in the table. Since this pattern is close to the real traffic burst, it verifies that PPTM is a much better MAC design than MCLSP for an All-IP wireless WAN.

The simulation verifies the necessity of prioritized transmission in All-IP wireless WAN. More important and time-delay sensitive packets should be transmitted more quickly than less important and time-delay non-sensitive packets. By dividing packets into different priority levels according to their importance and QoS requirement, and prioritized-transmitting a packet accordingly, PPTM gives good QoS differentiation to different kinds of services in an All-IP wireless WAN. It guarantees the fast transmission of more important and time-delay sensitive packets. Meanwhile, less important and time-delay non-sensitive packets are transmitted with longer time delay. Hence, with the same channel condition, PPTM reaches the same throughput but improves the overall system performance significantly compared with MCLSP.

Table 3.4 PPTM and MCLSP Performance Comparison with Pareto On/Off Traffic Pattern

Priority Rate	1		2		3		4		5		6	
	P	M	P	M	P	M	P	M	P	M	P	M
400	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
600	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
800	Y	N	Y	N	Y	N	Y	N	Y	N	N	N
1000	Y	N	Y	N	Y	N	Y	N	Y	N	N	N
1200	Y	N	Y	N	Y	N	Y	N	Y	N	N	N
1400	Y	N	Y	N	Y	N	Y	N	Y	N	N	N
1600	Y	N	Y	N	Y	N	Y	N	N	N	N	N
1800	Y	N	Y	N	Y	N	N	N	N	N	N	N

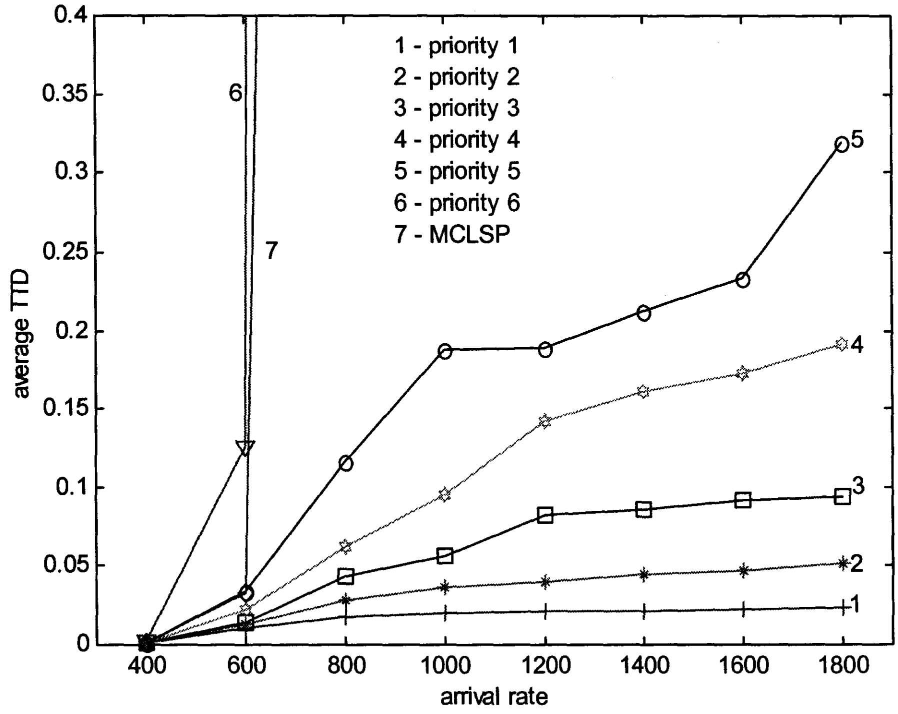


Figure 3.6 PPTM vs. MCLSP with exponential on/off traffic pattern.

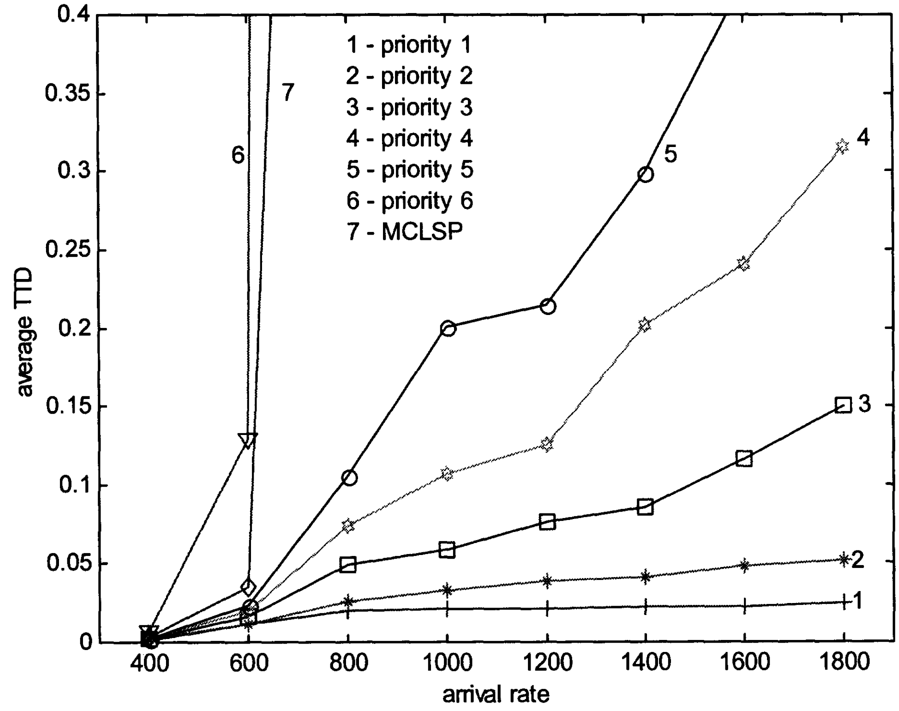


Figure 3.7 PPTM vs. MCLSP with Pareto on/off traffic pattern.

CHAPTER 4

DYNAMIC-RATE-WITH-COLLISION-AVOIDANCE MAC DESIGN FOR AD HOC WIRELESS NETWORK

Ad hoc wireless networks are very useful when infrastructure network is too hard or expensive to be built. Potential users of ad hoc wireless networks include public safety, the military, homeland security and commercial wireless organizations. However, available bandwidth for ad hoc wireless networks is very limited [97]. Ad hoc networks for military operation and applications in rural area may be allocated unlimited bandwidth, and thus bandwidth efficiency is not a major concern. In contrast, users like public safety, homeland security and commercial wireless organizations, often have their operations in population-intense areas like metropolitan areas, available spectrum is extremely limited and should be used very carefully. In [97], Dynamic Frequency Selection in 5230-5350 MHz and 5470-5725 MHz is recommended to use for ad hoc wireless networks.

ISM (Industrial, Scientific, and Medical) is license-free frequency band and three frequency ranges are authorized by FCC. The three frequency bands are: 902-928 MHz, 2.4-2.4835 GHz, and 5.725-5.850 GHz. However, only Spread Spectrum (SS) RF transmissions are currently allowed in ISM bands. There are many research efforts to investigate how to use the license-free ISM bands [89]. It is natural to consider using SS transmission in an ad hoc wireless network with ISM bands.

Compared with single channel MAC protocols, multi-channel MAC design can achieve higher capacity, less collision and more flexibility. But many multi-channel MAC protocols are static-bandwidth-allocation-based. In other words, the total available bandwidth is divided among mobile terminals and each mobile terminal receives a fixed amount of bandwidth. Consequently, bandwidth is wasted when some mobile terminals are inactive. The high peak rate is hard to achieve for a particular mobile terminal. A dynamic bandwidth allocation strategy is needed for the efficient usage of bandwidth and the realization of a high peak rate. Dynamic-Rate-with-Collision-Avoidance (DRCA) MAC design is SS transmission-based and it is proposed as a multi-channel design with a dynamic bandwidth allocation mechanism.

4.1 Dynamic-Rate-with-Collision-Avoidance

Dynamic-Rate-with-Collision-Avoidance (DRCA) MAC protocol for ad hoc wireless network is based on SS technology. In SS with fixed chip rate, the transmission rate of a channel is determined by the spread code for the channel; to be more explicitly, by the spreading factor of the spread code. For example, if the spreading factor is 4, a quarter of the whole available rate is allocated to the channel. In case if the spreading factor is 16, the channel receives one sixteenth of the total rate [98, 44]. In DRCA, transmission rate is allocated dynamically to a terminal by choosing a spread code with a proper spreading factor.

There are two ways to select a spread code for a mobile terminal.

1) When the number of mobile terminals in the network is not bigger than the number of usable spread codes with a spreading factor, then a spread code is allocated to a mobile terminal beforehand and does not change during the operation. The only thing that the mobile terminal needs to decide is which spreading factor to use. For example, if there are total ten mobile terminals, and the available spread codes with spreading factor 8 is thirty,

more than ten, terminal 1 is allocated with spread code 1, terminal 2 is with spread code 2, etc. If terminal 1 decides to use spreading factor 8 to transmit a packet, it uses spread code 1 with spreading factor 8 to transmit the packet.

2) When the number of mobile terminals in the network is bigger than the number of usable spread codes with a spreading factor, then spread codes should be allocated dynamically during the operation. For example, if there are ten terminals, and the available spread code with spreading factor 4 is less than ten; if terminal 1 decides to use spreading factor 4, a spread code is allocated to this terminal in the run and the spread code is taken back after terminal 1 finishes the transmission. To fulfill the spread code allocation and avoid collision, each terminal maintains a look-up table of available spread codes with these spreading factors. The data stored in the table can be changed during the operation. If a terminal needs to transmit a packet with a spreading factor in the table, it picks up a spread code with this spreading factor from the table. The selection algorithm guarantees that with this spreading factor, the packet is transmitted with a rate that is as large as possible; meanwhile, the received signal can still reach the required quality..

The size of the look-up table should not be too big. It just stores the available spread codes with a small spreading factor if the number of usable spread codes with this spreading factor is smaller than the number of mobile terminals in the network. The following is an example. There are ten mobile terminals, and the numbers of usable spread codes with spreading factors 1, 2, 3, 4, and 5 are one, two, four, eight, sixteen, respectively. The look-up table needs to store spread codes with spreading factor 1, 2, 3, and 4, since under these spreading factors there are not enough spread codes. It needs to store fifteen spread codes at most.

To combat the effect of secondary collision, large processing gain is needed for concurrent transmissions, which means the spreading factor cannot be too small. On the other hand, throughput decreases with a large spreading factor. The selection of a spreading factor is closely related to the total number of transmitting terminals. It is assumed that the channel condition is ideal, i.e., white Gaussian noise channel, and with ideal power control, i.e., a receiver receives equal power from each transmitter. If the received signal quality target is set as bit error rate of 10^{-6}, SNR is required to be 10.5 dB without FEC (Forward Error Correction) coding [80]. If there is just one pair of communication terminals, signal can be sent without spreading (spreading factor equals 1). However, if there are 10 pairs of communication terminals, the spreading factor should be at least 101 to reach the required quality. Table 4.1 gives the selection of spreading factor with the number of pairs of communication terminals if the required signal quality is set as BER = 10^{-6} under the ideal channel condition. With a fading channel condition, the required SNR is much higher than the ideal one with the same received signal quality. Correspondingly, the spreading factor can be much higher, i.e., the transmission rate is much smaller. For example, if with the Rayleigh fading channel condition, even with two independent fading replicas, if required BER is 10^{-6}, the SNR at a receiver should be at least 20 dB [81] and the spreading factor is at least 7149 when there are ten communication pairs. Table 4.2 gives the minimum spreading factor vs. the number of communication pairs under the Rayleigh fading channel condition with two independent fading replicas.

Table 4.1 Spreading Factor vs. Number of Pairs under Ideal Channel

# of communication pairs	1	2	3	4	5	6	7	8	9	10
Spreading factor	1	12	23	34	45	57	68	79	89	101

Table 4.2 Spreading Factor vs. Number of Pairs under Rayleigh Fading Channel

# of communication pairs	1	2	3	4	5	6	7	8	9	10
Spreading factor	1	795	1589	2383	3178	3972	4766	5561	6355	7149

Prioritized transmission is used in DRCA for real time applications. A packet with higher priority is always put in front of a lower priority one such that it is transmitted at the earlier time.

All control messages, including RTS, CTS and ACK, are transmitted with common codes, which are codes C_R, C_C, and C_A, respectively. Short message (SM) is with C_R. All idle terminals turn to C_R (common code for RTS and SM) to receive RTS and SM messages. The message format of RTS/CTS/SM/ACK is shown in Figure 4.1. An RTS message is sent to apply for a spread code. It contains Message ID, Receiver ID, Transmitter ID and the chosen spread code ID. A CTS message answers the application. The second part of a CTS message is one bit to indicate "Yes" or "No". The last part is a suggested code ID if "No" is presented in the second part or is blank in case of "Yes". An SM message is to broadcast the code ID to other terminals so that they know either the code is being used or can be re-used, depending on D/A indication. Note that D means "delete the code from your code-look-up table", and A means "add the code to your code-look-up table". It is designed to be with very small length (two to four bytes) to keep the possibility of collision with RTS message low. An ACK message contains the information whether a date message is received properly (Good/Bad indication).

Message ID	Receiver ID	Transmitter ID	Code ID

RTS format

Message ID	Yes/No	Code ID

CTS format

Message ID	D/A	Code ID

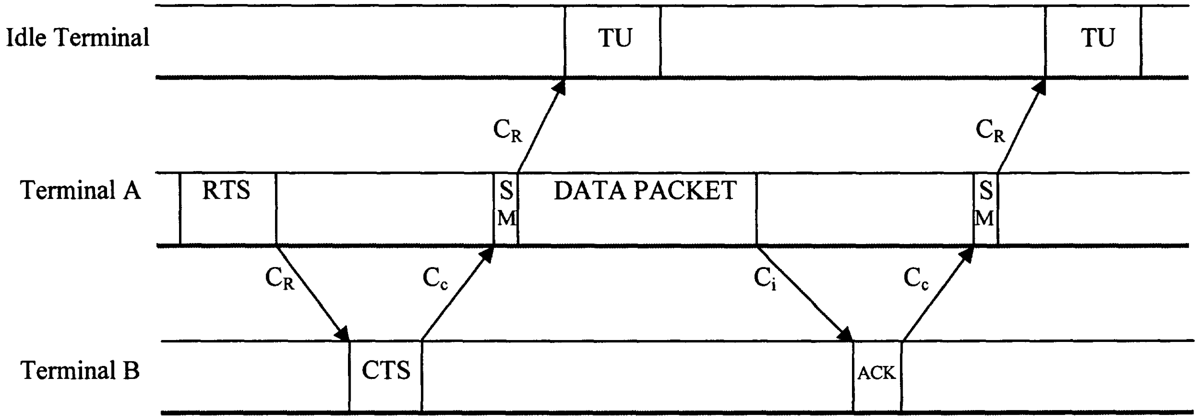
SM format

Message ID	Good/Bad

ACK format

Figure 4.1 Control message format.

The protocol can be depicted as the following procedure and illustrated in Figure 4.2 assuming that terminal A has a packet to send to terminal B:



TU: code-look-up Table Update

Figure 4.2 Operation of DRCA – successful transmission.

1) Terminal A chooses a spread code *i* from its code-look-up table according to the number of currently transmitting terminals and the length of the packet. The number is known by counting the available codes in the table. The code ID is contained at the end of its RTS message.

2) Terminal A sends an RTS message out and then turns to C_C to receive a CTS message from terminal B.

3) Terminal B sends a CTS message with "Yes" decision and then turns to code *i* to receive a data packet from terminal A if it agrees with the spread code requested by terminal A. Otherwise, it sends the CTS message with "No" decision to ask for a different code and attaches a code ID it believes proper. If so, terminal A

re-chooses a code from its code-look-up table and steps 1-3 are repeated till the code is accepted by terminal B.

4) If the spread code needs to be re-used, terminal A broadcasts an SM with C_R to all terminals in the network to inform that code *i* is being used. Eventually, all idle terminals receive the message and take the code off from their own code-look-up tables. By doing so, an idle terminal will not use the code so that primary collision can be avoided. If the spread code does not need to be re-used, step 4 is skipped.

5) Terminal A sends a data packet with code *i*. After that, it turns to C_A to receive ACK. Terminal B de-spreads the code and receives the packet. If B receives the packet properly, ACK with good indication is sent out with C_A. Otherwise it asks for packet re-transmission from A with a negative indication in ACK. Step 5 is repeated till the packet is correctly received.

6) Terminal A receives the ACK message and broadcasts an SM with C_R to ask all idle terminals in the network to update their code-look-up tables. The code can then be reused. If the spread code does not need to be re-used, terminal does not need to broadcast the SM in step 6.

Compared with MACA/CT (Multiple Access with Collision Avoidance/Common Transmitter based) and MACA/RT (Multiple Access with Collision Avoidance/Common Receiver based), DRCA uses bandwidth more efficiently when the ratio of inactive terminals to active ones exceeds a threshold, especially when this ratio is high. The reason is that an active terminal can ask for a higher transmission rate in DRCA but neither MACA/CT nor MACA/RT can do so. In addition to that, the prioritized-transmission mechanism in DRCA gives real-time application packets higher probability to access the channel. MACA/CT and MACA/RT do not have this kind of functionality. However, collision may occur due to the dynamical nature of DRCA. Collisions are classified into two categories: control message collision and data message collision. The first one can be further divided as:

a) RTS message collision, which is caused by two or more RTS concurrent transmissions;

b) CTS message collision, caused by more than one CTS concurrent transmission;

c) ACK message collision, caused by more than one ACK concurrent transmission; and,

d) SM/RTS message collision, caused by concurrent transmission of SM and RTS messages.

Since the size of RTS/CTS/SM message is much smaller than that of data packets, this kind of collision has very little negative effect on channel throughput. Data message collision is caused by two concurrent data transmissions with the same spread code. Although the "Do-No-Use" code broadcast mechanism is used to avoid it from happening, it can still occur with combination of the following five conditions as illustrated in Figure 5.3:

1) A terminal C is busy and misses an SM message when the SM of another terminal, e.g., A, is transmitting;

2) The terminal becomes idle and then needs to send a data packet;

3) It chooses the code contained in the previous SM message;

4) The receiver terminal, e.g., D is busy when the SM in 1) is transmitting and it misses the message, too; and,

5) The sending terminal C sends out the data packet to D. Meanwhile, terminal A is still transmitting its data message to terminal B.

From the above analysis, it is concluded that the possibility of data message collision is very low and its effect to the overall system throughput is small.

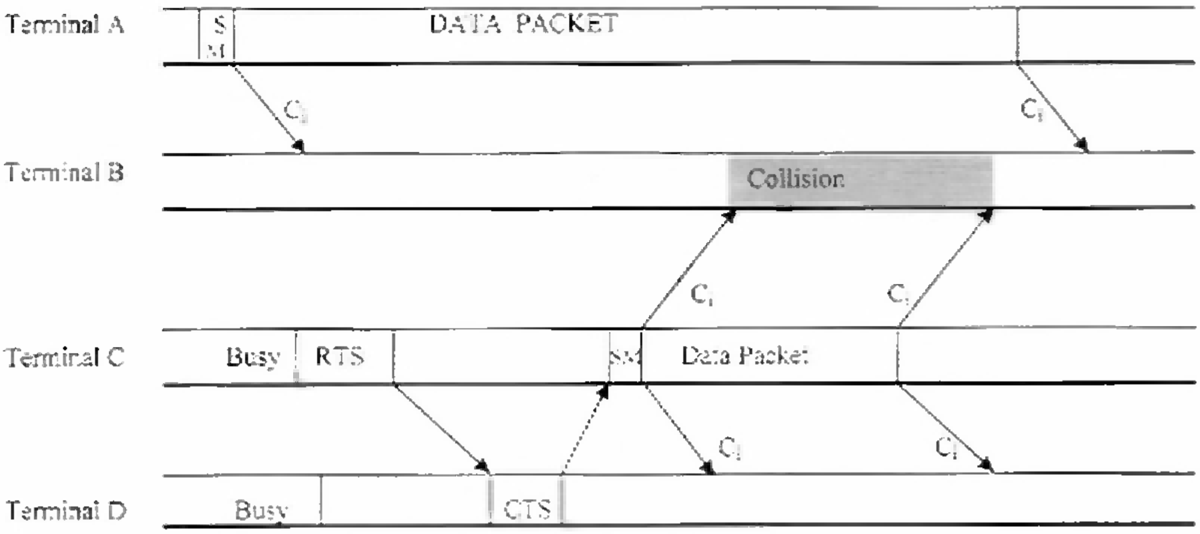


Figure 4.3 A data collision scenario of DRCA.

Beside bandwidth efficiency and collision-avoidance, DRCA has other advantages as:

a) The spread code strategy is a hybrid one composed of common, receiver-based and transmitter-based protocols. It uses common codes to transmit RTS/CTS/ACK/SM messages and all idle terminals turn to C_R to monitor RTS or SM message so that broadcast becomes easy. The spread code is determined by both transmitter and receiver thus collision caused by using the same code is reduced to the minimum. A receiver just needs to monitor one spread code to receive the data message since it knows which code the transmitter is using. Thus the circuitry of the receiver is simple.

b) The computational procedure is simple. Each terminal just needs to maintain a code-look-up table and executes a simple algorithm to choose a proper spread code.

c) It does not need any transmission power increase to achieve the same receiving quality compared with static code allocation protocols.

DRCA satisfies all the requirements for ad hoc wireless network MAC design presented in Chapter 1. At first, bandwidth is efficiently used because of its dynamical rate allocation strategy. Second, minimum interference and collision avoidance are achieved since any terminal in the network tries not to use the same spread code which is being used by another terminal. Additionally, it uses CTS/RTS dialog such that the hidden and exposed terminal problem can be solved properly. Finally, the prioritized transmission mechanism supports QoS for time-sensitive traffic in real-time applications. Therefore, it is concluded that DRCA is a proper MAC design.

4.2 Comparison of DRCA with MACA/CT and MACA/RT

In DRCA, bandwidth is allocated dynamically and collision avoidance is achieved by the "Do-Not-Use" code broadcasting mechanism. Compared with it, both MACA/CT and MACA/RT use static bandwidth allocation. Collision only happens when more than one RTS-CTS exchange exist simultaneously within the same region in MACA/CT and when more than one mobile terminal send RTS messages to the same mobile terminal in MACA/RT.

If the ratio of inactive mobile terminals to active ones exceeds a threshold, it is obvious that DRCA can use bandwidth more efficiently than both MACA/CT and MACA/RT. A prioritized transmission strategy in DRCA guarantees the QoS requirement of real-time application packets. On the other hand, neither MACA/CT nor MACA/RT distinguishes priority level of a packet and does not supports real time application if real-time and non real-time applications are run simultaneously.

DRCA is easy to be implemented with low hardware cost. Compared with MACA/RT, it needs SNIR (Signal to Noise and Interference Ratio) measurement functionality and allocates spread codes according to SNIR and priority information.

Since spread codes are assigned beforehand in both MACA/CT and MACA/RT, signaling overhead is very small. Compared with it, periodic broadcast in DRCA takes some bandwidth. Collision can happen in a specific scenario when a mobile terminal that does not receive the broadcast information in time and happens to move to the region of a mobile terminal transmitting with the same spread code.

The advantages of DRCA are concluded as follows:

- It is a multiple channel protocol and has all the advantages as other multi-channel protocols do;
- It uses dynamic allocation of bandwidth such that a peak high rate can be reached and bandwidth can be used efficiently. If a mobile terminal needs more bandwidth to reach the peak bit rate, it can do so if it finds that SNIR is low, which means neighing mobile terminals are not using much bandwidth;
- It reduces collision by not using the same spread code such that the throughput can be improved;
- It uses prioritized transmission such that the QoS for real time applications can be supported; and,
- It is easy to be implemented and hardware cost is low.

DRCA satisfies all the requirements for ad hoc wireless network MAC design concluded in Chapter 1. At first, minimum interference and collision avoidance are achieved since mobile terminals avoid using the same spread code and each mobile terminal accesses channel with equal chance. Second, bandwidth is used efficiently because of a dynamic spread code allocation strategy. Third, high throughput is reached due to the collision avoidance mechanism. Additionally, it uses CTS/RTS dialog so that the hidden and exposed terminal problem can be solved properly. Finally, the prioritized transmission mechanism gives QoS support for time-sensitive traffic in real-time applications. Hence, it is concluded that DRCA is a proper MAC design for ad hoc wireless network.

4.3 Potential Usage of DRCA in Industry and Standards

Due to the advantages concluded in the above section, DRCA has a good chance to be chosen by industry for a distributed wireless network like ad hoc wireless networks or mesh wireless networks [84]. A mesh network is a network that employs one of two connection arrangements, i.e., full and partial mesh topologies. In the full mesh topology, each pair of node is directly connected. In the partial mesh topology, only some nodes are directly connected but not each pair of nodes. Industry has expressed intense interest in both ad hoc wireless network and mesh network [84, 85]. Compared with some existing MAC designs for ad hoc wireless networks, DRCA is attractive and competitive in terms of bandwidth efficiency, support for real-time applications, and low cost of implementation. Compared with the benchmark MACA/CT, the computation is more complex and the hardware cost is a little bit higher since it needs to pick up a spreading factor in the run and maintain a code look-up table. The performance of DRCA is much better than MACA/CT when there are many inactive mobile terminals. However, the performance is not significant when most mobile terminals are active. It is recommended to use MACA/CT when all or most mobile terminals are active and use DRCA when there are many inactive mobile terminals from time to time.

The default MAC protocol for an ad hoc wireless network is IEEE 802.11 DCF. It uses SS technology in physical layer to mitigate the harsh channel environment. However, only one common code is used due to the difficulty to assign distinct spread codes in a distributed system. If this issue and other three related ones mentioned in Section 1.4.5, which are collision avoidance, bandwidth efficiency and high peak rate realization, are resolved properly, an SS-based MAC for ad hoc wireless network or mesh network can be accepted into IEEE 802.11 standard with a good chance. The proposed DRCA uses dynamic spread code allocation mechanism with collision avoidance. It provides a reasonable and practical solution to those difficult issues. Hence, it has a good opportunity to be accepted into the IEEE 802.11 standard as an optional MAC for a distributed wireless network like ad hoc wireless network.

CHAPTER 5

PERFORMANCE ANALYSIS OF DRCA

Chapter 4 proposes DCRA for ad hoc wireless network. This chapter gives the analysis of the performance of DRCA and compares it with that of MACA/CT. The performance analysis of a Spread Spectrum ad hoc wireless network system is an extremely complex task because the system is driven by a set of uncoordinated users that interfere with each other to various levels. There are usually two ways to analyze such system. The first method uses communication theory while the second one is communication network analysis method. A communication theory method analyzes signal at the bit level; and bit error analysis plays a key role. But it cannot account for realistic traffic models. By contrast, a communication network method takes the random pairs of terminals as transmitter/receiver pairs and investigates the probability of packet success by analyzing transmitter/receiver conflicts. However, it does not account for the system behavior at the bit level. Both methods are necessary for the analysis of an ad hoc wireless system. However, it is difficult to combine two together in one model. It has been shown that a model attempting to account for the two methods simultaneously is intractable [46].

In this chapter, it is focused on the use of a communication network analysis method to investigate how the proposed DRCA protocol impacts the system throughput and a communication network analysis method is used. To avoid involving into the details of bit error analysis as well as to achieve the desired accuracy of the analysis results, it is ensured that the processing gain is so large that a message is received with very low bit error rate or bit error rate is negligible.

In the landmark work of Spread Spectrum for wireless distributed network [46], the authors assume ideal channel condition and perfect power control to obtain the throughput of the system. In the work of the benchmark MACA/CT [24], the same channel condition and power control method are used. To compare the performance of DRCA with the benchmark MACA/CT with the same condition, the analysis of this research makes the same assumptions, i.e., white Gaussian channel and a receiver receives the same power from each transmitter.

There is mcuh work on determining the capacity of an ad hoc wireless network recently. The landmark work by Gupta and Kumar [94] gives the lower and upper bounds on the throughput of each node of ad hoc wireless networks, with the conditions that nodes are randomly located, a node randomly chooses a destination, and a noninterference protocol is used. Splitting the channel into several subchannels does not change any of the results. In another milestone work by Toumpis and Goldsmith [95] the set of achievable rate combinations between all source-destination pairs under different transmission strategies are investigated. It shows that multi-hop routing, spatial reuse and successful interference cancellation increase the capacity significantly but the capacity does not gain much from power control unless variable-rate transmission is used. The work of Grossglauser and Tse [96] finds that per-user throughput can increase dramatically when nodes are mobile rather than fixed with random source-destination pairs.

This research has more interest in the system overall performance rather than a single-user's performance. Hence, it focuses on the overall system throughput analysis.

The throughput in this work is defined as the number of bits per second that could be received correctly by destinations in the whole network. The definition is also used in [46, 24]. The benchmark protocol is MACA/CT.

The first part of this chapter derives the throughput of DRCA in a slotted, single-hop without mobility environment; in the second part of the chapter, it compares the throughput of DRCA with MACA/CT in a single-hop, mobility-free environment by simulation. The third part of the chapter gives the simulation results under a multi-hop, multi-terminal environment.

5.1 Throughput Analysis of DRCA

For the purpose of simplicity, the following assumptions are made in the analysis:

1) There are N terminals in the system.
2) Each terminal is directly connected, i.e., only one-hop connection and under perfect power control, i.e., a receiver receives the same power from each transmitter;
3) Each terminal's position is fixed without mobility;
4) The system is slotted and the slot time t is chosen to accomplish an RTS-CTS dialogue;
5) An idle terminal generates a packet with probability p in a given slot.

It is assumed that an RTS-CTS dialogue is completed within one slot since the size of RTS and CTS messages is small and the propagation time delay within the network is very short. Assume that a terminal generates a packet with length L, spreading factor for this packet is k_e, $k_{\min} \le k_e \le k_{\max}$, in which k_{min} and k_{max} are the minimum and maximum spreading factors, respectively. Chip rate after spreading is m chips per second (cps), which is a constant for all terminals. Correspondingly, the channel transmission bit rate is m/k_e bits per second (bps). The packet transmission time is Lk_e/m second, meaning that the packet lasts for $L' = \frac{Lk_e}{mt}$ slots, where t is the slot time. L' is called the quantized length and assumed that it is geometrically distributed with probability $q(k_e)$. That is, $P(L' = l') = (1 - q(k_e))q(k_e)^{l'-1}$. To simplify the problem, it is assumed that $q(k_e) = q$ for all k_e, $k_{\min} \le k_e \le k_{\max}$.

Since the geometrical distribution is memoryless and the number of transmitting terminals is always the same as the number of receiving terminals in DRCA, the number of communication terminal pairs a is used as a system state. Thus the system can be modeled as a discrete Markov chain.

Since an RTS message is transmitted with common code C_R, multiple RTS packets collide even if they are intended to different receivers. An RTS-CTS dialogue is successful if and only if there is one RTS-CTS transmission in this slot.

The dissertation defines P_{ab} as the transition probability from state a to b, i.e., from a communication pairs to b pairs. The transition probability is conditioned on i, the number of communication pairs that become idle from busy status at the beginning of slot f. Since the system state at slot f-1 is a, the number of terminals that are available to communicate is $N' = N$-$2a$+$2i$. Assume that the number of successful RTS-CTS dialogues in slot f is d, the author then has: $d+a-i = b$. Hence, $d = b-a+i$. Let c be the number of RTS transmissions at the beginning of slot f. The number of failed RTS transmissions thus is $d' = c-d$.

Let H be the event that a transition from state a to b happens; A be the event that exactly one transmission occurs and it is addressed to an idle terminal; B be the event that one transmission occurs and it is addressed to a busy terminal; C be the event that zero or more than one transmission occur; B_i is the event that i pairs of terminals become idle from busy status at the beginning of slot f. Thus:

$$\begin{aligned} P_{ab} &= \sum_{i=0}^{a} P(B_i)[P(H \cap A) + P(H \cap B) + P(H \cap C)] \\ &= \sum_{i=0}^{a} B(a,(1-q),i) \cdot \{\delta(d-1)\delta(d')B(N',p,1)\frac{N'-1}{N-1} \\ &\qquad + \delta(d)\delta(d'-1)B(N',p,1)\frac{N-N'}{N-1} \\ &\qquad + \delta(d)(1-\delta(d'-1))B(N',p,d') \end{aligned} \tag{5.1}$$

in which, $B(n,p,k) = \binom{n}{k} p^k (1-p)^{n-k}$ and $\delta(x) = \begin{cases} 1, \text{when} & x = 0 \\ 0, \text{when} & x \neq 0 \end{cases}$

From Equation (5.1), it gets:

$$\begin{aligned} P_{a,b} = (q)^{b-1}(1-q)^{a-b}\{&\binom{a}{b-1}(1-q)p(1-p)^{M+1}\frac{M^2+3M+2}{N-1} \\ &-\binom{a}{b}qp(1-p)^{M-1}\frac{M^2-M}{N-1} + \binom{a}{b}q\} \end{aligned} \tag{5.2}$$

where $M = N\text{-}2b$, $b \geq 0$, $a \geq 0$ and $a \geq b$. It also has:

$$P_{0,0} = 1 - \binom{\frac{N}{2}}{1} p(1-p)^{\frac{N}{2}-1} \tag{5.3}$$

$$P_{0,1} = \binom{\frac{N}{2}}{1} p(1-p)^{\frac{N}{2}-1} \tag{5.4}$$

$$P_{0,k} = 0, \quad k > 1 \tag{5.5}$$

$$P_{k,0} = (1-q)^k (1 - Np(1-p)^{N-1}, \quad k > 0 \tag{5.6}$$

and,

$$P_{k,m} = q^k (N-2k) p(1-p)^{N-2k-1} \frac{N-2k-1}{N-1}, \quad k>0, m>0, k=m-1 \tag{5.7}$$

Given the transition probability matrix, the steady state distribution S_a is given by:

$$SP = S \tag{5.8}$$

Since the above Markov chain is ergodic, the throughput in bits per second for DRCA is:

$$\gamma = \sum_{r=1}^{N/2} \sum_{j=1}^{r} CR_j S_r = \sum_{r=1}^{N/2} \sum_{j=1}^{r} \frac{m}{k_{rj}} S_r \tag{5.9}$$

where CR_j is the channel rate of terminal j, k_{rj} is the spreading factor for terminal j when there are r communication pairs, and S_r is the steady probability of r communication pairs.

With the static code allocation strategy like MACA/CT, spread code is assigned just once with the worst case consideration, which means that bandwidth is allocated according to $N/2$, the total pair of terminals; not r, the current pair of transmission terminals. Thus:

$$\gamma_S = m \sum_{r=1}^{N/2} S_r \sum_{j=1}^{r} \frac{1}{k_j} \tag{5.10}$$

To maintain good signal quality, the received packet BER (Bit Error Rate) is equal to or less than 10^{-g}, which requires that the receiving SNR (Signal to Noise Ratio) be at least u dB. Under the ideal channel condition (white Gaussian noise channel, without fading) and with binary signal, $u = Q^{-1}(10^{-g})/2$, where $Q(x)$ is the Q-function [81]. To simplify the analysis, it is further assumed that a receiver receives equal power from each transmitter. Hence, it has:

$$10\log_{10}\frac{k_j}{(N/2-1)} \geq u \tag{5.11}$$

Or,

$$k_j \geq 10^{u/10} \times (N/2-1) \tag{5.12}$$

Equation (6.10) then becomes:

$$\gamma_S \leq \sum_{r=1}^{N/2} S_r \frac{mr}{10^{u/10} \times (N/2-1)} \tag{5.13}$$

The equality exists when the received packet BER = 10^{-g}. In case of $\gamma_S \prec \sum_{r=1}^{N/2} S_r \frac{mr}{10^{u/10} \times (N/2-1)}$, the received packet BER $<10^{-g}$. In other words, for high quality signal, $\gamma_S = \sum_{r=1}^{N/2} S_r \frac{mr}{10^{u/10} \times (N/2-1)}$; implying high throughput.

By contrast, bandwidth is allocated according to real channel condition in DRCA. That is, k_{rj} is a function of r. If it is assumed that each terminal chooses a proper spread code and do not consider the collision affect, with the same received signal quality, it has:

$$k_{rj} \geq 10^{u/10} \times (r-1) \tag{5.14}$$

when $r > 1$. Assume that $k_1 \geq k_{rj}$ if $r > 1$, where k_1 is the spreading factor when there is only one communication pair. This assumption is true in real situation. Equation (5.9) then becomes:

$$\gamma_D \leq \sum_{r=1}^{N/2}\sum_{j=1}^{r} S_r \frac{m}{k_{rj}} = S_1\frac{m}{k_1} + \sum_{r=2}^{N/2} S_r \frac{mr}{10^{u/10} \times (r-1)} \tag{5.15}$$

Similarly, the equality exists when the received packet BER = 10^{-g}. In case of $\gamma_D \prec S_1 \frac{m}{k_1} + \sum_{r=2}^{N/2} S_r \frac{mr}{10^{u/10} \times (r-1)}$, the received packet BER <10^{-g}. In other words, for high quality signal, $\gamma_D = S_1 \frac{m}{k_1} + \sum_{r=2}^{N/2} S_r \frac{mr}{10^{u/10} \times (r-1)}$.

By comparing Equation (5.13) with (5.15), when either's equality holds, i.e., when the received signal BER =10^{-g}, since $r \le N/2$, it is easily concluded that $\gamma_D \succ \gamma_S$ when $N/2 > 1$.

Collision effect on throughput in DRCA is hard to be estimated accurately. However, the problem can be simplified with the assumption that each communication pair takes the same bandwidth for re-transmission due to collision and the value is m_s bps. Collision only happens when there are more than one communication pairs. Equation (5.15) then can be modified as:

$$\gamma_D \le \sum_{r=1}^{N/2} \sum_{j=1}^{r} S_r \frac{m}{k_{rj}} = S_1 \frac{m}{k_1} + m \sum_{r=2}^{N/2} S_r r \left(\frac{1}{10^{u/10} \times (r-1)} - \frac{m_s}{m} \right) \qquad (5.16)$$

If m_s is small enough compared with m, it is concluded that $\gamma_D \succ \gamma_S$ when $N/2 > 1$ with the same received signal quality. When $N/2 = 1$, $\gamma_D = \gamma_S$. Note that the number of terminals in any real system is far greater than 2. Hence, DRCA's throughput is certainly better than any protocol with a static code allocation strategy like MACA/CT. The next two sections present the simulation results to confirm the conclusion. With the ideal channel and perfect power assumptions, the results are upper bound of the performance. In a real situation, the channel condition can be much worse and power control could not be such good. In another word, the performance of both DRCA and MACA/CT decreases in a real environment.

5.2 Simulation in a Single-Hop Environment

To evaluate the performance of DRCA and compare it with static code allocation strategy, a simulator is created for a single-hop environment with Matlab [82]. The purpose of the simulation work is to see how the proposed DRCA protocol affects system level performance. The network throughput is mainly investigated. To simplify the simulation and avoid details of bit level error analysis, ideal channel condition is used in the simulator. In other words, our simulation concentrates on MAC layer instead of physical layer. To guarantee the quality of the received signal, the spread code is properly chosen with some restrictions such that the processing gain is big enough when there are concurrent transmissions. It is assumed that each packet is correctly received if no primary collision happens. Beside, the effect of mobility is not considered and only single-hop is used in the simulator in this section.

5.2.1 Simulation Setup

Table 6.1 gives the details of parameters of the simulation. Two different sets of the received signal quality target are used in the simulation. One is 10^{-5} and the other one is 10^{-6}. The corresponding minimum required SNR values are 9.5 dB and 10.5 dB, respectively. The slot time is defined as the transmission time of an RTS-CTS dialogue and set as 1.2 ms, which is slightly bigger than the sum of a RTS and a CTS message transmission time. The total simulation time is set to be 120 s for each set of parameters, i.e., p, q and N. The total number of terminals N is ranged from 2 to 20 in the simulation.

Table 5.1 Parameters Used in the Simulation

Parameter	Value
Chip rate	6.0Mbps
Number of terminals in the network	$N = 2\sim20$
Received signal quality target (bit error rate)	BER = $10^{-5}/10^{-6}$
Required minimum SNR	9.5 dB/10.5 dB
Slot time	1.2 ms
Simulation time	120 s
p	0.1-0.3
q	0.7-0.9

5.2.2 Simulation Results

The network running for 120 seconds is simulated for each set of parameters. The throughput of each time slot is recorded. The system throughput is the average throughput of all the time slots.

Figures 5.1 and 5.2 compare the throughputs of DRCA with those of the static code allocation strategy. The received signal quality target is set as 10^{-6}. From both figures, it is found that DRCA reaches much higher throughput than the static strategy when $N/2>1$. The difference is especially large with a big $N/2$ value. When there is just one pair of communication terminals, i.e., $N/2 = 1$, both DRCA and the static strategy have the same throughput.

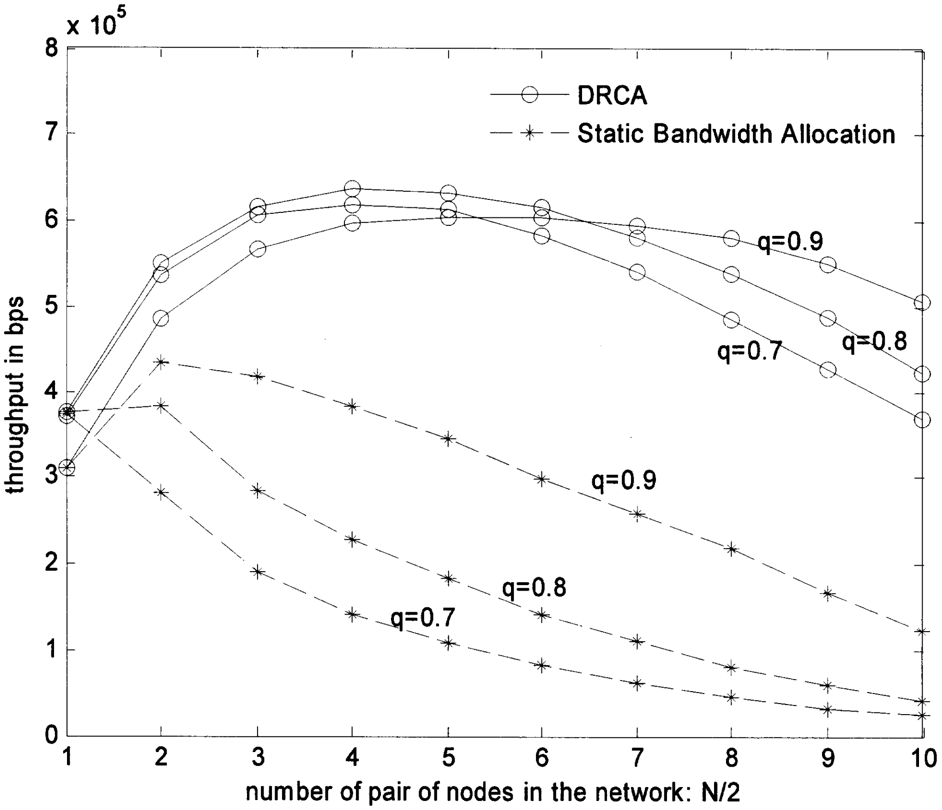


Figure 5.1 Throughput when p=0.15, q varies from 0.7 to 0.9 and BER is 10^{-6}.

Figure 5.1 shows the effect of q and N on the throughput. In this figure, p is fixed at 0.15, the value of q is from 0.7 to 0.9 and N/2 changes from 1 to 10. When N/2 >6, the throughput of DRCA increases when q becomes bigger. The bigger q is, the smaller the average packet length is. It means that when there are enough mobile terminals (like N/2 >6), DRCA achieves higher throughput when a mobile terminal produces a packet with smaller length.

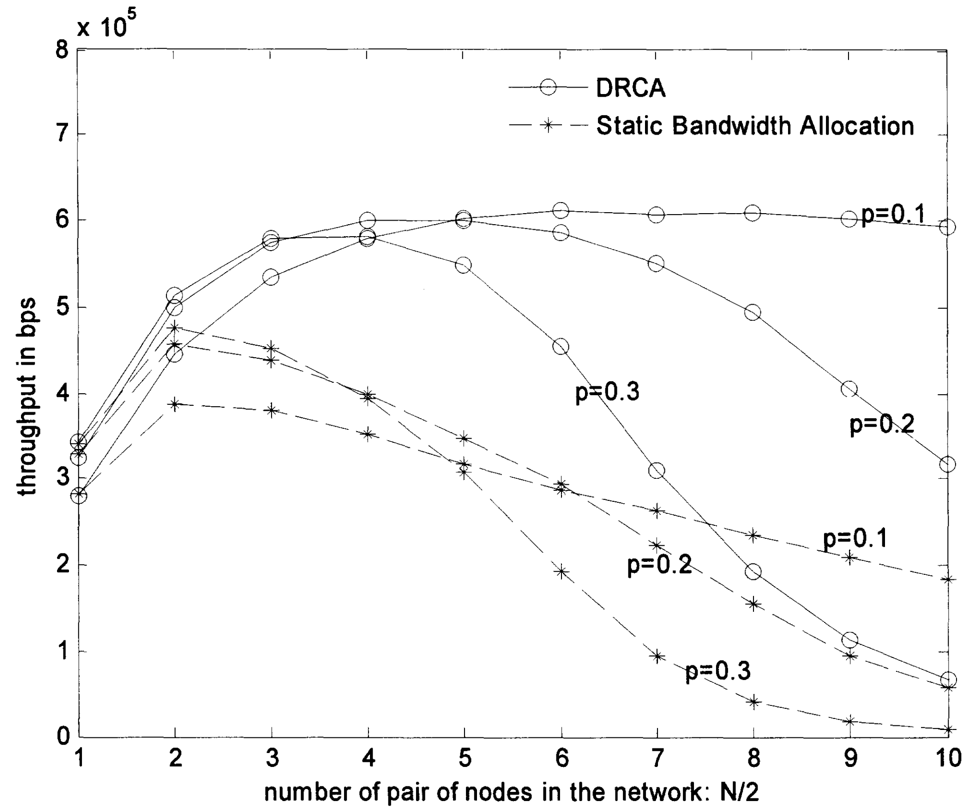


Figure 5.2 Throughput when q=0.9, p varies from 0.1 to 0.3 and BER is 10^{-6}.

Figure 5.2 compares the throughput of DRCA with that of a static code allocation method when q is fixed. In this scenario, q is set as 0.9, p changes from 0.1 to 0.3 and $N/2$ is from 1 to 10. It is noticed that when $N/2 > 5$, the throughput of DRCA becomes higher with lower p. In other words, when the total number of mobile terminal exceeds a threshold, e.g., $N/2 > 5$, DRCA achieves higher throughput if each mobile terminal produces a packet with lower possibility. This is caused by the RTS-CTS dialogue collision. When there are many mobile terminals and each one has a high probability to produce a packet in a certain slot, then the possibility of RTS-CTS dialogue collision becomes high, which refrains a new packet from being transmitted in the slot. Finally, the system throughput is degraded. Compared with it, when $N/2 < 4$, the throughput of DRCA decreases with p. In other words, when the total number of mobile terminals is small, the overall system throughput decreases if each mobile terminal produces a packet with lower probability. It is because the probability of RTS-CTS dialogue collision becomes small if there are few mobile terminals in the system. The system throughput is then mainly affected by the number of data packets. If a mobile terminal produces a packet with lower probability, obviously the system throughput suffers.

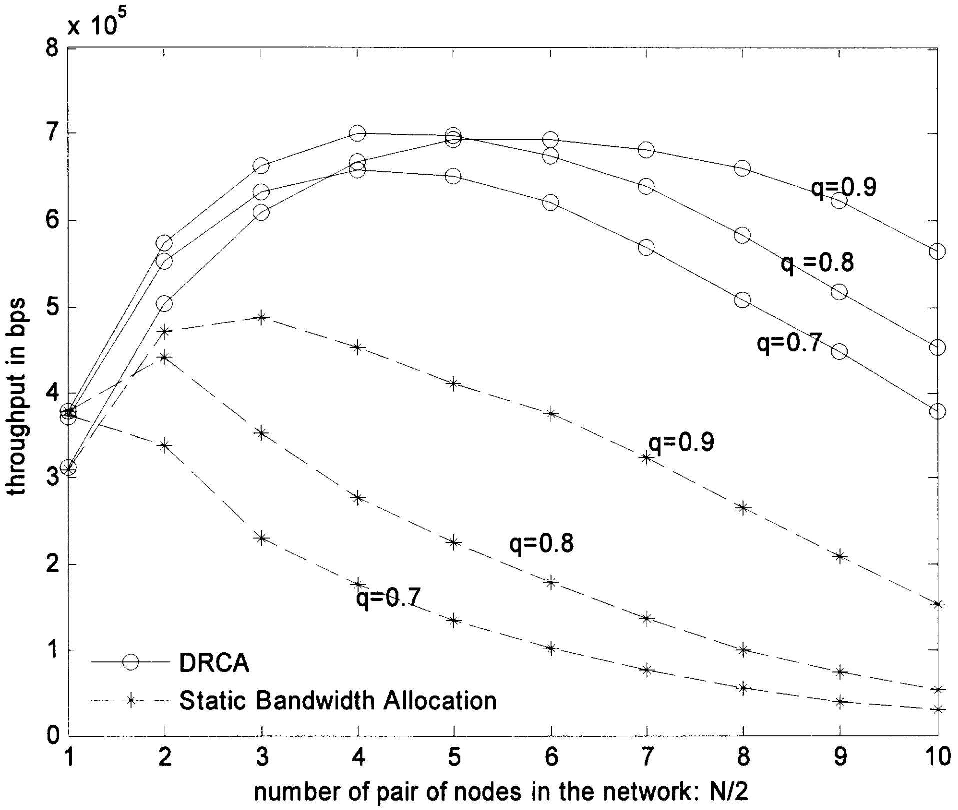


Figure 5.3 Throughput when p=0.15, q varies from 0.7 to 0.9 and BER is 10^{-5}.

Figures 5.3 and 5.4 compare the throughputs of DRCA and static code allocation design when receiving signal quality target is 10^{-5}. The trend of throughput with p, q and N is similar to that in Figures 5.5 and 5.6. It is noticed that the throughput of DRCA is a little bit higher than that in Figures 5.3-5.4. It is because with a lower required signal quality, a mobile terminal can transmit data with higher transmission rate. Although the BER is a little bit higher, the overall throughput still increases.

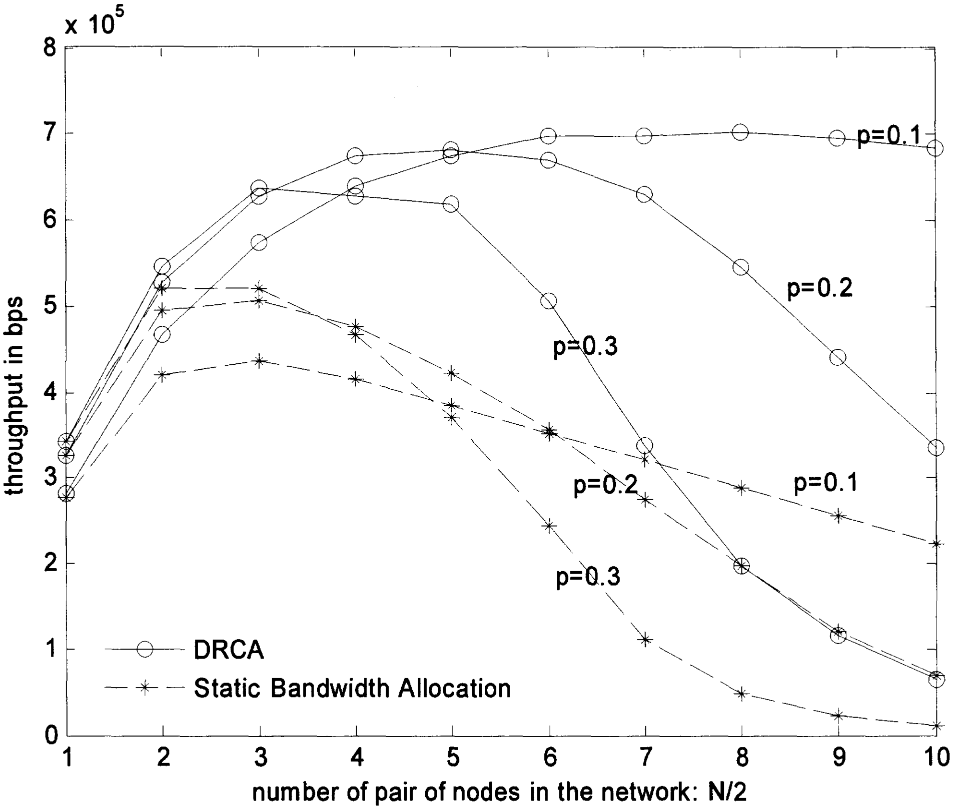


Figure 5.4 Throughput when q=0.9, p varies from 0.1 to 0.3 and BER is 10^{-5}.

It is concluded that if the ratio of active terminals is low, DRCA performs much better than a static method. Otherwise, the difference is smaller. This conclusion matches with the intuition of DRCA.

5.3 Simulation Results in a Multi-Hop Environment

5.3.1 Simulation Setup

To evaluate the performance of DRCA in an environment that is as close as possible to a real network scenario, a simulator in OPNET [56] is created. There are total 50 mobile terminals in the simulator. Multi-hop is used for delivering packets. AODV (Ad-hoc on demand Distance Vector) [50] routing protocol is utilized. Four different kinds of applications, i.e., voice call, video call, FTP (File Transfer Protocol) and IP Unicast, are deployed during the simulation. The detailed parameters in the simulation are given in Table 5.2.

Table 5.2 Simulation Parameters in a Multi-Hop Environment

Parameter	Value
Number of mobile terminals	$N = 50$
Mobility	Random Waypoint
Routing Protocol	AODV
Traffic Patterns	1. Voice call 2. Video Call 3. FTP 4. IP Unicast
Network Layout Size	100x100 meter
Chip Rate	2.2 M cps
Received signal quality target (bit error rate)	BER = 10^{-6}

Two spread code allocation methods, i.e., DRCA and MACA/CT, the static code allocation mechanism, are implemented in the simulator. The performance data of each method in the network are collected and compared.

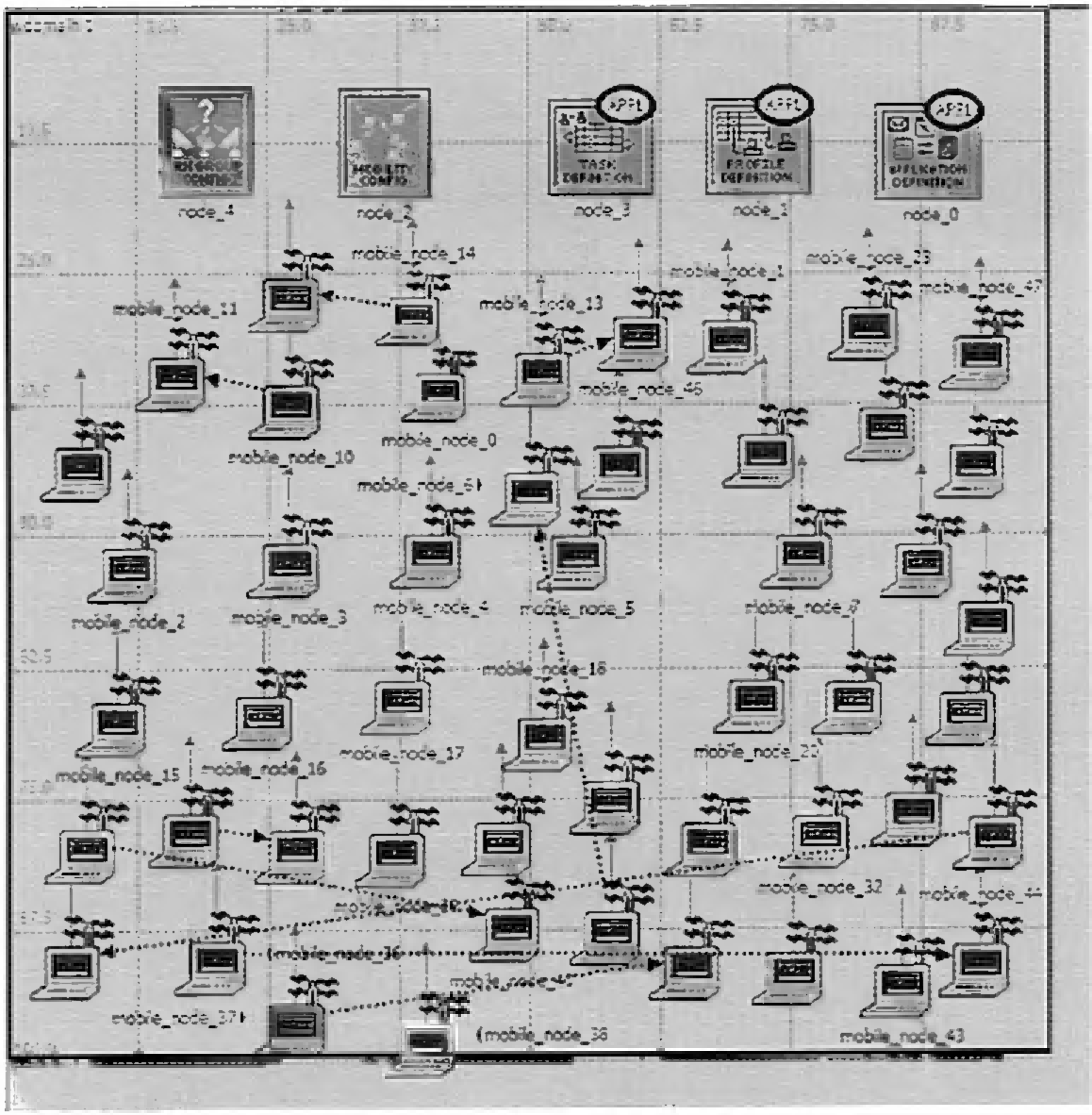


Figure 5.5 Network layout of the simulator.

During the simulation, each mobile terminals moves with a random mobility pattern profile. With this kind of mobility pattern, a mobile terminal moves randomly inside the network. When it reaches the boundary of network, it stops. Then the mobile terminal is "reflected" back and moves again. The speed of a mobile terminal is uniform distributed from 0-10 meter/second. Figure 5.5 gives the initial location of each mobile terminal in the network. Figure 5.6 shows the location of each mobile terminal after 30second. Figure 5.7 displays the location of each mobile terminal after the network running for 150 second. It is found that each mobile terminal keeps moving randomly inside the network during the simulation.

Four traffic patterns are used in the simulation. They are voice call, video call, FTP and IP Unicast, respectively. These traffic patterns are based on OPNET existing traffic models with some modifications. There are two types of traffic models in OPNET. The first one is simple source traffic, which can be described by packet size and packet inter-arrival time. IP Unicast belongs to this category. The second one is application traffic, which is represented by inter-request distribution, or file size distribution, or call duration. There is no single mathematical formula that can represent this kind of traffic as it does for simple source traffic. FTP, voice call and video call belong to the second category [56]. Although FTP, voice call and video call are session-oriented, they are set as discrete traffic and each packet from these services still goes through the RTS-CTS dialogue. The details of these traffic patterns are exemplified in Table 5.3-5.6.

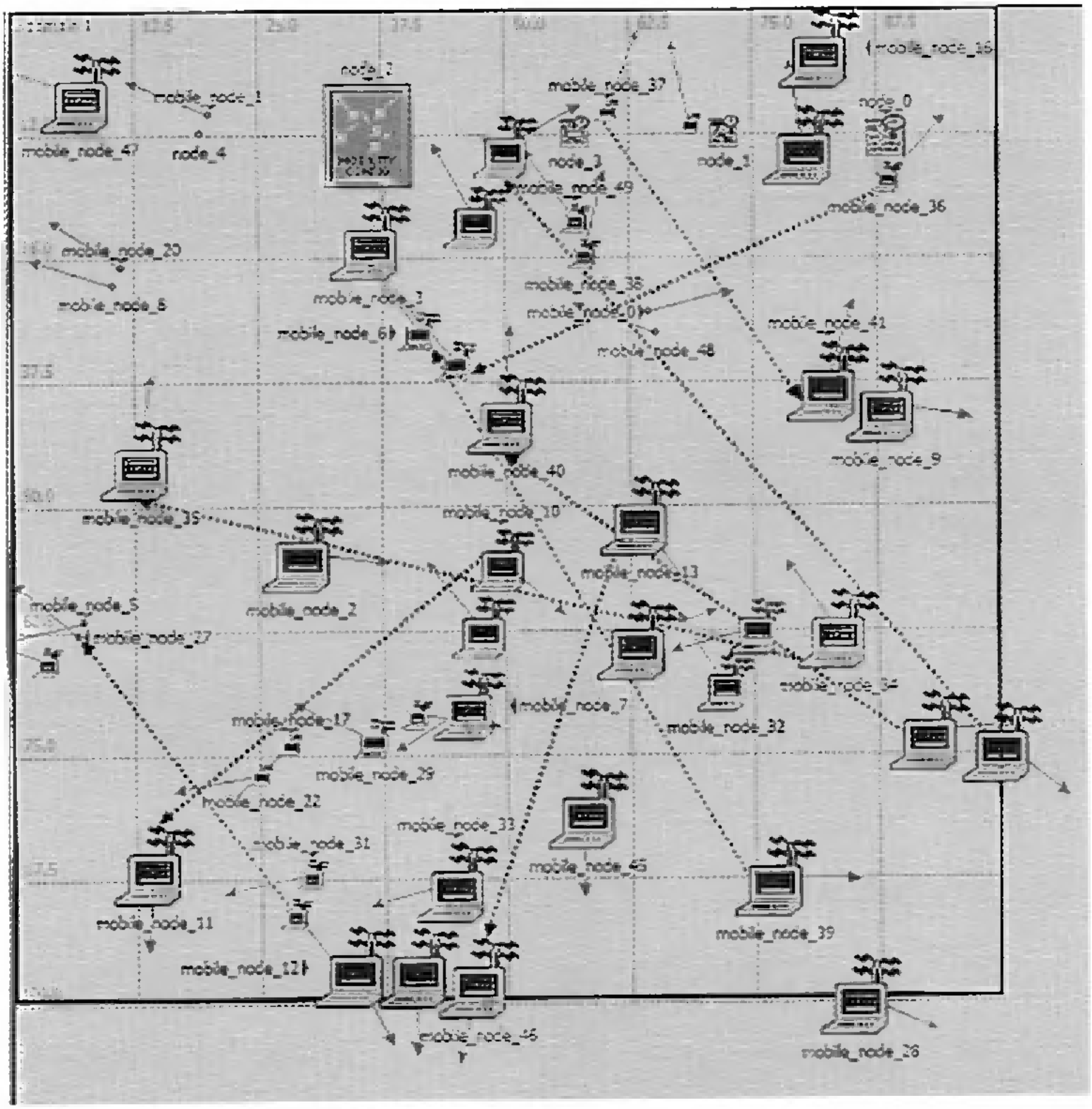


Figure 5.6 Locations of each mobile terminal after 30 second.

Table 5.3 FTP Traffic Parameters in the Simulation

Traffic Pattern	Type of Service	File Size	Inter-request time	Traffic Start time	Traffic Duration
FTP	Excellent Effort	Constant/50000	Exponential/720	Uniform/ (100-110)	End of Simulation

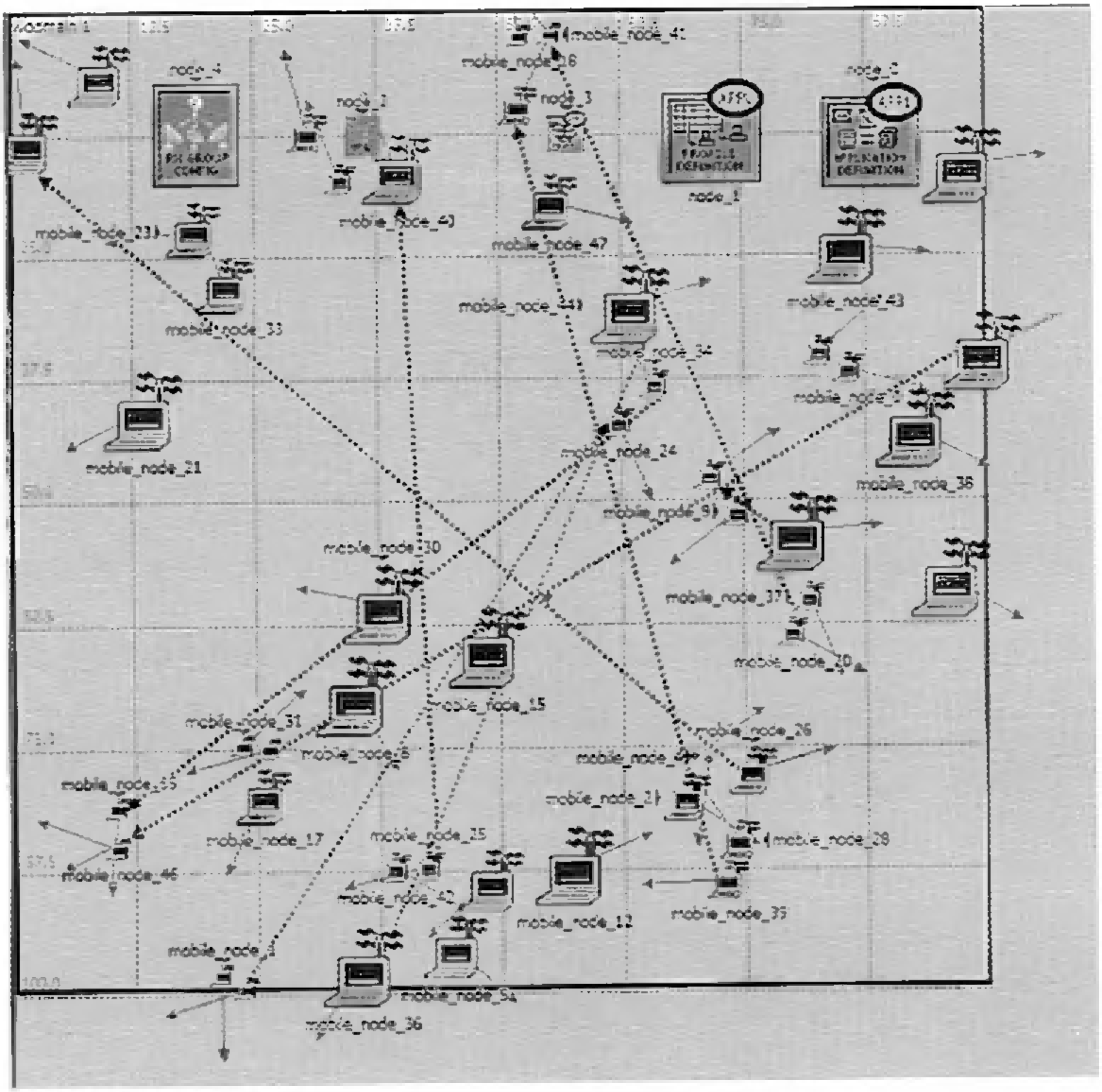


Figure 5.7 Location of each mobile terminal after 150s.

Table 5.4 Voice Call Parameters in the Simulation

Traffic Pattern	Type of Service	Talk Spurt length	Voice Frame per packet	Traffic Start time	Traffic Duration
Voice Call	In-active voice	Exponential (0.352)	1	Uniform (100-110)	End of Simulation

Table 5.5 Video Call Parameters in the Simulation

Traffic Pattern	Type of Service	Frame size	Frame inter-time	Traffic Start time	Traffic Duration
Video Call	Streaming Multimedia	128x240 bytes	15 frames/s	Uniform/ (100-110)	End of Simulation

Table 5.6 IP Unicast Traffic Parameters in the Simulation

Traffic Pattern	Type of Service	Data Rate	Packet size (distribution/average)	Inter-arrival time	Traffic Start time	Traffic Duration
IP Unicast	Best effort	100 packet /s	Exponential/1200	constant	180 s	3600 s

In the simulation, MT 23 is set as the server of FTP application, MT 22 is the source of the FTP application. MT 1 is the source of the voice call, MT 0 is the destination of the call. MT2 is the source of video call; and MT 3 is the destination of the call. All other MTs are either connected one by one randomly as an IP Unicast traffic pair or keep inactive during the simulation.

5.3.2 Simulation Results

The simulation duration time is set as 3000 seconds, i.e., it simulates fifty minute running of the network. The number of active mobile terminals in the network is changed for each running. The simulation results are shown in Figures 5.9 - 5.11.

From the figures, it is found that from the beginning of the simulation till the start of traffic, since there is no generated traffic, the throughput of both DRCA and static code allocation methods are both zero. From the time point when traffic begins to be generated to the end of the simulation, the DRCA always performs better than the static bandwidth allocation method. Table 5.7 exemplifies the average throughput difference between DRCA and the static spread code allocation method. The difference is calculated based on the static spread code allocation method. Positive value means the throughput improvement of DRCA compared with the static method. It is shown that DRCA achieves 9.48% higher throughput than the static method when there are 25 pairs of active MTs; 21.09% higher throughput if there are 21 pairs of active MTs; 40.57% higher when there are 16 pairs of active MTs; and 63.32% higher when there are 12 pairs of active MTs.

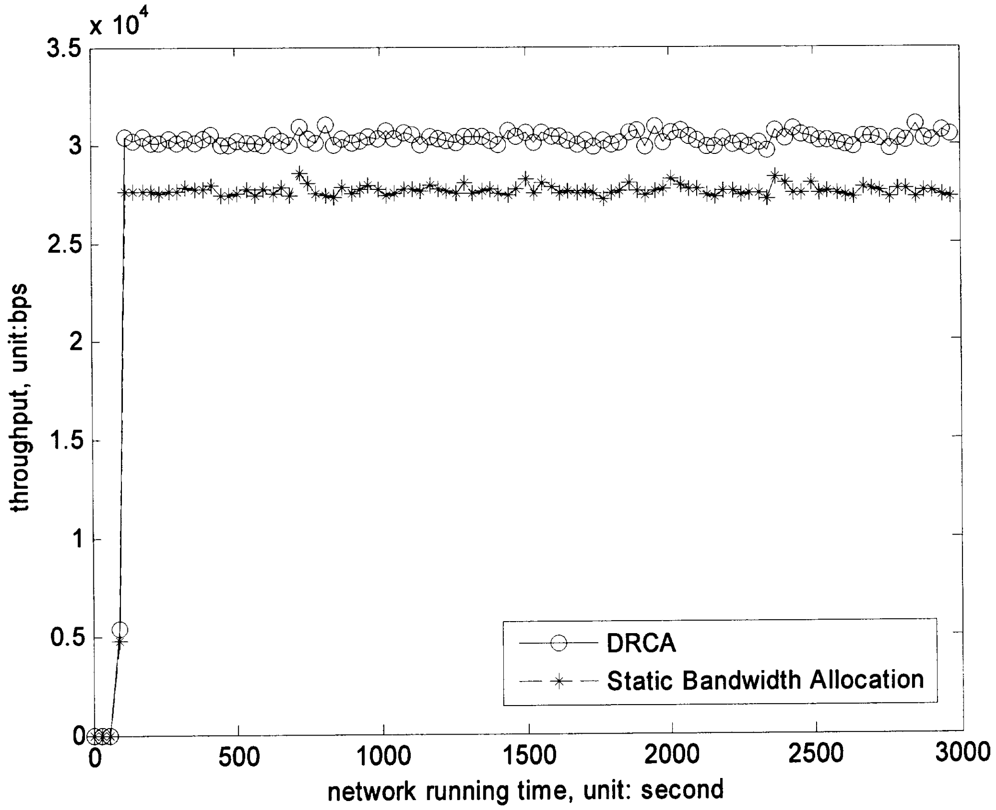


Figure 5.8 Throughput comparison between DRCA and static code allocation method: 25 pairs of active mobile terminals.

Figure 5.8 shows the throughput comparison between DRCA and static code allocation method when there are 25 pairs of active mobile terminals (one is in voice call, one is in video conference, one is with FTP; and the 22 pairs MTs are in IP Unicast). Figure 5.9 shows the comparison when there are 21 pairs of active mobile terminals.

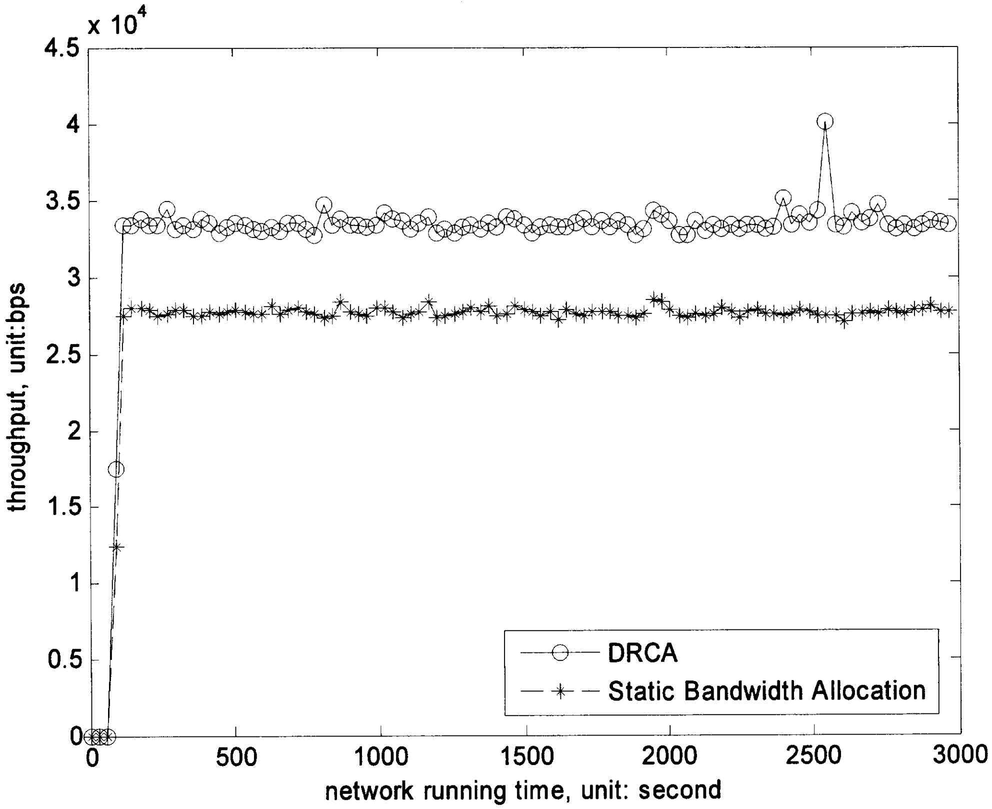


Figure 5.9 Throughput comparison between DRCA and static code allocation method: 21 pairs of active mobile terminals.

Figures 5.10 and 5.11 are with 12 and 16 pairs of active mobile terminals, respectively. From them, it is shown that the throughput difference between DRCA and MACA/CT increases when the number of active mobile terminals deceases. In other words, the lower the ratio of active MTs to inactive ones is, the better DRCA performs than a static code allocation method. It is because DRCA dynamically allocates rates according to the activity status of neighbors such that the available bandwidth is used more efficiently.

Compared with it, the static code allocation method allocates codes just once and cannot adjust the allocation even if neighbors' activity status changes. Therefore, if there are many inactive mobile terminals, for example, 52% of inactive mobile terminals, DRCA achieves 63% higher throughput than that of the static code allocation method, e.g., MACA/CT. However, if most of the mobile terminals are active, as shown in Figure 5.8, the performance difference between DRCA and MACA/CT is minor.

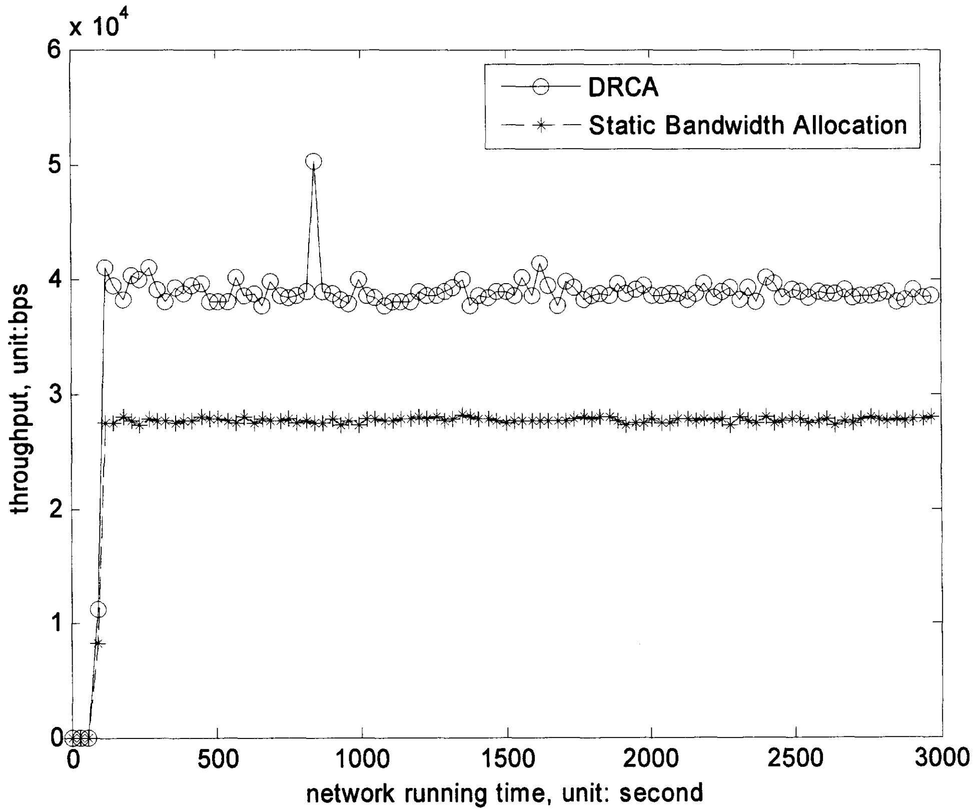


Figure 5.10 Throughput comparison between DRCA and static code allocation method: 16 pairs of active mobile terminals.

The simulation results verify that DRCA uses bandwidth more efficiently and can achieve better performance than the static code allocation method does in a multi-hop, multi-user environment with mobility. when there are many inactive mobile terminals in the network. The results also show that when most of the mobile terminals are active, DRCA's performance does not improve significantly from MACA/CT. Considering the higher implementation and computation cost of DRCA, it is recommended that DRCA is only used for environment when there are many inactive mobile terminals from time to time. If all or most of the mobile terminals are active, MACA/CT is preferred. It is also recommend that use MACA/CT for a large scale ad hoc wireless network due to the difficult to dynamically allocate spread codes in a large network.

Table 5.7 Throughput Difference between DRCA and Static Code Allocation Method

Number of active MT pairs	Average Throughput Difference
25	9.48%
21	21.09%
16	40.57%
12	63.32%

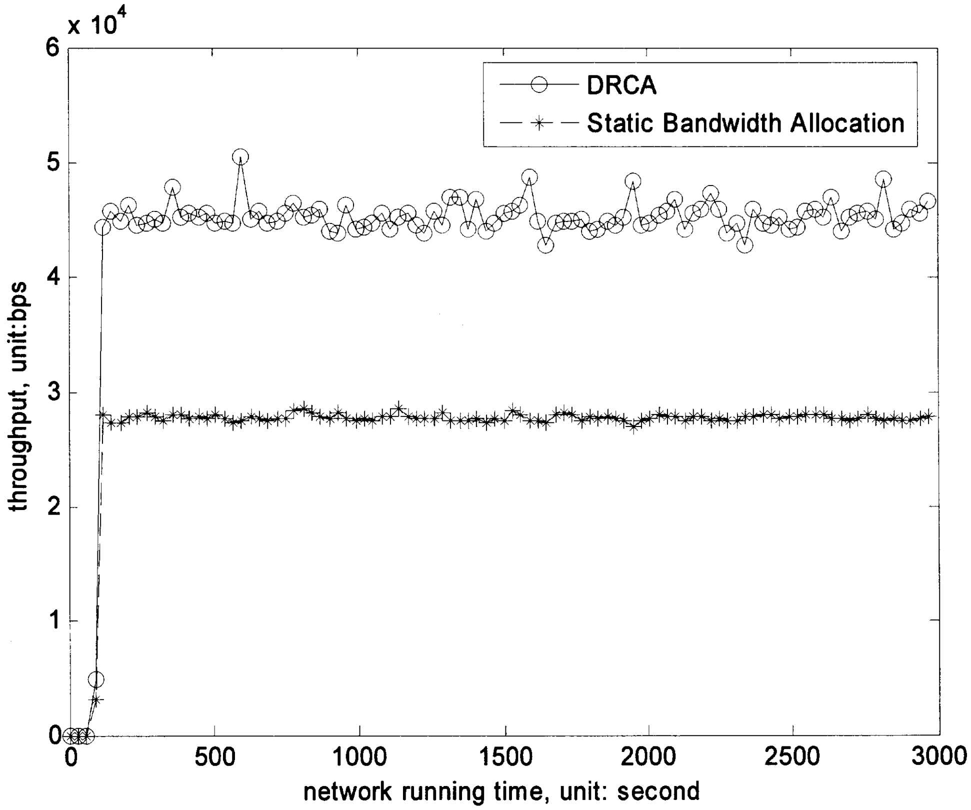


Figure 5.11 Throughput comparison between DRCA and static code allocation method: 12 pairs of active mobile terminals.

CHAPTER 6

CONCLUSIONS AND FUTURE RESEARCH

6.1 Conclusions

This research proposes PPTM for All-IP wireless WAN and DRCA for ad hoc wireless networks. The contributions and limitations of the research are concluded in the following two sections.

6.1.1 Summary of Contributions

The first part of the research proposes PPTM as a proper MAC design for All-IP wireless WAN. All-IP wireless WAN is a strong candidate beyond 3G. It is IP protocol-based, and it supports wide-area-coverage and high-mobility. Various kinds of service need to be supported. They bear different importance and pose various QoS requirements. The important levels or QoS requirements can be digitized and represented by transmission priority levels. Packets can then be allocated into different priority groups and a higher priority packet always carries more important information or more time sensitive than a lower priority one does.

The proposed PPTM is composed of two stages. A pre-transmission probability is calculated in stage 1 based on continuous observation of the channel load for a certain period of time. Packets are transmitted according to their priority in stage 2. PPTM has the advantages of both centralized and distributed MAC design and its control overhead is low.

To analyze its performance, PPTM is modeled as a nonpreemptive prioritized queueing system when packet arrival pattern is a Poisson process. Packet transmission time delay, throughput and average number of packets in the queue have been derived. The numerical results are obtained via simulating a simplified All-IP wireless WAN environment and find that the theoretical formulae match closely with them. Numerical results are derived under the assumption of other traffic patterns, which are CBR, Exponential On/Off and Pareto On/Off, too. From the numerical results, it is found that in PPTM, a higher priority packet achieves much less average TTD than a lower priority packet does. There are in general much fewer higher priority packets than lower priority packets in the queue. In PPTM, a more important packet always has higher priority than a less-important one does. By giving more important packets more transmission opportunity, more important information is transmitted with the same channel condition. A time-sensitive packet should be transmitted faster than a time non-sensitive packet. PPTM can do so but MCLSP (Modified Channel Load Sensing Protocol) cannot. Although the system throughput is the same, PPTM performs much better than MCLSP does from the QoS view point. With PPTM, it is much easier for a packet to meet its delay requirement than with MCLSP. The latter does not support prioritized transmission. In other words, MCLSP transmits all packets equally. Our simulation results verify that good QoS differentiation and support of prioritized transmission is very important and necessary in All-IP wireless WAN. PPTM satisfies the important transmission principle.

In the second part of the research, a MAC design called DRCA is proposed for ad hoc wireless network. Ad hoc wireless networks are found to be very useful in many areas when an infrastructure network is hard or unnecessary to be built. The areas include certain military applications, emergency operations, wireless sensor networks, and distributed computing, etc. Designing an effective, efficient and QoS supported MAC protocol for ad hoc wireless network is difficult without the help of a central coordinator, though. Based on the review of the existing MAC protocols and the analysis of design goals of MAC for ad hoc wireless network, DRCA is proposed as an efficient and reliable MAC design. DRCA allows the dynamical allocation of spread codes to achieve efficient bandwidth usage. The spreading factor of a code is set according to the neighboring nodes' activity level and the priority level of a packet to be transmitted. By doing so, it can take back bandwidth from inactive neighboring nodes and give more resource to an active node that needs it. Collision avoidance is achieved by broadcasting the spread code id that is being used so that other terminals avoid using it. Throughput performance is improved due to the collision avoidance mechanism. Its prioritized transmission mechanism gives QoS support for time-sensitive real time applications.

The throughput of DRCA is analyzed in a single-hop network without mobility for the purpose of simplifying and comparing it with static spread code allocation strategy. It is found that the throughput of DRCA is higher when there is more than one pair of communicating nodes. It verifies that DRCA uses bandwidth much more efficiently than static code allocation mechanism as MACA/CT. Simulation results from both single-hop and multi-hop environments verify that DRCA always achieves higher throughput than a static spread code allocation method does in an ad hoc wireless network. The difference becomes more significant if the ratio of active mobile terminals in the network decreases. It also finds that the difference between DRCA and MACA/CT is minor when most of mobile terminals are active. Take into account the higher implementation and computation cost of DCRA, it is preferred to deploy DRCA only when there are many inactive mobile terminals from time to time in the network and use

MACA/CT when all or most mobile terminals are active.

6.1.2 Limitations

This research has following limitations:

1) This research only considers HOL priority scheme for PPTM protocol. More kinds of priority scheme can be used in real implementation;
2) This research assumes an IMP has unlimited space to save packets in the theoretic analysis for the performance of PPTM. In real environment, an IMP cannot have unlimited space. Loss of packets could occurs;
3) Flexible code allocation method is not used in the performance analysis of PPTM;
4) The performance analysis of DRCA does not consider the prioritized transmission mechanism;
5) The performance analysis of DRCA assumes ideal channel condition and perfect power control, which is impossible to realize in real situation. The present analysis is thus the upper bound of the performance; and,
6) The performance of DRCA in multi-hop environment is given with simulation only. Theoretic analysis in a multi-hop environment is not performed.

6.2 Future Work

6.2.1 Future Work of PPTM Protocol

Further simulation work is needed to analyze the performance of PPTM. In the present simulation, the analysis is simplified by taking the processing time delay in state 1 as zero. In the future research, the effect of the processing time delays should be investigated. Packet length is set with only exponential distribution in the simulation. Other kinds of length distribution should be used in the future and the results need to be compared for the proposed PPTM and other protocols. More research is needed about the throughput, which is mostly physical layer related. Flexible bandwidth allocation for each IMT is an important mechanism in PPTM. It will be used in the future simulation work. The distribution of TTD and number of packets in the queue is also interesting to be further studied. Finally, the potential usage of PPTM for other wireless systems, for example robotic wireless communications, should be investigated.

There is some opportunity that PPTM can be accepted by industry or standards. Further research and effort will be exploited for its acceptance by industrial standards or its commercialization.

6.2.2 Future Work for DRCA

The further investigation of the impact of secondary collision onto the throughput performance is needed. In the performance analysis, it makes two assumptions - ideal channel condition and perfect power control. In real situations, the channel condition can be much worse and the power control cannot be so good. The effect of the fading channel condition onto the performance of DRCA still remains unknown. In the deep fading channel condition, the performance of DRCA could be worse than the static spread code allocation method like MACA/CT. Under DRCA, a mobile terminal can choose an improper spread code such that the received signal quality is very bad and needs to re-transmit the packet. It needs more research efforts to investigate the performance of DRCA under fading channel conditions with non-perfect power control.

In the performance analysis of DRCA, it is assumed that each communication pair takes the same bandwidth for re-transmission due to collision. It is just an approximation and it is not accurate in real situation. More research is required to investigate the collision effect. Signaling overhead is another interesting issue. Signaling messages take some bandwidth and it is interesting to know if there is a better way to reduce the overhead.

More theoretical analysis is necessary to derive the DRCA performance in a multi-hop environment with mobility. The results need to be verified with the simulation results. New simulation schemes need to be developed so that they can achieve good accuracy results with less computation. It is possible that DRCA is accepted by industry and IEEE standard due to some of its superior characteristics. More efforts and research are required for the acceptance of DRCA by industry and standards body.

Finally, further investigation should be exploited to know whether DRCA can reach the real time applications' QoS requirement. The transmission time delay will be measured as QoS reference for real time applications.

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