UNIVERSITY OF KWAZULU-NATAL

HYBRID TOKEN-CDMA MAC PROTOCOL FOR WIRELESS NETWORKS

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HYBRID TOKEN-CDMA MAC PROTOCOL FOR WIRELESS NETWORKS

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As the candidate's Supervisor I agree/do not agree to the submission of this thesis.

30th March, 2009
Fambirai Takawira

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PREFACE

The research work in this thesis was performed by Yi-Sheng Liu, under the supervision of Professor Fambirai Takawira and Professor Hong-Jun Xu, at the University of KwaZulu-Natal's School of Electrical, Electronic and Computer Engineering. This work was partially supported by Alcatel-Lucent, THRIP, National Research Foundation (NRF) and Telkom South Africa as part of the Centers of Excellence programme at the University of KwaZulu-Natal.

Parts of this thesis have been published in the IEEE Transaction on mobile computing. Furthermore, the work was presented by the author at the IEEE ICT'05 (international conference on telecommunication) conference, IEEE PIMRC'07 (personal indoor mobile radio communication conference), IEEE AFRICON'07 and the SATNAC '05 and '07 conference.

DECLARATION

I, Yi-Sheng Liu declare that

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ABSTRACT

Ad hoc networks are commonly known to implement IEEE 802.11 standard as their medium access control (MAC) protocol. It is well known that token passing MAC schemes outperform carrier-sense-multiple-access (CSMA) schemes, therefore, token passing MAC protocols have gained popularity in recent years. In recent years, the research extends the concept of token passing scheme to wireless settings since they have the potential of achieving higher channel utilization than CSMA type schemes.

In this thesis, a hybrid Token-CDMA MAC protocol that is based on a token passing scheme with the incorporation of code division multiple access (CDMA) is introduced. Using a dynamic code distribution algorithm and a modified leaky-bucket policing system, the hybrid protocol is able to provide both Quality of Service (QoS) and high network resource utilization, while ensuring the stability of a network. This thesis begins with the introduction of a new MAC protocol based on a token-passing strategy. The input traffic model used in the simulation is a two-state Markov Modulated Poisson Process (MMPP). The data rate QoS is enforced by implementing a modified leaky bucket mechanism in the proposed MAC scheme. The simulation also takes into account channel link errors caused by the wireless link by implementing a multi-layered Gilbert-Elliot model. The performance of the proposed MAC scheme is examined by simulation, and compared to the performance of other MAC protocols published in the literature. Simulation results demonstrate that the proposed hybrid MAC scheme is effective in decreasing packet delay and significantly shortens the length of the queue.

The thesis continues with the discussion of the analytical model for the hybrid Token-CDMA protocol. The proposed MAC scheme is analytically modelled as a multiserver multiqueue (MSMQ) system with a gated service discipline. The analytical model is categorized into three sections viz. the vacation model, the input model and the buffer model. The throughput and delay performance are then computed and shown to closely match the simulation results. Lastly, cross-layer optimization between the physical (PHY) and MAC layers for the hybrid token-CDMA scheme is discussed. The proposed joint PHY-MAC approach is based on the interaction between the two layers in order to enable the stations to dynamically adjust the transmission parameters resulting in reduced mutual interference and optimum system performance.

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LIST OF ABBREVIATIONS

Acronym	Description
ACK	Acknowledgement
ACL	Asynchronous Connectionless link
AM	Amplitude Modulation
AP	Access Point
ATM	Asynchronous transfer mode
AWGN	Additive White Gaussian Noise
BCH	Broadcast channel
BCH	Bose, Ray-Chaudhuri, Hocquenghem
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
BS	Base station
BSMA	Broadcast Support Multiple Access
BTMA	Busy-Tone-Multiple-Access
CBR	Constant bit rate
CCI	Co-channel interference
CD	Carrier detect
CDMA	Code Division Multiple Access
CR	Collision report
CSI	Channel State Information
CSMA	Carrier Sense Multiple Access
DB	Duplicate Bit
DCH	Data channel
DFWMAC	Distributed Foundation Wireless MAC
DIFS	Distributed inter frame space
DTMC	Discrete Time Markov Chain
EOT	End of Token
FAMA	Floor-Aacquisition-Multiple Access
FDD	Frequency division duplex
FDDI	Fiber Distributed Data Interface
FIFO	First In First Out
FSM	Finite State Machine
FT	Feedback tone
IEEE	Institute of Electrical and Electronics Engineers
ID	Identity
IDI	Idle detection interval
IS	Initialization State
ISA	Idle signal with acknowledgement
ITU	International Telecommunication Union
JS	Join State
Acronym	**Description**
LA	Load Awareness
LS	Lost State
MAC	Medium Access Control

MACA	Multi-Access with Collision Avoidance
MAI	Multi Access Interference
MMPP	Markov Modulated Poisson Process
MSMQ	Multi Server Multi Queue
MUD	Multi User Detector
NACK	Negative acknowledgement
NAV	Network allocation vector
NCS	Non-persistent Carrier Sensing
NOC	Number of Codes
OSI	Open System Interconnect
PAN	Personal Area Network
PCA	Packet Collision Avoidance
PDF	Probability Distribution Function
PER	Packet Error Rate
PHY	Physical
PS	Packet transmit State
QoS	Quality of Service
RBAR	Receiver-Based Auto Rate
RDI	Receiver detection interval
RP	Reservation packet
RTS/CTS	Request To Send/Clear To Send
SIFS	Short inter frame space
SNR	Signal-To-Noise Ratio
SS	Sense State
TCP	Transmission Control Protocol
TDD	Time Division Duplex
TS	Token transmit State
TVC	Token Visit Counter
UAV	Unmanned aerial vehicle
VBR	Variable bit rate
WCD	Wireless Collision Detect
WTRP	Wireless Token Ring Protocol

LIST OF SYMBOLS

Symbol	Description
M	Number of CDMA codes in the network
N	Number of nodes in the network
r	Traffic classes
T_i^{trans}	Mean token transmission time between two nodes
$\lambda_{ip,i}^{r}$	Packet arrival rate to node i of class r
α_r^i	Permit generation rare of node i of class r
$\lambda_{g,i}^{r}$	Designated date rate of node i of class r
ρ_r	QoS proportionality constant for class r
T_c	Token cycle
γ_i	Permit pool of node i
B_{pac}^i	Buffer length at node i when token arrives
B_{per}^i	Permit pool length at node i
TT_c	Target Token cycle
β	Constant parameter for enroll timer
ψ_L^i	Mean transition rate out of the Low load state
ψ_H^i	Mean transition rate out of the High load state
$\lambda_{r,L}^i$	Mean arrival rate of the Poisson process in the Low load state
$\lambda_{r,H}^i$	Mean arrival rate of the Poisson process in the High load state
s	Packet length
τ_{good}^i	Time that wireless channel is in good state
τ_{bad}^i	Time that wireless channel is in bad state
P_{BG}^i	Wireless link i's transition probability from the bad state to the good state
P_{GB}^i	Wireless link i's transition probability from the good state to the bad state
P_{good}^i	Steady-state probability that link i is in the good state
P_{bad}^i	Steady-state probability that link i is in the bad state
$\overline{\tau}_{good/bad}^{i}$	Mean length of the good (bad) states in a period
f_i	Maximum Doppler frequency of node i
v_i	Traveling speed of station i
PEP_{bad}^i	Packet-drop probability in the bad state
PEP_{good}^i	Packet-drop probability in the good state
$BER(j)$	Bit error rate of interfering j codes
$G_{spreading}$	Spreading factor
ε	Length of CDMA blocks
δ	CDMA channel rate
μ^{-1}	Mean service time of a packet
$\overline{C}_{code,p}^{i,j}$	Time elapsing between two consecutive arrivals of code B at the same queue i of class j where code B is not usable

$\overline{V}_i$	Server vacation time of node i
$\overline{C}^{i,j}_{code,c}$	Time elapsing between two consecutive arrivals of any code at the same queue i of class j where the code is usable
$\overline{C}^{i,j}_{code,q}$	Time elapsing between two consecutive arrivals of any code at the same queue i of class j where the code is not usable
$\overline{C}^{i,j}_{code}$	Time elapsing between two consecutive arrivals of code B at the same queue i of class j where code B is usable
p_i^j	Probability that queue i of class j captured the code
K	Random variable representing the total number of queue-code arrival-cycles contained within a queue-code polling cycle
$w^{i,j}$	Number of arrivals of any usable codes between two consecutive polls of the same code
$\overline{k}_C$	Mean number of token arrivals at the queue before it has a code available to poll the queue
$\Pr\left(Q^{i,j}_{Busy}\right)$	Probability that queue i of class j is busy
g_a^N	Number of combinations that n packets can be arranged in N queues
$\overline{n}_{i,j}$	Mean number of packets that are in the system
P_{B_n}	Steady-state joint probability distribution of the queue length and the permit pool occupancy at the slot boundary
P_{q_m}	M/D/1 queue length distribution in steady state
P_{RP}	Probability of having b residual permits and it is determined by the queue capacity from the previous sub slot
$B(z)$	Probability generating function of the packet departing process
P_{A_n}	Poisson probability mass function for the packet arrivals
P_{S_n}	Geometric probability mass function for the packet service time
$A(z)$	Probability generating function of P_{A_n}
$S(z)$	Probability generating function of P_{S_n}
P_{V_n}	Probability mass function of vacation time
$V(z)$	Probability generating function of P_{V_n}
X_i	Number of packets in the buffer Q_3 at the beginning of the slot i
B_i^j	Number of departures from buffer Q_1 to Q_2 during the jth service slot of the packet
W_{l+1}	Number of departures from buffer Q_1 to Q_2 during the vacation period in the $(l+1)th$ cycle
$X_{c_l}(z)$	Probability generating function of the number of packets in the queue at the end of the lth cycle
$W_0(z)$	Probability generating function of the number of departures from buffer Q_1 to Q_2 during the vacation period of a random cycle under the condition that there exists no packets in buffer Q_2 at the end of the slot preceding the vacation period
$\overline{W_0}(z)$	Probability generating function of the number of departures from buffer Q_1 to Q_2 during the vacation period of a random cycle under the condition that there is at least one packet in buffer Q_2 at the end of the slot preceding the vacation period
$X_d(z_1, z_2)$	Joint probability generating function of the queue length at the buffer Q_3 and Q_2 at the start of the slot right after a service of a packet from buffer

	Q_3
$X_d^*(z_1, z_2)$	Probability generating function of the buffer Q_3 and Q_2 queue length at departure epochs for this system
$D^*(z_1, z_2)$	Joint probability generating function of its delay in buffer Q_3 and Q_2 queues
$B^*(z)$	Probability generating function for batch departures
$S^*(z)$	Probability generating function for batch service time
P_i	Received power of user i
$a_{ik}(t)$	Pulse amplitude modulation signal
$b_{ik}(t)$	Spreading code waveform
T_i	Duration of rectangular pulse shape
ϕ_k	Modulator phase
γ_i	Signal strength of user i
N_i	Spreading factor used by user i
χ_i	Log-normal random variable
$\Omega_i(k)$	Gaussian random variable
$\rho_{i,j}$	Load condition of the node i with packet j
$D_{\min}$	Objective function for packet delay
$\rho_{\min}^i$	Objective function for work load of user i

CHAPTER 1

INTRODUCTION

With the explosive growth in cellular users and the ever increasing need for greater bandwidth and services [ITU, 2005], wireless ad hoc networks have been the centre of attention in wireless technology for several years. A wireless ad hoc network is a decentralized network of nodes, possibly mobile, sharing a wireless channel and asynchronously sending packets to each other. The most notable characteristics of an ad hoc network are a lack of infrastructure, distributed coordination among nodes, dynamic topology, and the use of a shared wireless channel. The potential for the deployment of ad hoc networks exists in many scenarios. For example, in situations where the construction of the infrastructure is not feasible or desirable, like disaster relief, sensor networks, etc. Ad hoc networks also have the potential of realizing a free, ubiquitous, omnipresent communication network for rural communities.

With no pre-infrastructure existed to enable the exchange of information among users' devices, the devices cannot communicate directly with each other if they are too far apart. The packets are then forwarded via intermediate devices that relay the packets on a node-by-node basis. As mentioned earlier, depending on the application or the scenario, nodes in a wireless ad hoc network may be mobile and free to organize themselves arbitrarily. This may result in intermittent connectivity and the network's topology may change rapidly and unpredictably. In these cases, routes to destination nodes may need to be computed dynamically and updated frequently. In addition, nodes may join or leave the network at anytime, with their availability constrained by the characteristics of the surrounding wireless medium. Figure 1.1 shows an example of a wireless ad hoc network. In this scenario, the ad hoc network consists of 6 nodes with 4 concurrent transmissions where Node 6 is transmitting data to node 5 and Node 1 is sending data to Node 5 via node 2 since Node 5 is out of range. Also Node 4 is transmitting data to Node 2 via node 3 and lastly Node 5 is sending data to node 3. Node 7 is the new user who wishes to join the network.

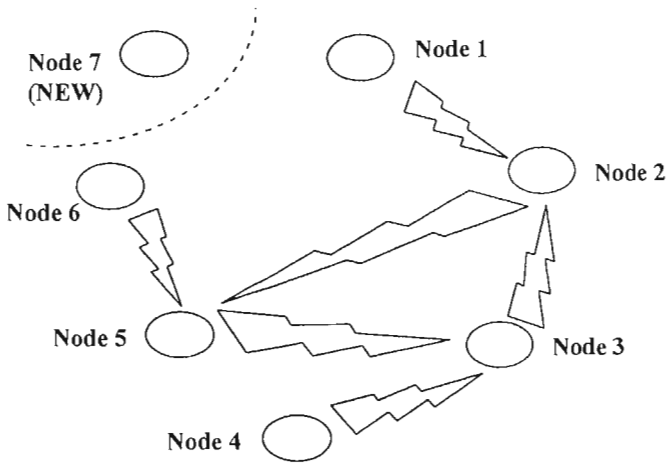


Figure 1.1: Ad hoc wireless network

The most prevalent standard used for wireless networking is the IEEE 802.11 [IEEE, 1997] which was released by the Institute of Electrical and Electronics Engineers (IEEE) in 1997. Different versions have since been created to extend and improve the IEEE 802.11 standard in many aspects, which varies from the support of quality of service (QoS) features to higher data rates. The importance of the IEEE 802.11 comes from its capability of two operational modes: the infrastructure mode and the ad hoc mode. The infrastructure mode is similar to a cellular infrastructure-based network, where a node acts as the access point (AP) for other nodes. This is the most common operational mode used to build Wi-Fi hotspots. Nevertheless, it is the ad hoc mode of operation that has attracted the largest attention within the research community working in the field of wireless ad hoc networks.

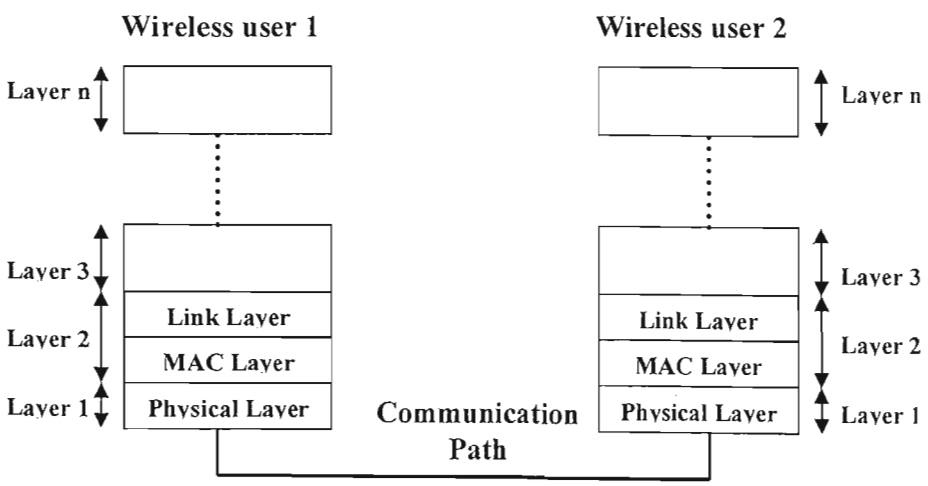


Figure 1.2: Network layers for wireless networks

The IEEE 802.11 standard is a platform that gives specifications for two of the fundamental layers in the protocol stack of any wireless ad hoc network: the physical (PHY) layer and the medium access control (MAC) layer. Figure 1.2 shows the locations of the PHY and the MAC layers on the protocol stack defined by the International Standard Organization's Open System Interconnect (ISO/OSI) model [Spragins, 1991]. A wireless network architecture is similar to that of a wired network as it normally consists of three or more layers.

The lowest layer in the model is the physical layer. This layer defines the characteristics of transmitting and receiving packets through the medium that interconnects the nodes of the network. It generally defines a number of parameters and procedures such as the bandwidth and channels allocation, signal modulation schemes, transmit power levels, error correcting/detecting codes, etc. The PHY layer is also responsible for mapping the information bits received from the upper network layers into a framing format suitable for transmission over the physical medium and also for the de-mapping operation of the information received over the medium.

The second layer, the data link layer, consists of two sub-layers: the medium access control (MAC) layer and the link layer. The MAC layer is a major component of many communication systems in which users transmit information over a common, shared channel. Therefore, the main task of the MAC layer is to enable nodes in the network to determine their right to access the available channel(s), while attempting to enforce a fair and efficient usage of the channel(s). The establishment of such access rights is far more difficult in a wireless ad hoc network than in a wired network, because the radio channels of an ad hoc network are broadcast in nature, and radio connectivity is such that the topology of an ad hoc network is not as clearly defined as that of point-to-point wired networks.

Wired channels are commonly known to be stationary and predictable. In contrast, radio channels are extremely random, and the connectivity between two nodes depends on many factors, such as the radio frequency used, power of the transmitters, terrain, antenna type, transmitter/receiver distance, multipath fading, etc. Furthermore, the quality of a radio link depends on the transmission activity of all other nodes in the entire system, whose aggregated signal powers can severely degrade the signal-to-noise ratio (SNR) at a particular receiver and, consequently, decrease the probability of successful reception of any on-going packet transmission.

1.1 Survey on MAC Protocols for Wireless Ad Hoc Network

As discussed earlier, wireless ad hoc networks rely on a common transmission medium and the transmissions of the network must be coordinated by a MAC protocol. Two methods are commonly implemented to achieve this coordination. In the first method, the coordination can be provided by the medium itself, using carrier sensing to identify the channel's state (idle or active). The second method achieves the coordination by means of using control information carried by a control message travelling along the medium.

The majority of MAC protocols used in ad-hoc networks implement a random access scheme as the method of sharing the common channel. A typical example is the carrier sense multiple access (CSMA) scheme. However, it is known from [Kleinrock, 1975] that with a CSMA based scheme, the performance is degraded by hidden and exposed terminal problems. In a wireless ad hoc network there is no guarantee that some terminals may not be hidden from the other terminals. A number of papers have proposed schemes to alleviate the problem using out-of-band or busy-tone signaling. This technique uses a very narrow frequency band (or channel) to carry a busy-tone signal, which warns the surrounding nodes not to transmit. The nodes in the network are required to listen to the busy-tone channel before they transmit any packet. A typical example of such model is the busy-tone-multiple-access (BTMA) protocol proposed by [Tobagi, 1975]. The BTMA protocol uses two channels: one channel is used for busy-tone signaling, and the other channel is used for data transmission. This eliminates the hidden nodes that surround the host node and the target node, but increases the number of exposed nodes. In 1988, Wu [Wu, 1988] introduced a method to alleviate the exposed node problem produced by the BTMA protocol. However, it still does not completely solve the hidden node problem but it does minimize the number of exposed nodes.

Dual-BTMA (DBTMA) [Deng, 1998] is an improved version of BTMA and was proposed to address the loss of channel utilization in the Request-To-Send/Clear-To-Send (RTS/CTS) based BTMA networks. In the DBTMA, the single common channel is divided into two sub-channels: a data channel and a control channel. Two busy tones are assigned on the control channel rather than one as in the BTMA. To alleviate the problem of hidden and exposed nodes, the WCD protocol [Gummalla, 2000] was introduced. This protocol is designed for a short radius network (< 50m). It splits the frequency channel into a data-channel and a feedback channel. A node can only operate in one of two modes, the data reception mode

and the data transmission mode. The most recent work that uses out-of-band signaling is [Hou, 2001]. This method uses a single channel for the signaling and the channel is divided into fixed size frames that consists of two types of slots: an elimination slot (to resolve contention) and a data slot.

Other derivatives of the CSMA type protocols have also been proposed, these systems rely on the method of control handshaking. Control handshakes are defined as short packets carrying messages to inform the nodes in the network about the packet transmissions. The handshake technique is similar to the busy tone technique, but carries more information. Three types of handshakes are commonly used by the collision avoidance protocols: request to send (RTS), clear to send (CTS), and acknowledgement (ACK). RTS is usually sent by a host node to a target node. The main purpose of the RTS is to inform the target node that the host node has data to transmit, and also to ensure the target node is available. If the transmission takes place when the target is not ready then collisions would occur. CTS is used by the target node to reply to the host node after receiving RTS, and ACK is used to inform the host node that its data has been successfully transmitted.

One of the first protocols that implemented a handshake mechanisms is multi-access with collision avoidance (MACA) protocol proposed by [Karn, 1990]. It uses a three-way handshake mechanism to avoid collisions. When the host node wants to transmit data to the target node, it sends RTS packet to the target node. All nodes that surround the host defer their transmissions when they hear the RTS. If the target node receives RTS successfully, it responds by broadcasting CTS packet. CTS is used to warn the nodes surrounding the target node not to transmit. On receiving the CTS, the host node assumes that the channel is acquired and sends its data to the target node. Distributed foundation wireless MAC (DFWMAC) [Crow, 1997] is a derivative of the MACA protocol and is the basic access protocol for distributed systems described by the IEEE 802.11 wireless LAN standard. The DFWMAC protocol consists of four handshakes, RTS-CTS-DATA-ACK. When the host node wishes to transmit data to the target node, it must detect the channel idle for a specified time interval before attempting an RTS transmission.

Broadcast support multiple access (BSMA) protocol [Tang, 2000] is an extension of the IEEE 802.11 protocol. The objective of this protocol is to provide an efficient broadcasting ability by incorporating both the collision avoidance scheme and the four handshake controls of IEEE 802.11. It relies on negative acknowledgement (NACK) to deliver broadcasted

packets. Another derivative of the handshake mechanism is the floor-acquisition-multiple access (FAMA) [Fullmer, 1995], where a node must acquire the surrounding channel "floor" before transmitting its data. To acquire the floor, the host node first transmits RTS to its neighbors, and if the target node receives the RTS, the CTS message is sent back to the host node. The host node then begins sending its data packets. The CTS also serves to warn other nodes against transmitting to the target node.

An improved version of FAMA is the Floor Acquisition Multiple Access with Non-persistent Carrier Sensing (FAMA-NCS) [Fullmer, 1999]. It provides better collision avoidance by modifying the length of CTS. The receiver-based auto rate (RBAR) [Vaidya, 2000] protocol and its derivatives [Wu, 2000] [Tang, 2000] [Chlamtac, 2000] are based on a three-way collision avoidance handshake. In RBAR, the RTS/CTS handshake is modified to allow the target node (receiver) to choose the data rate at which the packet will be transmitted. The RTS/CTS packets consist of two fields: data rate and data packet size. In the RTS dialogue, the rate field carries the data rate that the host node (sender) intends to use for the data packet, whereas the CTS dialogue carries the actual rate that will be used, selected by the receiver.

Apart from the protocols mentioned above, another important arena of research regarding hybrid MAC protocol has emerged for ad hoc networks. Hybrid MAC protocols are designed for networks that are implemented using an ad hoc centralized topology. In an ad hoc centralized network, there is a centralized administrator (e.g. a mobile base station) in the network and so the communication is centralized. Typical examples of ad hoc centralized MAC protocols are [Haartsen, 2000] and [Lihui, 2000].

In this thesis, a new hybrid MAC protocol is introduced. The modeling framework introduced focuses on the combination of a guaranteed access mechanism (token) and the capability of supporting multiple simultaneous transmissions (CDMA). A key feature of the hybrid MAC scheme is that the system can dynamically assign the bandwidth resources. Unlike the current CDMA type protocol [CDMA IS-95,1990], the token is used to allocate CDMA codes to nodes that need service. To account for the effects of interference among all nodes, a wireless error channel Gilbert-Elliott [Gilbert, 1960], [Elliott, 1963] model is introduced with which the topology and network aspects are naturally incorporated into the hybrid MAC scheme. The system is then simulated and investigated under realistic wireless channel conditions within the ad hoc wireless network environment.

A modeling framework for the analytical study of the hybrid MAC protocol is then introduced. Analytically, the hybrid MAC scheme can be considered as a system that consists of multiple queues that are serviced by multiple servers. This configuration is commonly denoted as a multiserver multiqueue (MSMQ) system. The novelty of the system is that a CDMA code is considered as a server in the analytical scenario. An approximated mean value analysis for the proposed gated multiple-vacation queue that supports multiple traffic classes is presented. Using the approximated approach, the mean server inter-visit and inter-arrival time and also the queue vacation time are derived. Based on the multiple-vacation queuing model, an approximated analysis is conducted using the probability generating function approach.

Motivated by the recent advances in cross-layer optimization of system performance, this thesis lastly investigates the cross-layer concept and implements it on the hybrid MAC scheme. The model focuses on the interaction between the physical (PHY) and the MAC layer. For cross-layer optimization, a rate-adaptation algorithm based on variable spreading factors is proposed. This algorithm adaptively transmits data and dynamically assign transmission rates based on channel state information.

1.2 Summary of Contributions

The main contributions of this thesis are as follows:

- The development of a new hybrid Token-CDMA medium access control (MAC) protocol for distributed wireless networks, built based on the concept of a token passing technique. Moreover, a quality of service guarantee is incorporated in the proposed conceptual MAC scheme.
- Modeling and performance evaluation of the hybrid MAC scheme that implements the multi-layered Gillbert-Elliot wireless channel model under different traffic load conditions.
- Development of a modeling framework for the analytical study of the hybrid MAC protocol. The model is made up of three sub-models that consist of the input, buffer and vacation models. The input model describes the QoS incorporation, the buffer model discusses the operation of the packets in the model and the vacation model discusses the operation of the network and its impact on the queue.

- Modeling and performance evaluation of the analytical model under different traffic load conditions. In particular, the mean server inter-visit and inter-arrival time and also the queue vacation time are derived. Based on the multiple-vacation queuing model, an approximated analysis is conducted using the probability generating function approach.
- A joint MAC-PHY solution for optimizing the system performance in the hybrid Token-CDMA MAC system. The cross-layer interaction is designed in order to provide continuous monitoring of the performance achieved by the users and adjusting transmission parameters using different spreading factors.

1.3 Publication List

The list of publication based on this thesis is shown below:

- I Liu, F. Takawira and H. Xu, "A Hybrid Token-CDMA MAC Protocol for Wireless Ad Hoc Networks", *IEEE Transaction on mobile computing*, vol.7, no.5, 2008.
- I Liu, F. Takawira and H. Xu, "Performance Analysis of Hybrid Token-CDMA MAC Protocol", *in Proc. IEEE PIMRC 2007*, Athens, Greece, Sept, 2007.
- I Liu, F. Takawira and H. Xu, "Approximate discrete time analysis of hybrid Token-CDMA system", *in Proc. IEEE Africon 2007*, Namibia, Sept 2007.
- I Liu, F. Takawira and H. Xu, "Optimization of hybrid token-CDMA MAC system using cross-layer information", *in Proc. SATNAC 2007*, Mauritius, Sept 2007.
- I Liu, F. Takawira and H. Xu, "Cycle and vacation time analysis of multiple source queue and multiple server system with data rate QoS", *in Proc. IEEE ICT 2005*, Cape Town, South Africa, Sept 2006.
- I Liu, F. Takawira and H. Xu, "Approximate discrete time analysis of Token-CDMA system", *in Proc. SATNAC 2005*, Cape Town, South Africa, Sept 2005.
- I Liu, F. Takawira and H. Xu, "Approximate analysis of multiple source queue system with input regulation", *in Proc. SATNAC 2004*, Drakensberg, South Africa, Sept 2004.

1.4 Thesis Organisation

The thesis is organized into five chapters. In this chapter, a brief introduction to the structure and concept of the wireless network is provided and a brief literature survey of the relevant

work that has been published on the subject of wireless MAC protocols is presented. The contributions from this research are stated in Section 1.2 with the remainder of this dissertation organized as follows:

Chapter 2 introduces a new MAC protocol for distributed wireless networks. The proposed hybrid Token-CDMA MAC protocol is based on a token passing scheme, and incorporates data rate quality of service guarantee. A simulation model is then presented, along with the environment for the hybird MAC scheme. The simulation is custom designed, and implements an event-driven architecture using the C++ programming language. The performance of the scheme is then evaluated.

In Chapter 3, an approximate delay analysis of the hybrid MAC scheme is presented. To conduct the delay analysis, the hybrid MAC scheme is treated as a multiple server network with multiple queues (MSMQ). Using the discrete time approach, the probability generating function for the moments of the packet delay at different buffers in the queue model are derived. To verify the analysis, the analytical result is compared with the simulation result.

In Chapter 4, a new concept in which the MAC layer incorporates the physical layer's characteristics is introduced. A literature survey is conducted on cross-layer approach, especially interaction between medium access control and physical (MAC-PHY) layers for CDMA type of protocols. The cross-layer interaction that optimizes the delay performance of the hybrid MAC scheme is then considered. By exchanging information between the two layers and with the rate-adaptation algorithm, the modified hybrid scheme is able to optimize the system performance.

Chapter 5 concludes this thesis with a summary of the research findings, including important concepts and techniques behind this research effort. Finally, the chapter presents recommendations for future research.

CHAPTER 2

HYBRID TOKEN-CDMA MEDIUM ACCESS CONTROL PROTOCOL

2.1 Introduction

An ad hoc network is constructed by mobile hosts and can be rapidly deployed without any established infrastructure or central administration. However, due to its self-organizing characteristic, it is very challenging to design an efficient and effective medium access control protocol for ad hoc networks. The majority of the ad hoc wireless networks implement a network based on a modified CSMA/CD scheme [Spragins, 1994]. It is known from [Tobagi, 1975] that with the CSMA based scheme, the performance is degraded by the hidden terminal problem. In a wireless ad hoc network there is no guarantee that some terminals may not be hidden from the other terminals. To alleviate or solve the problem, many protocols based on the RTS/CTS handshakes have been proposed, [Bharghavan, 1994], [Fullmer, 1999], [Karn, 1994], [Lin, 1997], [Talucci, 1997] and [Deng, 1998]. However, due to the nature of the RTS/CTS characteristics, those proposed MAC schemes still incur high packet collisions under heavy traffic load [Deng, 1998].

Both [Spragins, 1994] and [Ergen, 2003] demonstrated that token-passing MAC schemes (e.g. IEEE 802.5 [*IEEE*, 1989], FDDI [*ANSI*, 1987] and PROFIBUS [*DIN*, 1991]) outperform CSMA schemes and have proven to be the most reliable MAC schemes in the industry. It is illustrated in papers [Donatiello, 2003], [Malpani, 2005] and [Rajagopalan,1989] that the virtual-ring topology has many advantages when implementing it in the ad hoc networks. Some of the advantages are robustness against single node failure and support for flexible topologies, in which nodes can be partially connected and are not connected to the access point. Research has shifted to focus onto token passing schemes in wireless settings, since these have the potential of achieving higher channel utilization than CSMA type schemes [Ergen, 2003] and are also capable of including quality-of-service guarantees [Tobagi, 1975]. In general, the issues of QoS have only been concentrated on the

network layer and routing techniques [Nichols, 1998], but with an unreliable wireless medium, the QoS issues must also be addressed at the data link layer as discussed in [Ergen, 2004]. There exist a plethora of papers that propose token based MAC schemes with QoS incorporation for ad hoc networks [Ergen, 2004], [Donatiello, 2003], [Takahashi, 2001], [Davies, 2001], and [Taheri, 2002].

Among these protocols the general MAC operation is identical. A single token is generated for each network, the stations receive service by capturing the token, and the stations are serviced in a fixed and predetermined cyclic order. QoS guarantees have been incorporated into these schemes by providing delay bounded services. The work in [Ergen, 2004], [Donatiello, 2003], [Takahashi, 2001], [Davies, 2001], and [Taheri, 2002] proposed a wireless token ring network that has only one traffic type and supports no multiple transmissions. [Donatiello, 2002] proposed a token passing scheme that supports multiple simultaneous transmissions, however, the scheme is designed solely for low mobility nodes in small confined spaces (static environments). Since each station is assigned with only one code, this leads to a decrease in efficiency as the network capacity is not fully utilized.

A protocol that tends to exploit the advantages of both contention-free and contention-based protocols was proposed by [Chao, 2003]. This protocol (*LA* protocol) [Chao, 2003] switches between contention-based and contention-free schemes depending on the traffic loading conditions. However, the protocol does not support multiple transmissions and accommodates only one traffic type. The most significant drawback of these proposed token passing MAC schemes is that they do not discuss the wireless aspect of ad hoc networks.

It is known that a wireless link is much more error prone than cable-based links. Link layer retransmission triggered by corrupted data decreases the bandwidth efficiency which results in inferior performance. There are several physical considerations that cause errors in wireless links: multipath fading, path loss, co- and adjacent channel interference, man-made interference, dynamic topology, station mobility, partial connectivity and channel noise [Willig, 2001], [Blackard, 1993]. Wireless channel interference in the wireless token passing MAC network was discussed by [Willig, 2001]. It was discovered that the token passing MAC is vulnerable to channel errors. The protocol stability is severely hindered by the loss of a token due to interference and consequently reduces the utilization of the network bandwidth.

A hybrid token-CDMA multiple access control scheme, designed to handle heterogeneous classes of traffic in all traffic load types is proposed. Our scheme is based on the token passing concept but unlike conventional token passing MAC schemes, the proposed scheme incorporates the code division multiple access (CDMA) mechanism. There exist numerous papers [Qu, 2006] [Butala, 2005] and [Lal, 1999], that proposed implementing the CDMA system in Ad hoc networks. However, the majority of them still used the RTS/CTS handshake approach, while none proposed the hybrid token-CDMA methodology. The novelty of the proposed MAC scheme is that it combines the advantages of guaranteed-access characteristics of the token passing mechanisms and the supportability of multiple packet transmissions within the network with the incorporation of QoS guarantees for different classes of traffic.

The intriguing part of the proposed scheme is that the issue of scarce bandwidth is addressed where the token is used as the CDMA code distributor and the channels are shared amongst the nodes in the network. By integrating the CDMA mechanism into the MAC scheme, the CDMA codes are now effectively distributed amongst the nodes using the token. It is known that for a CDMA system, every user is equipped with a specific code so the maximum number of users that may join in a network is dependent on the number of codes available. With the newly proposed MAC, with the same number of codes used, the network can now support more nodes (users) since the CDMA codes are now dynamically assigned to the nodes. This in turn increases the utilization of the network which leads to greater system performance.

It is known that policing/shaping and monitoring of traffic flows is an important component of traffic management since the main cause of congestion in a network is a bursty and an unpredictable traffic. If traffic on a particular flow or connection could be made to transmit at a uniform and predictable rate, congestion would be less common. Traffic shaping configures the outgoing traffic to the agreed upon traffic profile for the flow. Control of the data rate is required to guard against flows that do not adhere to the contracted flow specifications. However, all the previously proposed wireless token MAC schemes do not provide this QoS guarantee. Most of the policing/shaping mechanisms used today are based on a leaky bucket mechanism. In our proposed hybrid MAC protocol, the data rate and fairness QoS guarantees have been enforced by the proposed MAC scheme by implementing a modified leaky-bucket traffic policing mechanism and gated service discipline at each node.

The performance of the proposed MAC scheme is evaluated in a wireless environment using simulation. A key part of the simulation is the channel link error model. Wireless channel errors are usually bursty and dependent, rather than independently distributed. To capture such behavior in the wireless channel, a multi-layered two-state Markov Chain model, commonly known as the Gilbert-Elliott model [Elliott, 1963], [Gilbert, 1960] is used to model channel link error. The novelty of this work lies in proposing and modeling a hybrid token-CDMA MAC scheme with data rate QoS guarantee and with consideration of wireless channel interference.

This chapter is organized as follows. Section 2.2 describes the proposed MAC protocol in detail. The finite state machine of the proposed MAC scheme is described in Section 2.3. The simulation model and results are presented in Section 2.4 and 2.5 respectively. Conclusions are drawn in Section 2.6.

2.2 Hybrid Token-CDMA Protocol Description

This section gives a detailed description of the proposed MAC protocol, including its structure, characteristics and properties. The proposed protocol is inspired and derived from IEEE 802.4 [*IEEE*, 1989] Token Ring structures that guarantees bounded delay and guaranteed access of the bandwidth.

2.2.1 Network Topology and Model

The network is ad hoc and distributed. It consists of N stations with M CDMA codes ($S_1 \ldots S_M$) ($M < N$) and r different traffic classes. Each station is assigned to a specific traffic class as illustrated in Fig. 2.1. In this figure Q_i denotes the queue model of station i (as illustrated in Fig. 2.1). T_i^{trans} is the token transmission time between two stations and $\lambda_{ip,}^{r}$ is the packet arrival rate for station i of class r. Each station is assumed to have the ability to communicate with its adjacent stations over a single-hop. It is assumed that the network has a partially connected topology.

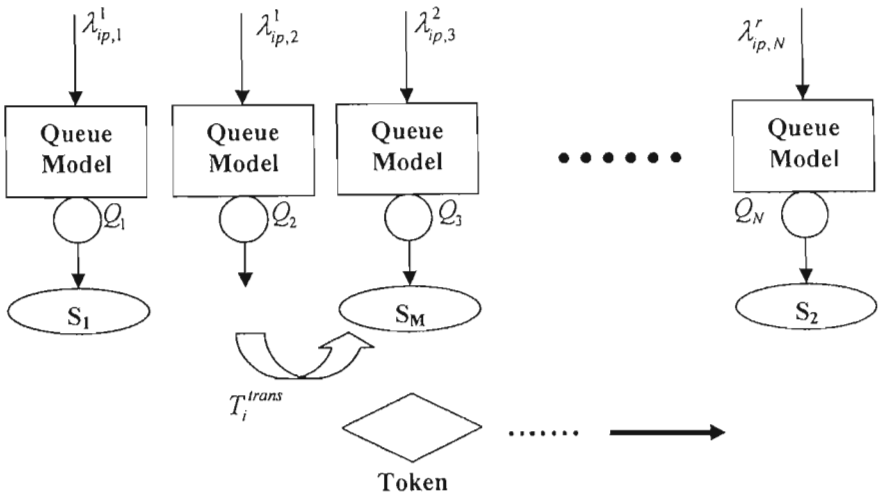


Figure 2.1: Network model for the hybrid Token-CDMA MAC protocol

The network implements a virtual ring topology with the OSI reference model as its backbone structure. Each station in the network is equipped with a queuing system that consists of a buffer. The token is used to distribute *M* CDMA codes in the network. Each station is provided with a common code channel that is used specifically for token transmissions. Each station is also assumed to be equipped with MUD (multi-user detection) capabilities [Verdu, 1998], in order to be able to receive multiple transmissions simultaneously. It is assumed that each station in the network has pre-defined knowledge of all the *M* CDMA code words used for the network.

The stations in the network maintain an updated *STATION_LIST* (as shown in Table 2.1) of their immediate neighbors in order to know where the token should be passed to next. Several timers are provided in each station for implementing various functions of the MAC scheme. Detailed applications of these timer mechanisms are discussed in later sections of this Chapter.

Table 2.1

The Station-List

Token Transmission Order	Station Address
1	101100
2	100000
3	011100
4	001100
5	010100

For the CDMA code allocation mechanism, unlike [Hu, 1993] which uses a distributed algorithm to assign a code to each node, the hybrid MAC scheme uses the token to perform the task. The structure of the token consists of a hop-leader address, a source address, a destination address, the number of codes available (*NOC*), and other network parameters as shown in Table 2.2.

Table 2.2

Token structure

PM	Hop Leader ID	Source ID	Destination ID	NOC	NA-List	C-List	DB	EOT

The following fields are used in the thesis and their sizes can be easily adjusted depending on the scale of the network. The capacity of the address field is kept to a reasonable size of ten bits, giving a maximum of 2^{10} stations in a single network.

- PM: Preamble is the PHY header used to perform synchronization with destination station using pilot, synchronization and paging channels in CDMA transmission. To conform with the 802.11 standard, the proposed protocol uses the same standardized PHY header with 128 bits.
- Hop Leader ID: the address of the station that created the token and initialized the network.
- Source ID: the address of the station that passed the token (predecessor's address).
- Destination ID: the address of the station that holds the token (successor's address).
- NOC (Number of codes available): this parameter is used to limit the number of simultaneous transmissions in the network. A detailed explanation of this parameter is given in Section 2.2.3.
- NA-List (Node Active list): this field displays the active status of the stations in the network. If a station is active, the bit allocation for that station is set to 1.

- C-List (Channel list): this parameter is used by the packet collision avoidance (PCA) algorithm to monitor the status of the receiver channels in a station, a detailed discussion of the PCA algorithm is presented in Section 2.2.5.
- DB (Duplicate Bit): this parameter is used by the token protection scheme to inform the receiver station that the generated token is for a retransmission.
- EOT (End Of Token): this parameter is used to indicate that the token has been received by the receiver station.

2.2.2 Assumptions of Hybrid Token-CDMA Scheme

In the proposed hybrid MAC scheme, there are some assumptions:

- The stations are deployed randomly, and all of them are traveling at the constant slow speed that simulates a normal office environment (i.e. 0.1km per hour).
- The proposed scheme is suitable for non-real-time traffic applications where they can tolerate temporarily lost of coverage.
- The routing of data in the network is single-hop routing in which the packet can reach its destination station either directly or via routing through the stations within the network.
- The network area is simulated to be within a 10 x 10 meter space.
- The Hybrid MAC scheme employs a Packet Collision Avoidance (PCA) algorithm to assist with the data packet transmission and a token protection scheme is also implemented during the token transmission process.
- Bi-directional communication links are considered for all communication links, this assumption is practical in the wireless network such as IEEE 802.11. The stations will be able to receive token transmission while transmitting data packets.
- All stations are assumed to be trustworthy and cooperative, no information security-related consideration such as malicious packet dropping is discussed.

2.2.3 Quality of Service Guarantee

Quality of Service (QoS) can generally be defined as a mechanism for networks to satisfy the varied quality and grade of service required by an application, while at the same time maximizing bandwidth utilization. In a wireless communication system, there are numerous methods to formulate the QoS objectives quantitatively. Amongst the papers that proposed Token based scheme for ad hoc networks, the majority of the papers provides QoS by means

of timing guarantees [Donatiello, 2003], [Takahashi, 2001], and [Taheri, 2002]. In our proposed MAC protocol, based on leaky-bucket traffic policing mechanism, a data rate QoS guarantee is enforced to support real time multimedia applications.

Figure 2.2 shows the queue model that is incorporated into each station. In order to provide this service, a modified leaky-bucket [Sidi, 1993] permit generation system is implemented. The queue inside the station i is equipped with a permit buffer for storing the generated permits. The permit generation rate of station i (α_r^i) that is assigned to traffic class r is proportional to a designated data rate ($\lambda_{g,i}^r$),

$$\alpha_r^i = \rho_r \cdot \lambda_{g,i}^r;\ \rho_r \geq 1 \tag{2.1}$$

Superscript i denotes the queue number (station number) and ρ_r is the proportionality constant, which is the same for all the stations in traffic class r. The main purpose of the QoS parameter ρ_r is to provide fairness in the network by ensuring that all stations receive sufficient access to the network. This fairness mechanism is achieved by constraining the station-transmit capacity, limiting the maximum number of packets that can be transmitted and varying the QoS parameter ρ_r. If the token has been captured and there is a code available for transmission by station i, then the packet buffer is emptied such that the number of packets removed is equal to the number of permits in the permit buffer. In other words, the scheme is gated, the maximum number of packets that may passed through the gate is dependent on the quantity of permits in the permit buffer.

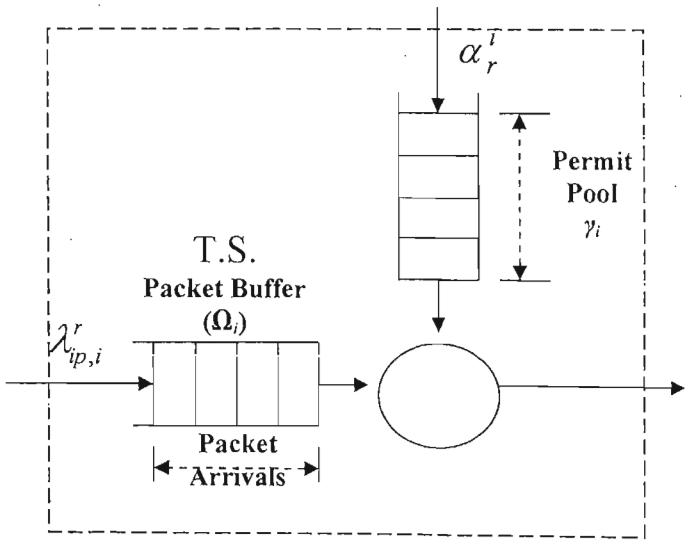


Figure 2.2: Station model with data rate QoS guarantee

2.2.4 Channel Access Control

Once the token is generated in the network, it continuously circulates, following a predetermined order. As the token constantly circulates within the network, it uses the parameter NOC ($0 \le NOC \le M$) to control the amount of traffic flow in the network. If a station has data packets in buffer Ω_i, it has to wait for the arrival of the token. When the station is visited by a token, it forwards the token to the successor station, the next available address in the *STATION_LIST*. The token will not be captured if the station is still busy servicing data packets from the previous token cycle. A token cycle (T_c) is the time for the token to visit all the stations in the network, $T_c = \sum_{i=1}^{N} T_i^{trans}$, where T_i^{trans} is the time for a token to travel from station i to its successor station $i+1$.

If the station is not transmitting when the token arrives, it may capture the token if there are packets and permits available. In order to satisfy QoS guarantee, only up to γ_i amount of packets will receive service (gated service scheme). If there are no permits available when the token arrives, the station will forward the token to its successor station. If the token is successfully captured, the station decrements the NOC value by one, indicating that it has occupied a code channel. Using that specified code channel, the network allows a station in the ring to send its packets. The gated service discipline has been applied on the waiting packets in the queue buffers. As illustrated in Figure 2.2, once the code is captured, the packets are then served according to the FIFO (first-in-first-out) policy.

The station forwards the token to its successor in the pre-defined order before it begins with its data transmission. This assumption permits the token to be relayed to the next station before the actual data transmission starts. The policy of not withholding a token while transmitting data packets has the advantage of decreasing the token rotation time. This consequently leads to an improvement in the utilization of network bandwidth. The assumption is that each station in the network is assigned a unique receiver-based code, and has the knowledge of the code sequences (transmitter and receiver) of every other station in the network using the code assignment table.

To transmit data packets, the sender station first checks the code assignment table to search for the available code of its intended receiver station. The code assignment table is downloaded from the token's Channel-List (C-List) when it visits the station. The C-List specifies the available code channels for each station. The data packets are then sent using

the received code. The receiving station, with its MUD ability, constantly monitors its code channels to detect any incoming data traffic destined for it. For the transmission and reception of data packets, the sender station inserts the destination station's address into the data packet before transmission. To avoid multiple simultaneous transmissions to the same receiver station, a packet collision avoidance (*PCA*) algorithm is implemented which is discussed in the next section. Once a code is released, the token increments its *NOC* value by one.

2.2.5 Packet Collision Avoidance Algorithm (PCA)

During the initialization stage or before joining the network, each station is equipped with the knowledge of all the *M* CDMA code words used for the network. With the MUD, the station is assumed to be able to receive *M* transmissions simultaneously. However, when there are multiple channels available for data transmission, there exists the possibility that multiple stations use an identical CDMA code to send data packets that are destined to the same destined receiving station. This effect creates packet collisions. Previously proposed CDMA MAC schemes either do not take this issue into consideration [Joa-Ng, 1999] or make the assumption that the receiver station is likely to have a sufficient offset in the code phase and is able to reject one of them and receive the other successfully [Sousa, 1988].

In the proposed MAC scheme, a packet collision avoidance algorithm is implemented to avoid packet collision over the receiver station's code channel. The station uses the Channel-List function *(C-List)* in the token (as shown in Table 2.2) to initiate the *PCA* algorithm. The *C-List* is structured to depict the status of the code channels that are being used in the receiving station. The *C-List* structure is shown in Figure 2.3. When the token visits the station and the QoS guarantee has been satisfied, the station then looks up the *C-List* in the token to determine whether the intended receiver station has a code channel to receive data transmission. If there is a code channel available, the sender station changes the status of the bit to 1 and uses that code channel to transmit data packets. On the receiving station side, it will change the status bit back to 0 once the transmission from the sender station is completed when the token revisits it.

Using this method, packet collisions can be avoided since each station can only transmit data if there is an appropriate code available in the C-List. If all the codes are in use, the sender will have to wait for other stations to finish their transmissions before it may start sending its packets.

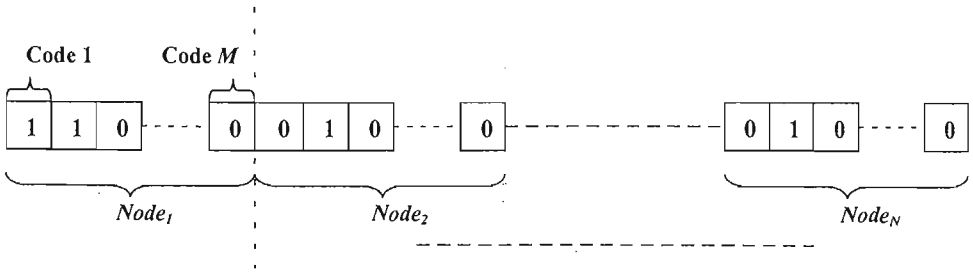


Figure 2.3: C-List (Channel-List) structure

2.3 Dynamic Topology and Finite State Machine

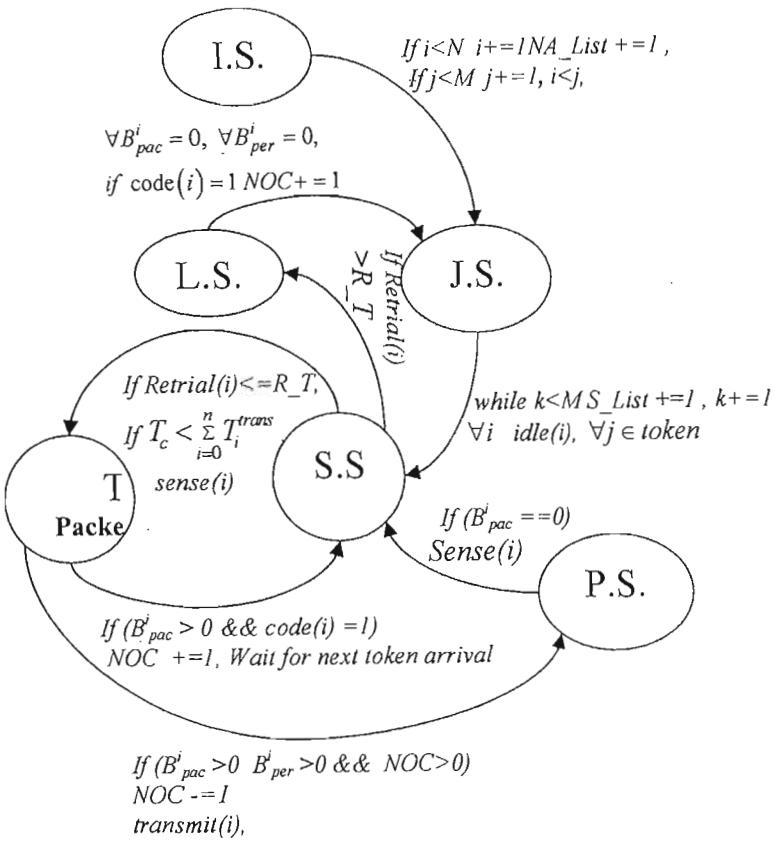


Figure 2.4: Finite state machine

The finite state machine (FSM) for the hybrid MAC scheme is presented in Figure 2.4. The states for the FSM are: IS (Initialization State), JS (Join State), SS (Sense State), TS (Token transmit State), PS (Packet transmit State) and LS (Lost State). The issue of mobility within the network has been addressed. As the hybrid MAC scheme is operated in the dynamic mobile wireless environments, the topology of the network changes frequently.

As the topology changes, a station may drop out or join the network due to its mobility. The FSM has incorporated both states of JS and LS to handle the process of joining and leaving the network. The sense state (SS) is for detecting the token transmission, where in this case the station checks the token code channel for reception. Once the token is captured and QoS is satisfied then the station sends the token to its successor station by going to the token

transmit state (TS) before it starts to service the packets (PS). The start of the protocol is created by the initialization state (IS).

2.3.1 Station Entering Routine

This section elaborates the process of the JS. To manage the insertion of the requesting stations without compromising the QoS mechanisms provided to the stations that are already part of the ring, an insertion algorithm is presented. As the token starts circulating in the network from one station to another, a token protection scheme is created for monitoring the token's activity.

A detailed description of the token protection scheme is discussed in the section 2.3.3. This section concentrates on the enrollment of new stations. If a new station wishes to join the network, it has to wait for *UPDATE_NETWORK* token cycles. The value of *UPDATE_NETWORK* is a predefined value stored in each station once the network is initialized. Each station in the network is equipped with a Token_Visit_Counter (*TVC*) to record the number of cycles that the token has visited it. Once the value of *UPDATE_NETWORK* is reached, the station that is currently visited by the token activates the insertion algorithm.

The flow chart of the insertion algorithm is displayed in Appendix B. The visited station first sets its *TVC* to zero and then checks its *STATION_LIST* to find the available empty slots. If there are empty slots, the station then broadcasts a *NODE_WELCOME* message using the Token code channel and activates the *REQUEST_TIMER* for the contending stations to respond. If no slots are available (network is performing at full capacity) or the *REQUEST_TIMER* has expired and no response is received, without compromising the QoS guarantees, the station will then simply relay the token to the next successor station.

For the stations that intend to join the network, they constantly monitor the Token code channel for detecting the *NODE_WELCOME* message. To avoid packet collision by sending responses in the Token code channel to the sender station at the same time, the contending stations use timer mechanism. As soon as the message is received, the contending stations start a *CONTEND_TIMER* where the value of the timer is proportional to its address and it has an upper bound of *REQUEST_TIMER*. The station whose timer expires first earns the permission to join the network by transmitting its address to the sender station. All other

contending stations which detect the activity in the token code channel before the timer expires will then have to abandon the contention and await for the next broadcast. The sender station receives the new station's address and inserts it to the *STATION_LIST*. The updated *STATION_LIST* is then broadcasted to all the stations in the network before the sender forwards the token to its successor station.

2.3.2 Station Lost Routine

The method for encountering the lost station is discussed in this section. There are two possible states that a station can renege, a) leave on demand, or, b) sudden death. Both scenarios have been taken into consideration. The flow charts for both scenarios are displayed in Appendix C and D respectively.

Leave on Demand

If station *j* intends to leave the network, it first waits for the arrival of the token. It then changes the address of the sender to *j*-1 instead of itself. Its successor station *j+1* knows the station *j*'s intention of leaving the network by discovering that the address of the sender in the token is no longer *j* but *j-1*. The station *j+1* will then remove the address of station *j* in the *STATION_LIST* and leaves the list space empty. It will also change the status bit of station *j* to 0 in *S-List* in the token. For station *j-1*, since it will always detect and decode the token sent from station *j* from Token protection scheme, it will also detect the changes in sender address and thereby make the same adjustments like station *j+1*. The remaining stations in the network discover the absence of the station *j* by finding out that the status bit of station *j* has been changed thereby removing station *j*'s address from their list.

Sudden Death

If station *j* leaves the network unintentionally, its predecessor station *j-1* will discover its absence when relaying the token to the station *j*. With the lost token, station *j-1* will perform token recovery mechanism as discussed in the following section where the issue of drop out station will be addressed.

2.3.3 Token Protection Scheme

Due to the mobile characteristics of ad hoc networks, the token, has the possibility of being lost during transmission. The token protection scheme is formulated to resolve these scenarios and the flow chart for the scheme is shown in Appendix E. To illustrate the function of the token protection scheme, Figure 2.1 is used. As in this network, station 1 (S_1) transmits the token to successor station 2 (S_2), and before relaying the token, station 1 first detects if there are any packet transmission activities on station 2 and then forwards the token to station 2. If there are no transmission activities, station 1 then executes ROUTE_1 algorithm. However, if station 2 is busy with packet transmission then ROUTE_2 algorithm is executed.

For the ROUTE_1 algorithm, station 1 first monitors the token code channel to determine whether station 2 has forwarded the token to station 3 or not. The monitoring is achieved by decoding the token code channel for transmission activity. After a predefined *TOKEN_TIMEOUT* period, if station 1 has not detected any token transmission activity, it will assume either one of two scenarios has occurred. In the first scenario, station 2 actually did receive the token but station 1 failed to detect the transmission due to interference. In the second scenario, the token is simply lost during the transmission process. To resolve the problem, Station 1 now proceeds to detect the data channel that is used by station 2 and if there is an ongoing packet transmission then station 1 can safely assume that the token has been successfully forwarded and abandon the monitoring process. If no packet transmission is detected, station 1 will now assume the token is lost. The token is then regenerated and retransmitted by station 1, but this time the *DUPLICATE_BIT* (*DB*) in the token will be set to one.

If after *RE_TRIAL* attempts are made to retransmit the token to station 2, and station 1 still detects no token transmission nor packet transmission, station 1 will assume that station 2 has dropped out. Station 1 will then update the *STATION_LIST* both in the token and the station. The token is then regenerated and transmitted to station 3 instead of sending it to station 2 again. This action is performed in order to avoid the generation of the looping effect. The looping effect is defined as the situation where the predecessor station repeatedly forwards the token to the successor station, which has already departed from the network.

On the token receiver side, if station 2 receives the token with DB set to one and it had already received the token within the target token cycle time (TT_c), the station will then

simply ignore and delete the bogus token. Station 1 will know the original token has been successfully forwarded to other stations by sensing activity in the token code channel. However, if the token is received within TT_c with DB set to one, station 2 acknowledges the fact that the token has been retransmitted therefore station 2 will relay the token to station 3 with DB set to zero.

ROUTE_2 algorithm uses the same approach as ROUTE_1 algorithm with the difference that it will not detect the data channel from the successor station as the data transmission may be from a previous token cycle, not the one that is granted by this token cycle. The proposed token protection scheme is more efficient than using the acknowledgment packet method. By sending an *ACK* packet to notify the successful token reception, more errors may be created, as *ACK* packets may be lost due to the wireless nature of the medium.

2.3.4 Network Initialization

The proposed hybrid token-CDMA protocol is considered to be self-stabilizing to topological changes in the network. Based on the algorithms mentioned previously, the topological changes can be contained where only the nodes in the vicinity of the change are affected. Therefore nodes inside the network may not have to assume a global time reference in which they do not need to be time-synchronized except in the initialization period.

During the initialization phase, the network is setup to support multimedia applications and provisions are also made to support multi-hop (multiple ring) capabilities with hops overlapping each other. A hop distinguishes itself by selecting a hop leader and labeling the token with the hop-leader address in its header. There are several other pre-determined properties during the initialization phase and they are given below:

- Each token in a network has its dedicated code channel for transmission and every single station in the network knows token's code sequence.
- Each station in the network has the ability to detect the token code channel unless it leaves the network.
- Hop-leader station is assigned using *INITIATE_TIMER* mechanism, each station is equipped with an *INITIATE_TIMER* and the upper bound of the timer is directly proportional to its address. Therefore the station with the smallest address has the largest opportunity to become the hop-leader.

When a station switches on, it has no knowledge of the status of the network, so it does not know if the network is still forming or is already established. It is therefore imperative for a newly switched on station to go through network initialization procedure. The procedure is shown in Appendix F and described below:

Once a station switches on, it monitors the token code channel for activities for the duration of *SENSE_TOKEN* seconds. The value of the *SENSE_TOKEN* has an upper bound of $3 \cdot T_i^{trans}$. If the station detects channel activity, it will decode the token message and activate the suitable response algorithm according to the type of the token message. If no activity is detected during the period, the station will assume the network is not yet established and claim itself as the Hop-leader for the new network. During the initialization phase, the hop-leader generates the token and broadcasts the ENROLL message with its address as the header in the message using the token code channel. All the stations which can detect the ENROLL message know if they are in the network and have knowledge who the Hop-leader is. This is done by making the assumption that each station has a unique station address built in it (e.g. IP address).

As soon as the ENROLL message is detected, the station in the network starts the ENROLL_TIMER with the value $ENROLL\_TIMER = \beta \cdot S_{ADDRESS}$, where β is a constant parameter ($0 \le \beta \le 1$). When the ENROLL_TIMER expires, the station transmits its address to the hop-leader using the token code channel. For the hop-leader, as soon as it broadcasts the ENROLL message, it waits for ENROLL_DEADLINE seconds. The upper bound of this deadline is set to $ENROLL\_DEADLINE = 2 \cdot \beta \cdot S_{MAX\_ADDRESS}$. After receiving all the stations' addresses, the hop-leader organizes these addresses in the *STATION_LIST* and again broadcasts the list to all stations using token code channel. An example of the *STATION_LIST* is shown in Table 2.1. By receiving the *STATION_LIST*, the station now has the knowledge of its predecessor and successor stations. The hop-leader now activates the network by generating the token and forwards it to the successor station according to *STATION_LIST*.

2.3.5 Provision for Multiple-Ring

The hybrid scheme may easily be modified to adapt to a multiple-ring structure. In this case, a station can belong to more than one ring therefore it can transmit or receive to all the networks that it is connected to. However, a station can not be the hop-leader for more than one ring. Based on the Hop Leader's ID property, each network will create its unique token; therefore preventing different networks generating identical tokens. With the scheme's CDMA properties, the spatial-reuse can also be incorporated to fully utilize the available bandwidth. As discussed in [Ergen, 2004], there are several extensions that can be used to support multiple-ring network. One typical example is the Star-Ring topology. The Star-Ring configuration merges the centralized star topology and the distributed ring topology. In this case, stations are served as access networks utilizing non-mobile relaying nodes to provide wireless backbone services for nomadic users to access the wired Internet. A typical application for such a configuration would be a wireless mesh network [Bruno, 2005].

2.4 Simulation Model

In this section, we present the simulation model for the proposed MAC protocol. A detailed simulation model using the C++ builder software package is built. The model is based on an event driven packet level simulator for monitoring and recording results. The built model consists of the link layer, and the token-CDMA MAC protocol at the MAC layer. It is assumed that all the properties of the timers are incorporated in the stations and all the delay properties (e.g token forward, transmission times) are also considered within the simulation model. The pseudocode for the simulation model is presented in Figure 2.5. The sub-section of the pseudocode for the MAC algorithm is presented in Appendix A.

The simulation model consists of five sub-models, namely: Traffic, QoS guarantee, wireless channel error, and station/token lost models. Traffic model is responsible for generating traffic flows within the network once the network is initialized. As discussed in section II, QoS guarantee model is in charge of the service level agreement for each station within the network.

```
I. Initialze
1 Network Topology G ←{n, m}
2 n = nodes in the network
3 m = CDMA codes used in the network
4 for ( ∀ i, node_i ∈ G) λ^r_ip,i = mean data rate of node_i of class r
5 for ( ∀ i, node_i ∈ G) α'_r = ρ_i · λ^r_ip,i ; ρ_i ≥ 1

II. Main Processing
1 INPUT: SimTimeLimit, Simtime = 0
2 if (SimTime≤ SimTimeLimit)
3   switch(event_i = GetNextEvent())
4     { ∀i, event_i, 1 ≤ i ≤ 6 } event_1 = TokenEvent(),
5     event_2 = PackGenEvent(), event_3 = PermitGenEvent()
6     event_4 = PackTXEvent(), event_5 = ChannelErrorEvent()
7     event_6 = MMPPEvent()
8   gap = SetEventVal / 2, dFlag = 0, index = 0
9   do
10    do
11      dFlag = 1, for (index < SetEventVal - gap))
12        if (Event_Table[index] > Event_Table[index + gap])
13          temp = Event_Table[index]
14          Event_Table[index] = Event_Table[index+ gap]
15          Event_Table[index + gap] = temp
16          dFlag = 0
17    while (dFlag != 1)
18    gap = gap / 2
19  while (gap >= 1)
20  SimTime = Event_Table[0]

GetNextEvent()
21 for ( ∀ i, node_i ∈ G)
22   if (SimTime = = QInfo[i].x)
23     if (x = = TokenTime) val =1, if (x = = GenPacTime) val =2
24     if (x = = PermitGenTime) val =3, if (x = = PackTXTime)val =4
25     if (x = = ChannelErrTime)val =5, if (x = = MMPPTime)val =6
26 return val
```

Figure 2.5: Main Pseudocode for the MAC algorithm

The wireless channel error model is used to simulate the multiple access interference (MAI) that the packet and token would encounter in the wireless environment. Using the finite state machine, the station/token lost model is implemented to realistically model the dynamic ad hoc wireless environment. A detailed explanation of the sub models is presented in the following sections.

2.4.1 MMPP Traffic Model

Most wireless MAC protocols assume that traffic inter-arrival times are independent renewal processes. In many cases, these processes are assumed to be independent, identically distributed (i.i.d) memoryless distributions (e.g Poisson). However, in real world situation, the processes may not be memoryless [Leland, 1994]. Input traffic processes in wireless networks have significant inherent correlation structure, which leads to burstiness in the arrival process [Luo, 2005].

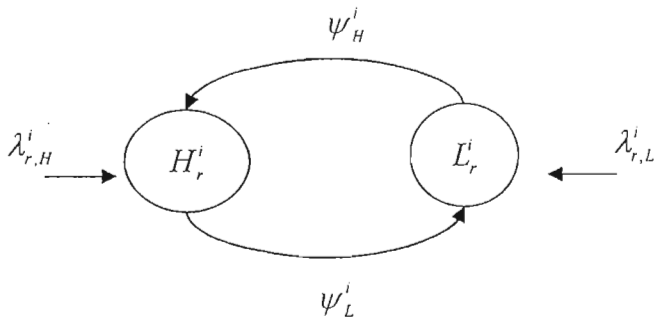


Figure 2.6: 2-state MMPP model for node *i*

The structure of these traffic processes does enable approximation by Markov-modulated Poisson processes (MMPP) and its variations [Heffes, 1986],[Kim, 2000],[Che, 1998]. For the proposed hybrid MAC scheme, it is assumed that the arrival traffic process is typically described by an MMPP as shown in Figure 2.6. In the MMPP model, packet arrival is a Poisson process whose rate is a deterministic function of the state of a discrete-time Markov chain (DTMC). This doubly stochastic process is commonly used to model typical network traffic.

$$\lambda_{ip,i}^r = \frac{\lambda_{r,H}^i \psi_L^i + \lambda_{r,L}^i \psi_H^i}{\psi_L^i + \psi_H^i} \tag{2.2}$$

The superposition of ON-OFF sources is approximated by means of a 2-state MMPP for each traffic class. Four parameters are required to represent the 2-state MMPP source of each traffic class, where ψ_L^i (ψ_H^i) is defined as the mean transition rate out of the Low load (High load) state, and $\lambda_{r,L}^i$ is the mean arrival rate of the Poisson process in the Low load state and $\lambda_{r,H}^i$ corresponds to bursts of the high arrival load state for node *i* of traffic class *r*. The effective combined Poisson arrival rate for node *i* is then given by (2.2) and we assume that traffic arrives as packets of fixed length of ξ_r bits.

2.4.2 Wireless Link Error Model

It is known that the CDMA codes can induce multiple access interference, resulting in secondary collisions at a receiver (collisions between two or more transmissions that use different CDMA codes). In the literature, this problem is known as the near-far problem [Pickholtz, 1984]. In the hybrid MAC scheme, the transmission powers are assumed to be dynamically adjusted and the codes are orthogonal such that the MAI at any receiver is not strong enough to cause a secondary collision.

To model the wireless characteristics of the CDMA channel within the network, a multi-layered Gilbert-Elliot channel error model [Elliott, 1963], [Gilbert, 1960] is implemented in the simulation. The Gilbert-Elliot error model is a two-state Markov Chain consisting of the *Good* state and the *Bad* state. The two-state Markov model captures the correlated errors that are typical for wireless links. This two-state model has been found to be a useful and accurate model for link-layer analysis [Bhagwat, 1997], [Wang, 1995]. In the good state, packet transmissions received have a high success probability. However, some of the packets may still fail to transmit with a probability that depends upon the interference level.

The bad state of the Markov Chain corresponds to a deep fade (or shadowing) in which all packet transmissions are unsuccessful [Blackard, 1993]. Using an approach similar to [Krishnam, 2004], we model the $M+1$ CDMA code channels in the network as $M+1$ independent Markov Chains in our simulation. M is the total number of codes used for data transmission within the network and the extra code (+1) is the token channel. The issue of dependencies between the links when modeling the link errors in the good state is also addressed in the following section. These dependencies illustrate the interference between the ongoing packet transmissions in the network.

2.4.2.1 Model Parameters

In order to simulate the wireless condition, we firstly define the period of the channel condition. A period consists of duration of time in which channel i is in the good (τ^i_{good}) and the bad state (τ^i_{bad}). To derive the length of each state in a period, we denote P^i_{GB} as the probability that a transition takes link i from the good state to the bad state, under the condition that link i is currently in the good state. Likewise, P^i_{BG} is denoted as link i's

transition probability from the bad state to the good state. The steady-state probability that link i is in the good (P^i_{good}) or bad state (P^i_{bad}), are derived from [Krishnam, 2004] to be,

$$P^i_{good} = \frac{P^i_{BG}}{P^i_{GB} + P^i_{BG}}$$
$$P^i_{bad} = \frac{P^i_{GB}}{P^i_{GB} + P^i_{BG}} \quad (2.3)$$

From (2.3), the mean length of the good and bad states in a period can be clearly derived to be $\bar{\tau}^i_{good} = 1/P^i_{GB}$ and $\bar{\tau}^i_{bad} = 1/P^i_{BG}$. For a flat-fading channel, [Krishnam, 2004] noted that the Markov Chain parameters may be derived in terms of the Rayleigh-fading envelope of the local root mean square level by defining

$$P^i_{good} = e^{-\omega_i^2}$$
$$P^i_{bad} = 1 - e^{-\omega_i^2} \quad (2.4)$$

where ω_i is the fade margin at the radio front end of the wireless channel with the typical values between 5dB and 20dB. Using (2.4), these values give typical P^i_{good} values between 0.9 and 0.999 and P^i_{bad} values between 0.001 and 0.1. The average sojourn time in the bad state is derived from [Bhagwat, 1997] to be,

$$\bar{\tau}^i_{bad} = \frac{e^{\omega_i^2} - 1}{2\pi\omega_i f_i} \quad (2.5)$$

where f_i denotes the maximum Doppler frequency given by $f_i = v_i / \lambda$. v_i is the speed of station i and λ is the carrier wavelength. The IEEE 802.11 system carrier wavelength of λ=0.159m is chosen for the simulation, i.e. the 802.11 system has a carrier frequency of 2.4GHz. By setting the speed of the station, we can derive the state durations.

2.4.2.2 Packet-Lost Probability in Good/Bad State

Once the length of the period is derived, the next step is to set up the packet loss probability for each state. The packet-drop probability (PEP'_{bad}) in the bad state for a wireless link is set to one. That is, if link i is in the bad state, all packets sent by code channel i are dropped on the wireless link with a probability of one. For the packet-drop probability in the good state, it is assumed to be a function of the interference level. In our case, the interference level is dependent on the total number of codes used in the network at that point in time with inclusion of additive white Gaussian noise (AWGN).

The hybrid scheme implements a binary phase shift keying (BPSK) modulation scheme. Let $j = 0,...,M+1$ denote the total number of currently interfering CDMA codes in the network. As discussed earlier, M is the number of codes used for data transmission and the extra channel is the token channel that is used solely for token transmission. The widely used Holtzman approximation [Holtzman, 1992] is then used to calculate the bit-error rate $BER(j)$ with BPSK modulation resulting from an interference level of j codes

$$\begin{aligned} BER(j) = {} & \frac{2}{3}Q\left[\left(\frac{j-1}{3G_{spreading}}+\frac{N_0}{2E_b}\right)^{-0.5}\right] \\ & +\frac{1}{6}Q\left[\left(\frac{(j-1)\left(G_{spreading}/3\right)+\sqrt{3}\delta}{\left(G_{spreading}\right)^2}+\frac{N_0}{2E_b}\right)^{-0.5}\right] \\ & +\frac{1}{6}Q\left[\left(\frac{(j-1)\left(G_{spreading}/3\right)-\sqrt{3}\delta}{\left(G_{spreading}\right)^2}+\frac{N_0}{2E_b}\right)^{-0.5}\right] \end{aligned} \tag{2.6}$$

where

$$\delta^2 = (j-1)\left[G_{spreading}^2\frac{23}{360}+\left(G_{spreading}-1\right)\left(\frac{1}{20}+\frac{j-2}{36}\right)\right] \tag{2.7}$$

and

$$Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^{\infty} e^{-t^2/2}dt, x \geq 0 \tag{2.8}$$

$G_{spreading}$ is the spreading gain. Based on (2.6) to (2.8), the Holtzman approximation calculates the *BER* caused by the multiple-access interference for a system with equal received signal powers and randomly interfering signature sequences. Based on the *BER*, and with incorporation of an error correction scheme which implemented *(31, 16)* BCH code, the packet-lost probability for the good state (PEP^{j}_{good}) can be calculated based on the bit error probability derived from (2.6),

$$PEP^{j}_{good} = 1 - \left(1 - \sum_{i=4}^{31} \binom{31}{i} \left(BER(j)\right)^{i} \left(1 - BER(j)\right)^{31-i}\right)^{\varepsilon} \tag{2.9}$$

where ε is the length of the blocks. By following this approach, the interference effect of the ongoing packet transmissions in the network can be realistically simulated.

2.5 Performance of Hybrid Token-CDMA Scheme

In this section, we evaluate the performance of the hybrid MAC scheme. The effectiveness of the Hybrid CDMA-Token, wireless token ring protocol (WTRP) [Ergen, 2004] and the standard CDMA scheme are compared for various performance metrics. The metrics we use for the evaluation are throughput and queuing delay of the packets. In particular, the packet delay and throughput were evaluated as a function of the number of nodes in the system, number of codes available for the network, node data rate and the system loading per code. The load condition of the network displayed in the results is defined as,

$$Normalized\ load = \frac{\sum_{i=0}^{N/r} \lambda^{1}_{ip,i} + \sum_{i=N/r+1}^{2(N/r)} \lambda^{2}_{ip,i} + \cdots + \sum_{i=N(N-1)/r+1}^{N} \lambda^{r}_{ip,i}}{M\beta} \tag{2.10}$$

where β is a CDMA code's transmission capacity in packet/s. Note that for WTRP protocol, a single Gilbert-Elliot AWGN channel error model is used since it only uses a single channel for transmission. The CDMA scheme implements the same wireless error model as the hybrid scheme as they both used CDMA codes. The model setting of the

TABLE 2.3
SYSTEM PARAMETERS

Symbol	Parameter
Number of nodes (N)	30
Number of codes (M)	18
Number of classes (r)	3
Traffic load for class 1 (λ_i^1)	$\lambda_i^1 = 1.5\lambda_i^2$
Traffic load for class 3 (λ_i^3)	$\lambda_i^3 = 2\lambda_i^2$
QoS parameter (ρ_i)	1.10
$G_{spreading}$	32
PHY header size	128 bits
Mean packet size (ξ_i^r)	796 bits
Mean frame size	1023 bits
FEC redundant bits	99 bits
FEC correctable bits	3 bits
CDMA channel bit rate ($1/T_c$)	1.28 Mcps
Modulation	BPSK
Token walk time (τ_i^{trans})	50 us
Permit pool capacity (γ_i)	20
Packet buffer capacity (Ω_i)	20000
Bad state duration ($\bar{\tau}_{bad}^{i}$)	3.2 ms
Bad state PEP_{bad}^{i}	1.0
Good state PEP_{good}^{i}	Holtzman's approximation
WTRP Channel bit rate	1.28 Mbps
Signal to Noise Rato (SNR)	8 dB

WTRP's Gilbert model is similar to the hybrid scheme's error model where four variables must be taken into consideration. The same channel error and error correction conditions of P_{good}^{i}, P_{bad}^{i} and PEP_{bad}^{i} have been used for the WTRP scheme. The BER of WTRP can be derived to be $BER(j) = Q\left(\sqrt{2SNR}\right)$, while PEP_{good}^{i} is derived using (2.9). For the performance comparison, the same parameters are used for all simulations. Parameters used in the simulation are summarized in Table 2.3.

In Figure 2.7, both the mean packet delay and code utilization graph are shown comparing the performance of the hybrid scheme using different sets of codes, and provides an indication of the optimum code usage in the network for the hybrid scheme. In Figure 2.7(a), the mean packet delay(a) is plotted against the normalized load, which is defined as the ratio of the traffic generated for the entire network and the capacity of the network as shown in (2.10).

Figure 2.7 shows the hybrid scheme with three different sets of codes assigned to the network. It is shown from the figure that the delay performance of the hybrid scheme is dependent on the number of codes used in the network. With fewer codes available, the scheme achieved low throughput and long packet delay. However, with large number of codes, it creates a high packet error probability due to severe multiple access interference. This effect is especially evident under heavy traffic load.

This effect consequently leads to traffic congestion and significantly increases both the packet delay and the length of the queue. Figure 2.7(b) investigates the dependence of throughput on the number of codes. As noted with the delay in Figure 2.7(a), there exists an optimal number of codes that maximizes the throughput for given load conditions. This optimal number is a function of the network load. Under load condition 0.9, it can be seen that the throughput increases with increase of codes used in the network. However, it is also observed from the figure that under heavy load conditions (0.95 and 0.98), the throughput starts to decrease when large numbers of codes are used; this result corroborates the discussion earlier where the deterioration is due to multi-code interference. It is shown from the figure that the scheme performs optimally when mid-range of codes with the optimal value is being used in the load function.

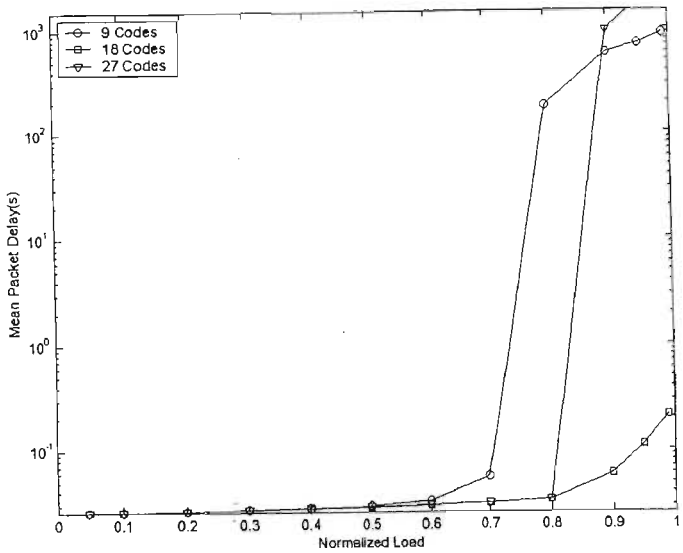
Figure 2.8 displays the packet error probability and throughput for all MAC schemes. This metric reflects the overall system performance of each traffic class in the three MAC schemes. It is clearly shown from Figure 2.8 (a) that the packet error probability increases with an increase in load for both the hybrid and CDMA MAC schemes. The WTRP exhibits relatively consistent error probability due to its single channel configuration. It is also shown that the packet error probability for the CDMA scheme achieves the worst performance due to severe interference. Based on the same token-access control mechanism, the hybrid and WTRP schemes achieve an identical throughput as displayed in Figure 2.8 (b). However, the CDMA scheme suffers rapid deterioration in throughput starting from medium loading condition due to its high packet error probability as shown in Figure 2.8 (a).

We also analyze the impact of different load conditions on the packet delay and buffer length of all three MAC algorithms. The packet delay is defined as the time period from the time when a packet arrives at the front of buffer Q_l of a node to the time it is successfully transmitted to the intended receiving station. The packet transmission time is not included, i.e., the packet delay is the time delay determined by the efficiency of each MAC algorithm.

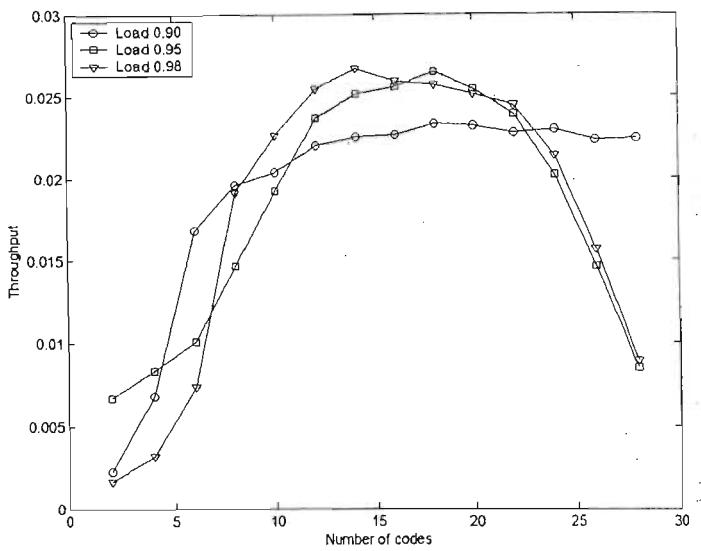
Figures 2.9 and 2.10 show the mean packet delay and buffer length for all MAC algorithms respectively. From the figures, it is clear that the hybrid algorithm outperformed the other two schemes for all traffic class nodes. When packets are lost due to interference, it is observed that the CDMA scheme suffered the worst delay performance and this corresponds to the discussion earlier. It should also be noted that the WTRP system experiences longer packet delay than the hybrid scheme. This is predicted as for most of the token-based protocols with single transmission medium available, long access delay is unavoidable in order to have guaranteed access. For the hybrid scheme, with its capability of dynamic channel allocation, the token can adjust itself to fit any asymmetric traffic loading condition to achieve low access delay as shown in Figure 2.9.

During the light load conditions, it is observed that all schemes have similar performance. When the traffic is light, system capacity is not fully utilized therefore it is relatively difficult to distinguish the performance of the MAC schemes. The number of codes used during the light load condition is significantly lower than during the medium and heavy load conditions. This effect reduces the MAI thereby decreasing the packet error probability which leads to smaller packet delay and buffer length.

The plots in Figure 2.10 show that the lengths of the buffers of other two schemes are longer than the hybrid scheme. This was predicted since as the packet waiting time increases, more packets would have to queue inside the buffer before receiving service. This is especially evident when the system is under a heavy traffic state, during which the length of the buffer increases drastically. The interclass effects in the network can also be seen in Figure 2.10, which becomes more pronounced for all MAC schemes in the case where the load condition is high. The mean queue length of class 3 is greater than that of class 2.

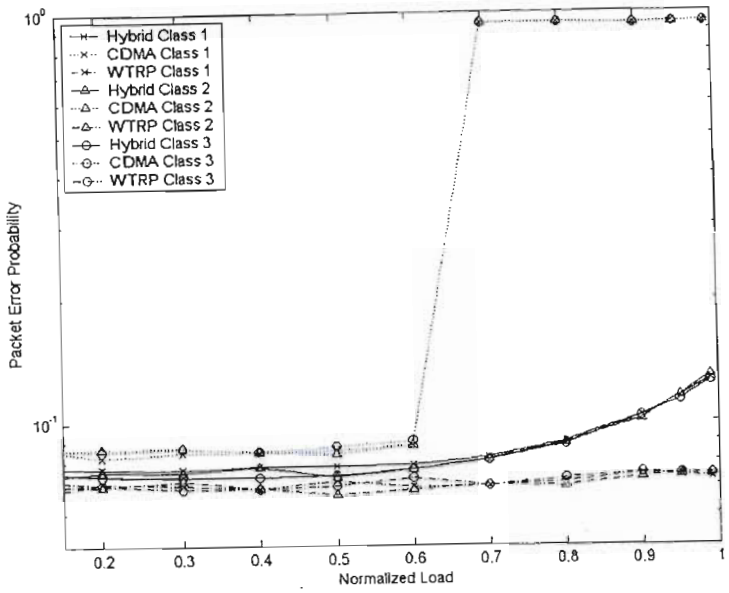


(a)

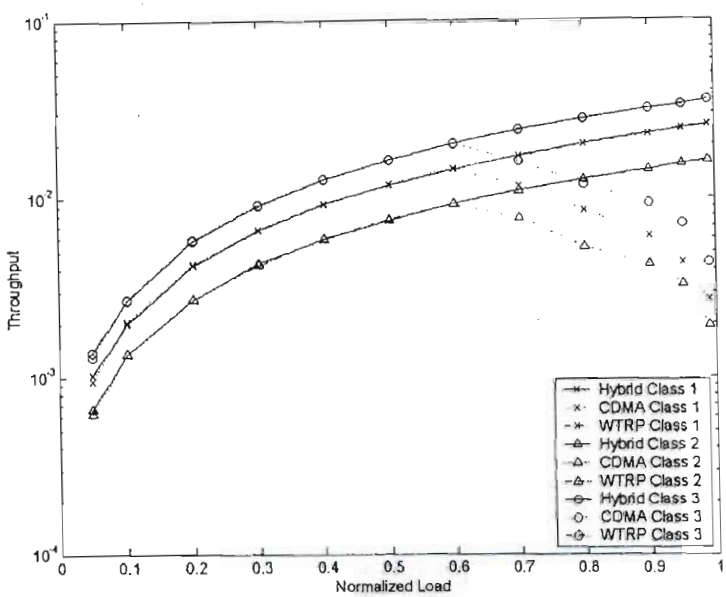


(b)

Figure 2.7: Mean packet (a) delay vs normalized load and (b) code utilization vs normalized load of class 3 node for hybrid MAC scheme under the condition that the link is in the good state with probability 0.9 with fixed QoS parameters that accommodate the maximum normalized load of 0.8

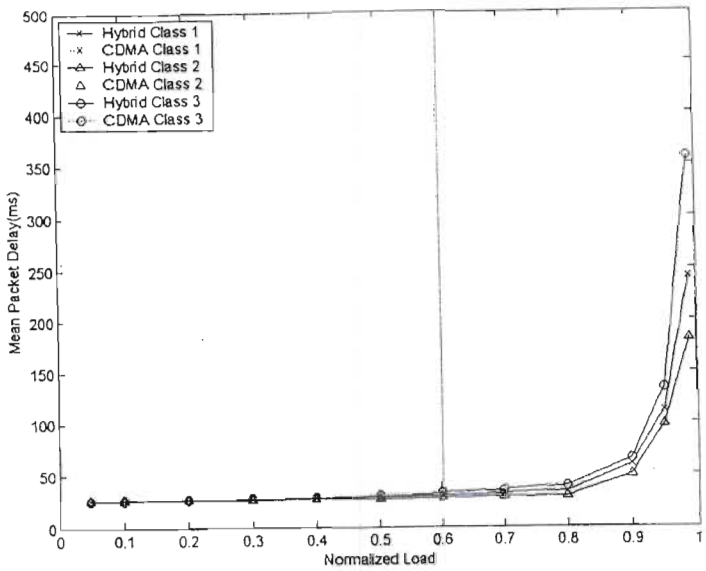


(a)

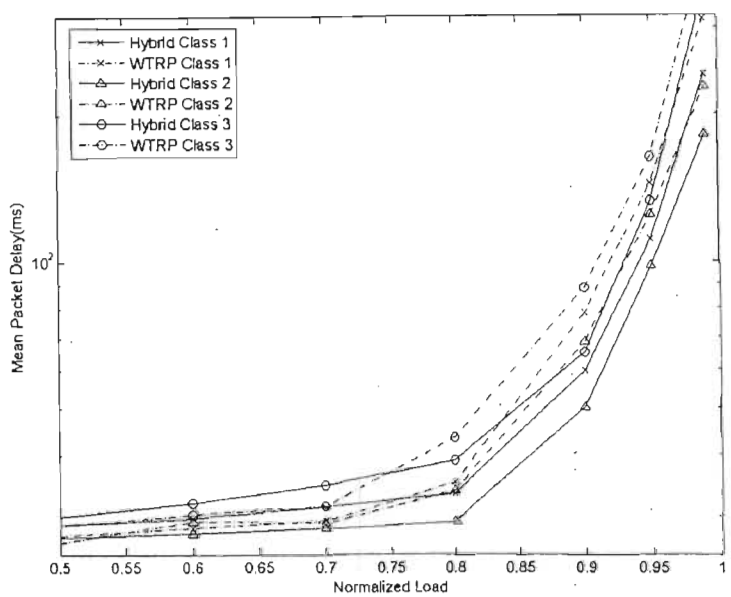


(b)

Figure 2.8: Packet error probability (a) vs normalized load and throughput (b) vs normalized load of all MAC schemes under the condition that the link is in the good state with probability 0.9 with fixed QoS parameters that accommodate the maximum normalized load of 0.8

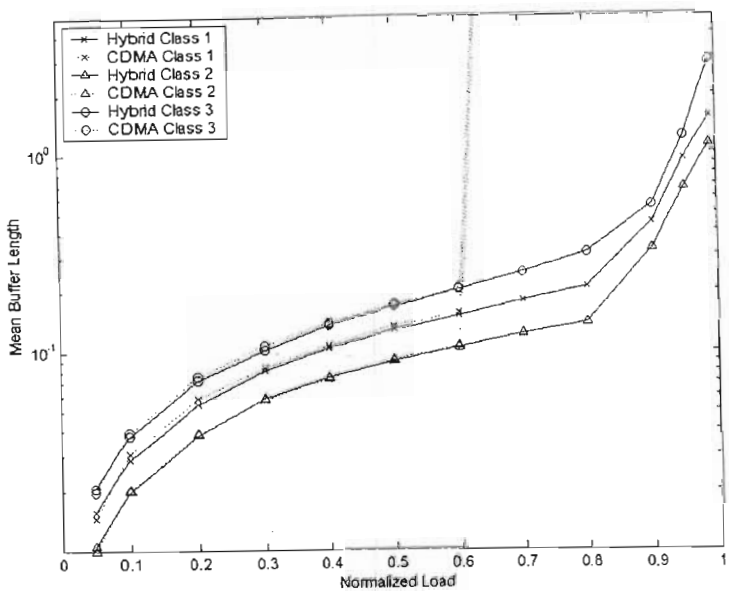


(a)

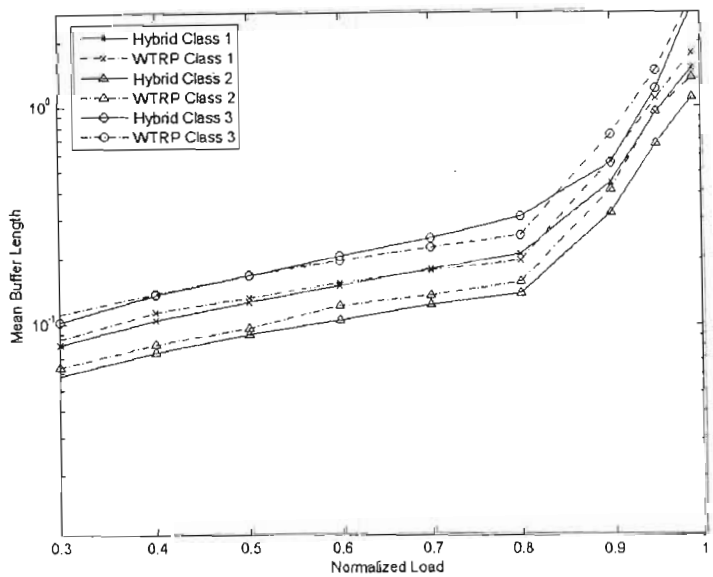


(b)

Figure 2.9: Mean packet delay of each traffic class for hybrid versus CDMA (a) and hybrid versus WTRP (b) schemes under the condition that the link is in the good state with probability 0.9 with fixed QoS parameters that accommodate the maximum normalized load of 0.8



(a)



(b)

Figure 2.10: Mean buffer length of each traffic class for hybrid versus CDMA (a) and hybrid versus WTRP (b) schemes under the condition that the link is in the good state with probability 0.9 with fixed QoS parameters that accommodate the maximum normalized load of 0.8

2.6 Summary

In this chapter, a de-centralized, QoS-aware medium access control for ad hoc wireless networks was presented. The approach is hybrid: a token scheme ensures the guaranteed access for all node in the network and CDMA is implemented to support simultaneous multiple data transmissions. The important features of our approach are that it exploits the availability of multiple transmissions, and it also takes the error-prone wireless channel condition into consideration.

Based on this approach, a novel hybrid Token-CDMA MAC protocol is proposed, where a token is used to distribute the CDMA codes and its rotation time is independent of the loading condition of the network. By making use of the token dynamics, the proposed scheme is able to efficiently distribute the available bandwidth to all the nodes in the network. Under the same loading condition, it provides the capability of supporting a larger number of nodes than the current CDMA system without affecting the system performance.

By incorporating wireless channel error models into the simulation programs, various performance measures of the hybrid MAC are compared with the single-token WTRP and CDMA MAC protocols under the same simulation conditions. Simulation results demonstrate that the hybrid scheme outperforms other two schemes in system performance. Although both the WTRP and hybrid schemes implement token passing strategy to distribute the bandwidth, the hybrid scheme achieves higher throughput, lower packet delay for all the traffic classes in the network and leads to relatively small buffer length for all nodes. The hybrid scheme can be easily implemented in a distributed fashion and, due to its token based design, it could effortlessly incorporate other QoS guarantees to provide better support of heterogeneous services in both the mobile ad hoc network and traditional wireless network.

CHAPTER 3

APPROXIMATE ANALYSIS OF THE HYBRID TOKEN-CDMA MAC SYSTEM

3.1 Introduction

There exists a number of papers that proposed MAC schemes using the token mechanism for Ad hoc networks. However, these contributions only considered the single token case in the network and performed minor or no statistical analysis for the system. A new hybrid Token-CDMA MAC protocol is proposed in Chapter 2 and its performance was compared with that of the single-token WTRP and standard CDMA MAC schemes.

The hybrid MAC scheme can be modelled as a multiple server system. From the literature, it is known from [Borst, 1997] that multiple server systems are extraordinarily hard to analyze, and no exact results are derived for models with independent servers, apart from some mean-value results for global performance measures such as cycle times, e.g., [Qing, 1989], [Hamacher, 1989], [Kamal, 1994], [Borst, 1997] and [Shieh, 2000]. Most of the proposed analyses use exhaustive, gated or 1-limited service policy to serve the packets, and none of these papers incorporate any QoS guarantees into the analysis.

As mentioned earlier, the hybrid MAC scheme can be considered as a system that consists of multiple queues which are serviced by multiple servers, where this configuration is commonly denoted as a multiserver multiqueue (MSMQ) system. The novelty of the system is that a CDMA code is considered as a server in the analytical scenario. There exist three packet transmission schemes for MSMQ systems [Marsan, 1992]. For the proposed system, the scheme is adopted where a queue may only be serviced by a single server during the packet transmission. All other servers in the network arriving at the queue during transmission must be passed onto the next queue in the network.

The storage capacity at each queue is assumed to be infinite and the queuing discipline is FIFO at each queue. The service discipline is gated at all queues. The polling order is given by servers visiting queues in a fixed index order. With the compact notation introduced in [Marsan, 1992] for MSMQ systems, the system studied in this case can be denoted as a

G/M/G/∞ queue model. The literature on the MSMQ networks that implements the 1-limited service discipline are [Hamacher, 1989], [Kamal, 1994], and [Cai, 2000]. In [Marsan, 1992] and [Chen, 1988] approximate analytical results for the average server cycle and vacation times, as well as approximate closed-form expressions for the average packet waiting time under 1-limited, gated and exhaustive service disciplines are given.

Queuing systems with server vacations [Takagi, 1991], [Doshi, 1986] have proven to be a useful abstraction of systems where several classes of customers share a common resource such as in polling [Takagi, 1987] systems. However, there exist only few papers that discuss the same packet transmission protocol for the gated type service discipline and vacation system. In this chapter, an approximate mean value analysis for the proposed gated multiple-vacation queue that supports multiple traffic classes is presented. Using the approximate approach, the mean server inter-visit and inter-arrival time and also the queue vacation time are derived. Based on the multiple-vacation queuing model, an approximate analysis is conducted using the probability generating function approach. The novelty of this work lies in viewing and modeling the hybrid MAC scheme as a queuing system with server vacation.

The remainder of this chapter is organized as follows. Section 3.2 describes the analytical model of the hybrid MAC scheme in detail. Based on the MSMQ approach, the approximate mean value analysis for the server vacation time is presented in Section 3.3. Section 3.4 presents an approximate discrete time analysis for the packet departure process and the moments of the packet delay for all traffic class queues. Results from simulation and analysis are compared in Section 3.5 and conclusions are drawn in Section 3.6.

3.2 System Model and Assumptions

In this section the description of the proposed MSMQ model for Hybrid MAC scheme, together with the assumptions made for the model are presented.

3.2.1 Analytical Model Description

The system model consists of M codes/servers and N queues as shown in Figure 2.1. The queue model in the system is displayed in Figure 3.1. It consists of three sub-models which are an input, a buffer and a vacation model. The input sub-model is responsible for handling the QoS guarantee for the incoming packets, and the buffer sub-model is used to manage the packets stored in the buffers of the queue model. The vacation sub-model is implemented to

monitor token activity. Detailed discussions of each sub-model will be presented in later sections. It is assumed that each server represents a code channel, each queue resembles a station and the system is operated in steady state. Each queue, i, is assumed to have an infinite capacity, into which packets arrive according to a Poisson process. The Poisson process is implemented instead of the MMPP process used in Chapter 2 as it makes the analysis tractable. With heterogeneous network configuration, the queues are categorized into r different traffic classes. Queues in each class have identical mean data packet arrival rates with notation $\lambda_{ip,i}^{r}$.

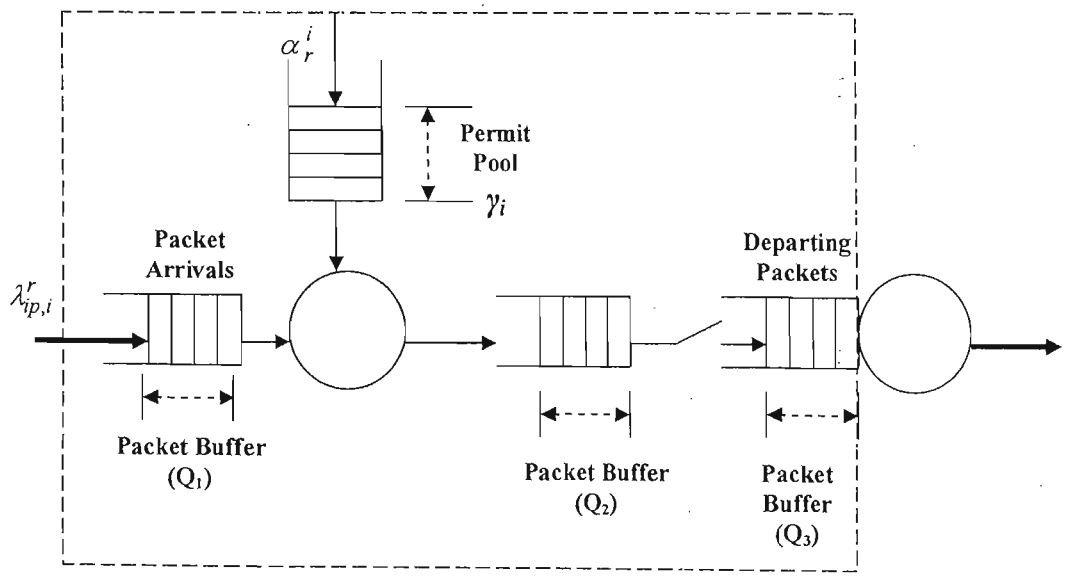


Figure 3.1: Queue model with data rate QoS guarantee

To provide data rate QoS, a modified leaky-bucket input regulation system is implemented. Each queue i has a permit pool for storing the generated permits. The permit generation rate of node i of class r (α_r^i) is proportional to the data rate as indicated from (2.1). The packet length is assumed to be geometrically distributed with the mean of s bits/packet. Since the code channel rate is assumed to be constant in the analysis, the service time of a packet is then also geometrically distributed with a mean of μ^{-1} slots in which the mean service rate is $\frac{s}{\mu^{-1}}$ (bits/slot).

Packets that arrive in buffer Q_1 have to gain the permission through a leaky-bucket policing mechanism, where it must obtain a permit from a permit pool. Once a packet obtains a

permit, it then passes through to buffer Q_2 where it will be stored until a token with available code arrives at the queue.

When the token visits a queue and there is a code available, the gated-service discipline is employed where all the packets in Q_2 will be moved to Q_3 and the server will empty the packet buffer Q_3 as illustrated in Figure 3.1. A detailed description of the transferring of packets between queues is discussed in Section 3.3. After servicing the packets, the queue returns the code to the token and enters the vacation period.

It is assumed that the token moves independently from one queue to another according to a predefined and fixed schedule. The walk time of the token from queue i to the subsequent queue $i+1$, is assumed to have a mean of $\overline{h_i}$ slots. The entire network is considered to be operated under steady-state. The vacation ends when the token with available codes visits the queue again. The approximate mean value analysis of the server vacation period for the proposed MAC scheme is presented in Section 3.3.

The analytical model is assumed to be symmetrical. In this case we assume that all servers are identical and carry the same load.

3.2.2 Assumptions

Throughout the chapter the following assumptions will be made:

- The queue denoted in the analytical model is represented by the three packet buffers (Q_1, Q_2 and Q_3) where Q_1 and Q_2 are used for QoS purpose. CDMA code in the model is represented by the server to constitute a MSMQ network and the packets in Q_3 are be served by the server.
- The packet arrival rate for each queue is *i.i.d* Poisson rvs with parameter $\lambda^r_{ip,i} > 0$, where there will be r traffic classes in the network.
- The permit generation rate of node i of class r (α_r^i) is proportional to the packet arrival rate.
- Length of a packet is assumed to be geometrically distributed with the mean of s bits/packet.
- The service time of a packet is geometrically distributed with a mean of μ^{-1} slots in which the mean service rate is $\frac{s}{\mu^{-1}}$ (bits/slot).

- For the analytical model, it is assumed that the permit pool i has the capacity of γ_i permits and for the packet buffers; it is assumed that each buffer Q_1, Q_2 and Q_3 has infinite capacity.
- For the token walk time, it is assumed that the token moves independently within the network, its walk time from queue i to the subsequent queue $i+1$ is assumed to have a mean of $\overline{h}_i$ slots.
- The proposed analytical model is assumed for small network due to computational complexity and it is operated under steady state.

3.3 Mean Value Analysis of the Queue Vacation Time

The queue's vacation time is defined as the time between the release of the CDMA code at the queue and the next capture of a usable CDMA code at the same queue. A usable code is defined as the code that can be used by the queue when it arrives at the queue, while a code is defined as not-usable if it arrives when there are no packets in the outgoing queue (Q_3) or the queue is busy servicing packets. This is illustrated in Figure 3.2.

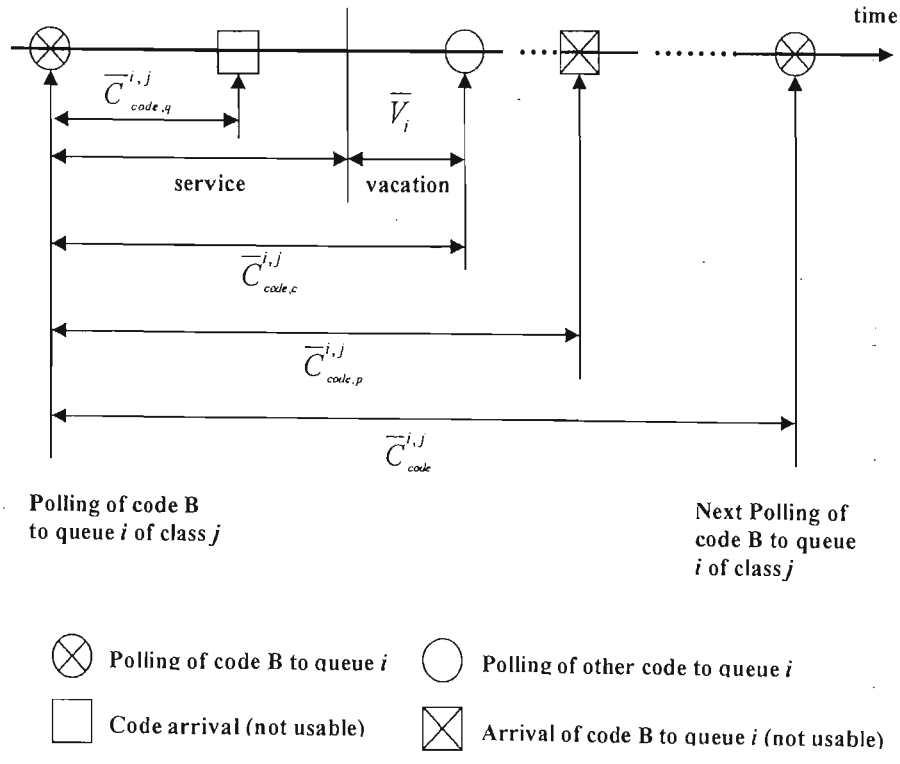


Figure 3.2: Sequence of events at a node

The notations displayed in Figure 3.2 are defined below:

- $\overline{C}^{i,j}_{code,q}$: It is the time elapsing between two consecutive arrivals of any code at the same queue i of class j where the code is not usable.
- $\overline{V}_i$: The vacation time, it is the time it takes for the token with available code to return to the same queue.
- $\overline{C}^{i,j}_{code,c}$: This is defined as the time elapsing between two consecutive arrivals of any code at the same queue i of class j where the code is usable.
- $\overline{C}^{i,j}_{code,p}$: The time elapsing between two consecutive arrivals of code B at the same queue i of class j where code B is not usable.
- $\overline{C}^{i,j}_{code}$: This is the time elapsing between two consecutive arrivals of code B at the same queue i of class j where code B is usable.

The time elapsing between two consecutive arrivals of code B at the same queue i of class j is denoted as $\overline{C}^{i,j}_{code,p}$, and it consists of two parts: the total amount of time that the code spent walking in the system which is denoted as the token cycle (T_c), and the total amount of time it spent on serving the queues during the cycle. It is indicated from [Marsan, 1992] that the latter part, when in steady-state, must be equal to a fraction of $1/M$ of the average total amount of work arriving during a cycle. And $\overline{C}^{i,j}_{code,p}$ can be derived as,

$$\overline{C}^{i,j}_{code,p} - T_c = \frac{1}{M}\left(N\lambda_i^j \mu^{-1} \cdot \overline{C}^{i,j}_{code,p}\right) \tag{3.0}$$

However, this condition can not suitably be used for the proposed analytical model, as in the hybrid-Token CDMA model the token is constantly circulating in the network. Once the queue finishes with its packet service, the code has to wait for the token to arrive at the queue and append with it to next queue. The time for the token to return to the queue i is denoted as δ and the number of queues that capture the particular code during a cycle as l $(0 \le l \le (N-1))$.

With some modifications, $\overline{C}^{i,j}_{code,p}$ is derived to be,

$$\overline{C}^{i,j}_{code,p} - \left(\left(\sum_{i=1}^{N} T_i^{trans}\right) + \bar{l}\cdot\bar{\delta}\right) = \frac{1}{M}\left(\left(\sum_{j=1}^{r}\sum_{i=1}^{q_j}\lambda_i^j\mu^{-1}\right)\cdot\overline{C}^{i,j}_{code,p}\right) \tag{3.1}$$

where T_i^{trans} is the token walk time between queue i and i+1 and the mean value for δ is approximated to be,

$$\bar{\delta} = \frac{1}{N}\sum_{i=1}^{N} iT_i^{trans} \tag{3.2}$$

and the mean value of l can be approximated to be,

$$\bar{l} = \left(q_j - 1\right)p_i^j + \sum_{j=2}^{r} q_j p_i^j \tag{3.3}$$

where q_j is the number of queues that belong to class j, and p_i^j is the probability that queue i of class j captured the code. Its derivation will be discussed later. Equation (3.1) can then be simplified to,

$$\overline{C}^{i,j}_{code,p} = \frac{M\left(\sum_{i=1}^{N} T_i^{trans} + \left(\left(q_j - 1\right)p_i^j + \sum_{j=2}^{r} q_j p_i^j\right)\cdot\left(\frac{1}{N}\sum_{i=1}^{N} iT_i^{trans}\right)\right)}{\left(M - \left(\left(\sum_{j=1}^{r}\sum_{i=1}^{q_j}\lambda_i^j\mu^{-1}\right)\right)\right)} \tag{3.4}$$

The mean value for the same code polling cycle time ($\overline{C}^{i,j}_{code}$) can be derived as,

$$\begin{aligned}\overline{C}^{i,j}_{code} &= \overline{K}\cdot\left(\overline{C}^{i,j}_{code,p}\right)\\ &= \overline{K}\cdot\frac{M\left(\sum_{i=1}^{N} T_i^{trans} + \left(\left(q_j - 1\right)p_i^j + \sum_{j=2}^{r} q_j p_i^j\right)\cdot\left(\frac{1}{N}\sum_{i=1}^{N} iT_i^{trans}\right)\right)}{\left(M - \left(\left(\sum_{j=1}^{r}\sum_{i=1}^{q_j}\lambda_i^j\mu^{-1}\right)\right)\right)}\end{aligned} \tag{3.5}$$

where K is a random variable representing the total number of queue-code arrival-cycles contained within a queue-code polling cycle. K is dependent on both the queue and the code

$$
\begin{aligned}
p_i^j &\approx \Pr\left\{Q^{i,j}_{\overline{Busy}\ and\ \overline{Empty}}\right\} \\
&= 1-\left(\Pr\left\{Q^{i,j}_{Busy}\right\}+\Pr\left\{Q^{i,j}_{Empty}\right\}\right) \\
&= \left[N\cdot\left(1-\frac{g^N_{\bar{n}_{i,j}}}{\left(\sum_{a=1}^{\bar{n}_{i,j}} g_a^N\right)+1}\right)\cdot\left(\frac{\lambda_i^j}{\sum_{j=1}^{r}\sum_{i=1}^{j}\lambda_i^j}\right)\right]-\frac{M-1}{M}\lambda_i^j\mu^{-1}
\end{aligned}
\tag{3.13}
$$

In this case, g_a^N denotes the number of combinations that n packets can be arranged in N queues where it may be derived using permutation technique, and $\bar{n}_{i,j}$ is defined as the mean number of packets that are in the system. $\bar{n}_{i,j}$ is approximated by summing the average amount of work that arrived at all the queues,

$$
\bar{n}_{i,j} \approx \sum_{i=1}^{N}\frac{\lambda_i^j\mu^{-1}}{1-\frac{M-1}{M}\cdot\lambda_i^j\mu^{-1}} \tag{3.14}
$$

3.4 Approximate Analysis of the Queue Model

In this section the input, buffer and the vacation sub-models are presented and incorporated into the system model. An approximated discrete time analysis is conducted for the hybrid MAC scheme.

3.4.1 Discrete Time Analysis for the Input Model

The input sub-model within the queue model is used to regulate the packet arrivals using data rate QoS guarantee. To monitor the flow of traffic in discrete time, an approximate analysis of the packet departure process of the input model is presented in this section. In this case, the probability generating function of the packet departing process from the proposed data rate QoS scheme is derived. In discrete time scenario, time is slotted where the length of each slot is the permit generation slots with the slot length T_p^i and a new permit is generated at each slot boundary as depicted in Figure 3.3.

The length of the slot is proportional to the mean arrival rate where $T_p^i = \left(\gamma_i \lambda_{ip,i}^r\right)^{-1}$. The QoS parameter γ_i is used to control the length of the permit slot. The main purpose of the parameter γ_i is to provide fairness in the network by ensuring that all nodes receive sufficient access to the network.

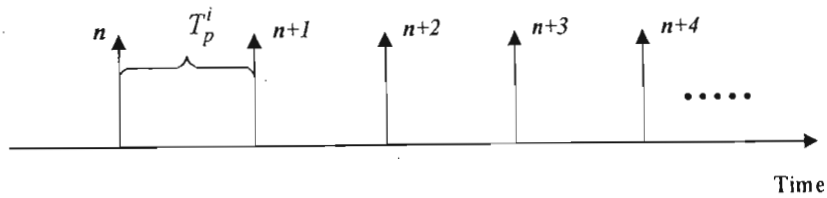


Figure 3.3: State diagram of the discrete time system for the packet departure from buffer Q_1 to Q_2

This is achieved by constraining the node-transmit capacity, limiting the maximum number of packets that can be transmitted and by varying the parameter γ_i. Detailed explanations of how to achieve this QoS is discussed in the next paragraph.

The generated permit joins the permit pool if the pool has less than γ_i permits, otherwise, the permit is discarded. In order to satisfy the proposed data rate QoS guarantee, packets arrive into an infinite buffer (Q_1 in Figure 3.1) according to a Poisson process with mean arrival rate $\lambda_{ip,i}^r$. Using modified leaky bucket traffic regulation system [Butto, 1991], if the arriving packet finds the permit pool nonempty, it then departs to buffer Q_2 and one permit is removed from permit pool. An arriving packet that finds the permit pool empty joins the queue. When the queue is not empty and a permit is generated, one packet departs the queue immediately (in FIFO order) and the permit is removed from the pool. It can be observed that the packet departure process from this modified Leaky-Bucket scheme constitutes the input process to the network that is intended to be regulated.

To derive the probability generating function (PGF) for the packet departing process, it is imperative that the steady-state joint probability distribution of the queue length and the permit pool occupancy (P_{B_n}) at the slot boundary must first be derived. Based on [Gautam, 2002], the probability distribution of the queue length of buffer Q_1 in steady state can be found at embedded permit generation point where the input queue buffer Q_1 can be modeled

as a M/D/1 queue [Sidi, 1993]. For the M/D/1 queue, its queue length distribution in steady state can be derived as,

$$P_{q_m}(a) = \Pr\{q_m = a\} = (1-\rho_i)\sum_{k=1}^{a}\left((-1)^{a-k}\, e^{k\rho_i}\left[\frac{(k\rho_i)^{a-k}}{(a-k)!} + \frac{(k\rho_i)^{a-k-1}}{(a-k-1)!}\right]\right) \tag{3.15}$$

where $\rho_i = \frac{\lambda_{ip,i}}{T_p^i}$ and with initial conditions,

$$\begin{aligned} P_{q_m}(0) &= (1-\rho_i) \\ P_{q_m}(1) &= (1-\rho_i)\left(e^{\rho_i} - 1\right) \end{aligned} \tag{3.16}$$

The number of packets that arrive in buffer Q_2 in the *nth* slot is dependent on the number of packets that depart from buffer Q_1 during the *nth* slot. However, there can be more than one departure in the *nth* slot since at the beginning of the *nth* slot, there may be residual permits from the previous slots, therefore the number of packets that can depart from buffer Q_1 during the *nth* slot is denoted as B_n, where $0 \le B_n \le 1+\gamma_i$. The notation γ_i is the permit pool capacity for queue *i*. In the one packet departure case, in order to have one packet depart in the *nth* slot, there must be at least one packet in the buffer Q_1, i.e. $\Pr(q_n \ge 1)$.

Using the iterative process and with memoryless characteristic of the M/D/1 queue, the steady state probability distribution of the departing packet at slot boundary can be derived as,

$$\begin{aligned} P_{B_n}(0) &= \Pr(q_n = 0) = (1-\rho_i) \\ P_{B_n}(1) &= \Pr(q_n \ge 1) \cap \Pr(RP = 0) = \Pr(q_n \ge 1) \cap \Pr(q_{n-1} \ge 1) \\ &= \left(\sum_{i=1}^{\infty} \Pr\{q_n = i\}\right) \cap \left(\sum_{i=1}^{\infty} \Pr\{q_{n-1} = i\}\right) = \rho_i \cdot \rho_i = (\rho_i)^2 \end{aligned} \tag{3.17}$$

where $\Pr(RP = 0)$ denotes the probability of having no residual permit (RP) in the buffer. Therefore, for one packet onwards,

$$P_{B_n}(2) = \Pr(q_n \geq 2) \cap \Pr(RP = 1) = \Pr(q_n \geq 2) \cdot P_{RP}(1) = \sum_{i=2}^{\infty} \Pr\{q_n = i\} \cdot \left(\Pr(q_n = 0)\right)^1$$

$$= \left(1 - \sum_{i=0}^{1} \Pr\{q_n = i\}\right)(1-\rho_i)^1$$

$$P_{B_n}(3) = \Pr(q_n \geq 3) \cap \Pr(RP = 2) = \left(1 - \sum_{i=0}^{2} \Pr\{q_n = i\}\right)(1-\rho_i)^2 \qquad (3.18)$$

...

$$P_{B_n}(\gamma_i + 1) = \left(1 - \sum_{i=0}^{\gamma_i} \Pr\{q_n = i\}\right)(1-\rho_i)^{\gamma_i}$$

$$P_{B_n}(\gamma_i + 2) = 0$$

$$P_{B_n}(\gamma_i + 3) = 0$$

...

In order to have more than one departure within the *nth* slot, there must be residual permits from previous slot and the maximum number of departures is dependent on the permit pool size L_i. In this case, there can only be two departures in the *nth* slot when there is one residual permit from previous *(n-1)th* slot. Therefore the probability of having two departures ($P_{B_n}(2)$) is equal to the probability of having two packets in queue buffer and with one residual permit from previous slot ($P_{RP}(1)$), which is given in (3.18).

The term $P_{RP}(b)$ is defined as the probability of having b residual permits and it is determined by the queue capacity from the previous slot. There will be a residual permit available only if the queue length from the previous slot is zero. Therefore the probability can be derived as,

$$\begin{aligned}
&\text{Prob}(\text{Residual Permit} = b) \\
&= \Pr(RP = b) \\
&= P_{RP}(b) \\
&= P(Q = 0 \text{ at previous slot}) \cap P(Q = 0 \text{ at previous 2 slots}) \ldots \cap P(Q = 0 \text{ at previous } b \text{ slots}) \\
&= P_{q_{n-1}}(0) P_{q_{n-2}}(0) \ldots P_{q_{n-b}}(0) \\
&= \left(P_q(0)\right)^b
\end{aligned} \qquad (3.19)$$

(3.17) and (3.18) can be simplified to

$$
\begin{aligned}
&P_{B_n}(0) = (1-\rho_i) \\
&P_{B_n}(1) = (\rho_i)^2 \\
&P_{B_n}(2) = \left(1-\sum_{i=0}^{1}\Pr\{q_n=i\}\right)(1-\rho_i)^1 \\
&P_{B_n}(3) = \left(1-\sum_{i=0}^{2}\Pr\{q_n=i\}\right)(1-\rho_i)^2 \\
&\cdots \\
&P_{B_n}(\gamma_i+1) = \left(1-\sum_{i=0}^{\gamma_i}\Pr\{q_n=i\}\right)(1-\rho_i)^{\gamma_i} \\
&P_{B_n}(\gamma_i+2) = 0 \\
&P_{B_n}(\gamma_i+3) = 0 \\
&\cdots
\end{aligned}
\tag{3.20}
$$

To summarize, the distribution function for the departing packets can be computed as,

$$
\Pr\{B_n=j\} = \begin{cases}
(1-\rho_i) & ,j=0 \\
(\rho_i)^2 & ,j=1 \\
\left(1-\sum_{i=0}^{j}\Pr\{q_n=i\}\right)(1-\rho_i)^j & ,2\le j\le 1+\gamma_i \\
0 & ,j>\gamma_i+1
\end{cases}
\tag{3.21}
$$

The probability generating function of the packet departing process $B(z)$ can now be derived using standard z-transform method,

$$
\begin{aligned}
B(z) &= \sum_{j=0}^{\infty}\Pr\{B_n=j\}\cdot z^j \\
&= (1-\rho_i)+(\rho_i)^2 z+\left(\sum_{j=1}^{1+\gamma_i}\left(1-\sum_{i=0}^{j}\Pr\{q_n=i\}\right)(1-\rho_i)^j\right)\cdot z^j
\end{aligned}
\tag{3.22}
$$

3.4.2 Discrete Time Analysis for the Buffer Model

In this section, the buffer Q_3 and its analysis are presented. The number of packets arriving in consecutive slots and the service time (in slots) of these packets are a series of independent identically distributed random variables with Poisson and geometric probability mass functions P_{A_n} and P_{S_n} and with corresponding probability generating functions $A(z)$ and $S(z)$, respectively.

For transferring of packets between all queue buffers, it is shown from the last section that packets depart buffer Q_1 and arrive at buffer Q_2 according to its QoS constraint. Once the packets arrive at buffer Q_2, they wait in the buffer and only move in batch to buffer Q_3 only when the gate opens. The gate is only opened at the end of the last slot of the vacation period. Once the gate is opened the packets in buffer Q_2 then move to buffer Q_3 and are then served according to the first-in-first-out (FIFO) principle before departing the system. A vacation starts when buffer Q_3 is emptied. However, if the server finds buffer Q_3 empty upon returning from vacation, it will immediately start another vacation until buffer Q_3 has packets when the server returns from the vacation (multiple vacation policy as discussed in section 3.3). The mean value of the vacation length is derived from Section 3.3 with its probability mass function defined as P_{V_n} and the corresponding probability generating function defined as $V(z)$.

3.4.2.1 Queue Length at Buffer Q_2 and Q_3

This section presents the derivation process and equations of the length of the queue for the packet buffer Q_2 and Q_3 at the start of the time slot within the queue cycle. For the analytical model under consideration, a queue cycle is defined to consist of a busy period that follows with a vacation period. When the busy period starts, the queue content in buffer Q_3 is emptied by serving all the packets, all the packets that arrived during the busy period is stored in buffer Q_2 as the gate is closed in busy period. Once the server has served the last packet in the buffer Q_3, it moves to the next queue in the system. In this case the server takes on the vacation after it finished serving the packets in buffer Q_3. At the end of the vacation period, the gate is opened and all the packets stored in buffer Q_2 are now conveyed to buffer Q_3 in the FIFO order.

To derive the queue length of the packet buffers, same approach is used from [Fiems, 2004] in which it first derived the number of packets in Q_3 at the beginning of the cycle. Let c_{l+1} be the slot following the l_{th} cycle and let X_i be the number of packets in the buffer Q_3 at the beginning of the slot i. [Fiems, 2004] indicated that the number of packets in the buffer Q_3 at c_{l+1} can then be defined as,

$$X_{c_{l+1}} = \sum_{i=1}^{X_{c_l}} \sum_{j=1}^{g_i} B_i^j + W_{l+1} \tag{3.23}$$

where g_i is defined as the number of time slots needed to service packet i during the lth cycle, B_i^j is defined as the number of departures from buffer Q_1 to Q_2 during the jth service slot of the packet and W_{l+1} is defined as the number of departures from buffer Q_1 to Q_2 during the vacation period in the $(l+1)th$ cycle. $X_{c_l}(z)$ is defined as the probability generating function of the number of packets in the queue at the end of the lth cycle. With some derivations, its pgf can be shown as,

$$\begin{aligned}
&X_{c_{l+1}}(z) \\
&= E\left[z^{\sum_{i=1}^{X_{cl}} \sum_{j=1}^{g_i} B_{ij}+W_{l+1}} \right] = E\left[B(z)^{\sum_{i=1}^{X_{cl}} g_i} z^{W_{l+1}} \right] \\
&= E\left[S(B(z))^{X_{cl}} z^{W_{l+1}} \right] \\
&= E\left[S(B(z))^{X_{cl}} z^{W_{l+1}} \{X_{c_l} > 0\} \right] + E\left[S(B(z))^{X_{cl}} z^{W_{l+1}} \{X_{c_l} = 0\} \right] \\
&= \overline{W_0}(z) E\left[S(B(z))^{X_{cl}} \{X_{c_l} > 0\} \right] + W_0(z) E\left[\{X_{c_l} = 0\} \right] \\
&= \overline{W_0}(z) E\left[S(B(z))^{X_{cl}} \left(1 - \{X_{c_l} = 0\}\right) \right] + W_0(z) E\left[\{X_{c_l} = 0\} \right] \\
&= X_{c_l}\left(S(B(z))\right) \cdot \overline{W_0}(z) + X_{c_l}\left(S(b_0)\right) \cdot \left(W_0(z) - \overline{W_0}(z)\right)
\end{aligned} \tag{3.24}$$

where $W_0(z)$ is defined as the probability generating function of the number of departures from buffer Q_1 to Q_2 during the vacation period of a random cycle under the condition that there exists no packets in buffer Q_2 at the end of the slot preceding the vacation period. $\overline{W_0}(z)$ is defined as the probability generating function of the number of departures from buffer Q_1 to Q_2 during the vacation period of a random cycle under the condition that there is at least one packet in buffer Q_2 at the end of the slot preceding the vacation period. It can be easily derived that $\overline{W_0}(z) = V(B(z))$ since under the condition that if there is at least one packet in buffer Q_2 before the vacation starts, the server will then only take one vacation.

However, the server will take multiple vacations until there is packet in the buffer Q_2 when it comes back from the vacation. Modifying the analysis from [Fiems, 2004] and by conditioning on the number of necessary vacations,

$$W_0(z) = \frac{V(B(z)) - V(b_0)}{1 - V(b_0)} \tag{3.25}$$

To find the probability generating function of the queue length at the end of the cycle, $X_c(z) = \lim_{l\to\infty} X_{c_l}(z)$ is defined as its pgf for the queue length at the end of the cycle in equilibrium. It is proven from [Sumita, 1989] that this condition is valid under the assumption,

$$\delta_i = S_i^{'}(1) B_i^{'}(1) < 1 \tag{3.26}$$

where δ_i is the load of the queue model i and from the equilibrium assumption, (3.24) can now be derived as,

$$X_c(z) = X_c\left(S\left(B(z)\right)\right) \cdot \overline{W_0}(z) + J \cdot \left(W_0(z) - \overline{W_0}(z)\right) \tag{3.27}$$

where $J = X_c\left(S(b_0)\right)$ is the probability that the buffer Q_2 is empty before the start of the vacation period. It is now clearly shown that various moments of $X_c(z)$ can be derived and that the value of J can be determined numerically using recursive techniques. In this case, the series $z_i = S\left(B(z_{i-1})\right)$, $z_0 = 0$, $i > 0$ is considered. Under the condition that $\delta_i < 1$, it can be determined that the series converges to one. Now, let $q_{i+1} = J / X_c(z_i)$, with the substitution of $z = z_i$ in (3.27), then

$$q_{i+1} = \frac{\overline{W_0}(z_i) q_i}{1 + \left(\overline{W_0}(z_i) - W_0(z_i)\right) q_i} \tag{3.28}$$

The value of J can then be determined recursively by starting from $q_1 = 1$ and $J = \lim_{i\to\infty} q_i$.

Once the queue length at the end of the cycle is found, the joint probability generating function of the queue length at other epochs in buffer Q_2 and Q_3 can now be derived. For the queue length at the end of packet service, $X_d(z_1, z_2)$ is defined as the joint probability generating function of the queue length at the buffer Q_3 and Q_2 at the start of the slot right after a service of a packet from buffer Q_3, its pgf can then be derived as,

$$
\begin{aligned}
& X_d(z_1, z_2) \\
&= E\left[z_1^{X_{d,1}} z_2^{X_{d,2}} \right] \\
&= \frac{1}{X_c^{'}(1)} E\left[\sum_{k=1}^{X_c} z_1^{X_c - k} z_2^{\sum_{i=1}^{k} \sum_{j=1}^{S_j} B_j^i} \right] \\
&= \frac{1}{X_c^{'}(1)} E\left[\sum_{k=1}^{X_c} z_1^{X_c} z_1^{-k} B(z_2)^{\sum_{i=1}^{k} S_i} \right] \\
&= \frac{1}{X_c^{'}(1)} E\left[z_1^{X_c} \right] \cdot E\left[\sum_{k=1}^{X_c} z_1^{-k} B(z_2)^{\sum_{i=1}^{k} S_i} \right] \\
&= \frac{X_c(z_1)}{X_c^{'}(1)} \cdot E\left[\sum_{k=1}^{X_c} \frac{B(z_2)^{\sum_{i=1}^{k} S_i}}{z_1^k} \right] \\
&= \frac{S(B(z_2))}{X_c^{'}(1)} \cdot \frac{\left[X_c(S(B(z_2))) - X_c(z_1) \right]}{\left[S(B(z_2)) - z_1 \right]}
\end{aligned}
\tag{3.29}
$$

Where $X_{d,1}$ and $X_{d,2}$ are defined as the queue lengths for buffers Q_3 and Q_2 at a random service epoch respectively and X_c is previously defined as the total queue length for buffers Q_3 and Q_2 at the end of the random cycle.

3.4.2.2 Packet Delay at Q_2 and Q_3

In the discrete time analysis for the proposed analytical model, the packet delay is denoted as the number of time slots between the end of the slot the tagged packet arrives in at buffer Q_1 and the end of the slot where that tagged packet leaves buffer Q_3. For the modified leaky-bucket QoS scheme, the exact delay expression for packets in Q_1 has been derived by [Sidi, 1993] therefore this thesis concentrates on the delay expressions on Q_2 and Q_3. The service time of the packet is taken into consideration in determining the delay from buffer Q_3 as the packet only departs from the queue once it is being served.

To derive the discrete-time expression for the packet delay, it is first assumed that the number of packets that depart from buffer Q_2 in a slot are grouped to form a batch-customer which forms a system with Bernoulli "batch-customer" arrivals [Fiems, 2004]. The probability generating function for the departures $B^*(z)$ and their service times $S^*(z)$ are given by,

$$B^*(z) = b_0 + (1-b_0)z,$$
$$S^*(z) = \frac{B(S(z)) - b_0}{1-b_0}, \tag{3.30}$$

where $b_0 = B(0)$. Illustrated in [Fiems, 2004], packet delay at Q2 and Q3 is related to the batch-customer processes shown above. Firstly, one denotes the probability generating function of buffers Q_3 and Q_2 queue lengths at departure epochs for this system as $X_d^*(z_1, z_2)$, in which the latter is given by equation (3.29). Then, consider a random batch-customer and let $D^*(z_1, z_2)$ denote the joint probability generating function of its delay in buffers Q_3 and Q_2. When the gate is opened, the packets that arrive in buffer Q_2 are moved as a batch to Q_3 along with the tagged packet. And after the gate is closed, all the packets that arrive during the departure of the tagged packet in buffer Q_3 are queued in buffer Q_2. It is then shown by [Fiems, 2004] that the probability generating functions of batch-packet delay and queue contents at batch-packet departure epochs can be related as,

$$D^*\left(B^*(z_2), B^*(z_1)\right) = X_d^*(z_1, z_2) \tag{3.31}$$

To relate the delay of the packet to the delay of its batch, the delay in the buffer Q_2 of a packet equals the delay of its batch as they enter and leave buffer Q_2 at the same time slot. The waiting time of a packet is denoted as the number of slots between the end of its arrival slot and the beginning of the slot where this packet starts its service. Therefore the waiting time in buffer Q_3 of a packet is then the sum of the waiting time of its batch, with combination of the service times of all packets that arrived during the same slot prior to the tagged packet. Based on [Fiems, 2004] and with modifications to our model, the packet delay in the Q_2 and Q_3 can be derived as,

$$D(z_1, z_2) = \frac{S(z_1)\left[B(S(z_1)) - 1\right]}{B'(1)\left[S(z_1) - 1\right]} \cdot \frac{X_d^*\left(\frac{z_2 - b_0}{1-b_0}, \frac{z_1 - b_0}{1-b_0}\right)}{S^*(z_1)} \tag{3.32}$$

Where $S(z)$ is the probability generating functions for the departures into Q_2, $B(z)$ has been derived from (3.22), and since the service times of the consecutive customers are a series of geometrically distributed random variables, its probability generating function is,

$$S(z) = \frac{z}{\mu^{-1} + (1-\mu^{-1})z} \tag{3.33}$$

where μ^{-1} denotes the mean service time of a packet. The vacation time is assumed to be a geometric distributed random variable with its mean derived in Section 3.3 and its probability generating function $V(z)$,

$$V(z) = \left(\frac{p_{nb}}{1-(1-p_{nb})z} \right) \tag{3.34}$$

Various moments of the packet delay for both buffer Q_2 and Q_3 queue buffers can now be derived using derivatives techniques for (3.32).

3.4.3 Summary of Analyze for Hybrid MAC Scheme

This section summarizes the approximated analysis conducted for the analytical model proposed for the hybrid MAC scheme. As stated in the beginning of the chapter, the model is assumed to be a MSMQ model with three packet buffers (Q_1, Q_2 and Q_3), the queue and packets behaviors are investigated as follows,

a. Q_1 packet departure process that incorporates modified leaky-bucket QoS criteria,
b. gated-service scheme for packets in Q_2 to Q_3
c. Q_3 packet service scheme with incorporation of queue vacations
d. vacation time for the proposed MSMQ model, where the vacation is linked to the interval between two consecutive token arrivals with available codes.

The approximated analysis begins with the mean value and distribution analysis of the proposed MSMQ vacation model. Based on the approach by [Marsan, 1992], the hybrid MAC scheme is modeled as a MSMQ model analytically and the period between the consecutive code capture interval is modeled as its vacation time. With this configuration and under the assumption that the system is under steady-state, the expression of the vacation time (3.12) and its approximated distribution are derived. The analysis continues with the discussion on the queue model behavior when the packets pass though the modified leaky bucket QoS mechanism from packet buffer Q_1 to Q_2. The sub-section concludes by defining the probability generating function for the packet departing process (3.22) where it is needed for the discrete time analysis for last sub-section.

The last part of the analysis uses (3.22) as the packet arrival process for Q_2 in which the packets are now linked to MSMQ model with gated service discipline. As discussed earlier, the packets in Q_2 will only move to Q_3 if the gate is open and the interval between two consecutive gate-open is dependent on the service time of the packets in Q_3 and the queue vacation time. Using [Fiems, 2004] and with packet departing (3.22), gated service (3.29) and queue vacation distributions derived (3.34), the analysis concluded with the discussion on the packet latency experienced in Q_2 and Q_3 (3.32).

3.5 Numerical Results

In this section the numerical results of MSMQ model for the hybrid MAC scheme are compared with simulation results. Results demonstrate the effect of the traffic loading condition, on the performance of the queue model. The simulation program is written in C++ Builder programming package and the analysis is computed using Matlab software language. Simulation and analysis are conducted using the parameters shown in Table 3.1.

TABLE 3.1
SYSTEM PARAMETERS

Symbol	Parameter
Number of nodes (N)	9
Number of codes (M)	6
Number of classes (r)	3
Traffic load for class 1 (λ_i^1)	$\lambda_i^1 = 1.5\lambda_i^2$
Traffic load for class 3 (λ_i^3)	$\lambda_i^3 = 2\lambda_i^2$
QoS parameter (ρ_i)	1.1
Mean service time (μ^{-1})	1.25 slot/packet
Mean Token walk time (T_i^{trans})	0.01 slot
Permit pool capacity (γ_i)	20

3.5.1 Mean Values and Distribution for Vacation Model

Figure 3.4 and 3.5 display the results from simulation and analysis of the probabilities that the queue is busy and it is empty when the token visits the queue under different loading conditions. It can be clearly seen from Figure 3.4 that the probability of the busy-queue increases with the increase in system loading. This is due to the fact that when the system load increases, the traffic class load also increases. It is also clear that the heaviest traffic class (Class 3) queue has the highest probability amongst all three classes and the lightest traffic class (Class 2) queue has the lowest probability.

This is as predicted since Class 3 and Class 2 queues accommodate the highest and lowest traffic load settings respectively. Figure 3.5 displays the probability that the queue is empty upon the arrival of the token. It can be observed that when the system load is low, the probability of the empty-queue is high for all three traffic class queues. This is as predicted as under light load state, the amount of packets generated per unit time is scarce. The probability decreases with the increase of the loading condition of the system.

Figure 3.6 displays the results of the mean time for consecutive arrivals of the specific code S_i at the specific queue in different classes ($\overline{C}^{i,j}_{code,p}$). It is observed from (3.4) that the value of $\overline{C}^{i,j}_{code,p}$ remains identical irrespective of the traffic classes. The assumption is validated from the results displayed in Figure 3.6. Both the simulation and analysis results of the mean time of the consecutive polling of the same code at the specific queue for different traffic classes ($\overline{C}^{i,j}_{code}$) are shown in Figure 3.7. It shows that $\overline{C}^{i,j}_{code}$ is high under light system load conditions. This is expected as under light traffic conditions, the time is spent on waiting for a packet to arrive before the code can poll the queue.

This effect is pronounced in the Class 2 traffic-class queue as it is the lowest traffic load class, yet it has the highest $\overline{C}^{i,j}_{code}$ time. As the system load increases, the $\overline{C}^{i,j}_{code}$ time decreases until the system is in the heavy traffic state. In this case, the queue has to wait for the code to be available before it may get serviced, $\overline{C}^{i,j}_{code}$ once again increases under heavy load condition. It can be seen that under the heavy load condition, the class 3 traffic-class queue has the highest $\overline{C}^{i,j}_{code}$ time. This is because as the token with the same code arrives at the queue, the probability that the code is usable by the Class 3 queue is lower than for the Class 1 queue since the probability that the queue is busy when the token arrives for Class 3 queue is higher than that of the Class 1 queue.

The mean queue vacation time ($\overline{V}_i$), results for various system load conditions are displayed in Figure 3.8. When the system is under a light traffic condition and the token with the codes arrives at the queue, it will see an empty queue. It is therefore forced to take on multiple vacations until there is a packet available in the queue in order for the code to be captured. Multiple vacations consequently lead to the increase in the code vacation time as shown in

Figure 3.8. Such condition is alleviated with the increase in system load. The vacation time decreases until the system is in the heavy traffic state. Under heavy loading condition, as discussed earlier, the queue has to wait for the code to be available before it may get polled, therefore the vacation time for all traffic classes then increases due to lack of available servers.

Figure 3.9 presents the analysis and simulation results of the vacation time distribution. It is clearly illustrated from the figures that the distribution time for the vacation fits tightly to the approximated geometric distribution for all traffic classes.

3.5.2 Mean Packet Delay at Buffer Q_2 and Q_3

For numerical examples, results from the simulation and discrete time analysis presented in Section 3.4.2 are presented to demonstrate the effects of the traffic loading conditions, on the performance of the packet delay at both packet buffers Q_2 and Q_3 of difference class queues. Figure 3.10 displays the results of the mean packet delay experienced by buffer Q_2 for all traffic class queues. From the figures, Class 3 queue buffer has the highest delay amongst all the class queue buffers and Class 2 buffer has the lowest delay. This is expected as for the system under consideration, Class 3 queue has the highest data rate therefore more packets are stored in the queue comparing to other classes subsequently leads to the increase in packet delay.

Figure 3.10 also shows that the analysis result of the delay for all classes under heavy system load conditions compare favorably to the simulation results. However, the effect of the independence assumption on the vacation time distribution starts to dominate, this leads to deviation between analysis and simulation. For the mean packet delay in queue buffer Q_3 of different class queues, the simulation and analysis results for various system load conditions are displayed in Figure 3.11. Clearly, when the system is under a light to medium traffic condition, the probability that a packet arrives during the cycle is low, therefore leading to low packet delay for all classes.

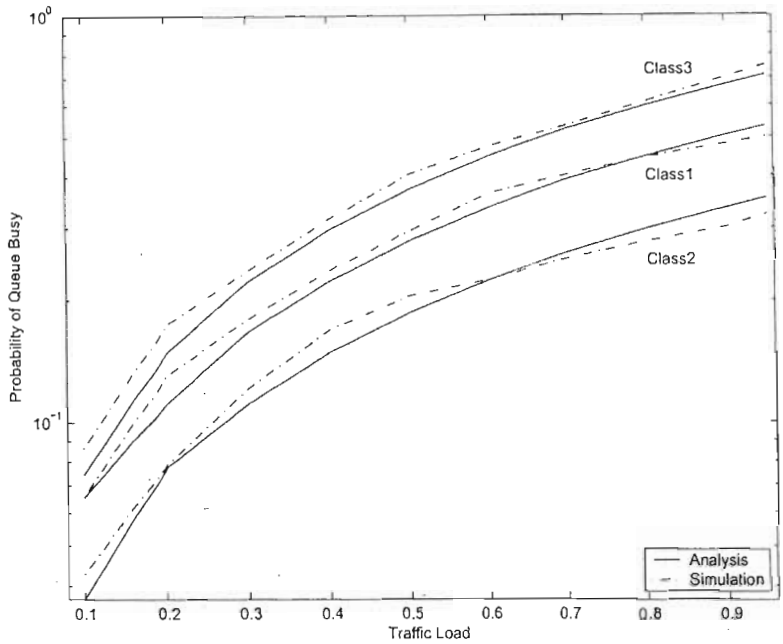


Figure 3.4: Simulation and analysis results for the probability that the queue is busy for all traffic class queues under various loading condition

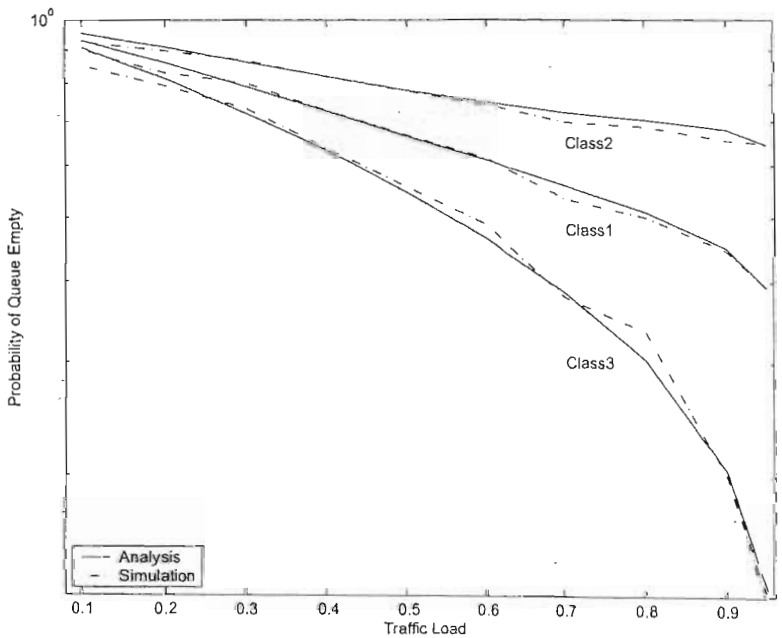


Figure 3.5: Simulation and analysis results for the probability that the queue is empty for all traffic class queues under various loading condition

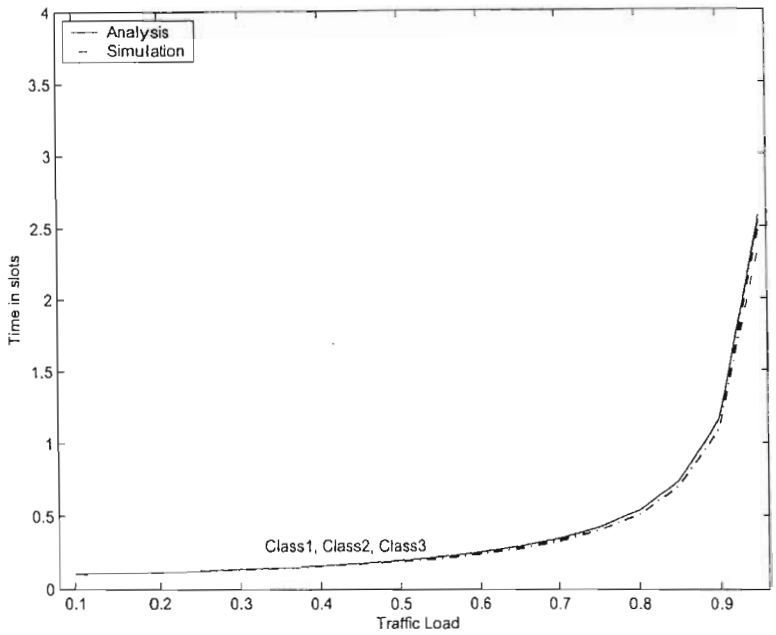


Figure 3.6: Mean time between two consecutive arrivals of the code S ($\overline{C}^{i,j}_{code,p}$) for all three traffic classes under different load condition

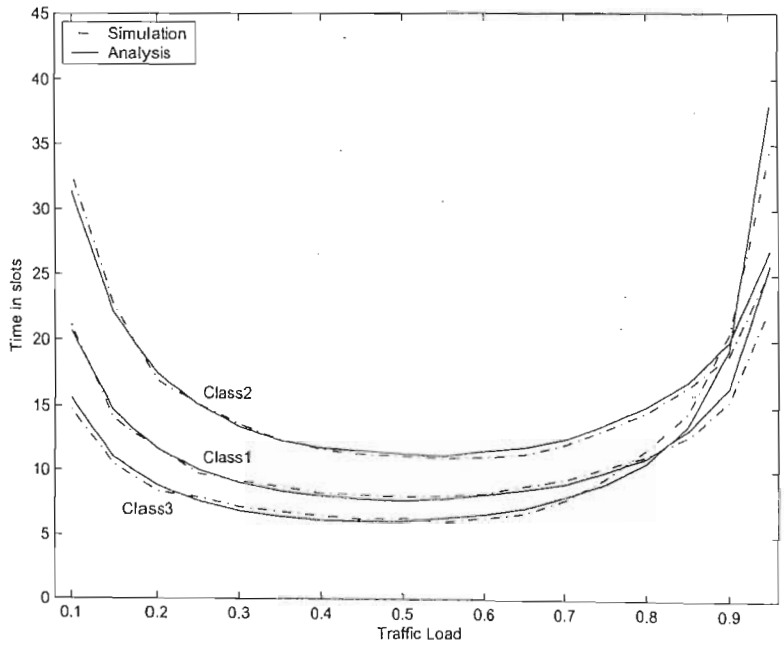


Figure 3.7: Mean time between two consecutive polls of code S ($\overline{C}^{i,j}_{code}$) for all three types of traffic classes under different load conditions

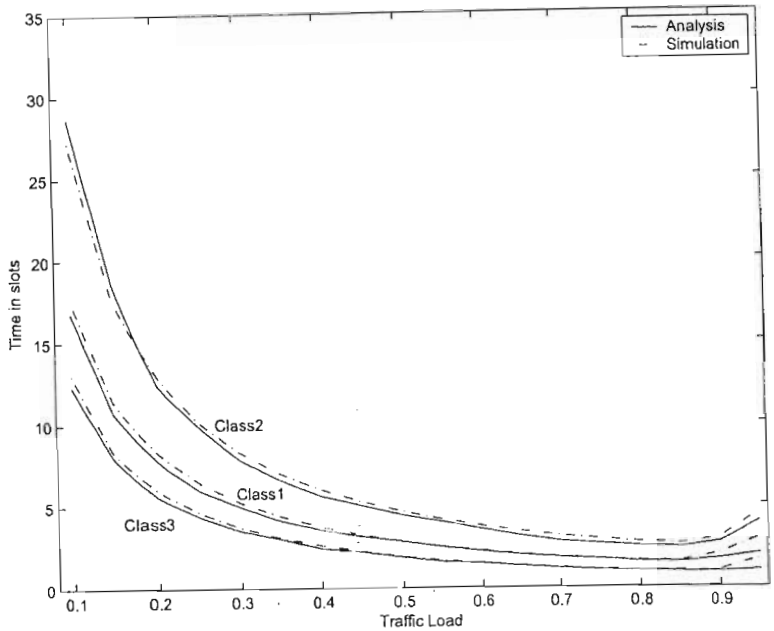


Figure 3.8: Mean vacation time ($\overline{V_i}$) for all three types of traffic classes under different load conditions

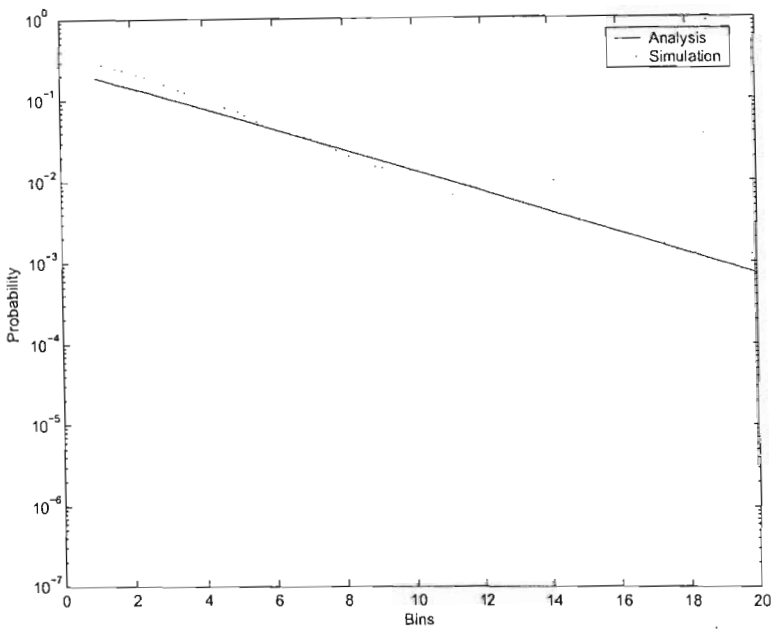


Figure 3.9 (a): Simulation and analysis results for vacation time distribution of class 1 queue

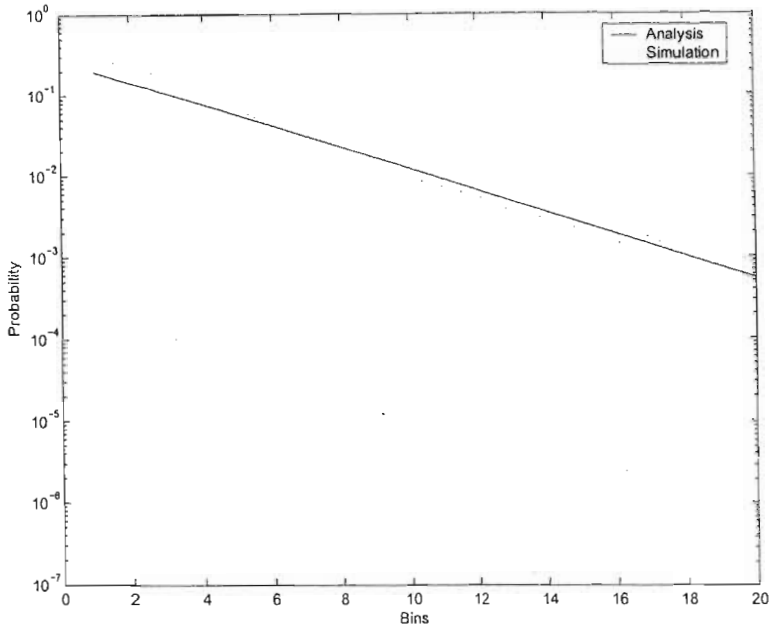


Figure 3.9 (b): Simulation and analysis results for the vacation time distribution of class 2 queue

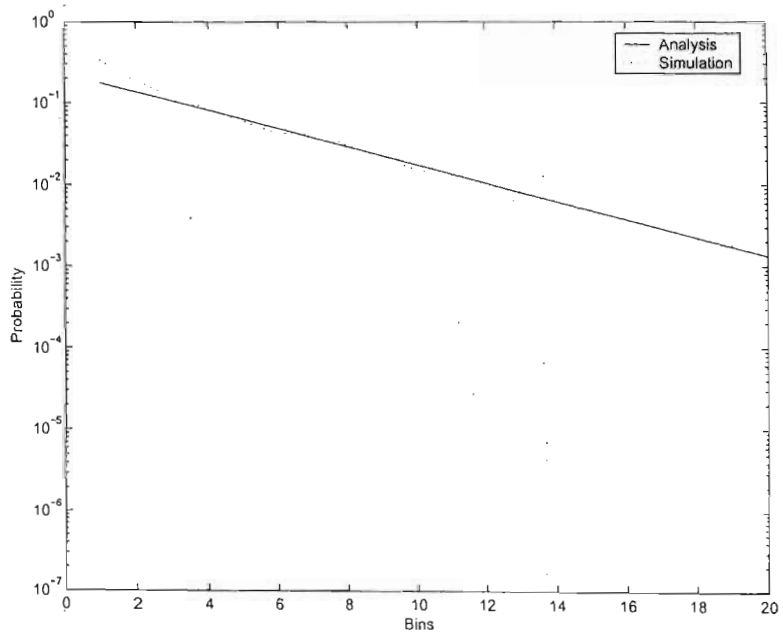


Figure 3.9 (C): Simulation and analysis results for the vacation time distribution of class 3 queue

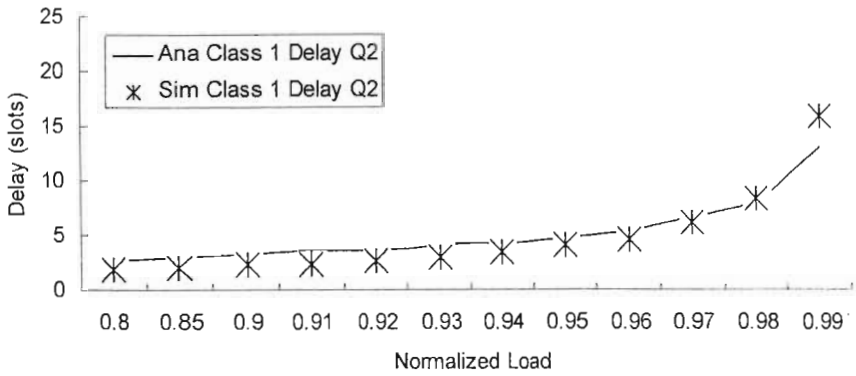


Figure 3.10 (a): Mean packet delay suffered in buffer Q_2 for class 1 queue in the network under different load conditions

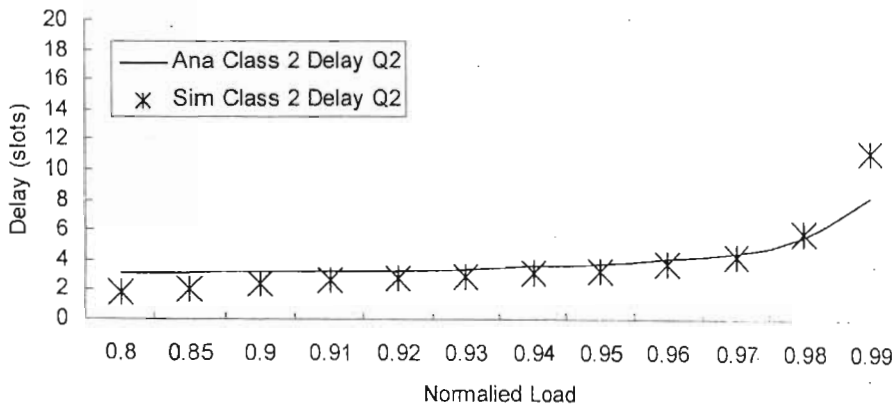


Figure 3.10 (b): Mean packet delay suffered in buffer Q_2 for class 2 queue in the network under different load conditions

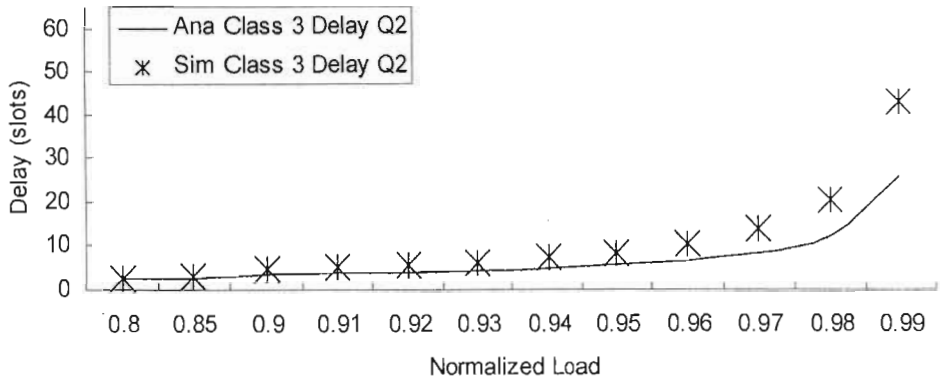


Figure 3.10 (c): Mean packet delay suffered in buffer Q_2 for class 3 queue in the network under different load conditions

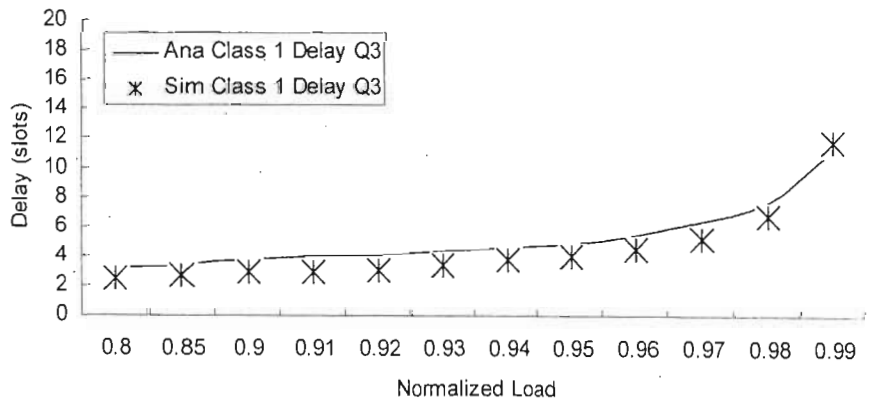


Figure 3.11 (a): Mean packet delay suffered in buffer Q_3 for class 1 queue in the network under different load conditions

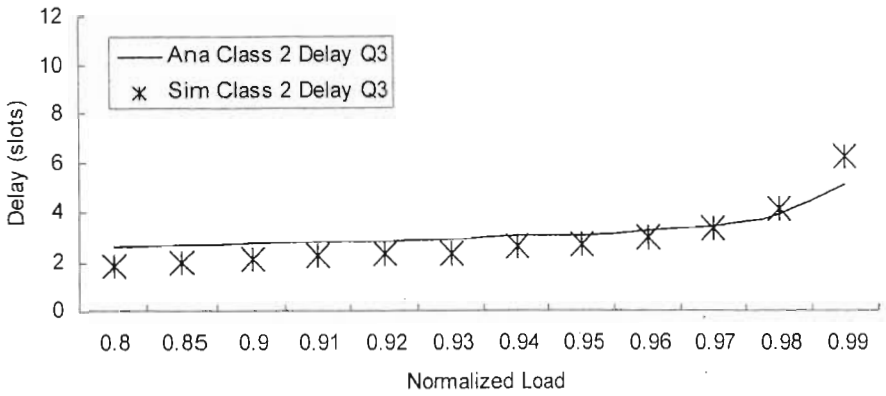


Figure 3.11 (b): Mean packet delay suffered in buffer Q_3 for class 2 queue in the network under different load conditions

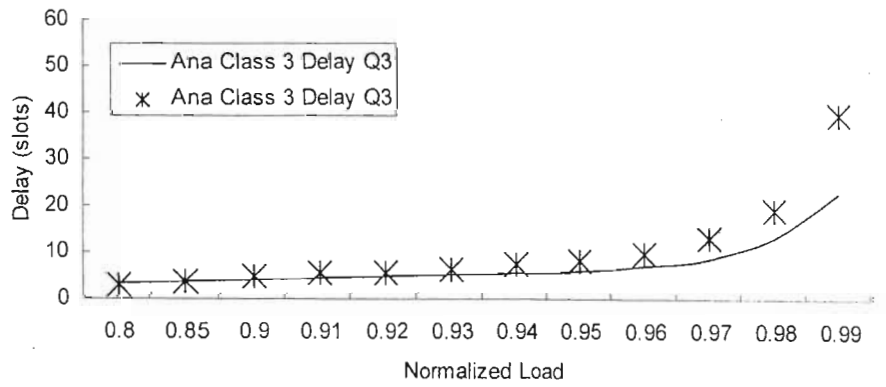


Figure 3.11 (c): Mean packet delay suffered in buffer Q_3 for class 3 queue in the network under different load conditions

3.6 Summary

In this chapter, an analytical model for the MAC scheme proposed in Chapter 2 was presented. Since the code-sharing behavior in the proposed CDMA MAC scheme resembles the token-sharing behaviour in the multiple server scheme, the proposed analytical model is therefore built based on a multiple sever multiple queue system. An approximate analysis of a MSMQ system that incorporated a data rate QoS guarantee was then presented.

The analysis started with the derivation of the approximate closed-form expressions for the mean server vacation time in the MSMQ system operating according to gated service discipline and code utilizations policies. Based on [Marsan, 1992], the server vacation time is defined as the time between the release of the CDMA code at the queue and the next arrival of the usable CDMA code at the same queue. The analysis continued by finding the relationship between vacation time and CDMA code interarrival time. The vacation model analysis concluded by deriving the relationship between the load conditions of the network and the server vacation time.

The analysis continued further with the approximate discrete time analysis of the packet departure from buffer Q_2 and for the moments of packet delay for all traffic class queue buffers. The same approach that is used by [Fiems, 2004] was used and the moments of packet delay for buffer Q_2 and Q_3 were derived. The main contributions of Chapter 3 are the presentation of the analytical model of the hybrid MAC scheme and the derivations of the mean vacation time and moments of delay of the proposed analytical model. The analysis was validated with the simulation. It was observed that the analytical results closely agreed with the simulation results. However, discrepancies can be seen under high load conditions caused by the simplifying assumptions made.

CHAPTER 4

HYBRID TOKEN-CDMA SYSTEM WITH CROSS-LAYER APPROACH

4.1 Introduction

A new research direction has recently been proposed where the cross-layer approach is used to improve the performance of wireless systems. It is suggested in [Goldsmith, 2002] that a cross-layer approach that supports multiple protocol layer adaptivity and optimization can attain significant performance gains. The design of the cross-layer protocol normally refers to the system design achieved by exploiting the dependence among protocol layers to obtain performance gains. Such design is therefore unlike layering, where the protocols at the different layers are designed independently.

Figure 4.1 illustrates the OSI-layered model and a subset of the possible cross-layer interactions that can be considered when performing a cross-layer design [Goldsmith, 2002]. To demonstrate, Figure 4.2 displays the different control flows needed to provide a cross-layer interaction between the physical and upper layers of two remote nodes. When two nodes communicate, the receiving one measures the physical state, which is generally a vector of real values. An entity named Agent Manager estimates, measures and selects the appropriate values to be sent to the upper layers of the transmitting node. These layers will accordingly adapt to the actual channel conditions, performing the cross-layer interaction.

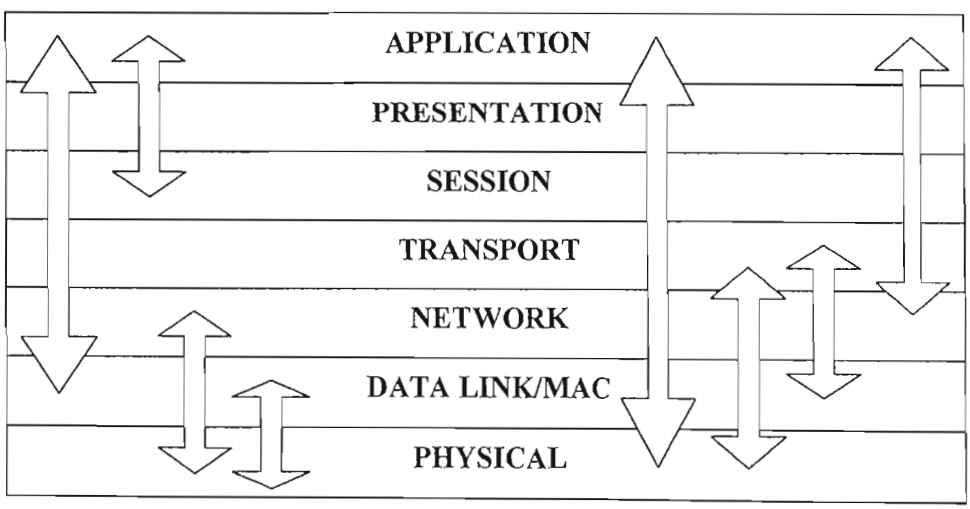


Figure 4.1: Different cross-layer design possibilities

The amount of literature on this issue is still relatively scarce and mostly at the physical layer [Sacchi, 2006], [Dimic, 2004], [Liu, 2004], [Wang, 2003], [Yeh, 2003], [Schaar, 2003], [Shakkottai, 2003], [Carneiro, 2004], [Toumpis, 2003] and [Alonso, 2003]. The authors in [Raising, 2004] present a survey of several cross-layer design proposals from the literature based on the layers that are coupled. It has been shown in this literature and references therein that from the perspective of the network, cross-layer design approach can benefit not only the nodes involved, but the whole network in many different aspects. Although originating from the physical layer cooperation, all the benefits cannot be fully realized until proper mechanisms have been incorporated at higher protocol layers (e.g., MAC, network) and the necessary information is made available from the lower layer (e.g., PHY).

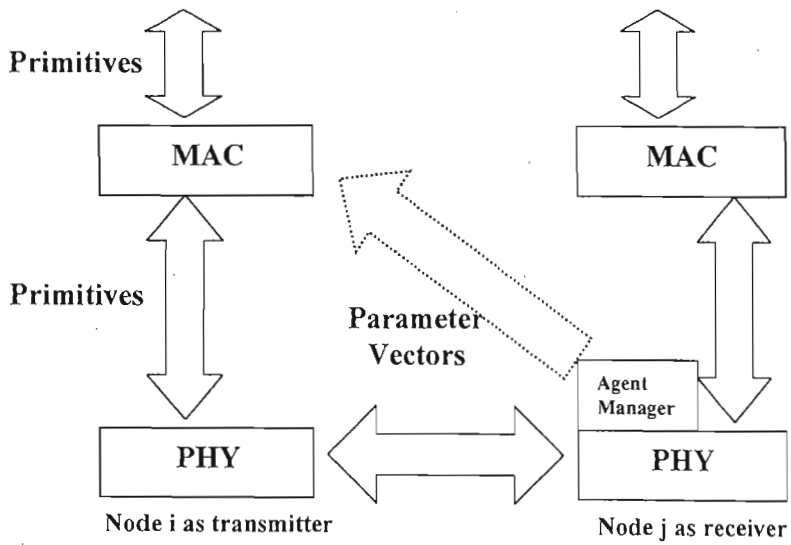


Figure 4.2: Cross-layer interaction through an agent manager

Further literature survey was conducted for CDMA system optimization using cross-layer approaches as the proposed hybrid MAC system has the characteristic of CDMA scheme. In recent years, there exist papers that propose cross-layer approaches to achieve system optimization in CDMA systems. Examples are [Alonso, 2004], [Yu, 2005], [Friderikos, 2004], [Price, 2004], [Hossain, 2004] and [Yao, 2004]. Yu proposed a cross-layer QoS guarantee by combining physical layer signal-to-interference ratio and network layer blocking probability to achieve optimum system performance. A set of PHY-MAC mechanisms is proposed by Alonso that is based on rate adaptation provided by the MAC and the channel state from the PHY to improve bandwidth allocation efficiency. Price

proposed the cross-layer interaction between MAC and transport layer, and optimised the system using dynamic rate adjustment. The data link and PHY level influence on the TCP behaviour was modeled and analysed by Hossain and the dependency between the 2 layers was proven. It is shown from the survey that abundant interpretations of "cross-layer" and resources belonging to these layers produce numerous cross-layer studies.

However, based on the survey conducted and to the best of author's knowledge, design of optimal CDMA-Token MAC schemes that consider cross-layer issues with adaptive rate technique has not been addressed in the literature. For example, [Ghavami, 2007] considers the cross-layer design that uses the relationship between the transmission mode at the physical layer and queue length behaviour at the data link layer but no MAC mechanism is involved. [Liu, 2004], and [Liu, 2005] consider the same approach where the cross-layer design only tackles the interaction of queuing at the data-link layer with adaptive rate at the PHY layer. [Lin, 2007] presents a cross-layer design where it exploits the time-varying property of the wireless link by leveraging on the MAC-PHY cross layer interaction. Adaptive channel coding and modulation (AMC) is used to adjust the data throughput by changing the amount of error protection incorporated at PHY layer. However, the goal of the cross-layer approach in [Liu, 2004] focuses mainly on reducing the energy efficiency and fairness on the PHY layer, which is different from the MAC scheme considered here.

[Alonso, 2004] proposes a cross-layer design in which that MAC algorithm estimates the traffic load and distributes rate adaptation through spreading factor selection using both the traffic information provided by MAC and channel state estimate from the PHY layer. However it is only for a CDMA MAC scheme where no hybrid token MAC interaction is considered. Moreover, from the literature survey conducted, it is discovered that majority of the conventional PHY-MAC cross layer design focuses on maximizing throughput (network utilization), the critical factor of packet latency is generally not considered in the cross-layer interaction.

This chapter presents a joint MAC-PHY solution for optimizing the system performance in the hybrid Token-CDMA MAC system. The proposed scheme is designed in order to provide continuous monitoring of the performance achieved by the users and adjusting transmission parameters using different spreading factors. Consequently, an optimization solution is formalized using one objective function, i.e. packet delay. As a result, unlike existing PHY-MAC cross layer designs which concentrate on optimizing the throughput

performance, a generic, cross-layer optimization framework is developed to determine the optimal spreading factor to be used under various traffic load conditions. The chapter is organized as follows: Section 4.2 presents the cross-layer design, paradigms, control information issues and it also outlines a classification of cross-layer mechanisms. Section 4.3 is devoted to the modeling of cross-layer framework between physical and MAC layers for the hybrid Token-CDMA scheme. Section 4.4 presents the numerical results of the cross-layer system and finally concluding remarks are given in Section 4.5.

4.2 Cross-Layer Concept

It is known from [Wang, 2003] that additional information from relating layers is needed when undertaking cross-layer designs. One example is the additional signalling needed to extract relevant parameters from one layer that could be useful for other layers. As discussed in Section 4.1, different cross-layer architectures can be envisaged. [Alonso, 2003] divide s the possible structures into two main categories. In the first category, the relating layer is modified according to the cross-layer interaction with the other layer. This means that certain parameters of the protocol stack at each layer are modified taking into account some information about the state of the other layers. The second category implements an external entity where it is used to manage the cross-layer interactions and also defines the corresponding interfaces and primitives with each layer.

4.2.1 Definition of control information for cross-layering

It is considered by [Alonso, 2003] that at least four classifications can be formed for cross-layer information:

- Channel state information (CSI)
- QoS related parameters
- Resources made available in the corresponding node
- Traffic pattern offered by each layer to the other layers

CSI includes estimation for channel impulse response, either in time or frequency domain, location information, mobile speed, signal strength, interference level and modelling, etc. Parameters that related to QoS guarantee include packet delay, throughput, bit error rate (BER), frame error rate (FER) measurements for each one of the layers involved in the cross-layer interaction. Resources that are available from the other nodes can be categorized as multi-user reception capabilities, number and type of antennas, battery depletion levels,

etc. The traffic pattern from each layer may include data traffic information, data rate, data burstiness, data fragmentation, packet sizes, information about the buffer sizes, etc.

As discussed earlier, a cross-layer approach to ad hoc network design can significantly increase the design complexity. The 7-layer OSI model are useful in allowing researchers to focus and optimize a single protocol layer design without the complexity and expertise associated of other layers. The goal of cross-layering should be keeping some form of separation, while allowing layers to actively interact; this is a good compromise for enabling interaction between layers without eliminating the layering principle. In this structure, each layer is characterized by some key parameters and they are passed to the adjacent layers to assist them determining the operation modes that will best suite the current channel and network conditions. Based on such design framework, each layer is now aware of the other layers, and interacts with them to find its optimal operational point.

The main design difficulty in the cross-layer approach for ad hoc network is in the characterization of the essential information that should be exchanged between layers. For example, the link layer might be characterized by parameters representing the link layer state information such as bit error rate (BER) or supported data rate. Similarly, the network and MAC layers might exchange the requested traffic rates and supportable link capacities. More detailed discussion on the cross-layer approach is presented in the following sections.

4.2.2 Classification of cross-layer interactions

As mentioned in Section 4.1, there exists a wide-range of possible cross-layer interactions. The cross-layer techniques can be divided into following categories:

Cross-layer inside a single node

The cross-layer design is confined inside a single node where different layers of the protocol stack communicate with each other depending on the information they exchange.

Cross-layer between nodes

In this case, mobile nodes in the network can exchange cross-layer information through a control channel, and thereby adapting their layers using measurements done in the remote node.

Two-layer interaction

It is the basic cross-layer approach involving only two layers that communicate with each other in order to optimise the transmission efficiency.

Multi-layer interaction

It is the interaction between more than two layers where each layer can adapt taking into account the information received from all the other layers.

From the classification mentioned above, the most prevalent research topic is the two-layer interaction approach. In this setup, the higher-layer protocol requires information from the lower layer at runtime, such action leads to the information exchange between the two layers. Examples of this back-and-forth information flow can be seen in the literature quoted above and it is likely to be in the form of channel-adaptation modulation or link adaptation schemes. The concept is to adapt the parameters of the transmission (e.g., power, modulation, code rate) in response to the channel condition. The vertical calibration of adjacent layers' parameters is popular amongst researchers since the performance result from the upper layer is a function of the parameters at all the layers below it. Therefore, it is assumed that joint tuning can help to achieve better performance than individual settings of parameters.

One of the most relevant areas in cross-layer optimisation is the interaction between physical (PHY) and medium access control (MAC) layers in wireless networks. This is due to the fact that the PHY layer is the most time variant entity in a wireless communications system and due to the proximity of the two layers in the OSI model stack and the inherent variability of the channel state. The MAC layer in wireless network is implemented to enable nodes to access the available channel(s) while attempting to enforce a fair and efficient usage of the channel(s). To accomplish this task, the MAC protocol makes use of input or feedback information that other layers of the protocol stack may forward to it directly or indirectly. Typically, however, the MAC layer is mostly interested in the information it receives from the underlying physical (PHY) layer regarding the state(s) of the channel(s) and/or the occurrence of any events that are key to its operation (e.g., the successful transmission of a frame over the channel). Based on the feedback information, the MAC protocol dynamically adjusts its behavior in order to better allocate the channel(s) among those competing nodes within the network.

The PHY layer, on the other hand, has the main job of receiving the bits of information from the MAC layer and, at the MAC's discretion, transmits the bits across the underlying communication channel(s) as fast and reliably as possible, according to appropriate (de)coding and (de)modulation schemes. The likelihood with which a transmission is successful will depend on how well the signaling defends against channel impairments and interference from any source. In wireless networks, in particular, the signal transmissions

from any node can potentially interfere with signal receptions at another node in the network. Hence, the quality of a radio link depends on the transmission activity in the entire system. As a result, each node's transmission activity can affect the PHY-layer performance at every node in the network, which, in turn, can affect their MAC dynamics. Clearly, the dynamics of the MAC layer is tightly connected to the dynamics of the PHY layer, and the cross-layer interactions at each node will depend, fundamentally, on the activity of every node in the network.

With this idea in mind, this chapter describes a jointly optimal design of the medium access and physical layer protocols for the hybrid Token-CDMA network. Using the cross-layer interaction, the PHY layer provides channel state information to be fed to the MAC layer and based on the information, the MAC scheme accurately estimates the traffic load and modifies the transmission rate by changing the spreading factor of each transmission. Therefore, the distributed rate adaptation [Adachi, 1997], [Adachi, 1998] through spreading factor selection uses both the traffic information provided by the MAC algorithm and the channel estimate from the PHY layer, which constitutes the cross-layer concept. A detailed description of the interaction between the two layers is presented in the following section.

4.3 Cross-Layer Modelling Framework for Hybrid Token-CDMA MAC System

The optimization framework is formalized based on end-to-end communication performance metric, the packet latency. The proposed approach is based on the interaction between the PHY and MAC layers inside a single node system and the information on both layers is used to enhance the MAC mechanism. The objective of the cross-layer dialogue is to enable the nodes to dynamically adjust the spreading factors for reducing interference thereby optimizing the system performance. In the proposed system, the code resources are controlled by means of two degrees of freedom, the frame error probability (FER_j) from the PHY layer to MAC layer and the spreading factor (N) from the MAC layer to PHY layer to be allocated to the particular node. Based on these two variables, an optimization solution is formalized using an objective function in which the cross-layer interaction is used in order to improve and reach an optimal system performance.

4.3.1 PHY-MAC Cross-layer framework

Using a similar system model as discussed in Chapter 2, the considered scenario is a wireless network where the token is created and circulated inside the network distributing the CDMA codes. The network is capable of simultaneously processing a maximum number of *M* transmissions, i.e., the maximum number of active simultaneous users supported by the network is *M*. Each active user's data is BPSK modulated and is transmitted to the receiver node asynchronously. Following the cross-layer philosophy, assume that the MAC protocol is aware of the channel state of the links between nodes. Among the functions of the MAC layer, the main objective of optimizing the packet delay is achieved where the MAC layer monitors the information forwarded from the PHY layer and its own layer and changes its transmission rate by selecting the appropriate spreading factors accordingly thereby reducing the mutual interference. Recent works in cross-layer design of PHY-MAC layers in CDMA networks demonstrated the possibility of designing more flexible collision recovery strategies [Dimic, 2004] by employing signal processing methodologies to discriminate multiple colliding frames on the medium. The effect leads to reduction in collision intervals and number of retransmissions. In this chapter, the concept is applied with the aim of enabling dynamic adaptation of the transmission parameters in order to improve data transmission performance.

PHY Layer Properties

A. CDMA System

BPSK modulation is used in the system as in Chapter 2. With the implementation of dynamic spreading factor adjustment, the current system can be denoted as a multi-rate CDMA system that supports *n* different rates or subsystems. The transmitted signal of user *k*, in subsystem *i*, is then of the form [Ottosson, 1995]

$$r_{ik}(t) = \sqrt{2P_i}\, a_{ik}(t)\, b_{ik}(t) \cos(\omega_c t + \phi_{ik}) \tag{4.1}$$

where P_i is the power of each user in the subsystem, $a_{ik}(t)$ is the modulation signal with a rectangular pulse shape of duration T_i, and $b_{ik}(t)$ is the spreading code waveform, consisting of N_i periodically repeated chips in a binary polar format with rectangular pulse shape of duration T_c (duration per chip). Therefore $T_i = N_i T_c$. The modulator phase ϕ_{ik} are modelled as independent random variables, uniformly distributed over $[0, 2\pi)$.

B. Channel Model

In mobile radio environments, the channel link performance is known to be dependent on the received desired signal strength which in turn depends on the propagation loss and shadowing. In this chapter, the shadowing effect (i.e., slow fading) is assumed to be a log-normal distributed random variable [Stuber, 2001]. Based on [Gudmundson, 1991] and [Stark, 2002], the shadowing spatial correlation is assumed to be exponential and dependent on the distance between any two separate positions and the variation is modelled as a Gaussian-Markov stochastic process.

The channel interference is approximated as Gaussian and the bit error rate performance of user i without a RAKE receiver and antenna diversity is known to be

$$BER(\gamma_i) = Q\left(\sqrt{2\gamma_i}\right) \tag{4.2}$$

where γ_i is the signal to interference ratio strength and it can be derived as [Stark, 2002]

$$\gamma_i = \frac{1}{2} \cdot \frac{\chi_i^2}{\left[\frac{N_0}{E_b} + \frac{\left[\sum_{j \neq i}^{K} \frac{R_j}{R_i} \chi_j^2\right]}{3N_i}\right]} \tag{4.3}$$

where, E_b/N_0 represents the signal-to-noise ratio (SNR), K is the number of codes that are currently being used in the system and N_i is the spreading gain used by user i, R_i is the user i's bit rate, and χ_i is a log-normal random variable representing shadowing effect of user i and can be defined as

$$\chi_i = P_i \cdot 10^{\frac{\Omega_i(s)}{10}} \tag{4.4}$$

where P_i is the power of user i and $\Omega_i(s)$ is the received co-channel interference power at location s. With the spatial correlation property of shadowing effect modelled as a Gaussian-Markov process, the spatial distance between s and $s+1$ can be represented [Gudmundson, 1991] as

$$\Omega_i[s] = \upsilon \cdot \Omega_i[s-1] + (1-\upsilon) \cdot V_i[s] \tag{4.5}$$

where υ is the spatial correlation coefficient and the received co-channel interference power $\Omega_i(s)$ is a Gaussian random variable with mean of ∂_i and variance σ^2. The term $V_i[s]$ is a Gaussian random variable with mean ∂_i and variance

$$\sigma_V^2 = \frac{(1+\upsilon)\sigma^2}{(1-\upsilon)} \tag{4.6}$$

The frame error rate is determined using the same equation in Chapter 2 as,

$$FER_{good}^{i} = 1 - \left(1 - \sum_{j=4}^{31} \binom{31}{j} \left(BER(\gamma_i)\right)^j \left(1 - BER(\gamma_i)\right)^{31-j}\right)^{\varepsilon} \tag{4.7}$$

where ε is the length of the (31, 16) BCH code.

MAC Layer Properties

The model of a MAC layer is described in Chapter 2 and a specific property is augmented into the layer. The property is to implement the rate-adaptation algorithm based on variable spreading factor principles. More explicitly, the users' MAC layer increases its transmission rate if the number of active interfering users decreases (decreases in FER). It decreases its transmission rate in response to an increased number of active interfering users. The information on number of active interfering users is forwarded to the user by the token in the network. Detailed description of the cross-layer interaction is presented in the Section 4.3.2.

4.3.2 Objective function

The optimization metric is defined as the packet delay as shown in (4.8) where it is dependent on the variable spreading factor, N_i, used by node i to transmit jth packet where the setting of N_i will effect $FER_{i,j}$, the frame error rate of node i's jth packet. The objective function (4.8) is to minimize the end-to-end packet delay (D_{min}) of the transmitted packets by monitoring and adjusting these two variables depending on the traffic load. The PHY-MAC cross-layer interaction is achieved in order to improve and reach an optimal system performance. The derivation of the term in the objective function is presented in the following sections.

$$D_{\min} = \underset{N_i}{\arg}\left(\min\left(D_{FER_{i,j},N_i}\right)\right) \tag{4.8}$$

4.3.3 Cross-layer interaction

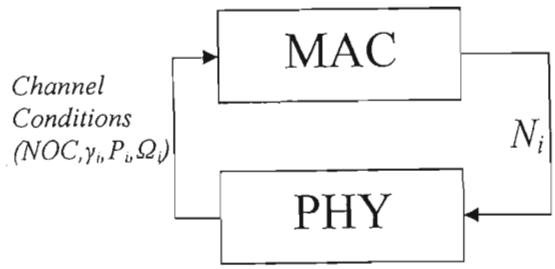


Figure 4.3: MAC-PHY cross-layer interaction

As the objective function (4.8) indicates the end-to-end packet delay is the key indicator in determining the optimum system performance. Therefore, this chapter focuses on delay optimization for the wireless system. From the discussion in Chapter 3, (3.32) ($D(z_1, z_2) \approx X_d^* \left(\frac{z_2 - b_0}{1 - b_0}, \frac{z_1 - b_0}{1 - b_0} \right)$) illustrates that the packet delay is dependent on the length of the queue where itself is dependent on the arrivals of the packets during gated queue-service time and the vacation time (3.23) ($X_{c_{l+1}} = \sum_{i=1}^{X_{c_l}} \sum_{j=1}^{g_i} B_i^j + W_{l+1}$). It is shown in the results that the packet delay increases with the increase in queue-length therefore the two are co-related and co-dependent.

From the queue length interpretations derived in Chapter 3, the length of the queue depends on the packet arrivals during the service time ($\sum\sum B_i^j$) and the code vacation time (W). The packet arrivals, service time of the packets and the code vacation time are all related to each other and the queue length can be minimized by minimizing the service time of the queued packets and the code vacation time. For the CDMA system, the packet service time ($\mu_i = \alpha_{i,j}(N_i T_c)$) is determined by the spreading factor (N_i), and for the system with no rate-adaptation, this value is fixed. In this case, in order to minimize the service time, the traffic load ($\lambda_{i,in}$) has to be low (with low packet arrivals) in which the work load ($\rho_{i,j} = \lambda_{i,tot} \cdot \mu_i^{-1}$) is dependent only on the traffic load.

For the minimization of the vacation time with fixed Ni, however, it is shown in Chapter 3 that it is minimized when the average traffic load is used. It is derived from Chapter 3 that

$V_i \approx k \cdot C_{code}^{i,j} = k \cdot \sum T_i^{trans} + \bar{l} \cdot \bar{\delta} \Big/ 1 - \frac{\sum\sum \lambda_i^j \mu^{-1}}{M}$, and under light traffic load with one N_i setting, it would result $\sum\sum \lambda_i^j \mu^{-1} \ll \mathrm{M}$ as the work load is small. Therefore the vacation time can be simplified to $V_i \approx k \cdot \sum T_i^{trans} + \bar{l} \cdot \bar{\delta}$. But value k will be high as the total number of code arrivals is high. This explains the high vacation time during the light load condition. Under high traffic load with one N_i, work load is high where $\sum\sum \lambda_i^j \mu^{-1} \approx \mathrm{M}$, therefore $\left(1 - \sum\sum \lambda_i^j \mu^{-1} / M\right) \ll 1$, in which results long vacation time.

With no control over the service time, the system mentioned above can not be optimized as the queue length and delay can not be minimized. However, if the rate-adaptation algorithm is used for dynamic spreading factor selection, both service times of the queued packets and the code vacation time can be minimized. In this case the work load is now dependent on both the traffic load and the service time of the packet where work load can be low even if traffic load is high under the circumstances that low N_i is selected for transmission. However, by selecting the low spreading factor, it can have detrimental effect on the total packet rate as it is related to retransmission rate $\lambda_{i,tot} = \lambda_{i,in} + \left(\lambda_{i,tot} \cdot FER_{i,j}\right)$, it is known from literature and shown in Chapter 3 that low N_i can cause high error rate (*FER*) which leads to increase in erroneous packets and increased the queue length. This effect can therefore lead to increase in total service time of the packets in the queue even though the service time is low with the low N_i selection.

Therefore, the best approach in minimizing the service time and vacation time is to optimize the selection of N_i from the MAC layer by monitoring its effect on the *FER* in the physical layer. This is best achieved by optimizing the work load $\rho_{j,i}$ as it is already shown above that work load is closely related to both the service time and the vacation time. The objective function (4.8) can therefore be modified to

$$\rho_{\min}^{i} = \underset{N_i, N_i \in \{\text{integer}\}}{\arg} \left(\min \left(\rho_{FER_{i,j}, N_i} \right) \right) \tag{4.9}$$

If M nodes are transmitting packets in the network (M codes are active) where $\rho_{\min}^{i} = \underset{N_i, N_i \in \{\text{integer}\}}{\arg} \left(\min \left(\rho_{FER_i(N_i, N_{i+1}, \ldots, N_{i+M})} \right) \right)$. From (4.7), it is derived that *FER* is the function of *BER* (4.2) and *BER* is the function spreading factor N_i. Therefore (4.9) is a

function of N_i. If the network has M active codes, then there will be M equations with M unknown variables (N_i), therefore to solve for (4.9),

$$\begin{aligned}
\rho_{\min}^{1} &= \underset{N_1,\, N_1 \in \{\text{integer}\}}{\arg}\left(\min\left(\rho_{FER_1(N_1,N_2,\ldots N_M)}\right)\right) \\
\rho_{\min}^{2} &= \underset{N_2,\, N_2 \in \{\text{integer}\}}{\arg}\left(\min\left(\rho_{FER_2(N_1,N_2,\ldots N_M)}\right)\right) \\
&\bullet \\
&\bullet \\
&\bullet \\
\rho_{\min}^{M} &= \underset{N_M,\, N_M \in \{\text{integer}\}}{\arg}\left(\min\left(\rho_{FER_M(N_1,N_2,\ldots N_M)}\right)\right)
\end{aligned} \tag{4.10}$$

In the real system however, each node can not determine all the N_i values, so a single node only determines its optimal N_i. To do so it would use whatever advertised N_i value from other active nodes. From the single node perspective, a dynamic work load adjustment mechanism is implemented using the rate-adaptation algorithm where the rate is modified according to the spreading factor chosen for the packet transmission. The detailed explanation of the approach is presented below.

In the initialization stage, each node that enters the network transmits data using a pre-defined set of transmission parameters that enables the highest bit-rate on the channel. In parallel, it listens to the token channel for token reception. For data transmission, it is assumed that a data packet is a frame. At MAC layer, it is assumed that there are n spreading factors having integer values ($N_i \in \{\text{integer}\}, N_{i,1} < N_{i,2} < \cdots < N_{i,n}$).

For the transmission of the frame, the spreading factor N_i is selected from the set $\{N_{i,1}, N_{i,2}, \cdots N_{i,n}\}$, based on the information forwarded from the MAC layer. The frame error rate is recorded from the previous transmission and forwarded from the PHY layer to the MAC layer (cross-layer information) as shown in Figure 4.3. At the MAC layer, a rate-adaptation algorithm is implemented where it will choose the suitable spreading factor for the transmission of the next frame.

Rate-adaptation algorithm at MAC layer

The algorithm is responsible for selecting the suitable spreading factor based on the cross-layer information forwarded from the PHY and MAC layers itself. For each packet transmission, the frame error rate is feedback to the MAC layer from the PHY layer. If the FER is high, then the algorithm will choose a higher spreading factor to counter the interference. However, it is known that high spreading gain can result an increase in packet delay. Therefore in order to efficiently maintain an equilibrium between a low FER and low packet delay, the MAC layer, in this case, monitors the load condition (ρ) of the node.

It is discussed previously that the work load is dependent on both the arrival rate and the service time, under this condition, the total packet arrival rate of node i is defined as $\lambda_{i,tot}$, where it includes retransmitted packets to node i. It is assumed that the packet buffer in node i has infinite capacity and the packet will not be dropped if it fails to arrive at the destination node. μ_i is defined as the service time of packet j, $\lambda_{i,in}$ is defined as the packet arrival rate to node i (offered load) and $FER_{i,j}$ is the approximated frame error rate of node i's jth packet.

From the basic input/output model for the queue i shown in Figure 4.4, one can easily assume that the total packet arrival rate is the summation of the offered load and the re-transmitted load. Therefore the total packet arrival rate can be derived as,

$$\lambda_{i,tot} = \lambda_{i,in} + \left(\lambda_{i,tot} \cdot FER_{i,j}\right), \tag{4.11}$$

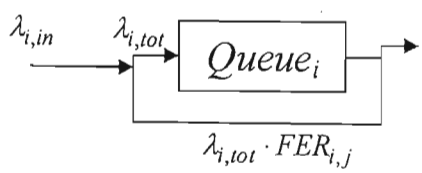


Figure 4.4: Input and output model for Queue i

Now, for the service time of the packet, it is assumed that the node i's packet j has length of $\alpha_{i,j}$ and it is also assumed that the code chip duration is set to T_c. Therefore the bit rate shown in (4.3) for user i (R_i) can be derived as $R_i=1/(N_iT_c)$. The service time can now be derived as,

$$\mu_i = \alpha_{i,j}\left(N_iT_c\right) \tag{4.12}$$

The work load as stated in previously, for the node i with packet j ($\rho_{i,j}$) can now be derived as

$$\rho_{i,j} = \lambda_{i,tot} \cdot \mu_i = \left(\frac{\lambda_{i,in}}{1 - FER_{i,j}} \right) \cdot \alpha_{i,j} N_i T_c \tag{4.13}$$

With the derivation of the work load and as discussed previously for the objective function (4.9), the system can be optimized with the minimization of the work load where both the *FER* and the spreading factor are taken into consideration.

Using this approach, equation (4.13) shows that the *FER* can be defined to be the measured quantity and the spreading factor N_i is the variable that needs to be optimized. It is commonly known that the packet delay is related to the loading condition, therefore if the low loading condition is achieved; the packet delay will also be minimized. In this case, low loading condition is attained by choosing an optimum spreading factor from the set of predefined spreading factors and it is selected based on the *FER* feedback from the PHY layer. The objective function (4.10) can now derive to be

$$\begin{aligned}
\rho_{\min}^{1} &= \underset{N_1, N_1 \in \{\text{integer}\}}{\arg} \left(\min \left(\left(\frac{\lambda_{1,in}}{1 - FER_1(N_1, N_2, \ldots N_M)} \right) \cdot \alpha_{1,j} N_1 T_c \right) \right) \\
\rho_{\min}^{2} &= \underset{N_2, N_2 \in \{\text{integer}\}}{\arg} \left(\min \left(\left(\frac{\lambda_{2,in}}{1 - FER_2(N_1, N_2, \ldots N_M)} \right) \cdot \alpha_{2,j} N_2 T_c \right) \right) \\
&\bullet \\
&\bullet \\
&\bullet \\
\rho_{\min}^{M} &= \underset{N_M, N_M \in \{\text{integer}\}}{\arg} \left(\min \left(\left(\frac{\lambda_{M,in}}{1 - FER_M(N_1, N_2, \ldots N_M)} \right) \cdot \alpha_{M,j} N_M T_c \right) \right)
\end{aligned} \tag{4.14}$$

Using the algorithm (4.14), the system performance is monitored using the frame error rate and packet delay. In this way, if few nodes are active in the network, they can exploit the available resources by decreasing their spreading factors; while as the number of nodes or traffic intensity grows, those nodes which suffer most from interference can self-adjust to different transmission parameters in order to provide a higher level of robustness. The proposed rate adaptation scheme is aimed at providing continuous monitoring of the

performance achieved by the users and selecting better transmission parameters to those who are suffering severe signal degradation due to interference.

TABLE 4.1
SYSTEM PARAMETERS

Symbol	Parameter
Number of nodes (N)	30
Number of codes (M)	15,25
$G_{spreading}$ set	8,16,32,64,128
Mean packet size ($\alpha_{i,j}$)	256 bits
Error correction scheme	BCH (16,31)
FEC correctable bits	3 bits
CDMA chipping rate ($1/T_c$)	3.84 Mcps
Modulation	BPSK
Fading channel	Log-nomal
Token walk time (T_i^{walk})	100 us
Packet buffer capacity (Ω_i)	20000
Bad state duration ($\bar{\tau}_{bad}^{i}$)	3.2 ms
Bad state PEP_{bad}^{i}	1.0
Signal to Noise Rato (SNR)	5 dB
Spatial correlation coefficient (υ)	0.82
Variance of Vi r.v.(σ^2)	7.5dB

4.4 Simulation Results

The proposed approach is validated through extensive simulations. The effectiveness of the cross-layer approach scheme and the original hybrid MAC scheme are compared for various performance metrics. The metrics used for the evaluation are throughput and queuing delay of the packets. In particular, the packet delay and throughput were evaluated as a function of the number of nodes in the system, number of codes available for the network, node bit rate and the system loading. The simulation parameters are tabulated in Table 4.1.

In Figure 4.5 (a) and (b), the code utilization graphs comparing the performance of the cross-layer hybrid scheme with normal hybrid schemes using different sets of codes are shown. Two different spreading factor settings are used, namely low spreading gain setting of 16 (displayed SG16 in the figures) and high spreading gain setting of 64 (displayed SG64 in the figures).

As discussed in Chapter 2, these plots provide an indication of the optimum code usage in the network. The code utilization is plotted against the offered load, which is defined to be the traffic created for the entire network as

$$Offered\ load = \sum_{i=0}^{N/r} \lambda_{ip}^{1} + \sum_{i=N/r+1}^{2(N/r)} \lambda_{ip}^{2} + \cdots + \sum_{i=N(N-1)/r+1}^{N} \lambda_{ip}^{r} \qquad (4.14)$$

In each figure, the cross-layer hybrid scheme's performance is compared with standard hybrid scheme that implemented fixed spreading factors. It is shown from the figures that the cross-layer hybrid scheme performed well under both code settings. With fewer codes available (Figure 4.5(a)) in the system, low spreading factor clearly has the advantages during the light load condition as the multiple access interference (MAI) is small and the frame transmission time is shorter comparing to high spreading factor.

However, the situation changes drastically when the traffic load increases in the network as shown in the Figure. The increase in the traffic has a significant effect on the frame error probability (illustrated in Figure 4.6), as the channels become more erroneous. This leads to the drastic increase in code usage as the nodes contend for the code to retransmit the packets. A cross-over of the two fixed spreading factor settings can be observed from Figure 4.5, this is expected as the FER increases with the increase in traffic load. And with the low SG16 setting, though the service time is quicker than SG64, it is more susceptible to channel noise. Therefore under light load the SG16 has better code utilization but it changes when the traffic load increases as illustrated in Figure 4.6.

The same tendency is observed with code setting of 25 (shown in Figure 4.5 (b)), the increases in the traffic load creates high packet error probability due to severe multiple access interference (MAI) as displayed in Figure 4.6. This effect is especially evident under heavy traffic load, and it is known that low spreading factor always generates high packet error rate, therefore it reaches maximum code utilization before the other two scheme due to high retransmission rate caused by high packet error rate. Using the rate adaptation algorithm and cross-layer dialogue, the cross-layer hybrid scheme is able to maintain optimum code utilization under any code setting conditions.

Figure 4.6 (a) and (b) display the frame error probability for all schemes. This metric reflects the overall system performance of the schemes. It is clearly shown in the figures that the frame error probability increases with an increase in load and the low spreading factor

scheme suffered the worst performance when either the code or the load increases. The high spreading factor and cross-layer schemes exhibit relatively consistent error probability due to their high spreading gain and dynamic spreading factor settings. It is also shown in Figure 4.6 (b) that the frame error probability for cross-layer hybrid scheme is similar to the high spreading gain hybrid scheme. This is expected since the rate adaptation algorithm dynamically chooses different spreading factors for data transmission according to traffic load condition. The algorithm finds the equilibrium between the frame error rate and spreading factor, lower spreading factor would be chosen if it is needed to minimize delay performance, and under the condition that packet error rate is still within tolerable range. This is illustrated in delay performance shown in Figure 4.8.

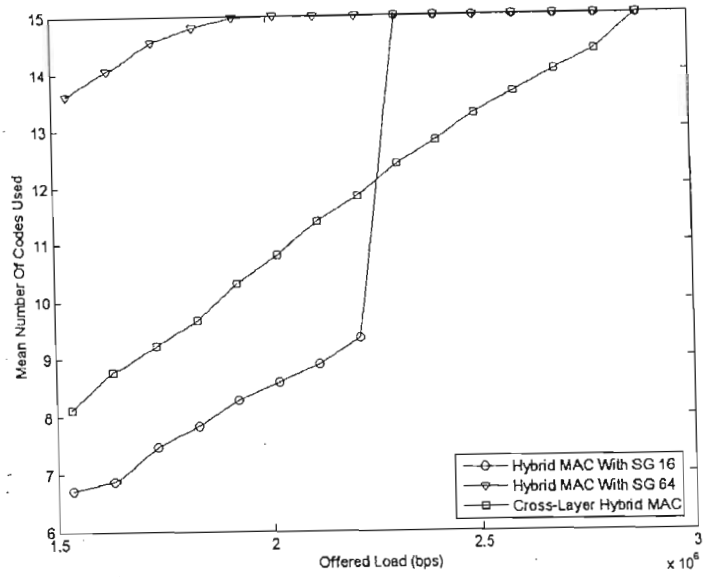
Throughput performance of all the schemes is shown in Figure 4.7 (a) and (b). Throughput is determined by the number of packets that are successfully transmitted over the simulation time. It is clearly shown from Figure 4.7 (a) that the cross-layer scheme achieves better throughput performance than other two schemes. In this figure, when the code setting is small, small spreading factor hybrid suffered the worst performance as its code setting is maximized earlier than other two schemes due to long transmission time as displayed in Figure 4.5 (a). However, as the load increases, the performance for the high spreading factor hybrid scheme quickly deteriorates with the significant increase in its frame error probability. The packets are therefore suffering from high retransmission rate, which consequently leads to stalemate of the throughput as shown in the figure. With the increase in the code setting, it is known from previous figures that the cross-layer hybrid scheme adopts the high spreading gain setting to achieve optimum performance. Therefore it can be observed from Figure 4.7 that the throughput performance of the high-N_i scheme and cross-layer scheme are similar as the offered load increases.

The packet delay has been denoted in Chapter 2 as the time period from the time when a packet arrives at the front of buffer Q_i of a node to the time it is successfully transmitted to the intended receiving station. Figure 4.8 (a) and (b) display the mean packet delay for all schemes respectively. From Figure 4.8 (a), it is clearly indicated that the cross-layer hybrid scheme outperformed the other two schemes. Under the small code setting condition as shown in Figure 4.8 (a), it is observed that high spreading factor hybrid scheme suffered the worst delay performance during light-medium load condition. This corresponds to the discussion earlier and also the low spreading factor hybrid scheme experiences longer packet delay than the cross-layer hybrid scheme with the increase in load.

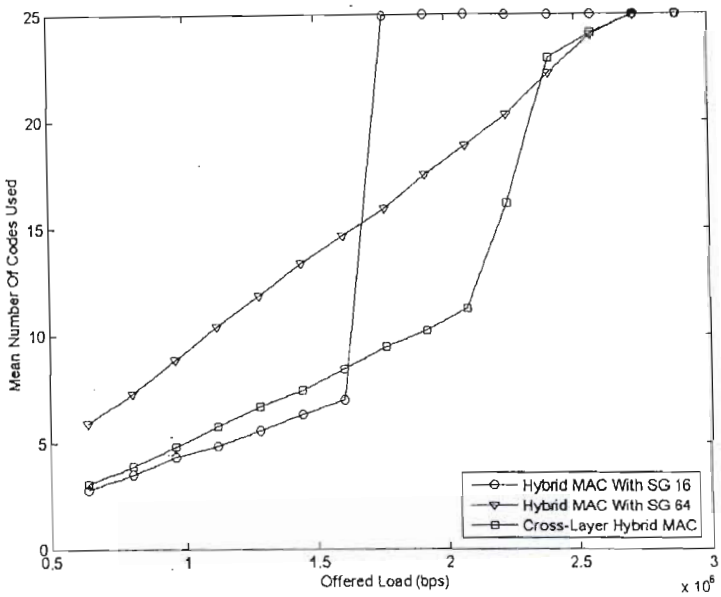
This is predicted as the rate adaptation algorithm is implemented to choose an optimum spreading factor for data transmission. To illustrate the effect of high *FER* on the long transmission time, Figure 4.10 displays the mean delay suffered for all three schemes with delay limit of 12s. It can be seem that as the load continues to rise, low spreading factor eventually underperforms the other two schemes due to its high packet error rate as discussed previously. The same tendency is observed in Figure 4.8 (b) but in this case the cross-layer algorithm adapts to high spreading gain setting during high load condition in order to achieve optimum performance as discussed earlier.

The plots in Figure 4.9 (a) and (b) display the lengths of the buffers of all schemes under different traffic load conditions. It can be clearly seen that the mean buffer length results complement the mean packet delay as shown in Figure 4.8 as the buffer length shares the similar characteristics with the packet delay.

As the packet waiting time increases, more packets would have to be queued inside the buffer before receiving service. This is especially evident when the system is under a heavy traffic state, during which the length of the buffer increases drastically. In this case, low spreading factor hybrid scheme performed well under low load condition and suffered large queue length due to high packet delay as soon as the traffic load increase. Similar mean buffer length can be observed during high load condition for cross-layer and high spreading gain hybrid scheme. The result correlates to the mean packet delay results shown in Figure 4.8 (b).

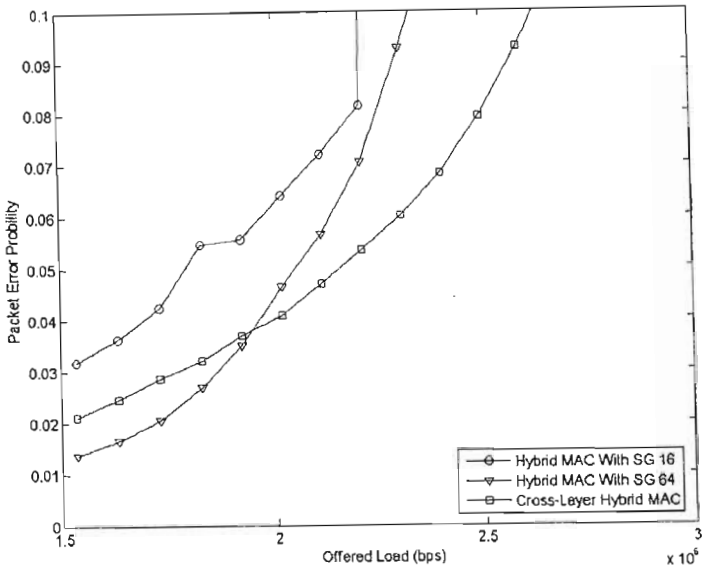


(a)

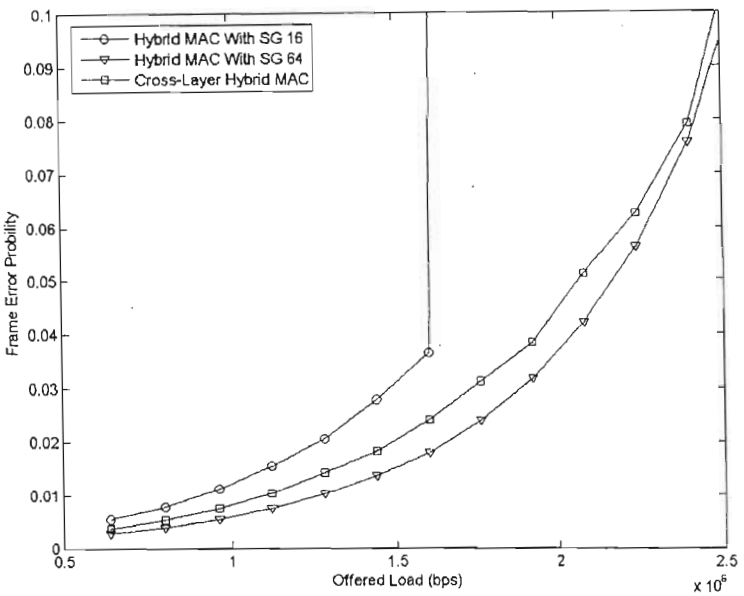


(b)

Figure 4.5: Code utilization of standard hybrid protocol with different spreading gain settings and hybrid MAC protocol with cross-layer optimization with (a) 15 and (b) 25 CDMA codes assigned in the system under different load conditions

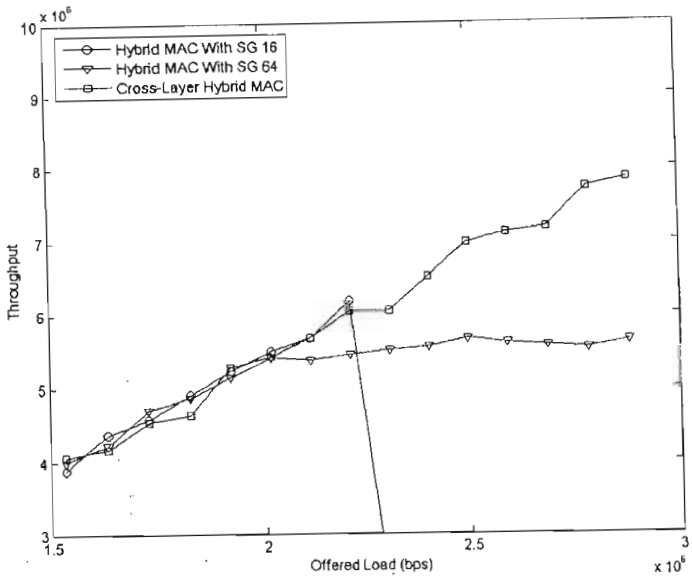


(a)

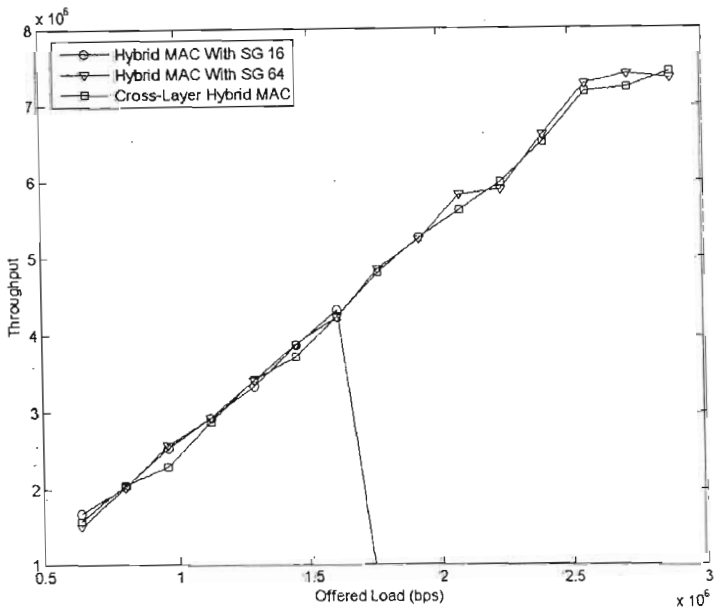


(b)

Figure 4.6: Packet error probability of standard hybrid protocol with different spreading gain settings and hybrid MAC protocol with cross-layer optimization with (a) 15 and (b) 25 CDMA codes assigned in the system under different load conditions

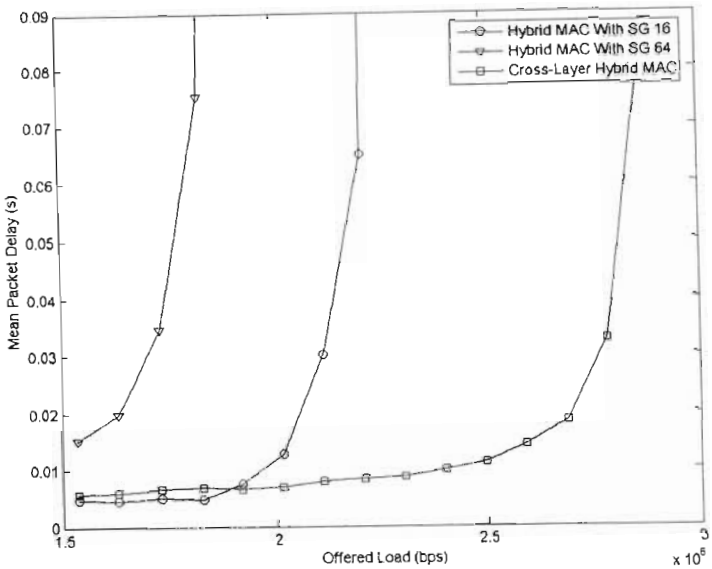


(a)

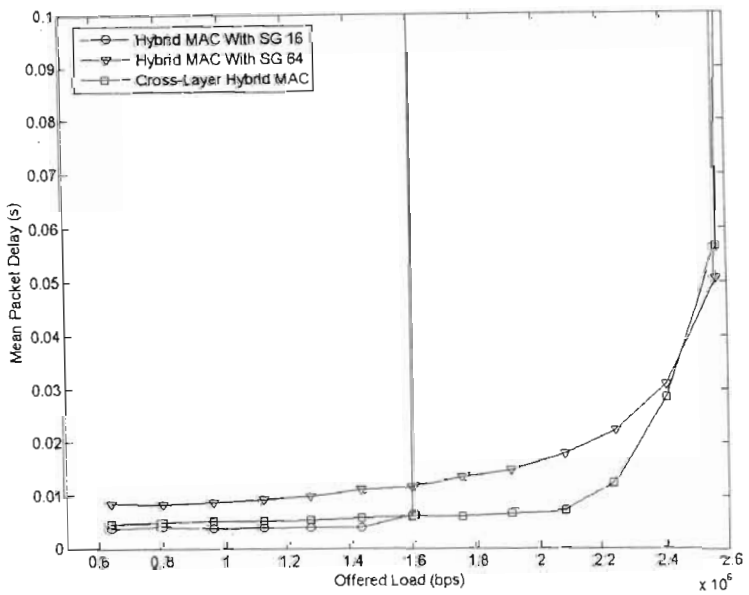


(b)

Figure 4.7: Throughput of standard hybrid protocol with different spreading gain settings and hybrid MAC protocol with cross-layer optimization with (a) 15 and (b) 25 CDMA codes assigned in the system under different load conditions

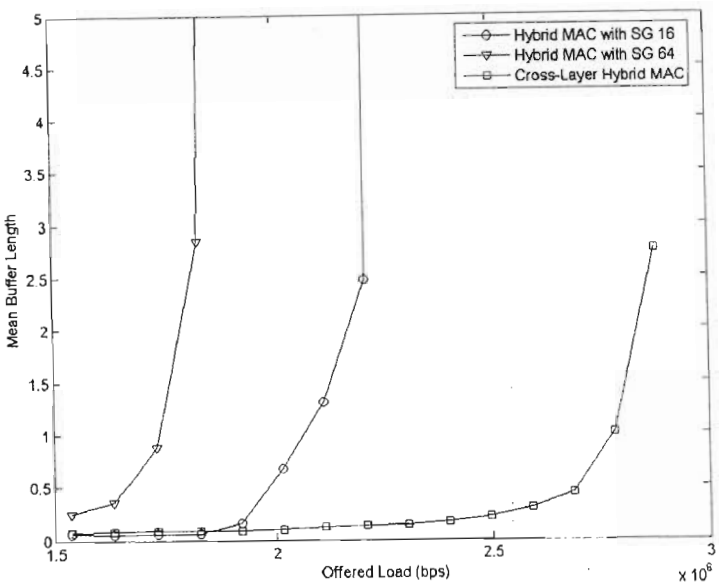


(a)

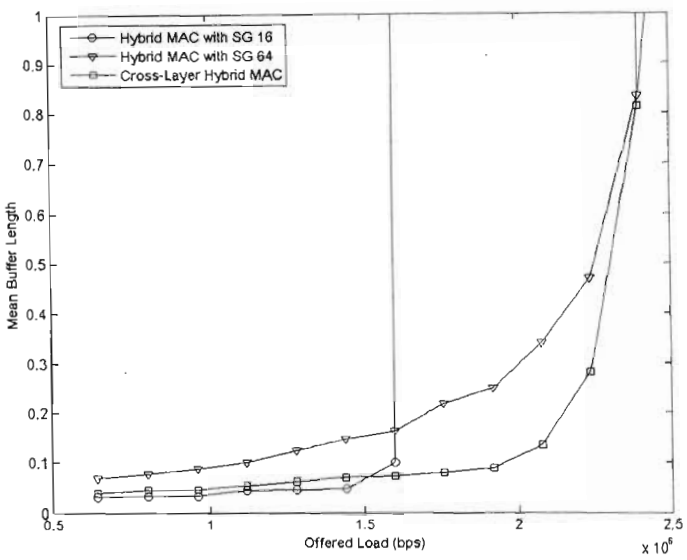


(b)

Figure 4.8: Mean packet delay of standard hybrid protocol with different spreading gain settings and hybrid MAC protocol with cross-layer optimization with (a) 15 and (b) 25 CDMA codes assigned in the system under different load conditions



(a)



(b)

Figure 4.9: Mean buffer length of standard hybrid protocol with different spreading gain settings and hybrid MAC protocol with cross-layer optimization with (a) 15 and (b) 25 CDMA codes assigned in the system under different load conditions

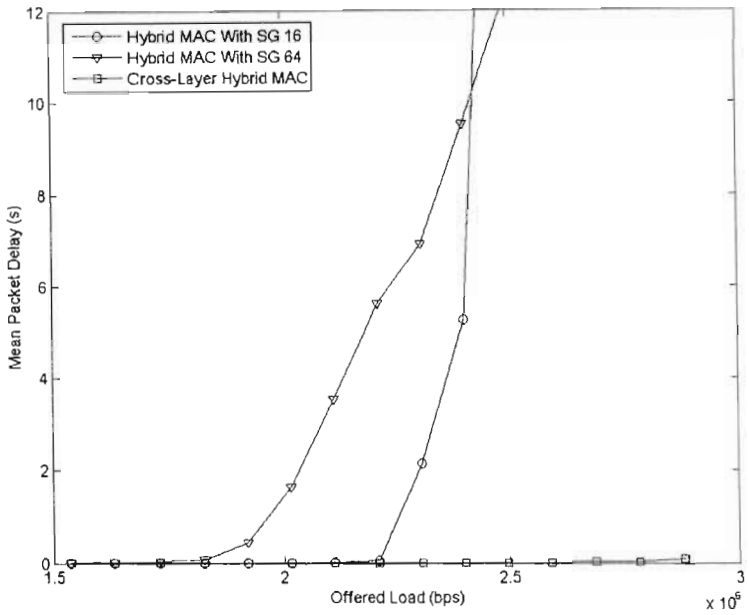


Figure 4.10: Mean packet delay of standard hybrid protocol versus hybrid MAC protocol with cross-layer optimization with 15 CDMA codes assigned in the system that illustrates the change of performance with the fixed spreading gain settings.

4.5 Summary

Cross-layer techniques in which different layers of wireless communication systems interchange control information in order to optimize the use of the scarce bandwidth are proven to be a relatively unexplored research area where tremendous potential benefits can be achieved. In this chapter, a PHY-MAC cross-layer approach for hybrid token-CDMA based wireless networks has been presented.

To account for the effects of both cross-layer interactions and the interference among all nodes, a novel model was introduced with which topology and PHY/MAC-layer aspects are naturally incorporated into the nodes. The model is used to build a bridge between the physical and MAC layers and to balance the efficiency and fairness of resource allocation. In particular, the necessary and sufficient condition for finding an optimum system performance for the hybrid scheme is investigated when rate-adaptation algorithm is used. The cross-layer interaction improves the spectrum efficiency, keeping the packet delay at the minimum possible value for different code and traffic load settings.

CHAPTER 5

CONCLUSION

In this final chapter, the work presented in this thesis is summarized and concluded. In addition, several avenues for future research in the area of hybrid token-CDMA MAC scheme is discussed.

5.1 Conclusions

This thesis began by introducing the structure of the wireless network, followed by a brief review of the relevant existing literature on wireless MAC protocols. The section examined the protocols that are used in distributed ad hoc wireless networks. Ad hoc MAC protocols use an ad hoc topology, in which each device in the network has the same functionality and is free to manoeuvre in the network. Collision avoidance algorithms are comprehensively used in these types of networks. The focus of this thesis is on distributed wireless networks, and hence more time was spent investigating the various protocols that were proposed. Next, the protocols proposed, known as hybrid networks was examined. Normally, a network is denoted as an ad hoc network when it is formed without any central administration and it consists of mobile nodes that use a wireless interface to send packet data. However, in a hybrid network, there is a centralized administrator (e.g. a mobile BS) in the network.

In Chapter 2, building upon a token passing strategy, a new concept of data transmission assignment was introduced. This concept allows the token to be constantly circulating in the distributed network, with transmission being granted by distributing CDMA codes to the mobile device, eliminating the problem of hidden and exposed terminals. Based on this concept, the token passing based code assignment protocol was developed. The hybrid token-CDMA protocol not only provides guaranteed access for each node in the network, it also has unrivalled advantage over the CDMA type protocol where the codes are now dynamically assigned rather than fixedly allocated to the node. With hybrid MAC protocol's architecture, the network is able to support more nodes than the conventional CDMA network where it has the user-constraint due to severe interference caused by users. With the increasing popularity of multimedia applications, quality of service is an important part of the MAC protocol design. Therefore, data rate quality of service guarantee was incorporated

into the proposed MAC scheme. Data rate QoS is implemented to ensure fairness and it is enforced using modified leaky bucket mechanism. Simulation model was then setup where it comprises of system, input traffic and wireless channel error models. The proposed hybrid protocol was then evaluated through event driven computer simulations. The results obtained give a clear indication that the hybrid protocol outperformed both the wireless token ring (WTRP) and CDMA MAC systems.

Chapter 3 presented the analytical model and approximating methods for analyzing the hybrid MAC scheme. The scheme's analytical model is built based on the multi server multi queue (MSMQ) framework where the CDMA codes were assumed to be servers and nodes are queues. The queue model within the system consists of three sub-models; they are the input, buffer and vacation models. The analysis started with the derivation of the mean server vacation time for the vacation model of the system. The probability generating function for the packet departure process for the input model was then derived. Using the discrete time approach, the vacation model and input model were merged with buffer model and the moments of queue length and the packet delay were derived. Numerical results were presented where the analysis results were compared with the simulation results. It can be observed that the analysis results compares favorably to the simulation, although the analysis presented is approximate and the simplifying assumptions cause deviations from the simulation results at heavy loads. It may, however, give insight into a more accurate approximate analysis.

Chapter 4 presents the cross-layer concept in which a joint physical and medium access control layer optimization was proposed for the hybrid token-CDMA scheme. This chapter began by providing a comprehensive overview of the cross-layer concept and structures. The approach used to establish the link between the PHY and MAC layer was then discussed. Using the cross-layer interaction, the PHY layer derives the optimum number of simultaneous communications to be handled and the MAC scheme estimates the traffic load and modifies the transmission rate by changing the spreading factor of each transmission. As a result, distributed rate adaptation through spreading factor selection uses both the traffic information provided by the MAC and the channel estimate from the PHY layer, which constitutes the cross-layer concept. The simulation model and parameters were then presented, and the model was simulated in an event driven program. The results have shown that the cross-layer interaction proves to improve the spectrum efficiency, keeping the packet delay at the minimum possible value for different traffic load.

5.2 Future Work

During the course of this research, there were issues that had the potential to improve further the overall performance of the system, but have fallen outside the research scope. One of them is taking the effects of multi-ring configuration into consideration. It would be valuable to investigate the cross ring activity interaction and monitor the packet transmission activity, together with the system performance evaluation. Secondly, it is also assumed that near-far problem is mitigated using the MUD and perfect power control. However, the near-far problem is a commonly existing hindrance to the CDMA-based systems. It would be worth investigating the methods to thoroughly resolve near-far problem. Lastly, although the hybrid MAC scheme investigated the mobility of nodes in a wireless single-hop environment, it would be worth researching how the scheme would behave in the more complicated multi-hop system. In addition, it is proven that cross-layer design improves the system performance. Given that the PHY and the MAC layers play such a fundamental role in the performance of any wireless networks and because all other layers in the protocol stack rely on the PHY/MAC performance. The focus on the modeling of PHY/MAC layer interactions deserves a study on its own, and it should be fully exploited in the design and optimization of wireless networks. Current interaction between the PHY and MAC layers can be extended to incorporate the upper layers. As future work, the modeling framework can be extended to incorporate the impact of network routing operations from upper layers (network layer) or the impact of transport layer protocols, such as transport control protocol (TCP) used in the internet and its variants designed for ad hoc networks.

A protocol based on token passing code assignment has the potential of providing a flexible and intelligent accessing control to the wireless channel in distributed networks. Although the hybrid MAC protocol achieves greater performance than the current WTRP and CDMA MAC protocols, it could be further improved by incorporating several other factors that have been described earlier. This is left for further research.

APPENDIX A

PSEUDO CODES FOR HYBRID MAC PROTOCOL

```
TokenEvent()
1 QInfo[i].x_j, j ∈ {1,2,3}, NOP_i = QInfo[i].x_1,
2 ANOC_i = QInfo[i].x_2, TX_i = QInfo[i].x_3
3 if (TX_i = = 0 && NOP_i != 0)
4   if (QInfo[i].HasCode = = 1)
5       TInfo.AddNoc()++, Tflag = 1
6   if (Tflag = = 0 && ANOC_i > 0)
7     if (NOP_i != 0)
8       QInfo[i].SetPackTrans(NOP_i)
9       NOC- -, QInfo[i].CaptureCode()
10      MonitorTokenNextVisit()
11 if (TX_i = = 0 && NOP_i != 0)
12  if (QInfo[i].HasCode = = 1)
13    NOC++
14    TInfo.AddNoc()++
15    MonitorTokenNextVisit()
16 if (TX_i = = 1)
17  MonitorTokenNextVisit()
18 ChannelErr =
CEM→ActivateModel(SimTime, ANOC_i)
19 if (ChannelErr = = 1)
20   if (TInfo.GetFailTX(i) ≤ ErrTrial)
21     TInfo.SetFailTX(i)++
22     TInfo.SetNextVisitTime(), TrialFlag = 1
23   if (TrialFlag == 0 &&
TInfo.GetFailTX(i)> ErrTrial)
24     TokenORNodeLostAction()
25     TInfo.SetFailTX(i)++
26     TInfo.SetNextVisitTime(), TrialFlag = 1
27 if (ChannelErr = = 0)
28   if (TInfo.GetFailTX(i) > 0)
29     TInfo.ClearErrCounter()
30   TInfo.NextQ(TInfo.FindNextQ)
31   TInfo.SetNextVisitTime()
32 Event_Table[event_number] =
TInfo.GetNextVisitTime()
33 event_number++
PackGenEvent()
34 for ( ∀ i, node_i ∈ G)
35   if (QInfo[i].GenPackTime = = SimTime)
36     q = i
37 if (QInfo[q].LoadPack() < BufferLimit)
38   QInfo[q].PacketBuffer()++
39   QInfo[q].SetNextPackGenTime()
40
Event_Table[event_number]=QInfo[q].GetPackG
enTime()
41  event_number++
PackTXEvent()
42 flagA = 0, PAC = 0, counter = 1
43 for ( ∀ i, node_i ∈ G)
44   if (QInfo[i].PackTXTime = = SimTime)
45     q = i
46 QInfo[q].PackTX() - -
47 while (counter > 0)
48   while (flagA != 1)
49     flagA = 0
50       if (PInfo[PAC].TX() = = 2)
51         PAC_counter - -
52           for ( ∀ j, PAC ≤ j ≤ PAC_counter)
53             PInfo[j] = PInfo[j+1]
54             flagA = 1
55   flagA = 0, PAC = 0, counter - -
56 if (QInfo[q].LoadPack() > 0)
57
Event_Table[event_number]=QInfo[q].NextPackT
XTime()
```

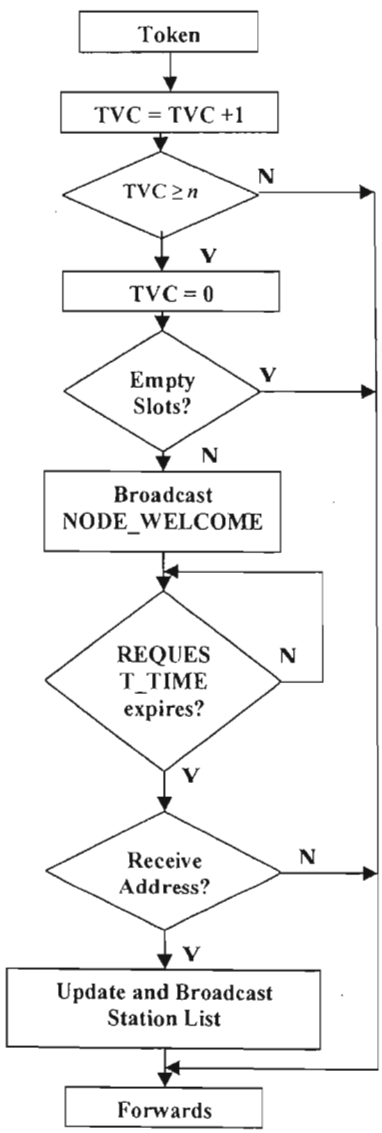
```
PermitGenEvent()
60 for ( ∀ i, node_i ∈ G)
61   if (QInfo[i].GenPermitTime = = SimTime)
62     q = i
63 if (QInfo[q].LoadPermit() <
PermitPoolLimit)
64   QInfo[q].Permit()++
65   QInfo[q].SetNextPermitGenTime()
66
Event_Table[event_number]=QInfo[q].GetPmt
GenTime()
67  event_number++
ChannelErrorEvent()
68 Time_OFF = SimTime + T_off
69 Time_ON = SimTime + 1 / ((1/T_off)/P_GOOD)-(1/T_off)
70 CEM→UpdateModelPeriod (Time_OFF +
Time_ON)
71 Event_Table[event_number]=
CEM→GetModelPeriod()
72  event_number++
MMPPEvent()
73 TQueue = 0, Cflag = 0
74 for ( ∀ i, node_i ∈ G )
75    if (Cflag = = 0 &&
       SimTime = =
QInfo[i].GetNextMMPPTransisionTime())
76     TQueue = i
77     Cflag = 1
78 if (Cflag = = 1)
79   QInfo[TQueue].SetNextMMPPTime(0,
SimTime)
80   Event_Table[event_number] =

QInfo[TQueue].GetNextMMPPTransisionTime
()
81   event_number++
TokenORNodeLostAction()
82 FailNodeErrCount++,
TInfo.SetFailTX(Dqueue,0)
83 FailQueue = TInfo.FindNextNode()
84 TInfo.RemoveNodeFromNodeList(FailQueue)
85 for ( ∀ i, i < eventno)
86   if (QInfo[FailQueue].PackTime() = =
Event_Table[i])
87     Event_Table[i] = SimTimeExceedLimit,
event_number--
88   if (QInfo[FailQueue].PermitTime() = =
Event_Table[i])
89     Event_Table[i] = SimTimeExceedLimit,
event_number--
90 if (QInfo[FailQueue].Txmit()= =1)
91   for ( ∀ i, i<eventno)
92     if (QInfo[FailQueue].TransTime() = =
Event_Table[i])
93       Event_Table[i] = SimTimeExceedLimit
94       event_number--
95   QInfo[FailQueue].ClearCode()
96
TInfo.AddNOC((TInfo.GetNOC()+1),FailQueue)
97 else
98   if (QInfo[FailQueue].HasCodeOrNot()= =1)
99     QInfo[FailQueue].ClearCode()
100
TInfo.AddNOC(TInfo.GetNOC()+1,FailQueue)
101   QInfo[FailQueue].CleanQueue()
102 Ftemp_packet_counter = packet_counter
103 for ( ∀ i, i<packet_counter)
104   if (PInfo[i].InWhichQueue() = = FailQueue)
105     PInfo[i].SetPacketFlag()
106     LostNodePacs++
107 while (LostNodePacs > 0)
108   while (flagA != 1)
109     flagA = 0
110       if (PInfo[PAC].Txmited() == 2)
111         Ftemp_packet_counter--
112           for ( ∀ j, j = PAC, j <
packet_counter)
113             PInfo[j] = PInfo[j+1], flagA = 1
114       flagA = 0, PAC = 0, LostNodePacs--
```

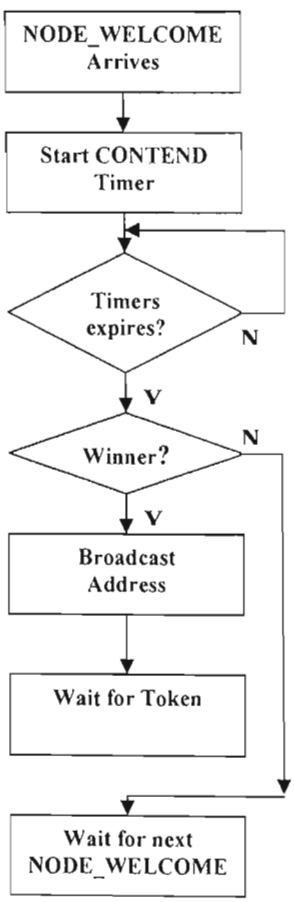
APPENDIX B

FLOW CHART OF THE INSERTION ALGORITHM FOR

a) sender stations b) contender stations



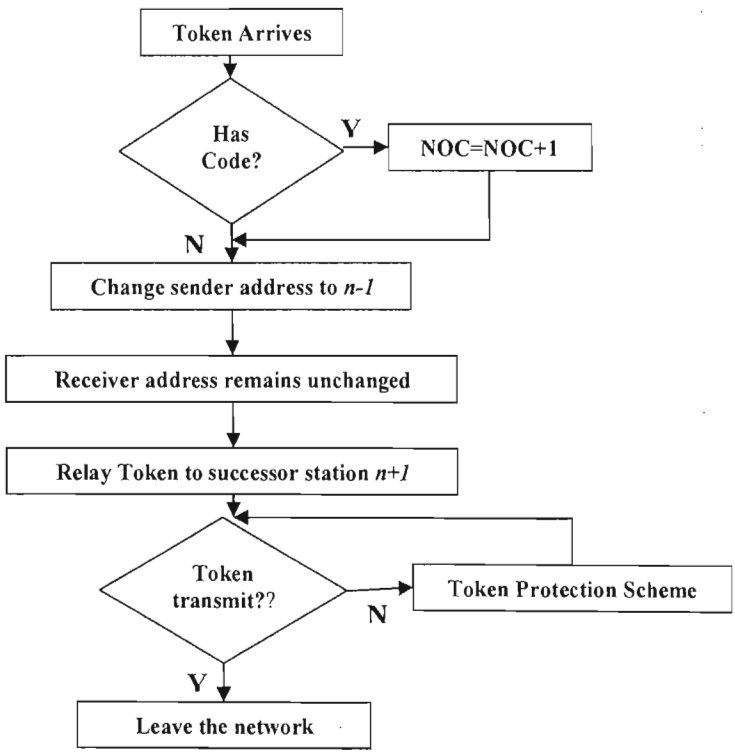
a)



b)

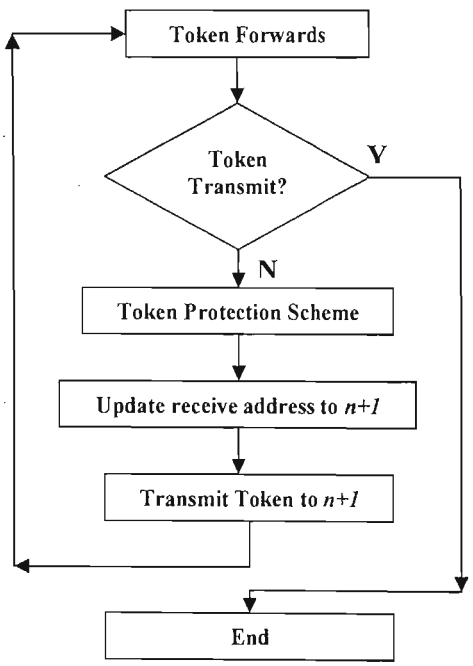
APPENDIX C

FLOW CHART FOR RESOLVING LEAVE-ON-DEMAND STATIONS



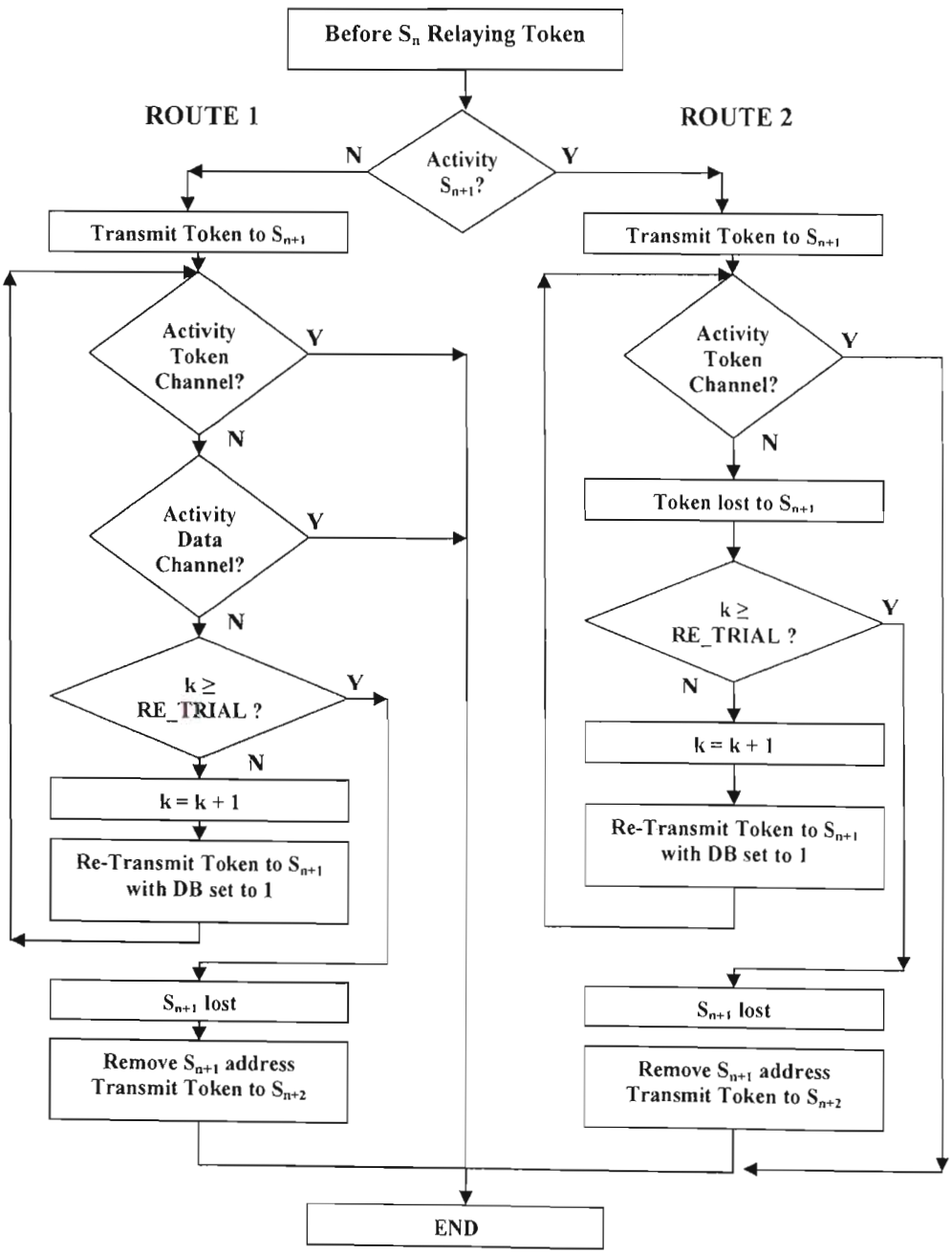
APPENDIX D

FLOW CHART FOR REOLVING SUDDEN DEATH STATIONS



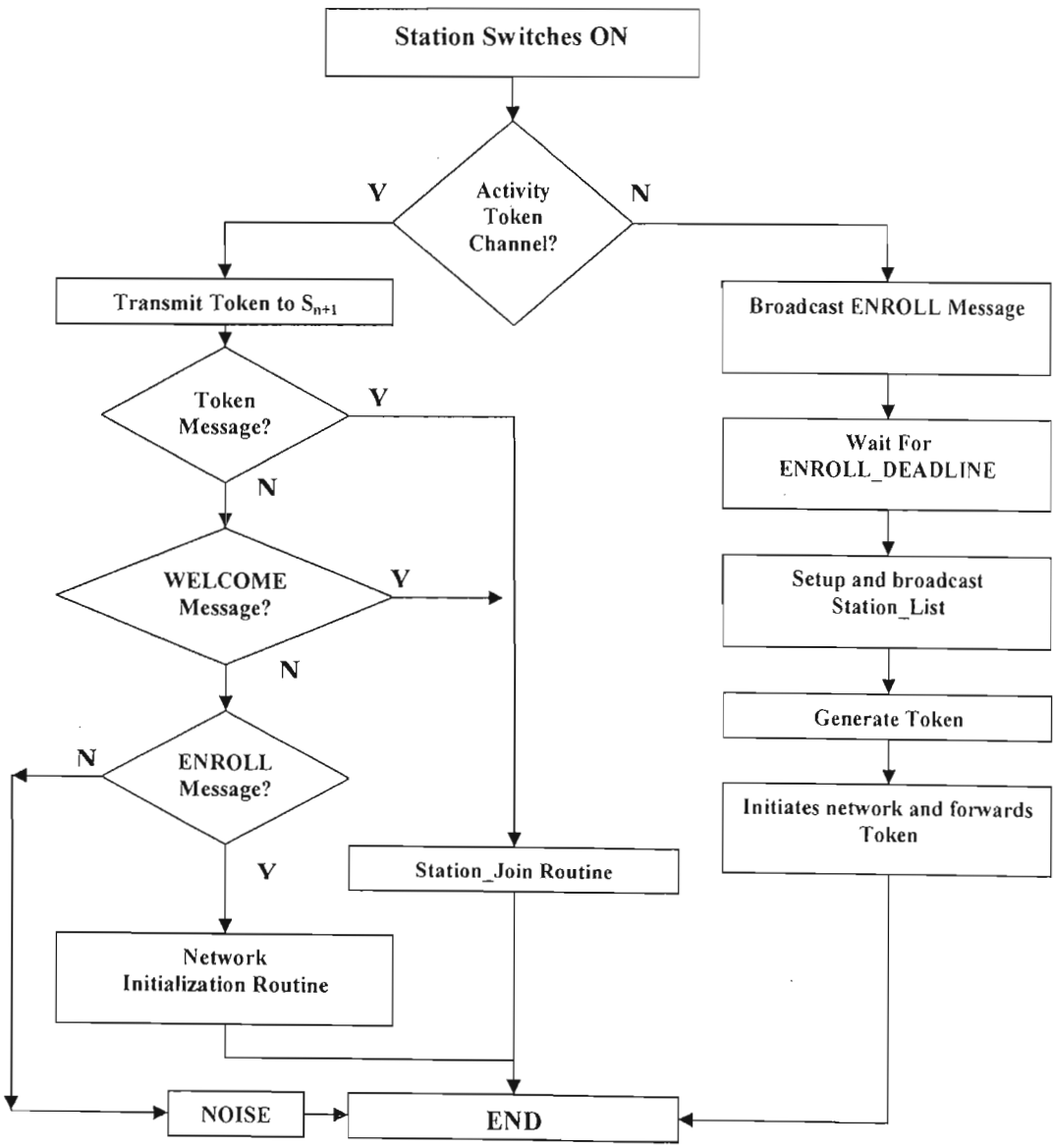
APPENDIX E

FLOW CHART FOR TOKEN PROTECTION SCHEME



APPENDIX F

FLOW CHART FOR NETWORK INITIALIZATION



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