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Modelos de Desempeño y Optimización del Rendimiento de Transmisión en Redes Metropolitanas Heterogéneas

Tesis presentada por:
Martha María Hernández Ochoa

para obtener el grado de:
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Director de Tesis:
Dr. Mario Angel Siller González Pico

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Performance Models and throughput Optimization for Heterogeneous Metropolitan Networks

A thesis presented by:
Martha María Hernández Ochoa

to obtain the degree of:
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Thesis Advisors:
Dr. Mario Angel Siller González Pico

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Por:
Martha María Hernández Ochoa
Ingeniero en Ciencias Computacionales
Universidad de Guadalajara 2003-2007

Becario de CONACYT, expediente no. 219148

Director de Tesis:
Dr. Mario Angel Siller González Pico

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Master of Science Thesis
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Resumen

Las redes heterogéneas son redes interconectadas con diferente software, protocolos, hardware, velocidades de transmisión, etc. Existen factores que afectan la eficiencia de transmisión en estas redes, los cuales incluyen: retardo (Delay), protocolos de acceso al medio (MAC), tasa de paquetes perdidos (Loss Packet Ratio), Jitter, tamaño optimo del paquete, ancho de banda (bandwidth), entre otros. Existen modelos matemáticos de desempeño para analizar el comportamiento de redes homogéneas pero hay pocos modelos que analizan redes heterogéneas.

La red metropolitana analizada está integrada por los estándares IEEE 802.11 y IEEE 802.16. Nos enfocamos en los factores descritos anteriormente que afectan el desempeño de la red. Proporcionamos un estudio analítico de algunos factores como son: el retardo fin a fin, tasa de pérdida de paquetes, el throughput fin a fin, tasa de error de bit y tamaño optimo del paquete.

El objetivo principal de esta tesis es desarrollar un modelo matemático tomando en cuenta los factores que consideramos y comparando nuestro modelo con la simulación de red en NS3. Considerando también el diseño por cruces de capas (Cross-Layer Design) entre la capa 2 y la capa 3 del modelo OSI. De esta manera mejorar la eficiencia de transmisión en términos del rendimiento (throughput) fin a fin de nuestra red.

Abstract

Heterogeneous networks are interconnected networks with different software, protocols, hardware, operation speed, etc., which are capable to transmit information without any drawbacks. However, there are some factors that decrease the transmission efficiency between these networks. Some of these factors are: (1) quality of service (QoS), (2) delay, (3) access medium protocols, (4) loss packet ratio, (5) Jitter, optimal packet length, (6) bandwidth, among others. There are many performance models that have analyzed the homogeneous network behavior while on the contrary, there are a few studies conducted about heterogeneous networks that analyze their behavior.

The Metropolitan Area Network (MAN) pretended to analyze an integrated network through IEEE 802.16 Protocol and IEEE 802.11 Protocol. We focused on the different factors that study network performance, this includes: (1) medium access protocols in MAC layer, (2) BER (bit error rate) and (3) optimal packet length. Also, we intended to give an analytic study of metrics such as delay, packet loss and throughput through our network. Further, an analysis of Cross-Layer Design (CLD) based on the communications between different layers on heterogeneous network.

Our chief aim is to propose a refurnished mathematical model or an existing mathematical model to improve the performance transmission of throughput end to end for a Heterogeneous MAN.

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Chapter 1

Introduction

1.1 Overview

In recent years. the increase of mobile devices has led wired networks to support wireless connectivity. Wireless networks are easy to install in contrast to wired connections. A Metropolitan Area Network (MAN) can be found in high schools, research centers, hospitals, government sites, etc., where an increased number of users can utilize it. However, network performance is an open issue. The heterogeneous network was considered in this thesis due to the fact that the interconnection is not a constraint for communications between network domains with different protocols, software, etc. Ultimately, the data communication should be transparent for the end user.

1.2 Problem Description

In recent times, both information and users quantity on networks have rapidly grown in geographical areas which are required to analyze the data transmission efficiency. We strongly considered a heterogeneous. Wireless network case which is key towards 4G systems. This technology proved less expensive to deploy and lead to a more ubiquitous broadband access. There are some key barriers to overcome such as scalability, interoperability, Quality of Service (QoS) and security. Our current research involves the performance analysis network.

There are studies related to heterogeneous networks, some of which are: (1) An Optimized Handover Decision for Heterogeneous Wireless Networks, (2) Spectrum access scheduling among heterogeneous wireless systems, (3) Worldwide Interoperability for Microwave Access (WiMAX) Wi-Fi Convergence with Orthogonal frequency-division multiplexing (OFDM) Bridge and (4) Bridging Solutions for a Heterogeneous WiMAX-WiFi. In (1) the authors proposed a Cross Layer Design (CLD) on layer 2 and layer 3 with a handover decision algorithm of Neyman-Pearson method [1]. In (2) the authors presented a new spectrum sharing scheme by heterogeneous wireless networks to time-share the spectrum, they used General packet radio service (GPRS)/WiMAX and GPRS/Wi-Fi, also they use Constant Bit Rate (CBR) traffic to evaluate throughput, delay and packet loss, their simulation results showed that the spectrum access scheduling was a feasible solution to the spectrum sharing problem [2]. The research in (3) represented a mathematical model to unify the WiFi-WiMAX Frequency Bands [3]. The authors in (4) proposed two interconnection bridging solutions between WiMAX and Wi-Fi systems; the first solution was based on end-to-end QoS level independently from wireless technologies and the second solution was focused to reduce implementation complexity at minimal cost [4]; to name a few research works. We intended to analyze a heterogeneous MAN based on mathematical model (see section 1.3). Further, we wanted to calculate back-to-back delay between IEEE 802.11 and IEEE 802.16 environments, as well as to calculate the metrics mentioned above under a CLD. Although, there are some studies that researched previous issues separately, we intended to transmit a general study by illustrating these points. Thus, there are many challenges to the wide adaptation of networks and interoperability along with other technologies of this kind, integrated in a metropolitan area (e.g. embedded system, devices) [5]. Our studies are based on IEEE 802.16 (WiMAX) and IEEE 802.11(Ad-Hoc).

1.3 Rationale and Motivation

Some key factors that should be understood about network performance for efficient data transmission are: delay, packet loss, throughput, bit error rate, optimal frame size, among other factors. We intended to analyze these factors in a heterogeneous MAN. Although, much research has been done for homogeneous networks, such as Vianci's model (IEEE 802.11 Saturated) [6], Ken s model (IEEE 802.11 Non saturated) [7], or Lian and Wong's model (IEEE 802.11n) [8] (which is an extension of Vianci's model) there has been only little research for heterogeneous networks such as Assaid Sabir (Integrated IEEE802.11 and IEEE 802.16) [9]. We based (our research) on a mathematical model for performance purposes because it is an accurate method for generating quantitative results. In addition we used a mathematical formula to analyze behavior of complex systems that are difficult to observe in reality.

1.4 Objectives

1.4.1 General Objective

Our aim is to develop a mathematical model or extend an already existing mathematical model for performance as well as to optimize data transmission over heterogeneous network environments. We study several factors such as medium access protocol, Bit Error Rate (BER), Optimal Packet Length (OPL) and QoS requirements. Also we intended to characterize the heterogeneous network with Markov chain and CLD.

1.4.2 Specific Objectives

- Analyze Performance and Optimize Models about transmission efficiency on homogenous networks using IEEE 802.11 Protocol.

- Analyze Performance and Optimize Models about transmission efficiency on homogenous networks using IEEE 802.16 Protocol.
- Analyze Performance and Optimize Models about transmission efficiency over IEEE 802.16-IEEE 802.11 Protocols.
- Utilize a CLD to increase network efficiency and better QoS support.
- Probe and compare our model with the current performance model from [9] and to test and to compare its efficiency.
- Implement our heterogeneous network scenario on NS3.
- Obtain metrics such as delay, throughput, packet loss and bit error rate.

1.5 Organisation of Thesis

This thesis is structured as follows: Chapter 2 outlines the state of the art and some of the basic concepts regarding our research; we provide an overview description about Performance Analysis Models of IEEE 802.11, IEEE 802.16 and develop a solution proposal in Chapter 3; in Chapter 4 we provide an experimental result that supported our proposal. In addition, Conclusions and Future Work are mentioned in Chapter 5.

Chapter 2

State of the Art and Basic Concepts

2.1 Introduction

The following chapter presents an overview about the state of the art and a description of the basic concepts such as: metropolitan area networks characteristics, performance network factors, analysis models, queues disciplines and performance modeling. Similarly, we introduced a few performance metrics for example, delay, throughput, packet success ratio and the related work for each of the mentioned categories.

2.2 Metropolitan Area Networks

2.2.1 Introduction

Nowadays, the increase of metropolitan area networks has required developing performance models or improving existing performance models for transmission efficiency in which both network manager and end users have knowledge of network behavior. The following subsection illustrates an overview of the basic definitions and main characteristics for Metropolitan Networks, particularly wifi Ad-hoc and WiMAX networks.

2.2.2 Overview and Characteristics for Metropolitan Networks

According to [10] a Metropolitan Area Network is defined as: A group of devices or computers interconnected over a large geographical area like metropolis, intranets, and countries, which can transmit voice, video and data. Some characteristics of metropolitan area network are:

- Network Extension: Achieves a diameter of 50 km.
- Number of nodes: Over 600 nodes.
- Transmission of data, video and voice.
- Speed: 10Mbps, 20Mbps, 45Mbps, 75 Mbps (Copper Pairs) and 100 Mbps, 1Gbps y 10Gbps (Fiber Optic).

A wavelength-division multiplexing (WDM) MAN based on CSMA/CA is analyzed in [11] where the authors mentioned a SONET network which is overloaded, thus is being insufficiently used and inefficient. Hence, the authors implement HORNET to address the problems of SONET. HORNET uses CSMA/CA instead of permanent connection. They designed a model based in an algorithm that proves that the transmitter's time cannot exceed 10% of the packet transmit time.

Tang and Baker in [12] analyzed the Metricom metropolitan area network packet radio wireless for a seven week period in a mobile environment to observe how users take advantage of this type of environment. The authors used three different clustering algorithms.

In [13] the authors executed a study on the performance of metropolitan area based on optical networks which are used for impairment constraint routing. The authors created a simulation to use an impairment constraint routing algorithm. The underlying results showed a blocking probability and other characteristics such as span length, amplifier noise figure and bit rate in order to obtain admissible network performance.

2.2.3 Ad Hoc Network

Overview and Characteristics

Wireless Ad Hoc Network is defined as a collection of wireless mobile devices that dynamically construct network topology. However, this sort of network lacks an infrastructure or centralized management [14]. The capacity of Ad Hoc network depends on network size, traffic patterns, and detailed local radio interactions. In recent studies ad hoc networks included topology control, data communications, and service access. There are a variety of problems that we can detect in this kind of network, such as: bandwidth optimization, power control, transition mission-quality enhancement, network configuration, device discovery, topology maintenance and ad hoc addressing as well as self routing.

The ad hoc networks are sorted by their applications which are as follows:

- Mobile Ad hoc networks (MANETs)
- Wireless sensor networks
- The sensor networks are known as hybrid ad hoc networks too; one function is to monitor applications to obtain data information such as movement, temperature, control break, emergency, stop advice, etc.
- Wireless mesh networks

2.2.4 WiMAX Network

Overview and Characteristics

WiMAX (World Interoperability for Microwave Access) is a technology based on IEEE 802.16 standard and ETSI HiperMAN from the European standard [15]. This technology handles 70 Mb/s for theoretical data rate with a maximum geographical area of 50 km. This standard supports OFDMA (Orthogonal Frequency Division Multiple Access) that allows up to 30 Mbps data rates for an assured channel and a mobility speed of up to 80 miles per hour [16]. In addition, one type of MAC Layer of IEEE 802.16 could be R-MAC. R-MAC is a reservation multiple access protocol which sorts time into sized frames. Each frame is split into two time segments. Contention Slot (CS) and Data Slot (DS). For non-real traffic classes in IEEE 802.16 implement contention to medium access which is called contention-based traffic.

The protocol layer of IEEE 802.16 is depicted in figure 2.1. The physical layer has the following characteristics: OFDM, Ranging, Power Control, Tx, Rx. The Mac security sub layer is responsible for Authentication purposes, Key exchange and Encryption of information. Similarly, MAC CPS performs the Packing, fragmentation, ARQ and QoS. Moreover, Convergence Sublayer performs two tasks: (1) Packet Classification and (2) Payload Headed Suppression [17].

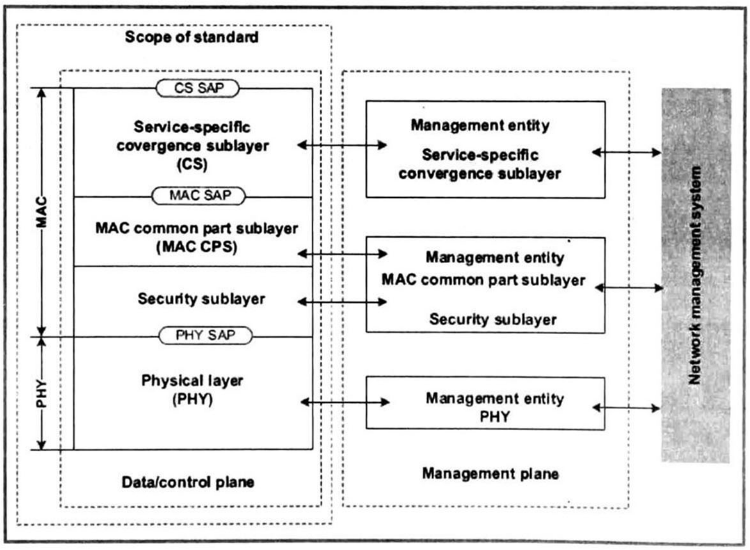


Figure 2.1 Protocol layer of IEEE 802.16 Standard [17]

2.3 Performance Factors

2.3.1 Introduction

The factors that affect network performance are quality of service (QoS), delay, jitter, packet loss, bandwidth, protocols of layer 2, among others. Some researchers employ scheduling algorithms to handle flows of network traffic. Also, assigning a service level deal such as the maximum amount of traffic allowed, the values of weights, etc.

2.3.2 Scheduling Algorithm

In this subsection, we present some common scheduling algorithm:

- First-In/First-Out (FIFO)

The mean throughput is defined in [51] with the equation (2.1) as follows:

$$Th = c\,(1 - a_0 s_0) \tag{2.1}$$

c depicts the likelihood that a packet leaves the queue, s_0 is the probability that the queue is empty and a_0 is the probability that packets do not arrive during a time step. The mean lost traffic $N_{a(lost)}$ is obtained in equation (2.2) as:

$$N_{a(lost)} = N_{a(in)} - N_{a(out)}$$

where $N_{a(out)} = Th$, therefore:

$$N_{a(lost)} = N_{a(in)} - Th$$

The input traffic $N_{a(in)}$ is defined as:

$$N_{a(in)} = \sum_{i=0}^{m} ia_i = ma$$

where m is the maximum number of packets that could arrive at the queue input, then the $N_{a(lost)}$ is given by:

$$N_{a(lost)} = m\,a - c\,(1 - a_0 s_0) \quad (2.2)$$

- Weighted Round Robin Scheduler (WRR)

The authors in [18] argued that WRR handles three traffic classes, which are: expedited forwarding (EF), assured forwarding (AF) and best effort forwarding (BF). The coming flows are classified into three buffers which every buffer represents a class. The EF class has the high priority level while the AF and BF class are served in a round robin mechanism. Also, a queuing model is used to solve the mean waiting or response time for the AF class under its worst case. The authors proposed that the traffic flow per class arrives depending of the Poisson Process and the infinite buffer size.

- Random Early Detection (RED) [52]

RED belongs to the early drop scheduler class where a packet is dropped even when the buffer is not full. In RED the switch calculates the average queue size at each time step.

The average queue size has two thresholds Q_{min} and Q_{max}:

a) Packets are not marked, when $Q_a < Q_{min}$

b) Packets are marked, when $Q_a > Q_{max}$

c) Packets are marked with a probability P_a is defined in equation (2.3)

$$P_a = {}^{P_b}/_{1 - QP_b} \tag{2.3}$$

where Q is packet numbers received from the last marked packet and P_b (equation 2.4) is defined as:

$$P_b = Q_a - Q_{min}/Q_{max} - Q_{min} \tag{2.4}$$

where Q_a is the average queue size using a low-pass filter.

2.3.3 Medium Access Protocol

Medium Access Protocol is a sub layer of data link layer (layer 2 from OSI Model), the main functions of these layers are: To manage the physic medium access for transmission per every dispositive that shares the same communication channel, adds MAC addresses from source nodes to destination nodes in each transmitted frame, effects error detections and corrections, rejects corrupted and duplicated frames, adds flags for the receptors that can acknowledge the start and the end per frame.

In [19] the authors proposed an analytical model and performance evaluation results based on Reservation multiple access protocol (R-MAC) in IEEE 802.16, they demonstrated metrics such as: contention delay, data transmission delay, and throughput. They utilize Little's theorem to calculate the required Bandwidth Request (BWR) contention delay that is observed in equation (2.5) which it was a previous successful delay transmission.

$$D_c = {}^{E[B]}/_{\mu_B} \tag{2.5}$$

where μ_B is rate of BWRs depart backlog state and E[B] is the expected number of backlog in the system (equation 2.6) as follows:

$$E[B] = \sum_{b=0}^{M} b \cdot \pi_b \quad (2.6)$$

M is the amount of Subscriber Stations (SSs) that transmits a BWR in contention slot, b is the number of backlogged users (BWRs) at principle of convergence sublayer (CS) and π_b is the sum from w=0 to L (finite length of service queue) of $\pi_{(B,W)}$ which is the probability's discrete time state with the use of backlogged users (B) and the waiting BWRs (W) at starting point.

The delayed data transmission as seen in equation (2.7) is the sum of the following times: the time it spends in the service queue, the time it reaches a successful contention and finally the time it takes for a successful transmission.

$$D_t = {E[W]}/{\mu_W} \quad (2.7)$$

where μ_W is the rate of packets depart to service queue and E[B] is the expected number of backlog in the system (equation 2.8) as follows:

$$E[W] = \sum_{w=0}^{L} w \cdot \pi_w^a \quad (2.8)$$

L is a limited length of service queue they used in the First Come First Serve (FCFS), w is the number of waiting BWRs in service queue and π_w^a is the probability of the steady state of w at all times.

The throughput in [19] is an effective frame ratio utilized for data transmission and is defined in equation 2.9 as follows:

$$Th = \frac{(E[N_{WS}]*T_{DS})}{T_f} \quad (2.9)$$

T_{DS} is the data slot (DS) time, T_f is uplink frame time and the meaning of $E[N_{ws}]$ is the expected amount of data packets transmitted in a frame and is computed through the equation (2.10):

$$E[N_{ws}] = \sum_{w=0}^{L} \pi_w^a \sum_{b=0}^{M} \pi_b \left[\left(\sum_{n_{ws}=w}^{\varepsilon} n_{ws} \sum_{b_{f+1}=0}^{M} \Psi_2 P^{(\tau)}_{(b,0),(b_{f+1},n_{ws}-w)} \right) + \left(\sum_{w_{f+1}=1}^{L} \varepsilon \sum_{b_{f+1}=0}^{M} \Psi_1 P_{(b,w),(b_{f+1},w_{f+1})} \right) \right] \quad (2.10)$$

Number of DSs in the same frame is represented for ε, n_{ws} is the number of served data packets per frame, Ψ_2 presents contention slot, τ is number of CSs in a frame, the term $\Psi_2 P^{(\tau)}_{(b,0),(b_{f+1},n_{ws}-w)}$ is obtained from transition probability matrix where τ denotes τ-step and one-step transition probabilities from state (b,0) to state $(b_{f+1,n_{ws}-w})$ of Markov process Ψ_2.

Replacing the $E[N_{ws}]$ equation, the throughput is formulated in the equation (2.11):

$$Th = \frac{T_{DS}}{T_f} \sum_{w=0}^{L} \pi_w^a \sum_{b=0}^{M} \pi_b \left[\left(\sum_{n_{ws}=w}^{\varepsilon} n_{ws} \sum_{b_{f+1}=0}^{M} \Psi_2 P^{(\tau)}_{(b,0),(b_{f+1},n_{ws}-w)} \right) + \left(\sum_{w_{f+1}=1}^{L} \varepsilon \sum_{b_{f+1}=0}^{M} \Psi_1 P_{(b,w),(b_{f+1},w_{f+1})} \right) \right] \quad (2.11)$$

2.3.4 Channel Capacity

One important factor in data transmission is the speed transmission through a channel defined as bits per seconds. Data speed is based on three main factors:

- Available bandwidth
- Signal levels that are used
- Channel quality (noise level)

There are two equations to calculate the data rate: Nyquist to non noise channel (2.12) and Shannon to noise channel (2.13).

Non noise channel: bits rate by Nyquist.

$$Bits\ Rate = 2\ x\ bandwidth\ x\ log_2 L \qquad (2.12)$$

The above expressions bandwidth is channel bandwidth, L is the number of level signals used to represent data and bits rate is the speed of data in bits per second.

Noise channel: bits rate by Shannon.

In reality it is not possible to get a channel without noise. In 1944, Claude Shannon defined the formula *Capacity from Shannon* (2.14), in order to determine the maximum

$$Capacity = bandwidth\ x\ log_2(1 + SNR) \qquad (2.13)$$

In the above expression *bandwidth* was channel bandwidth, *SNR* was signaled to noise ratio and *capacity* was the channel capacity in bits per second.

$$SNR = \frac{P_{signal}}{P_{noise}} \qquad (2.14)$$

P_{signal} was the average power of signal and P_{noise} was the average power of noise.

In [21] the authors presented a new architecture for IEEE 802.16 Wireless Metropolitan Area Network and its performance analysis. This architecture was developed based upon MAC protocol and provided QoS support to real time traffic. They stressed the following arguments: 1) BS broadcasted a back-off window size B; 2) there was N SSs in the system; 3) the probability was defined to select a given slot m; 4) p = 1/B; and 5) the probability was not selected through a given slot by any SS is defined in equation (2.15):

$$P_{NS} = (1-p)^N \tag{2.15}$$

These events were independent. They analyzed an analytical model that had already existed for channel utilization as depicted in equation (2.16).

$$C = p_1 + p_2 + \ldots + p_i \quad C \leq 1 \tag{2.16}$$

In the above equation, C is a server capacity and channel utilization for each class i. Therefore, this equation shows results of throughput and channel utilization.

In [22] the authors formulated the capacity of Ad Hoc Networks with the following assumptions: the density of each node δ is uniform, the network area physical A describes total number of nodes and is shown in equation (2.17):

$$A = \frac{n}{\delta} \tag{2.17}$$

The capacity is proportional to the area, therefore the total one-hop network capacity C, should be equal to the superficies and C is expressed as: $C = kA = k\, n/\delta$ for any constant k. Furthermore, they assumed that each node generates packets with rates of λ, they expressed an expected physical path length $\bar{l}$ from source to destination, in other terms the minimum number of hops to delivery packets is defined as: $\bar{l}\,/\,r$ where r is a fixed radio transmission range. Hence, the total one hop capacity required to send and forward packets in the networks established $C > n \cdot \lambda \ \bar{I}/r$. To substitute $C = k\, n/\delta$ we get $k\, n/\delta > n \cdot \lambda \cdot \bar{I} / r$, thus the capacity available per node, λ, is limited by equation (2.18).

$$\lambda < \frac{kr}{\delta} \ \frac{1}{\bar{I}} = \frac{C/n}{\bar{I}/n} \qquad (2.18)$$

The former inequality can be seen in two aspects: (1) the expected path length based on the routing increment and (2) the available bandwidth per node decrease.

2.3.5 Bit Error Rate (BER)

BER is defined as: the number of received bits of information over a communication channel. Some of the factors that alter these bits are: noise, distortion, bit synchronization errors or interference [23].

The error rate P_e in [8] of MQAM in AWGN channels is given by [24] with equation (2.19):

$$P_e(\gamma) = 4\left(1 - 2^{-\frac{b}{2}}\right) Q\left(\sqrt{\frac{3}{2^b - 1}}\gamma\right) \qquad (2.19)$$

In [25] the authors defined the probability of the first two bytes that were received without any bit errors while the remaining bytes contain at least one bit error for each given byte as seen in the equation (2.20).

$$\mathrm{E}(X_i) = (((1 - P_e)^8)^2 (8P_e(1 - P_e)^7))^{L-2} \qquad (2.20)$$

where P_e is the bit error probability. The authors proposed that each packet contains L bytes, emphasizing that a byte is equivalent to 8 bits.

2.4 Network Modelling

2.4.1 Introduction

According to [27] a model of a physical system is "a mathematically precise representation of the interaction of several variables and functions governing the original system" We introduce a few models such as: queuing models, performance modelling and CLD.

2.4.2 Queueing Models

One important tool for communication system is *queueing analysis.* This tool is similar to Markov's chains. Some examples of queues are: the number of customers in a bank line, the number of tasks needed to be processed, the number of messages in a network to be sent to their destiny, the amount of patients in a hospital's waiting room, etc. The main purpose of *queueing analysis* is to predict the system performance. For instance, the average delay a customer endures before served, the number of customers that are processed per time step and the queue size or waiting room requested [27].

One definition of simple *queueing models* according to the author in [27] is a single *FIFO queue*, which is concentrates on the arrival time instants and service time periods of customers. Similarly, *FIFO* queue model can be represented by arrivals, waiting line, service area and departures.

The *queueing model* has the following characteristics [26]:

- Arrival Process of customers. This characteristic assumes that inter-arrival times have a common distribution and thus are independent. In some cases the customer arrival ratio is based on *Poisson Stream* such as exponential inter-arrival times. The number of customers can arrive individually or in groups.

- Behavior of customers. We can observe two kinds of customer's behavior. Either a customer could have the patience to wait for a short or long period and or could be impatient or leave after a short time.
- Service Times. Based on [26] we must assume that these kinds of times are independent and identically distributed and are also considered independent of inter-arrival times.
- Service Discipline. There are two disciplines for customers: (1) they are served individually or (2) in groups. We present some of the common disciplines:
  - First in – first out
    Last in – first out
  - Priorities (e.g. hierarchical token bucket filter)
  - Random order
    Stochastic Fair
- Service Capacity. The service capacity is handled by a single server or several servers to provide support to the clients.
- Waiting Room. Every system has a limited size of customers. Waiting room is less when a buffer size tends to be infinity. This is an important factor to the number customers that can be stored in system.

Some main of the performance metrics in *queueing* models are:

- The waiting time distribution and sojourn time per customer, where sojourn time is defined as the sum of waiting time and service time.
- Distribution of customer numbers in the system (can be one or those in service).
- Distribution of work amount in the system, which is defined as the waiting time of customers and the residual service time.

- Distribution of busy period server. This period is considered as the time in which the server is performing tasks continuously.

In [26] the authors considered the mean performance measures, such as the mean waiting time and the mean sojourn time.

Kendall Notation

In 1953, David George Kendall (1918-2007) introduced a notation to show the modules that represent a single waiting line queue [27]. The *queueing* models are characterized by a shorthand notation. We can find the Kendall notation represented as: **a/b/c/d/e**. The meaning of each letter is presented in table 2.1.

Shorthand	Meaning
A	The interarrival time distribution
B	The service time distribution
C	Number of parallel servers
D	The system capacity (usually omitted so by default ∞)
E	Queuing discipline (usually omitted so by default ∞)

Table 2.1 Kendall Notation Meaning [27]

Queue Throughput (Th)

Efficiency (η) or Access Probability (p_a) is defined in equation (2.21)

$$\eta = p_a = \frac{N_a(out)}{N_a(in)} \tag{2.21}$$

The above expression is based on throughput as presented in equation (2.22):

$$\eta = p_a = \frac{N_a(out)}{N_a(in)} = \frac{Th}{N_a(in)} \tag{2.22}$$

Traffic Conservation

In [26] defined the traffic conservation as follows (2.23):

$$N_a(in) = N_a(out) + N_a(lost) \tag{2.23}$$

Once the traffic conservation $N_a(in)$ is normalized, see equation (2.24):

$$\eta + L = 1 \tag{2.24}$$

Traffic lost probability is seen in equation (2.25):

$$L = 1 - \eta \tag{2.25}$$

Occupation rate

In [26] mentions the occupation rate of a G/G/1 system with λ (arrival rate) and E(B) (mean service time) so $\lambda E(B)$ is the arrival amount per unit time. The server can manage 1 unit job per unit time. When the *queue* grows to infinity the arrival amount per unit time $\lambda E(B)$ is less to 1 ($\lambda E(B) < 1$). We can see that $\lambda E(B) = 1$ is the mean *queue* length exploded. This notation is illustrated below (equation 2.26):

$$\rho = \lambda E(B) \tag{2.26}$$

where λ is arrival rate, E (B) is mean service time if $\rho < 1$ so ρ is called occupation rate or server utilization because it presents a time fraction when a server is working. When we have a G/G/c (multi-server system) the $\lambda E(B) < c$. In this case the occupation rate per server is $\rho = \lambda E(B)/c$.

Little's Law

Little's law sets that equation (2.27):

$$E(L) = \lambda E(S) \tag{2.27}$$

E(L) is the average number of customers in the system, λ stands for the arrival number of customers in the system and E(S) is the average of the sojourn time. We can speculate that the number of customers do not extend to infinity. In other words, the system capacity in the system is more than enough.

PASTA Property

The Poisson Arrivals See Time Averages (PASTA) is the Poisson arrivals property. This property handles the fraction of arriving customers in state B. This property is fulfilled primarily in Poisson arrivals due to the fact that each arrival occurs exclusively in random times.

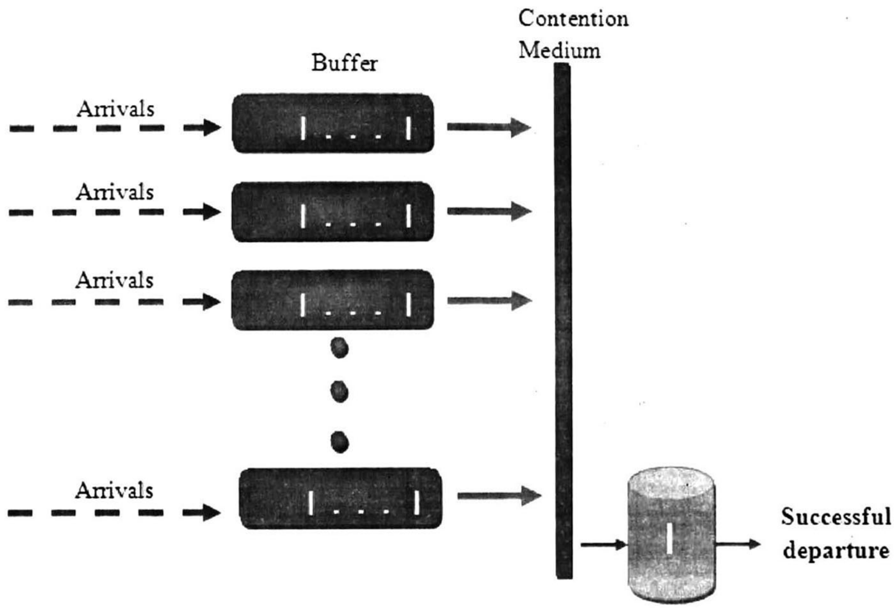


Figure 2.2 Multiple Queues with one server [26]

The *queuing model* depicted in figure 2.2 is an example of a complicated *queuing* model. In some cases, this specific type of model can be developed with the help of some interconnections or variations of simple models.

2.4.3 Performance Modelling

Performance modelling is a real system abstraction of a simplified representation to realize the performance's prediction [28]. Although there are different working domains to the basic principles of modeling they are the same. However, the people who are working under those domains have to adapt them in accordance to their needs. The two main domains for telecommunications are: (1) Network performance and (2) IT (Information technology) System Performance. Performance *modelling* has the following advantages:

a. inexpensive predictions for future performance

b. designed to allow objective polls to be made

c. support to decide for future of existing systems

d. a clear understanding of characteristics for system performance

e. a management mechanism for risks and reduction

Figure 2.3 shows confidence level of system performance obtained from performance *modelling* and performance testing [28]. There is no doubt that performance testing with full transactions running; full volume and full-sized representative would provide the most confidence of the system. Unfortunately, these types of tests are uncommon due to the necessary full test range and full transactions that have to be processed by the system. Furthermore, these tasks are expensive and take a massive responsibility.

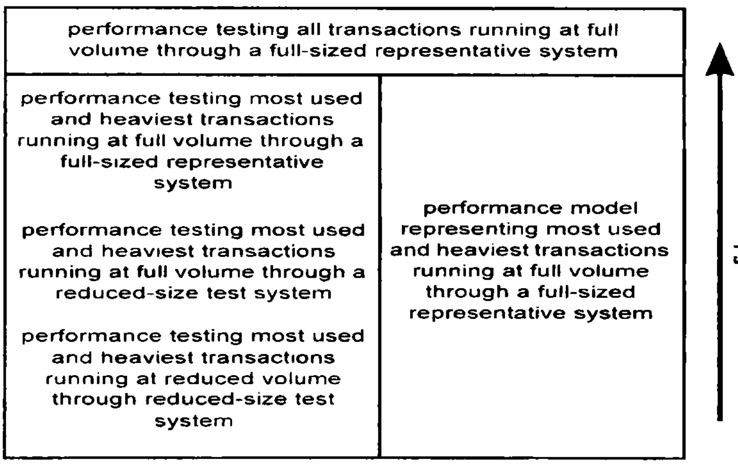


Figure 2.3 Confidence level in performance *modelling* and performance testing [28]

Some main techniques for IT performance systems are: volumetric analysis which is mainly use for capacity purposes although it can be also be use for simple throughput with a large amount of data required. *Queueing* theory modelling will be later described. Discrete event simulation modelling is used to model any level of system; with this tool it's possible to capture more system complexity. Also, capacity and throughput are well defined. The strengths and weaknesses of *queueing* theory are described as follows: *queueing* theory began with a simple mathematical model to represent the behavior of simple *queue* server models. New kinds of queue server and system complications (e.g. combinations of servers, unusual queueing disciplines, etc.) would be modeled. Using BCMP (Baskett Chandy Muntz Palacios) techniques [29] is likely to form a network in order to define key performance factors and mathematically behavior. However, the mathematics employed in this theory can become easily complicated, yet when system model abstraction requires very early and simple predictions, *queueing* theory can be appropriate.

A Spectrum Assignment Method based on Genetic Algorithm in WiMAX/WiFi Integrated Network [30] is designed with a genetic algorithm where WiMAX-WiFi shares the spectra and AP (Access Point) of WiFi that supports a lot of users can use an extra spectrum. Show results: average throughput (Mbps) with Arrival Rate [1/sec].

2.4.4 Cross Layer Design

Currently, *Cross Layer Design* has become a great potential in wireless communication systems. If we review the historical background of interconnection with network devices we can learn that the International Organization for Standardization (ISO) which was designed in the 1980s, [31] opened a set of protocols which its purpose was to interact and communicate with one another and was named Open Systems Interconnection (OSI).

In [32] the authors proposed a scheduling Algorithm that utilized CLD (Cross-Layer Design) between MAC layer and PHY layer where each connection used an AMC (Adaptive modulation and coding) and QoS requirements. The simulations were implemented for IEEE 802.16 standard. They focused on delay and rate performance and these parameters were set heuristically.

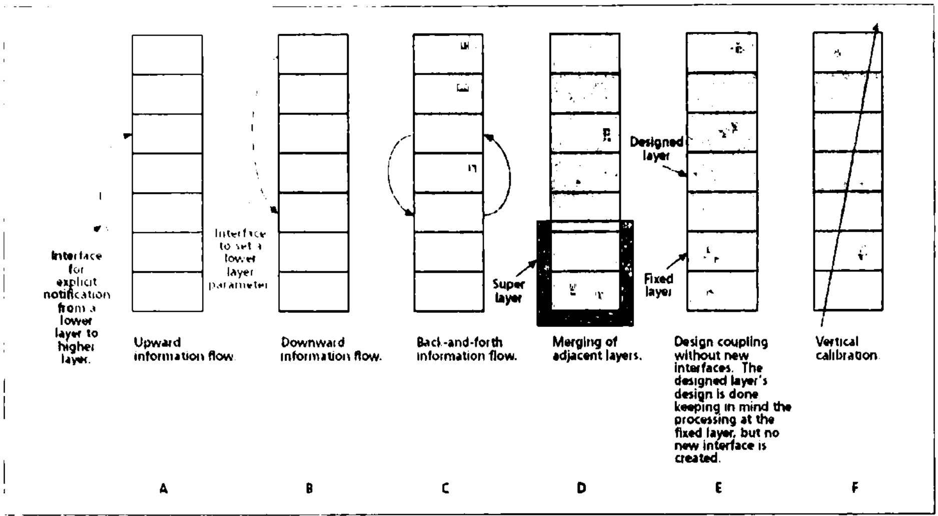


Figure 2.4 Different Cross-layer proposals [33]

Different Cross-Layer proposals are depicted in figure 2.4 [33]. In [33] the authors mentioned that layered architecture could be violated in the following different ways:

- Creation a new interfaces (figs.2.4 a-c).
- Fusion of adjacent layers (fig. 2.4 d).
- Design coupling without new interfaces (fig. 2.4 e)
- Vertical calibration across layers (fig. 2.4f).

2.5 Description of Performance Metrics

2.5.1 Introduction

In this subsection we introduce some optimization metrics that affect data transmission quality in area networks. We focus mainly on: throughput, delay and packet loss rate.

2.5.2 Some Performance Metrics

- **Throughput**

In [8] throughput is defined as: the number of payload bits received with no error per second and kept this quantity as high as possible. They used the equation 2.28:

$$T = \sum_{i=1}^{N} \frac{L-C}{L} * R_i * f(\gamma_i) \quad (2.28)$$

where R_i is the , $f(\gamma_i)$ is the packet success rate (PSR) defined as the probability to receive a correct packet, and γ_i is the SNR defined by (equation 2.29):

$$\gamma_i = \frac{P_i}{N_0 * R_i} \quad (2.29)$$

whereP_i is the received power in sub-carrier i, and N_0 is one-side noise power spectral density.

Ben-Jye Chang and Chien-Ming Chou in [34] analyzed throughput using the Markov chain model of Vinel et al. under different sizes of contention window and numbers of SS′s based on Uplink subframe in WiMAX Networks where adopts polling MAC instead of random access control. They presented results about average polling delay and throughput with different cases.

In [35] the researchers designed and implemented a new MAC based on IEEE 802.16 standard with point-to-multipoint mode for ns2, showed results of channel throughput in 20 sec time, average delay ratio versus different number SS beneath maximum transmission power (IEEE 802.16 ns-2), among others.

- **Delay**

According with [36] the delay is defined as the time that a complete message takes to arrive to its destiny from the very moment the first bit is sent through its source. Delay is composed in the following times (equation 2.30):

- ✓ Propagation time
- ✓ Transmission time
- ✓ Processing time
- ✓ Queuing time

$$D_x = T_{Pg} + T_{Tx} + T_{Ps} + T_Q \qquad (2.30)$$

where: T_{Pg} is Propagation time which is represented in [36] such as (equation 2.31):

$$T_{Pg} = {dx}/{S_{Pg}} \qquad (2.31)$$

The propagation speed of electromagnetic signals depend of medium and frequency signal. T_{Tx} is Transmission time which is represented in [36] such as (equation 2.32):

$$T_{Tx} = {message\ lenght}/{bandwidth} \qquad (2.32)$$

In [37] the authors performed a research about throughput and delay of unslotted IEEE 802.15.4. This study compared the theoretical analysis with real-life examples. The authors defined Throughput, delay, back off period, total duration of frame, bandwidth efficiency through mathematical formulas.

◆ **Packet Loss Rate**

In [8] the authors presented a mathematical technique for optimum transmission rate and packet size in wireless system for OFDM modulation in downlink transmission. The Packet success rate was defined by equation 2.33:

$$f(\gamma) = [1 - P_e(\gamma^*)]^{L/b} \qquad (2.33)$$

where $P_e(\gamma^*)$ is the binary error rate, γ^* is the optimal signal to noise ratio, L is total packet length (bits). A packet is transmitted symbol by symbol through the channel, where each MQAM symbol has b bits in it.

In [38] Packet Loss Rate for user i is defined as (equation 2.34) the ratio of the total number of lost packets $N_{lost}^{i}(t)$ between the sum of $N_{lost}^{i}(t)$ and the total served packets $N_{served}^{i}(t)$ per subchannel, as follows:

$$PLR = \frac{N_{lost}^{i}(t)}{N_{lost}^{i}(t) + N_{served}^{i}(t)} \qquad (2.34)$$

Chapter 3

Heterogeneous Metropolitan Networks Modelling

3.1 Introduction

In this chapter, we present a model for a heterogeneous MAN (HMAN) that is based on Rachid and Sabir's model [9], Vianci's model [6], Yuxia Lin and Vicent Wong's model [39] and Fakhri, Nsiri, Driss and Vidal's model [8].The proposed heterogeneous model is derived for a MAN based on the IEEE802.16 and IEEE802.11 standards. Later, both IEEE802.11 and IEEE802.16 mathematical models are analyzed based on knowledge of previous research. Also, we describe the CLD and the mathematical model for HMAN which is based on Sabir model [9]. Furthermore, we extend the Rachid and Sabir's model with the following performance metrics: BER and OPL. Thus, we get end to end Throughput and end to end Delay.

The scenario is depicted in figure 3.1 shows the HMAN (WiMAX-Ad-Hoc). We defined the HMAN as a *septuple* $\Phi = \{S_a, S_w, S_g, s, d, i, N(i)\}$ where S_a is a finite set whose elements are Ad-hoc nodes and is defined as $S_a = \{n_{a1}, n_{a2}, \dots, n_{ax}\}, x \in \mathbb{N}$, S_w is a finite set whose elements are WiMAX nodes and is defined as $S_w = \{n_{w1}, n_{w2}, \dots, n_{wy}\}, y \in \mathbb{N}$, S_g is a finite set whose elements are Gateways nodes which have two interfaces (1) IEEE802.16 and (2) IEEE802.11 and is defined as $S_g = S_a \cap S_w = \{n_{g1}, n_{g2}, \dots, n_{gz}\}, z \in \mathbb{N}$, s is a source which generates the packet, d is the destination, i is an intermediate node on path $R_{s,d}$ and $N(i)$ is a finite set whose elements are neighbors of node i.

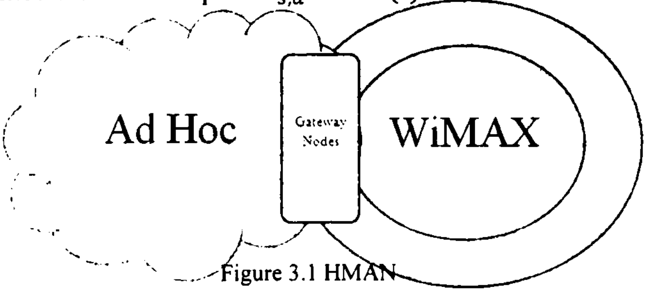


Figure 3.1 HMAN

Some differences between the 802.11 and 802.16 are shown in Appendix B.

CROSS LAYER DESIGN

The CLD is based on [9] which both network and MAC parameters are jointly considered. The network layer handles two queues scheduled using a Weighted Fair Queueing (WFQ) scheme [48]. We modified the CLD. The WFQ is between the Network Layer and the MAC Layer. Each node has the same network layer and WFQ. This design permits both communication and information in different layers and is more flexible. The queue handles two queues F_i and Q_i which have an infinite capacity. The F_i is the forwarding queue which carries generated packets from other nodes to some destination and the Q_i generates its own packets. Each queue has its own transmitted probability. f_i is the probability to transmit from F_i whereas $1 - f_i$ is the probability to transmit from Q_i. The HMAN is considered a *saturated system* which means that each node always transmits packets from Q_i while F_i could be empty. The CLD for HMAN is shown in figure 3.2.

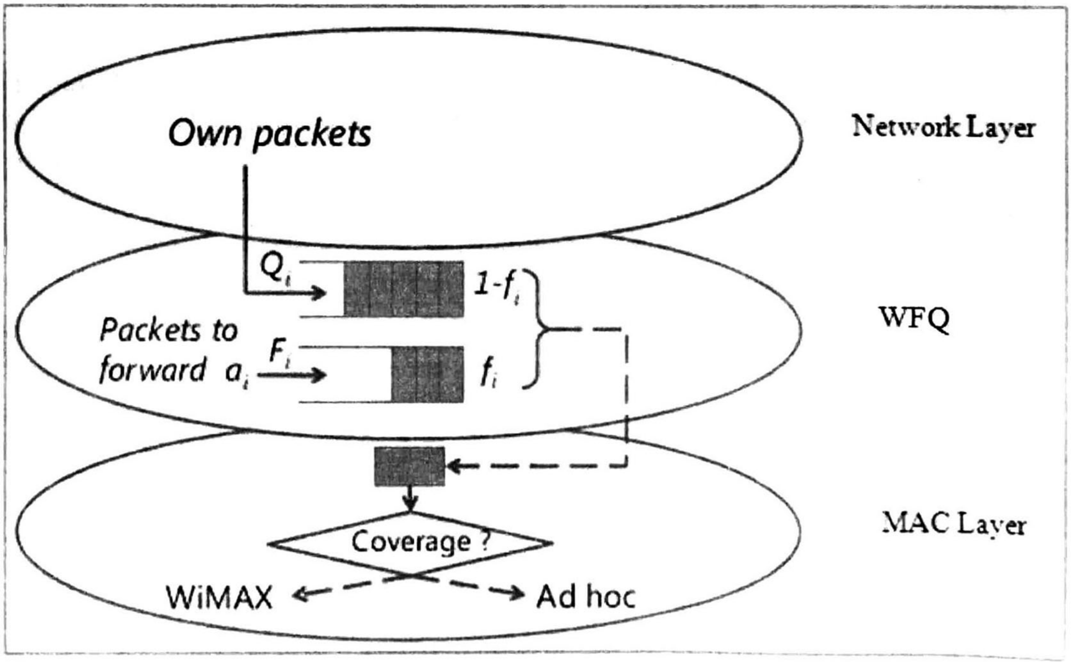


Figure 3.2 CLD for HMAN

3.2 Analysis of IEEE 802.16

3.2.1 Introduction

In this section, the MAC layer and Physical layer are summarized to understand this work. Later, the mathematical model for IEEE 802.16 is analyzed thoroughly.

MAC LAYER

This layer was summarized in chapter 2. We focused only in The *Time Division Duplexing* (TDD) that is depicted in figure 3.3 which is divided into two transmission periods: downlink (DL) and uplink (UP). The DL is generally broadcasted. TDD handles a duplex scheme where DL and UP transmissions occurs in different times but share the same frequency. The maximum transition time from Tx and Rx and from Rx and Tx is 2 μs. TDD is built from base station (BS) and subscriber station (SS) transmissions [44].

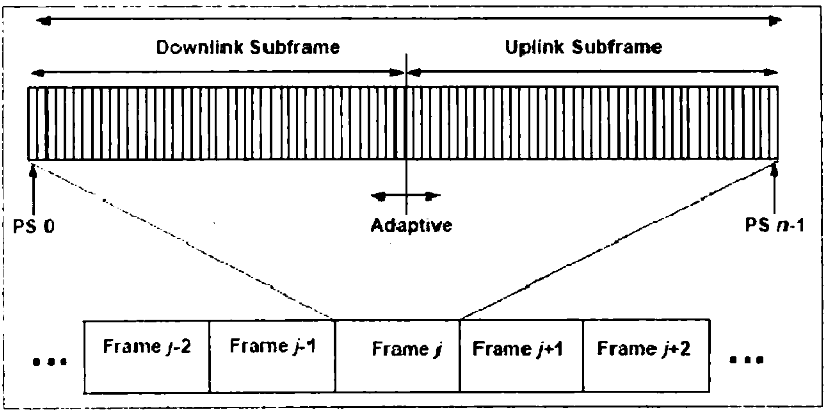


Figure 3.3 TDD frame structure [44]

PHYSICAL LAYER

The physical layer is based on WirelessMAN-OFDM interface according to Standard IEEE 802.16-2004[44]. This interface used 256 subcarriers where 192 are data subcarriers, 8 are pilot subcarriers and 56 are null. The pilot subcarriers are used to minimized frequency and phase shift. The 56 null carriers are used for guard band and direct current (DC) frequency (see figure 3.4)

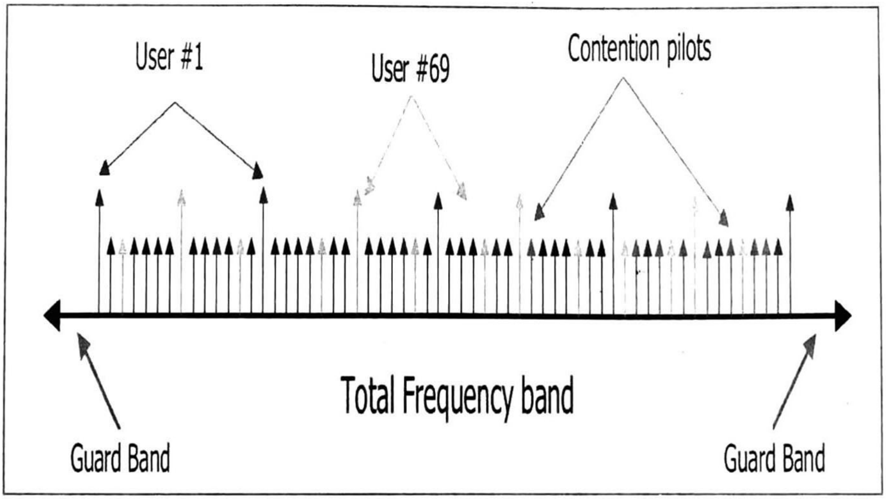


Figure 3.4 OFDM Subcarriers [44]

3.2.2 Mathematical Model for IEEE 802.16

The mathematical model for IEEE 802.16 is based on Fakhri, Nsiri, Driss and Vidal's model [8]. This model is focused on *optimization throughput*, BER and OPL in wireless system for OFDM modulation. There are some assumptions for this mathematical model. The transmitter sends packets of L bits in a continuous stream. The transmitter attaches a C bit as CRC ensures that errors are detected in each bit received. The throughput is defined as the number of payload bits per second received correctly [8] (equation 3.1):

$$T = \sum_{i=1}^{N} \frac{P_{wload}}{L_w} R_i f(\gamma_i) \tag{3.1}$$

$P_{wload} = L_w - O_{bytes}$, L_w where is the total packet length (bits), $O_{bytes} = H_{MAC} + S_{FSH} + C)$, H_{MAC} is general MAC header size, S_{FSH} is fragmentation subheader size, C is a bit CRC, R_i is the symbol rate assigned to sub-carriers i, $f(\gamma_i)$ is the packet success rate (PSR) per user i with m-QAM modulation scheme and γ_i is the SNR given by equation 3.2

$$\gamma_i = \frac{P_i}{N_0 * R_i} \tag{3.2}$$

where P_i received power in sub-carriers i, N_0 one-sided noise power spectral density.

A symbol error in the packet, automatically results in a packet loss, the PSR is given in terms of symbol error rate P_e by (equation 3.3)

$$f(\gamma_i) = (1 - P_e(\gamma))^{L_w/b} \quad (3.3)$$

b is the number of bits per each MQAM symbol. In equation (3.4) the P_e of M-QAM in AWGN channels is (approximately) given by [45]:

$$P_e(\gamma) = 4\left(1 - \frac{1}{2^{b/2}}\right) Q\left(\sqrt{\frac{3}{2^b - 1}\gamma}\right) \quad (3.4)$$

where

$$Q(x) = \frac{e^{-x^2/2}}{4mod} + \frac{1}{2mod} \sum_{i=1}^{mod-1} exp\left(\frac{-x^2}{2\sin^2\theta_i}\right) \quad (3.5)$$

with $\theta_i = \frac{i\pi}{2mod}$, mod is modulation type.

3.3 Analysis of IEEE 802.11

3.3.1 Introduction

In this section, the MAC layer is summarized to understand its work. Later, the mathematical model for IEEE 802.11 is analyzed.

MAC LAYER

The IEEE 802.11 standard [46] presents the architecture of MAC layer that includes the distributed coordination function (DCF) and the point coordination function (PCF) which provides services for time-bounded traffic. In this research we limit to the DCF scheme. The DCF is the fundamental mechanism to access the medium based on the carrier sense multiple access with collision avoidance (CSMA/CA). The flowchart of CSMA/CA is illustrated in figure 3.5 where K is number of attempts.

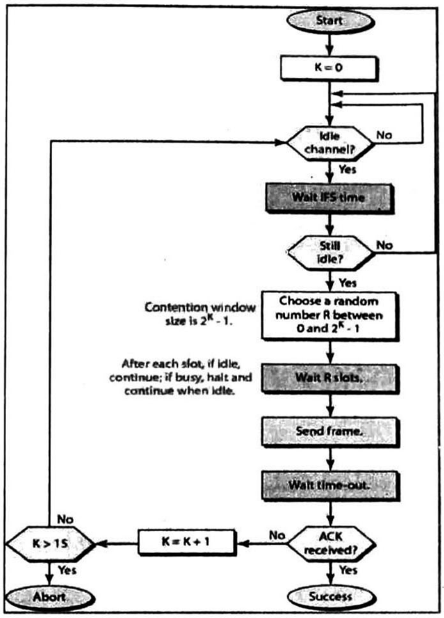


Figure 3.5 CSMA/CA Flowchart [36]

The DCF employs a binary exponential back-off scheme. When a station wants to transmit a new packet it monitors the channel activity. If the channel is idle for a period equal to the distributed inter-frame space (DIFS) the station transmits the packet. On the other hand, if the channel is busy (either during or immediately the DIFS), the station continues to monitor the channel until it senses the idle for a DIFS. In this section, the station generates a random back-off interval before it transmits the packet. After an idle DIFS, the time is slotted and a station can only be transmitted at the start of each time slot. The slot time depends on PHY layer (see table 3.1). The back-off time is chosen in the interval 0 to W-1 in each packet transmission. The value W represents the Contention Window (CW) that is the amount of time that is split in slots [36]. In the first attempt, the W is equal to CW_{min} (minimum CW), after each unsuccessful transmission the W is doubled up to CW_{max} (maximum CW). $CW_{max}=2^m CW_{min}$, m is the maximum back-off stage. The values of CW_{min} and CW_{max} are shown in table 3.1. The back-off time counter decreases while the channel is sensed idle, yet it stops when there is a transmission in the channel.

PHY	Slot Time	CW_{min}	CW_{max}
Frequency Hopping Spread Spectrum (FHSS)	50 μs	16	1024
Direct Sequence Spread Spectrum (DSSS)	20 μs	32	1024
Infrared (IR)	8 μs	64	1024

Table 3.1 Three PHY layers specified by The IEEE802.11 Standard [46]

The DCF handles two techniques to employ for packet transmission. The default scheme is a two-way handshaking (basic access mechanism) and the optional scheme is a four-way handshaking know as request to send/clear to send (RTS/CTS). We focus on RTS/CTS is depicted in figure 3.6. We can observe in figure 3.6 if the source wants to transmit a packet, it waits until the channel is sensed idle for a DIFS, later it transmits a RTS short frame. Once the destination detects the RTS it transmits a CTS after a short inter-frame space (SIFS), the source will transmit the packet only if the CTS is correctly received. The RTS and CTS frames carry the length of the transmitted packet. This information is stored in the network allocation vector (NAV). The NAV is a *timer* which indicates the required time that other stations wait until the channel is idle.

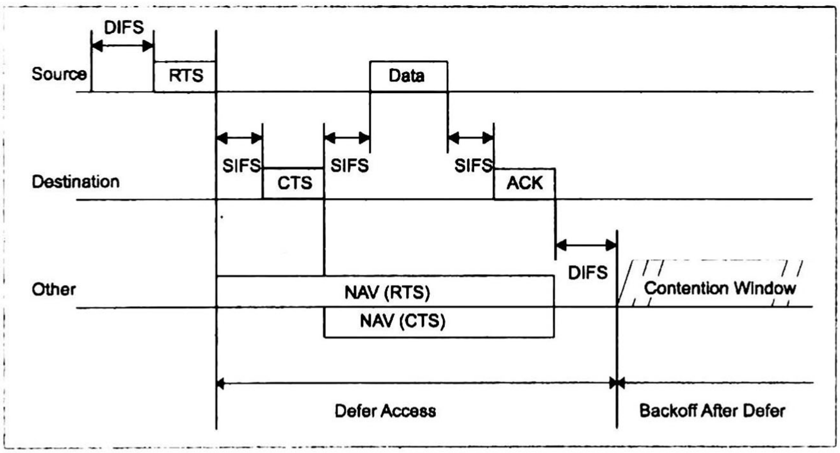


Figure 3.6 RTS/CTS Access Mechanism [46]

3.3.2 Mathematical Model for IEEE 802.11

The mathematical model for IEEE 802.11 is based on (1) Vianci's model [6], (2)Yuxia Lin, (3) Vicent Wong's model [39], [40] and [49]. In (1) this research proposed an analytical model to compute the 802.11 DCF throughput for ideal channel conditions. In (2) the model incorporates packet loss, either from collisions or channel errors. The authors in (3) proposed an optimal frame size under prone errors channels. In (4) the authors presented an optimal frame length in terms of maximizing the channel utilization. Some assumptions are considered in this model. Let τ^aduration of Ad Hoc slot (sec), L_a length per Ad Hoc packet (bits), π_i probability that F_i has at least one packet to be forwarded in the start the of cycle. A *cycle* is the total number of required slots to transmit one packet until it's successful or dropped, $\pi_{i,s,d}$ is the probability that F_i has a ready packet at the first position which is then forwarded to path $R_{s,d}$ at the start of each cycle. Therefore, π_i is presented in equation 3.6:

$$\pi_i = \sum_{s,d} \pi_{i,s,d} \tag{3.6}$$

The attempt rate is given by [6](equation 3.7):

$$P = \frac{2(1-2P_c)}{(1-2P_c)(CW_{min}) + P_c CW_{min}(1-(2P_c)^m)} \tag{3.7}$$

Proof: See Appendix A

where Pc is the conditional collision probability, CW is the contention window, and m is the maximum back-off stage (equation 3.8)

$$m = log_2\left(\frac{CW_{max}}{CW_{min}}\right) \tag{3.8}$$

For convenience $W = CW_{min}$, m is the maximum back-off stage such that $CW_{max} = 2^m W$, hence the back-off stage is represented as $W_i = 2^i W$ where $i \in (0,1,\dots,m)$. The Markov chain is depicted in figure 3.7.

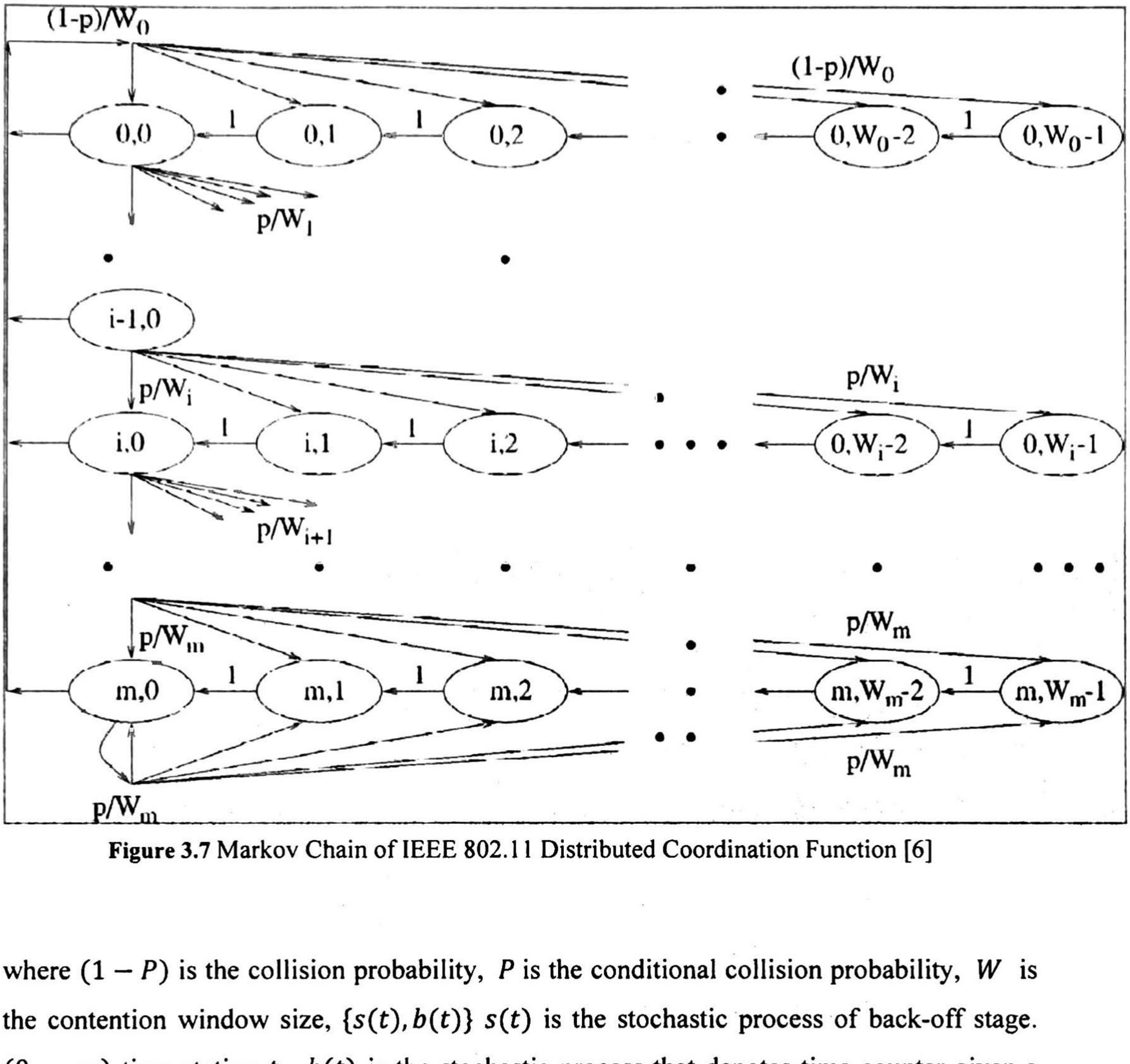


Figure 3.7 Markov Chain of IEEE 802.11 Distributed Coordination Function [6]

where $(1-P)$ is the collision probability, P is the conditional collision probability, W is the contention window size, $\{s(t), b(t)\}$ $s(t)$ is the stochastic process of back-off stage. $(0, \ldots, m)$ time station t, $b(t)$ is the stochastic process that denotes time counter given a station. The transition probabilities non null of Markov chain are:

- $P\{i,k \mid i,k+1\} = P\{s(t+1) = i,\ b(t+1) = k \mid s(t) = i,\ b(t) = k+1\} = 1$
- $P\{0,k \mid i,0\} = P\{s(t+1) = 0,\ b(t+1) = k \mid s(t) = i,\ b(t) = 0\} = (1-P)/W_0 \quad k \in (0, W_0 - 1)\ i \in (0,m)$
- $P\{i,k \mid i-1,0\} = P\{s(t+1) = i,\ b(t+1) = k \mid s(t) = i-1,\ b(t) = 0\} = P/W_i \quad k \in (0, W_i - 1)\ i \in (1,m)$

- $P\{m,k \mid m,0\} = P\{s(t+1) = m,\ b(t+1) = k \mid s(t) = m,\ b(t) = 0\} = P / W_m \quad k \in (0, W_m - 1)$

In our research, we considered the *packet error rate* (PER) which is determined by the BER. The BER is defined as the number of bit errors divided with the total number of transfer bits in a time interval and the packet length [39]. The PER is denoted as p_e while the BER is P_{BER}. The PER is defined as:

$$p_e = 1 - (1 - P_{BER})^{L_a} \tag{3.9}$$

L_a is the DATA packet length in bits, which includes physical layer header (PHY_H), MAC layer header (MAC_H) and packet load. The payload information is defined as :

$$P_{aload} = \frac{L_a - H_{total}}{\tau^a} \tag{3.10}$$

where

$$H_{total} = (\mathrm{PHY_H} + \mathrm{MAC_H}) \tag{3.11}$$

Physical layer header and MAC layer header are defined in [46].

3.4 Reference Model

The mathematical model for HMAN is based primarily on Rachid and Sabir's model [9]. This model is referred as the reference model within this thesis. The Rachid and Sabir's model is focused t obtain the throughput and end to end delay for an integrated network (WiMAX cell and Ad-hoc). The HMM is based on the followings assumptions: The Base Station (BS) uses OFDM scheme and let $\tau_{i,B}^{m}$ is the transmission time (seconds) of WiMAX packet, where $\tau_{i,B}^{m} = \frac{L_w}{P_{i,B}^{m}}$ s.t. L_w is number of bits in a WiMAX packet, $\rho_{i,B}^{m} = \sum_{l \in \mathcal{L}_i} \gamma_{i,B,l}^{m} \Delta_f$ is the aggregation transmission rate (bps), when nodes use a m-QAM modulation level, $\gamma_{i,B,l}^{m} \Delta_f$ is the transmit rate (bits per subcarrier), l is a subcarrier, Δ_f is the bandwidth of one single subcarrier, K is maximum number of transmissions allowed by a gateway *i*/packet/ all paths. Let $K_{i,s,d}$ is the maximum number of transmissions allowed by a mobile node i per packet on the path $R_{s,d}$. $\Psi_{i,s,d}$ is the number of attempts until it reaches success or drop from node i on the path $R_{s,d}$. $\overline{\Psi}_i$ is the average of all $\Psi_{i,s,d}$ overall sources s and destinations d. $P_{i,j}$ is the probability that a node i generates and transmits a packet to node j, the attempt φ_i is only valid for IEEE802.11 systems and non for heterogeneous network, let x_i the total proportion of WiMAX cycles for a given node i, $\tau_i^w$the average needed number of slots to send a WiMAX packet. In [9] a heterogeneous Network formed by WiMAX and an Ad hoc a system is modeled. The proportion of WiMAX traffic in a gateway is given by:

$$x_i = P_{i,B}(1 - \pi_i f_i) + f_i \sum_s \pi_{i,s,B} \quad (3.12)$$

Proof: see Appendix A

The attempt rate for any node i in the system is

$$\bar{\varphi}_i = \frac{\overline{\Psi}_i(1 - x_i)}{\overline{\Psi}_i(1 - x_i) + \tau_i^w x_i \varphi_i} \varphi_i \quad (3.13)$$

Proof: see Appendix A

3.4.1 End to End Throughput and Stability Region

In [9] reference model derives the end to end throughput and stability region. Let $j_{i,s,d}$ be the entry of the $R_{s,d}$ after the node $i \in S_a \cup S_w$, $N(i)$ is the neighboring set of node i, then, the probability that a transmission from node i over the path $R_{s,d}$ over the Ad-hoc network is successful by:

$$P_{i,s,d} = \prod_{j \in j_{i,s,d} \cup N(j_{i,s,d}) \setminus i} (1 - \bar{\varphi}_j) \quad (3.15)$$

where $\bar{\varphi}_j$ is the attempt rate and $(1 - \bar{\varphi}_j)$ is the successful rate, The expected number of attempts per packet until successful or dropped from i on the path $R_{s,d}$ is

$$\Psi_{i,s,d} = \frac{1-(1-P_{i,s,d})^{K_{i,s,d}}}{P_{i,s,d}} \tag{3.16}$$

where $1 - P_{i,s,d}$ is the probability that a transmission is not successful. In WiMAX the probability that a transmission is successful from a gateway $i \in S_g$ (using a m-QAM modulation) to the tower B is

$$\varphi_i^m(\gamma_i) = 1 - \prod_{n=1}^{K}(1 - f(\gamma_i)) \tag{3.17}$$

The expected number of attempts until successful or dropped from i on the path $R_{s,B}$ is

$$\Psi_{i,s,B} = \sum_{k=1}^{K} kf(\gamma_i)\prod_{n=1}^{K}(1 - f(\gamma_i)) + K\prod_{n=1}^{K}(1 - f(\gamma_i)) \tag{3.18}$$

Let T_i be the average service time per packet at node i. Therefore,

$$T_i = \sum_{s,d:i \epsilon R_{s,d}} (\pi_{i,s,d} f_i T_{i,s,d} + \sum_{d}(1 - \pi_i f_i)P_{i,d}T_{i,i,d}) \tag{3.19}$$

where $T_{i,s,d}$ is the average service time per packet at node i on the path $R_{s,B}$ and is given by

$$T_{i,s,d} = \begin{cases} \left\lceil \tau_{i,B}^{m} \frac{M_a}{M_w} \right\rceil \Psi_{i,s,d} & if\ i \in S_g, \quad d = B \\ \frac{\Psi_{i,s,d}}{\varphi_i} & otherwise \end{cases} \tag{3.20}$$

Departure rate

Because the F_i queue of node i for $R_{s,d}$ connection is

$$d_{i,s,d} = \frac{\pi_{i,s,d} f_i}{T_i} \tag{3.21}$$

When the WiMAX tower B transmits to node d, g (gateway) in first hop on the path $R_{s,d}$. The long term of arrival rate in transmission queue $F_i$of node i for connection $R_{s,d}$ is

$$a_{i,s,d} = \alpha_{s,d} \prod_{k \in R_{s,i}} \left[1 - (1 - P_{k,s,d})^{K_{k,s,d}}\right] \quad (3.22)$$

where $\alpha_{s,d}$ is given by

$$\alpha_{s,d} = \begin{cases} \frac{P_{s,d}(1 - \pi_s f_s)}{T_s}\left[1 - (1 - P_{s,s,d})^{K_{s,s,d}}\right] & if\ s \neq B \\ P^m_{B,g} \quad P^m_{g,B,d}\varphi^m_B(\overrightarrow{\gamma_B}) & if\ s = B \\ \frac{P_{s,d}(1 - \pi_s f_s)}{T_s}\varphi^m_s(\overrightarrow{\gamma_s}) & if\ s \in S_g\ and\ d = B \end{cases} \quad (3.23)$$

$\alpha_{s,d}$ indicates the departure rate from source s. Note: $a_{s,s,d} = 0\ \forall_s\ and\ d$

End to End Throughput

End to end throughput between nodes *s* and *y* is the exact arrival time to destination *d*.

$$thp_{s,d} = a_{d,s,d}$$

$$thp_{s,d} = \frac{Y_s}{T_s} \prod_{k \in R_{s,i} \cup_s} [1 - (1 - P_{k,s,B})^{K_{k,s,B}}] \quad (3.24)$$

Stability Region

The transmission queue F_i is stable if the departure's rate is at least the same as the arrival rate. If all the queues are in a stable state, then for each one $i, s\ and\ d$ such that $i \in R_{s,d}$ leads to:

$$d_{i,s,d} = a_{i,s,d}$$

$$\frac{\pi_{i,s,d} f_i}{T_i} = \alpha_{s,d} \prod_{k \in R_{s,i}} \left[1 - (1 - P_{k,s,d})^{K_{k,s,d}}\right]$$

$$\pi_{i,s,d} f_i = \alpha_{s,d} T_i \prod_{k \in R_{s,i}} \left[1 - (1 - P_{k,s,d})^{K_{k,s,d}}\right]$$

For a global rate balance it leads to:

$$\sum_{s,d} \pi_{i,s,d} f_i = \sum_{s,d:i\in R_{s,d}} \alpha_{s,d} T_i \prod_{k\in R_{s,i}} [1-(1-P_{k,s,d})^{K_{k,s,d}}]$$

The unknown rate balance for all *i, s, d* is:

$$Z_{i,s,d} = \pi_{i,s,d} f_i$$

Ad-Hoc WiMAX Case

The RBE (Rate Balance Equation) from Ad Hoc to WiMAX on $R_{s,d}$ is reduced as follows:

$$\pi_{i,s,B} f_i = \alpha_{s,B} T_i \prod_{k\in R_{s,i}} [1-(1-P_{k,s,B})^{K_{k,s,B}}]$$

$$= \frac{P_{s,d}(1-\pi_s f_s)}{T_s} [1-(1-P_{s,s,B})^{K_{s,s,B}}] T_i \prod_{k\in R_{s,i}} [1-(1-P_{k,s,B})^{K_{k,s,B}}]$$

$$= \frac{P_{s,d} Y_s T_i}{T_s} [1-(1-P_{s,s,B})^{K_{s,s,B}}] \prod_{k\in R_{s,i}} [1-(1-P_{k,s,B})^{K_{k,s,B}}]$$

where $Y_s = (1-\pi_s f_s)$, depicts how all nodes have the same destiny, hence $P_{s,d} = 1$

$$\pi_{i,s,B} f_i = \frac{T_i}{T_s} Y_s \prod_{k\in R_{s,i} \cup s} [1-(1-P_{k,s,B})^{K_{k,s,B}}]$$

A queue is stable when its arrival rate is less (or equal) than its departure rate, thus:

$$\pi_{i,s,B} f_i \geq \frac{T_i}{T_s} Y_s \prod_{k\in R_{s,i} \cup s} [1-(1-P_{k,s,B})^{K_{k,s,B}}], \forall_s$$

To consider an asymmetric mesh network which each node has the same number of Ad hoc neighbors *n*, the same transmission probability and $\varphi_i \equiv \varphi$. Assume a minimized delay $K_{i,s,B} = 1$ or a maximum throughput $K_{i,s,B} = \infty$. As $\pi_{i,s,B} \leq 1$ and $|(s,B)|$ the number of intermediate nodes *s* and *B*, then:

$$f \geq \frac{T_i}{T_s} Y_s (1-\varphi)^{n(|(i,B)+1|)}$$

The throughput is defined as:

$$thp_{s,B} = \frac{Y_s}{T_s}(1-\varphi)^{n(|i,B|+1)} \quad (3.25)$$

END TO END DELAY

The arrival rate of packets is based on the general process with an average $a_i = \sum_{s,d:i\in R_{s,d}} a_{i,s,d}$. note that a_i is exactly the arrival rate of packets with different paths and different connections to be forwarded to buffer F_i to node i. F_i constituted to G/G/1 queue. Let $\bar{W}_i^w(\bar{W}_i^a)$ be the average waiting time on forwarded queue F_i in an arrival to WiMAX (Ad hoc) node i. Let $\bar{R}_i^w(\bar{R}_i^a)$ be the average residual service time of a WiMAX (Ad hoc) packet in MAC layer.

$$\bar{W}_i^w = \bar{R}_i^w + \bar{B}_i \qquad \bar{W}_i^a = \bar{R}_i^a + \bar{B}_i \quad (3.26)$$

where $\bar{B}_i$ is the average time to tend all packets that arrived before it (in the buffer).

Average Residual Service Time

One arrival packet of F_i can find a packet service that corresponds to $R_{s,d}$. $\bar{R}_{i,s,d}^w$ ($\bar{R}_{i,s,d}^a$) is the mean residual service time of a WiMAX (ad Hoc) packet in service.

Lemma 4. The mean residual time of a packet for a (s,d) connection is lead as:

$$\bar{R}_i^w = \sum_{s,d} \pi_{i,s,d} f_i \bar{R}_{i,s,d}^w + \sum_d P_{i,d}(1-\pi_i f_i)\bar{R}_{i,i,d}^w \quad (3.27)$$

$$\bar{R}_i^a = \sum_{s,d} \pi_{i,s,d} f_i \bar{R}_{i,s,d}^a + \sum_d P_{i,d}(1-\pi_i f_i)\bar{R}_{i,i,d}^a \quad (3.28)$$

where

$$\bar{R}_{i,s,d}^w = \begin{cases} \dfrac{T_{i,s,B}^{(2)}}{2T_{i,s,B}} - \dfrac{1}{2}, & if\ i \in S_g\ and\ d = B \\ \dfrac{T_{i,s,d\cdot}^{(2)}}{2T_{i,s,d}} + \dfrac{1}{2}, & otherwise \end{cases} \quad (3.29)$$

$$\bar{R}^{a}_{i,s,d} = \begin{cases} \dfrac{T^{(2)}_{i,s,B}}{2T_{i,s,B}} - \dfrac{1}{2}, & if\ i \in S_g\ and\ d = B \\ \dfrac{T^{(2)}_{i,s,d}}{2T_{i,s,d}} + \dfrac{1}{2}, & otherwise \end{cases} \quad (3.30)$$

The second moment of $T^{(2)}_{i,s,B}$ service time is given by:

$$T^{(2)}_{i,s,B} = \begin{cases} \Psi^{(2)}_{i,s,d} \left\lceil \dfrac{\tau^{m}_{i,B}}{\tau^{a}} \right\rceil^2 & if\ i \in S_g\ and\ d = B \\ \dfrac{\Psi^{(2)}_{i,s,d} + \Psi_{i,s,d}(1 - \varphi_i)}{\varphi_i^2} & otherwise \end{cases} \quad (3.31)$$

Based on the following equation:

$$\tau_i = \pi_i f_i \tau_i^F + (1 - \pi_i f_i)\pi_i^Q \quad (3.32)$$

Considering only the mean residual service time, we have:

$$\bar{R}_i = \pi_i f_i \sum_{s,d} \frac{\pi_{i,s,d}}{\pi_i} \bar{R}_{i,s,d} + (1 - \pi_i f_i) \sum_{d} P_{i,d}\, \bar{R}_{i,i,d}$$

$$= \sum_{s,d} \pi_{i,s,d}\, f_i \bar{R}_{i,s,d} + (1 - \pi_i f_i) \sum_{d} P_{i,d}\, \bar{R}_{i,i,d} \quad (3.33)$$

The proof of $\bar{R}_{i,s,d}$ is in [9]

$$\bar{R}_{i,s,d} = \frac{T^{(2)}_{i,s,d}}{2T_{i,s,d}} + \frac{1}{2} \quad (3.34)$$

The extended proof of $T^{(2)}_{i,s,d}$ is in [9]. As $\tau^{m}_{i,B}$ is constantly, the second moment of service time on WiMAX is given by $\Psi^{(2)}_{i,s,d} \left\lceil \frac{\tau^{m}_{i,B}}{\tau^{a}} \right\rceil^2$ [9].

Waiting Time in the Buffer

$\bar{B}_i$ is derived from: the mean service time of forwarded connections and own connection nodes are:

$$\tau_i^F = \sum_{s,d} \frac{\pi_{i,s,d}}{\pi_i} T_{i,s,d} \qquad\qquad \tau_i^Q = \sum_d \varphi_i T_{i,i,d} \tag{3.35}$$

If $\overline{N}_i^F$ is the number of mean packets in the queue F_i(not MAC packet), then:

$$\bar{B}_i = \overline{N}_i^F \tau_i^F + (\overline{N}_i^F + 1)\tilde{n}_i^Q \tau_i^Q \tag{3.36}$$

where $\tilde{n}_i^Q$ is the mean number of packets Q_i that are served before one packet is at the initial of $F_i$queue. After the departure of a forwarded packet, a head of queue F_i of packets, if it exists, it will have to wait a needed number of cycles V (random variable) to serve packets from Q_i before it can access to MAC layer. The probability of waiting k cycles is $P\{V = k\} = (1 - f_i)^k f_i$. For each node i, the mean value of V random variable is $E[V] \equiv \tilde{n}_i^Q \approx \sum_{k=0}^{\infty} k(1 - f_i)^k f_i = \frac{1-f_i}{f_i}$.Proof of $E[V]$ see Appendix A. This is an approximation of $\tilde{n}_i^Q$ given that V cannot take a long value in practice. By the *Little Formula*, we obtained:

$$\overline{N}_i^F = a_i \overline{W}_i \tag{3.37}$$

Then for w and a:

$$\overline{W}_i = \bar{B}_i + \bar{R}_i \tag{3.38}$$

$$\overline{W}_i = \frac{\bar{R}_i + \tau_i^Q \frac{1 - f_i}{f_i}}{1 - a_i\left(\tau_i^F - \tau_i^Q \frac{1 - f_i}{f_i}\right)} \tag{3.39}$$

Proof of $\overline{W}_i$ see Appendix A

The service time τ_i^F is added to $\overline{W}_i$. For additional precision, a packet that belongs to path $R_{s,d}$ has to expect the waiting time in the F_i queue plus the service time in the same path, so:

$$D_{i,s,d} = \overline{W}_i + \tau_{i,s,d} \tag{3.40}$$

The delay is a decreased function of f_i. The authors in [9] reduced it to assign $f = 1$ as a more precise configuration. In fact, when $f = 1$ the delay of forwarded queue is minimized, the throughput and energy consumption remain without change. The mean end to end delay $D_{s,d}$ of a packet on the path $R_{s,d}$ is the mean time taken from the instant that a packet reaches the MAC layer of the source to the time that is received. They derived the waiting time per forwarded packet in node i without worrying if the packet will be successfully transmitted or dropped to the end of service in MAC layer. That delay time is both success packets as dropped packets. However, in the *end to end* delay formula, the dropped packets are considered the finite number of transmissions which cannot be included in the calculation. Therefore:

$$D_{s,d} = \frac{\Psi_{s,s,d}^{succ}}{\varphi_s} + \sum_{i=1}^{|R_{s,d}|} (\bar{W}_i + \tau_{i,s,d}^{succ}) \qquad (3.41)$$

Where $\tau_{i,s,d}^{succ}$ is the mean service time of a successfully transmitted packet and on the same path $R_{s,d}$. $\tau_{i,s,d}^{succ}$ which has the same form as $\tau_{i,s,d}$ can be expressed as:

$$\tau_{i,s,d}^{succ} = \frac{\Psi_{i,s,d}^{succ}}{\varphi_i} \qquad (3.42)$$

where $\Psi_{i,s,d}^{succ} = \sum_{k=1}^{k_{i,s,d}} k(1 - P_{i,s,d})^{k-1} P_{i,s,d}$ is the average number of attempts until it reaches a successful point.

3.5 The Proposed Model

The Vianci's model [6], Yuxia Lin and Vicent Wong's model [39], Fakhri, Nsiri, Driss and Vidal's model [8] Song Ci and Hamid Sharif [49] are integrated in the heterogeneous mathematical model (HMAN).

Throughput Optimization

The throughput is defined as the payload (bits) per second received successfully. Based on equation 3.25, we made a variable change using $v, h, z(L_a, L_w)$ *and* u which the $thp_{s,B}$ is defined as follows:

$$thp_{s,B} = \frac{v}{\sum_{s,d:i\in R_{s,d}\setminus i\in S_g} h + z(L_a, L_w) + u} \quad (3.43)$$

where:

$v = Y_s(1-\varphi)^n$, $h = \pi_{i,s,d} f(\varphi_i)^{-1}$, $z(L_a, L_w) = \pi_{g,s,d} f T \left[\frac{P_{aload}}{\rho_{g,B}^m(1-p_e)}\right]$, and $u = Y_s\left[\frac{1}{\varphi_s}\right]$

where: $T = \sum_{j=1}^{N} \frac{P_{wload}}{L_w} f(\gamma_j)$

Optimal WiMAX Packet Length

We get the optimal WiMAX packet length L_w to differentiate (3.43) with respect to L_w and using (3.1), (3.2) and (3.3) produces:

$$\frac{dthp_{s,B}}{dL_w} = -\frac{v[z'(L_a, L_w)]}{\left[\sum_{s,d:i\in R_{s,d}\setminus i\in S_g} h + z(L_a, L_w) + u\right]^2} \quad (3.44)$$

$$z(L_a, L_w) = \pi_{g,s,d} f \sum_{j=1}^{N} \frac{L_w - O_{bytes}}{L_w}(1 - P_e(\gamma_j))^{L_w/b} \left|\frac{P_{aload}}{\rho_{g,B}^m(1-p_e)}\right|$$

The derivative of $z(L_a, L_w)$ is calculated with respect to L_w as:

$$\frac{dz(L_a, L_w)}{dL_w} = \pi_{g,s,d} f \left|\frac{P_{aload}}{\rho_{g,B}^m(1-p_e)}\right| \left[\frac{O_{bytes}}{L_w^2} f(\gamma_j) + \left(1 - \frac{O_{bytes}}{L_w}\right)\frac{f(\gamma_j)\ln(1-P_e(\gamma_j))}{b}\right] \quad (3.45)$$

Setting this to zero produces an equation in L_w:

$$-\frac{v[z'(L_a, L_w)]}{\left[\sum_{s,d:i\in R_{s,d}\setminus i\in S_g} h + z(L_a, L_w)\right]^2} = 0 \tag{3.46}$$

$$-\frac{v\left[\pi_{g,s,d} f\left[\frac{P_{aload}}{\rho_{g,B}^{m}(1-p_e)}\right]\left[\frac{O_{bytes}}{L_w^2} f(\gamma_j) + \left(1 - \frac{O_{bytes}}{L_w}\right)\frac{f(\gamma_j)\ln\left(1 - P_e(\gamma_j)\right)}{b}\right]\right]}{\left[\sum_{s,d:i\in R_{s,d}\setminus i\in S_g} h + z(L_a, L_w)\right]^2} = 0$$

$$v\left[\pi_{g,s,d} f\left[\frac{P_{aload}}{\rho_{g,B}^{m}(1-p_e)}\right]\left[\frac{O_{bytes}}{L_w^2} f(\gamma_j) + \left(1 - \frac{O_{bytes}}{L_w}\right)\frac{f(\gamma_j)\ln\left(1 - P_e(\gamma_j)\right)}{b}\right]\right] = 0$$

$$\frac{O_{bytes}}{L_w^2} f(\gamma_j) + \left(1 - \frac{O_{bytes}}{L_w}\right)\frac{f(\gamma_j)\ln\left(1 - P_e(\gamma_j)\right)}{b} = 0$$

Solving to L_w:

$$L_w^* = \frac{O_{bytes}}{2} + \frac{\sqrt{{O_{bytes}}^2 - \frac{4bO_{bytes}}{\ln(1 - P_e(\gamma))}}}{2} \tag{3.47}$$

Thus, In WiMAX system the optimal packet length L_w depends on the SNR per symbol γ, symbol error probability P_e and the constellation size 2^b

Optimal Ad Hoc Packet Length

We differentiate (3.43) with L_a (using equation 3.9 and 3.10) and set it to zero to obtain the next condition:

$$\frac{dthp_{s,B}}{dL_a} = -\frac{v\left(\pi_{g,s,d} f \frac{T}{\tau^a \rho_{g,B}^m}\right)(1 - P_{BER})^{-L_a}[1 - \ln(1 - P_{BER})(L_a - H_{total})]}{\left[\sum_{s,d:i\in R_{s,d}\setminus i\in S_g} h + z(L_a, L_w) + u\right]^2} \tag{3.48}$$

Next we set the derivative to zero:

$$\frac{v\left(\pi_{g,s,d} f \frac{T}{\tau^a \rho_{g,B}^m}\right)(1 - P_{BER})^{-L_a}[1 - \ln(1 - P_{BER})(L_a - H_{total})]}{\left[\sum_{s,d:i\in R_{s,d}\setminus i\in S_g} h + z(L_a, L_w) + u\right]^2} = 0 \tag{3.49}$$

$$v\left(\pi_{g,s,d} f \frac{T}{\tau^a \rho_{g,B}^m}\right)(1 - P_{BER})^{-L_a}[1 - \ln(1 - P_{BER})(L_a - H_{total})] = 0$$

$$1 - \ln(1 - P_{BER})(L_a - H_{total}) = 0$$

Solving to L_a:

$$L_a^* = H_{total} + \frac{1}{|\ln(1 - P_{BER})|} \tag{3.50}$$

Thus, In Ad-Hoc system the optimal packet length L_a depends on the bit error rate P_{BER}.

Chapter 4

Analysis of Results

4.1 Introduction

This chapter describes simulation scenarios of WiMAX and Ad- Hoc Networks, the environment they were conducted in and an analysis of the results obtained. The process of implementing the test scenarios described below will also help to evaluate the simulation's environment. The objective is to validate and evaluate the proposed model versus reference model.

4.2 Study Case: MAN base on WiMAX and WiFi

The experimental work was carried out in the ns3 network simulator [47]. The simulation experiment is a network of 9 subscribed stations (SS) which 5 are ad-hoc nodes, 2 are gateways (multiple interface ad-hoc and WiMAX), 2 are WiMAX nodes, and a Base Station (BS WiMAX) where each node has an ID, these IDs are listed from 1 to 9; node IDs are sorted as follows: 2 to 6 IDs are ad-hoc nodes, 8 and 9 are WiMAX nodes, 1 and 7 are gateways nodes (IEEE802.11 and IEEE802.16) and B for the Base Station. The network topology is depicted in figure 4.1. The nodes are distributed based on Table 4.1. IEEE 802.11 PHY is DSSS [39]. IEEE 802.11 MAC was used as the MAC protocol. Some characteristics of the model were based on IEEE 802.11 and IEEE 802.16 standards. The simulation time was 500s and the maximum sent packets were 500.

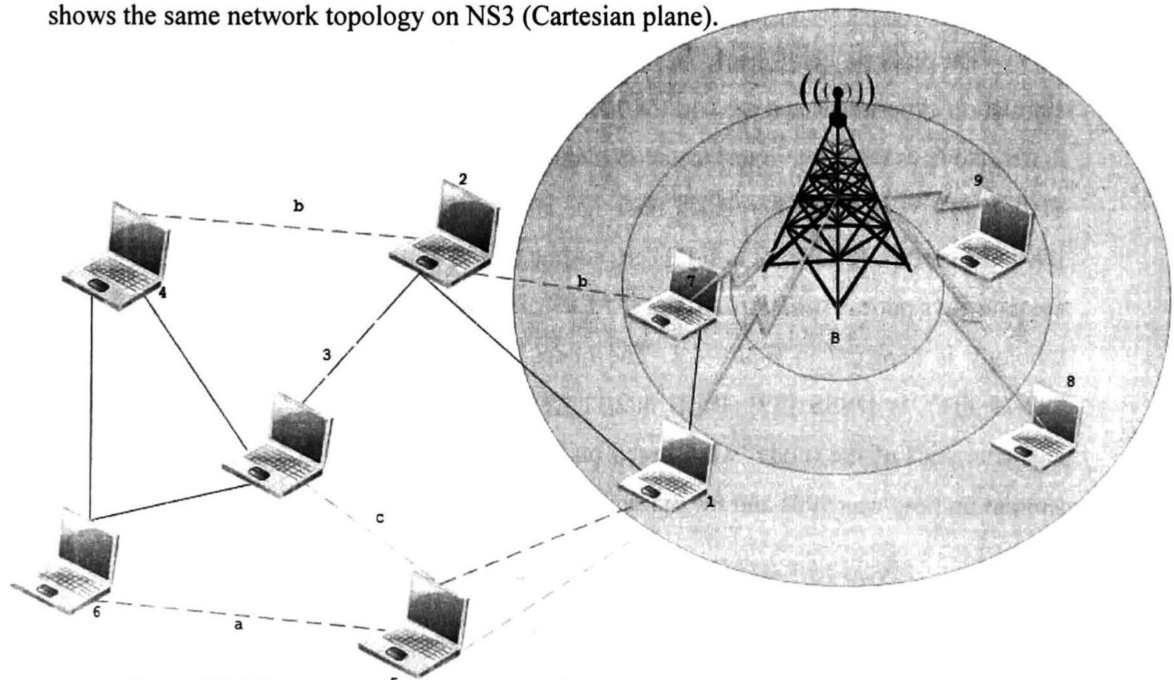
Node ID	1	2	3	4	5	6	7	8	9	B
X (m)	190	160	60	0	135	0	230	2300	1400	1000
Y (m)	10	80	60	80	0	30	60	10	60	30

Table 4.1 Nodes Coordinates

We considered a Constant Speed Propagation Delay Model for the propagation delay and a Friss Propagation Loss Model for propagation system loss which has a wavelength of 5.5 GHz at 300 000 km/s and it corresponds well with our model. Optimized Link State Routing (OLSR) [50] was used for instantaneous updates for each routing table. There are tree data flows: a, b and c (figure 4.1). We developed two scenarios in where both had the same simulation scenario: (1) we configured gateway 1 with one subcarrier and QPSK modulation (see table 4.3) and gateway 7 with one subcarrier and 16-QAM modulation (see table 4.3), the cross traffic average was 47.5% Rx and 52.5% Tx; (2) we configured to gateway 1 with one subcarrier and 16-QAM modulation (see table 4.3) and gateway 7 with one subcarrier and QPSK modulation (see table 4.3) which the cross traffic average was 16% Rx and 26.5% Tx.

4.1.1 Network Topology

The network topology was designed based on [9] as depicted in figure 4.1. The figure 4.2 shows the same network topology on NS3 (Cartesian plane).



flow a: 6-5-1-B flow b: 4-2-7-B flow c: 3-5-1-B

Figure 4.1 HMAN Topology

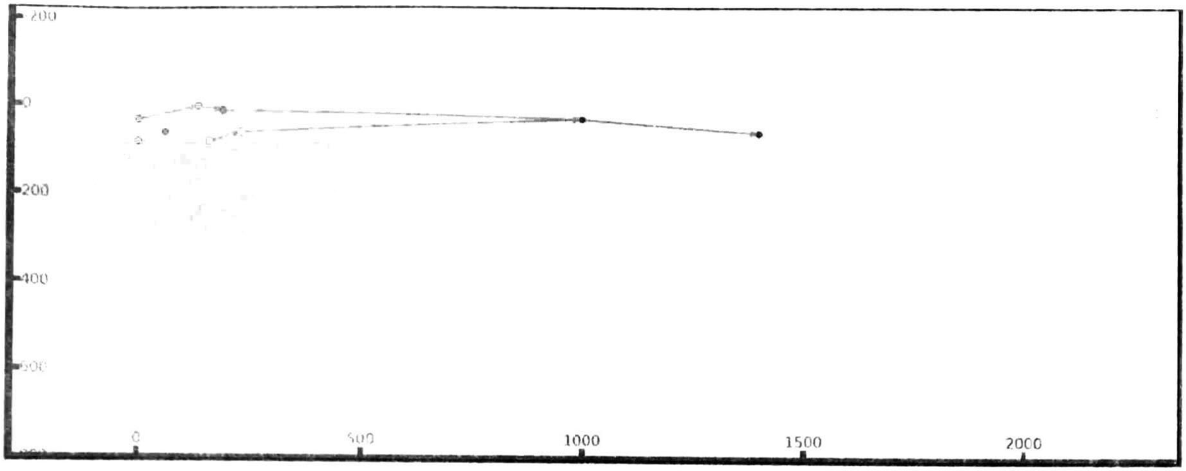


Figure 4.2 Scenario on PyViz illustration of NS3.

4.1.2 Simulation Parameters

Some simulation parameters are summarized in table 4.2, table 4.3, table 4.4, and table 4.5. The following parameters are used in both scenarios.

Parameter	Value
Simulator	NS-3-dev
Simulation length	500s
Transmission start	0.6s
PHY WiMAX Layer	OFDM
PHY Ad-Hoc Layer	DSSS
MAC Ad-Hoc Layer	CSMA/CA
Code Division Multiplexing (CDMA) codes	256
τ^w and τ^a	2ms
Bandwidth	10 MHz
ARQ	Selective Repeat

Table 4.2 Simulations Parameters

Table 4.3 shows the spectrum efficiencies (rate) by IEEE 802.16 Adaptive Coding and Modulation (ACM) settings.

Modulation Order	Target SINR (db)	Coding Order	Spectral efficiency (bits/symbol)
BPSK	6.4	½	0.5
QPSK	9.4	½	1
QPSK	11.2	¾	1.5
16-QAM	16.4	½	2
16-QAM	18.2	¾	3
64-QAM	22.3	2/3	4
64-QAM	24.4	¾	4.5

Table 4.3 ACM Settings for IEEE 802.16 [44]

P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**
0.5	0.7	0.4	0.3	0.7	0.4	0	0	0

Table 4.4 Attempt Rate Probability (for each node *i*)

Header	Size
GMH (General Mac Header)	6 bytes
GMSH (Grant Manager Sub Header)	2 bytes
PSH (Packing Sub Header)	3 bytes
FSH (Fragmentation Sub Header)	2 bytes
CRC (Cyclic Redundancy Check)	4 bytes

Table 4.5 IEEE 802.16 MAC Headers [44]

4.2 Analysis of Performance model

To validate the model, we compared the obtained results from Reference Model [9] and HMAN Model based on [9] with the simulations results. Node 4 was considered as the source for all the data flows. The packet length varies from 100 to 1200 bytes for both scenarios. We analyzed the following metrics: Packet Success Rate (PSR), End to End Throughput, End to End Delay, BER, and Optimal Packet Length (OPL). The main goal for this analysis was to determine if HMAN Model shows a better network performance than Reference Model [9] and if HMAN model is similar to the Simulation Model.

Packet Success Rate

Packet Success Rate was analyzed in both scenarios. We obtained the SNR results with the average SNR of packet length variable from left to right. Figures 4.3 and 4.4 show PSR vs SNR in flow *a* and *c* respectively using scenario 1 while figure 4.5 shows the results of scenario 2 in connection *b*. We can see in figures 4.3, 4.4 and 4.5 that PSR is *high* when the SNR has a value that reaches 6 in both 16-QAM (Quadrature amplitude modulation) and QPSK (Quadrature Phase Shift Keying).

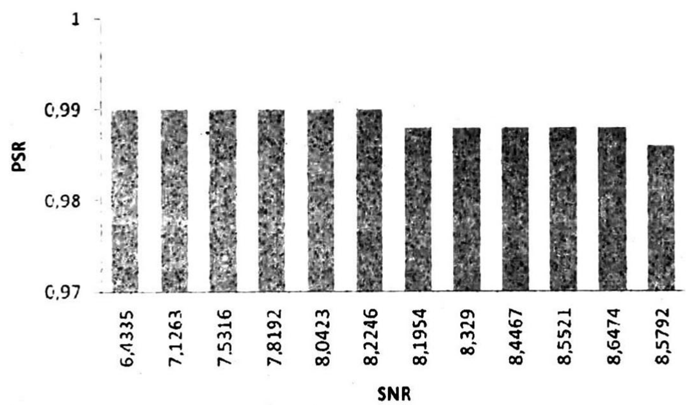


Figure 4.3 Packet Success Rate versus Instantaneous SNR in connection *a*

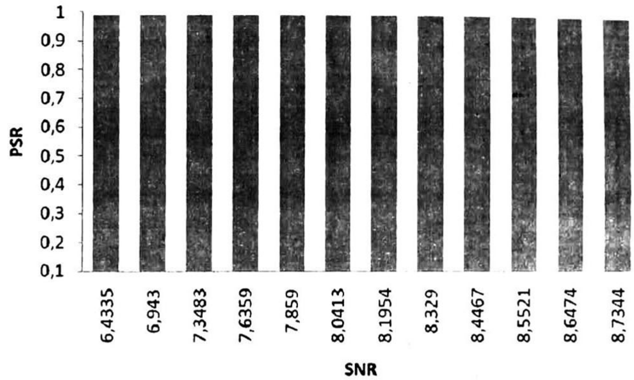


Figure 4.4 Packet Success Rate versus Instantaneous SNR in connection *c*

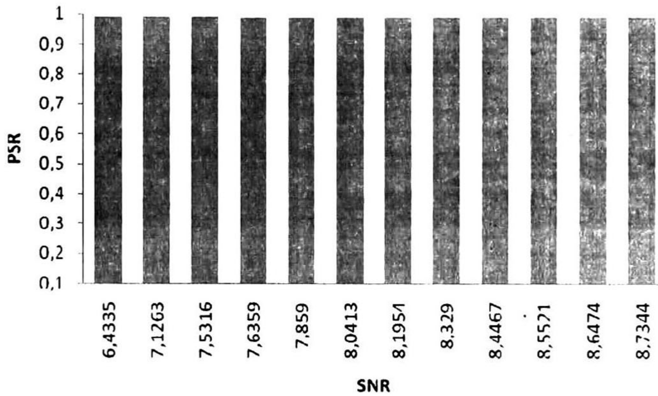


Figure 4.5 Packet Success Rate versus Instantaneous SNR in connection b

We obtained SNR results with an average SNR packet length variable (100 to 1200 bytes) from left to right. Figures 4.6 and 4.7 show PSR vs SNR in flow *a* and *c* respectively by using scenario 1 while figure 4.8 show results from scenario 2 in connection *b*. We can see in figures 4.6, 4.7 and 4.8 that PSR is *low* when the SNR has values down to 6 in both 16-QAM (Quadrature amplitude modulation) and QPSK (Quadrature Phase Shift Keying).

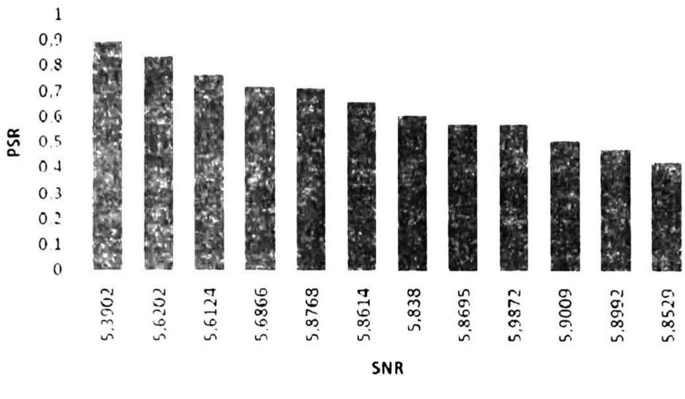


Figure 4.6 Packet Success Rate versus Instantaneous SNR in connection a

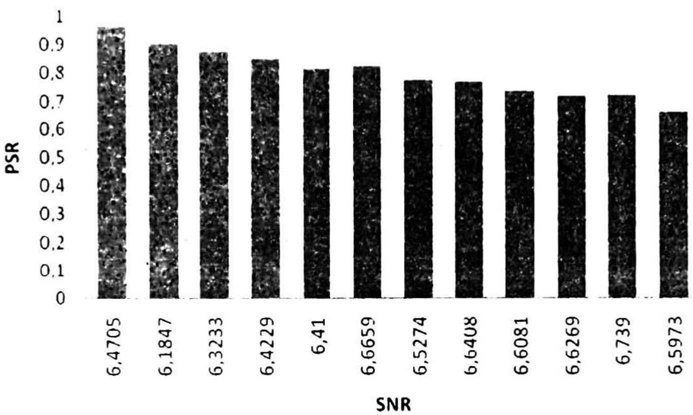


Figure 4.7 Packet Success Rate versus Instantaneous SNR in connection b

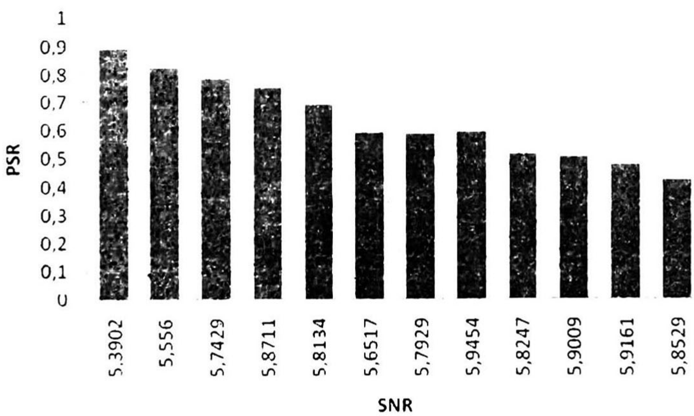


Figure 4.8 Packet Success Rate versus Instantaneous SNR in connection *c*

We concluded in these previous scenarios that when *Gateways* and their destination nodes are configured with the same modulation then the PSR is higher relation to different modulation schemes are employed.

We can see in figure 4.9 the packet success rate with a different modulation mode; we can conclude that higher values of SINR lead to a high packet success rate. Figure 4.10 shows the PSR vs BER. This figure shows that when BER is very low the PSR is almost 100%

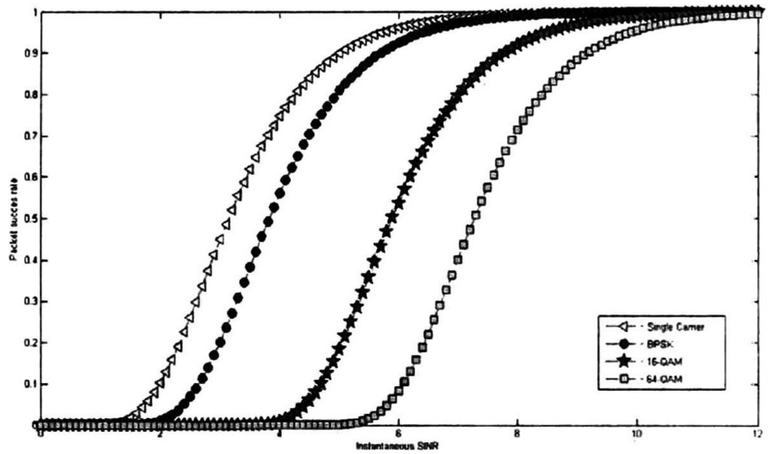


Figure 4.9 Packet Success Rate versus SNR [9]

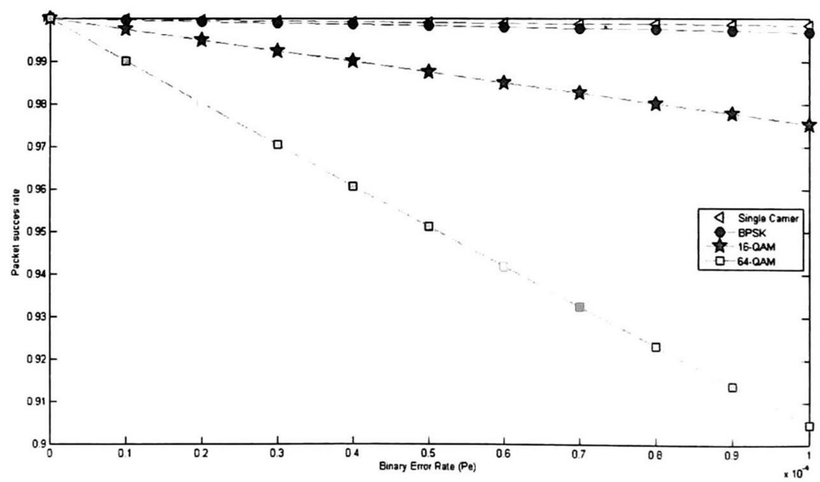


Figure 4.10 Packet Success Rate versus BER

End to End Throughput

End to End Throughput was analyzed in both scenarios in an error-prone channel with different BER for CSMA/CA with RTS/CTS. Figures 4.11 and 4.13 show Throughput vs variable packet length in flow *a* and c respectively using scenario 2 with BER=5e-7 in flow *a* and flow *c*, while figure 4.12 shows results from scenario 2 in connection *b* with BER= 9e-6.

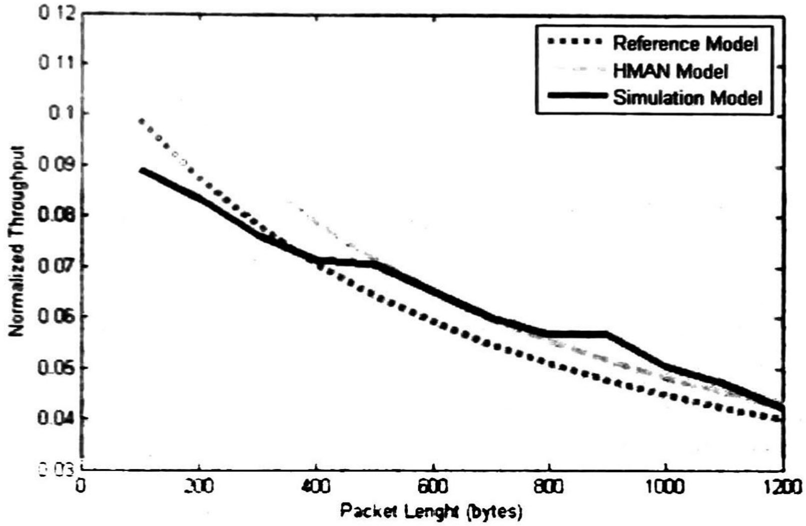


Figure 4.11 End to end throughput versus Packet Length (bytes) in connection *a*

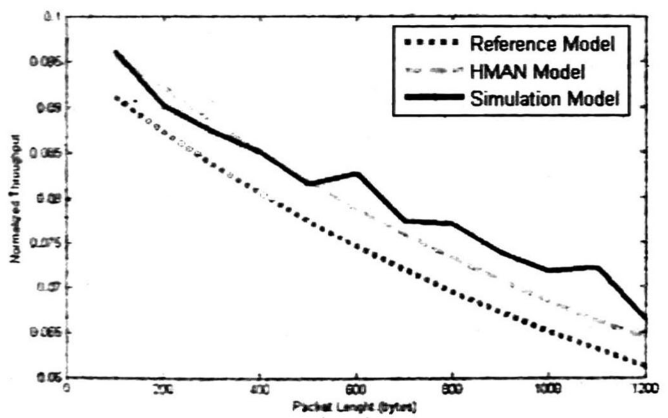


Figure 4.12 End to end throughput versus Packet Length (bytes) in connection *b*

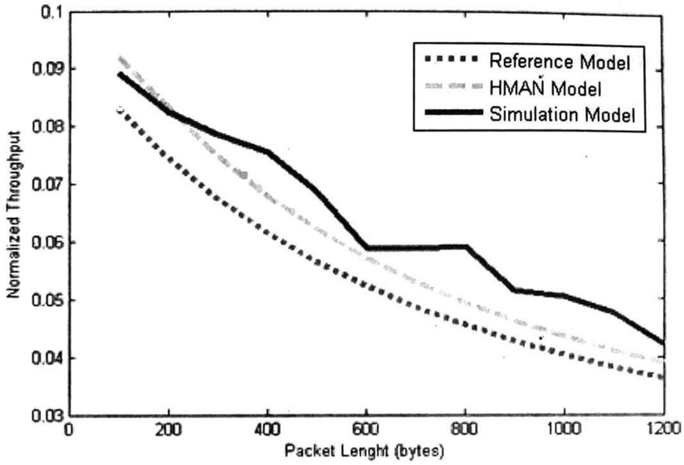


Figure 4.13 End to end throughput versus Packet Length (bytes) in connection *c*

End to end delay

End to End delay was analyzed in both scenarios. Figure 4.14 shows End to End delay vs variable packet length in flow *a* using scenario 1 while figure 4.15 shows results from scenario 2 in connection b. In figure 4.14 delay increases with increasing packet length in where there is 15% approximation error between simulation model and HMAN model with a small packet size. On the contrary, when we have an increase, the packet length HMAN is close to Simulation Model. In figure 4.15 HMAN Model is similar to Simulation Model in 400 to 600 packet size.

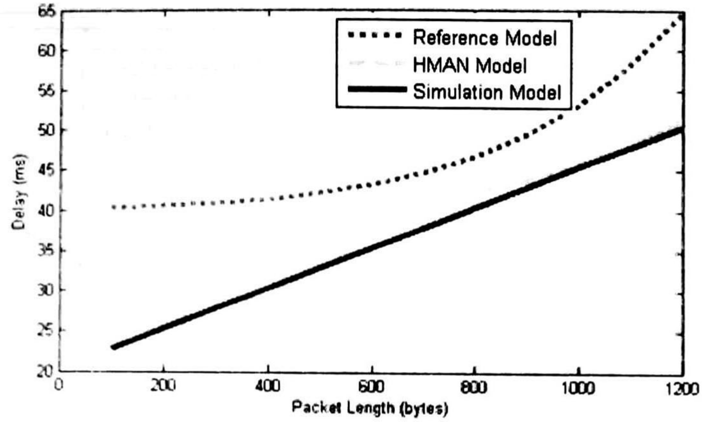


Figure 4.14 End to end delay (ms) versus Packet Length (bytes) in connection a

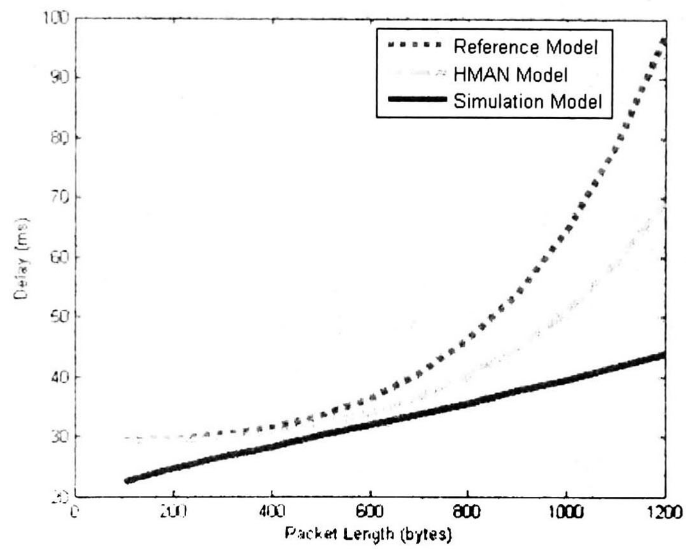


Figure 4.15 End to end delay (ms) versus Packet Length (bytes) in connection b

Figures 4.16 and 4.18 show End to End delay vs variable packet length in flow *a* and *c* respectively using scenario 2 while figure 4.17 shows results from scenario 1 in connection *b*, for an error-prone channel with different BER in both scenarios. When the HMAN model considers a BER=5e-6, HMAN Model is close to the Simulation Model compared to the Reference Model.

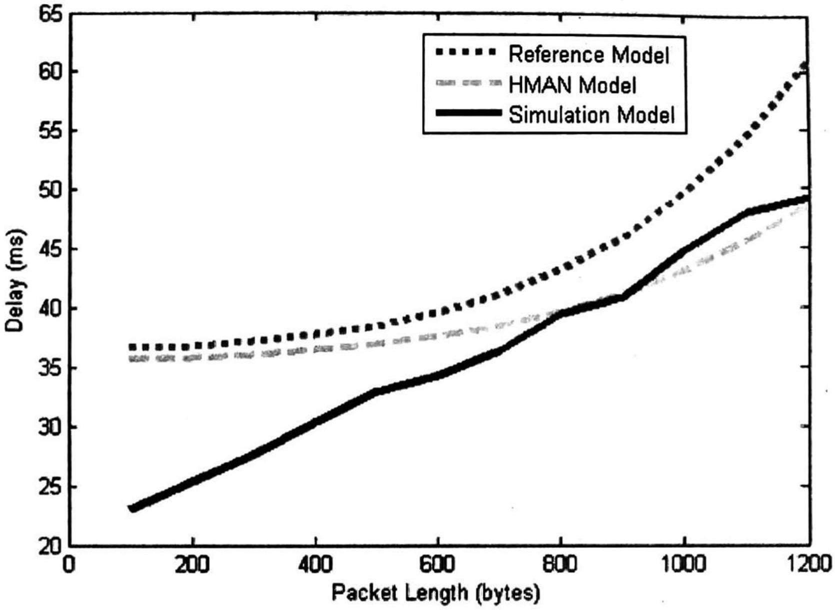


Figure 4.16 End to end delay (ms) versus Packet Length (bytes) in connection *a*

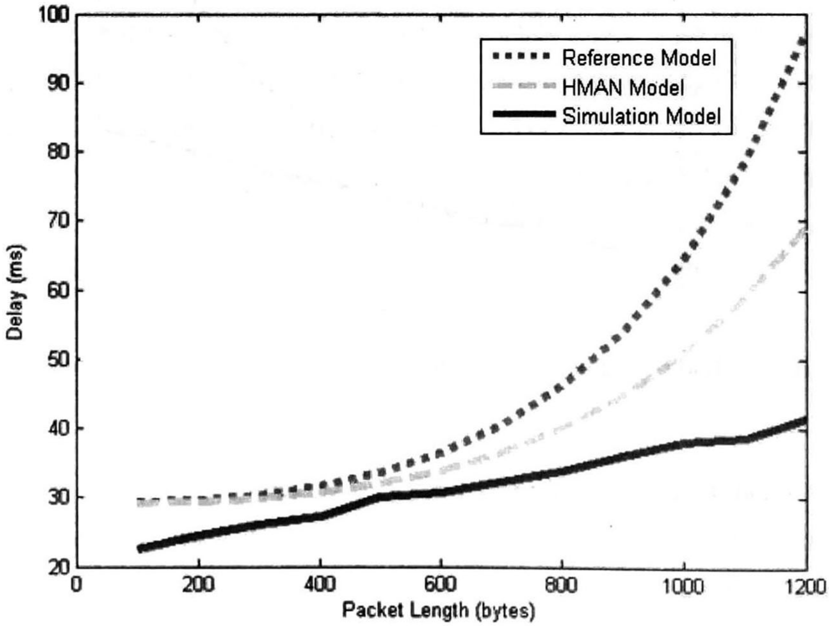


Figure 4.17 End to end delay (ms) versus Packet Length (bytes) in connection *b*

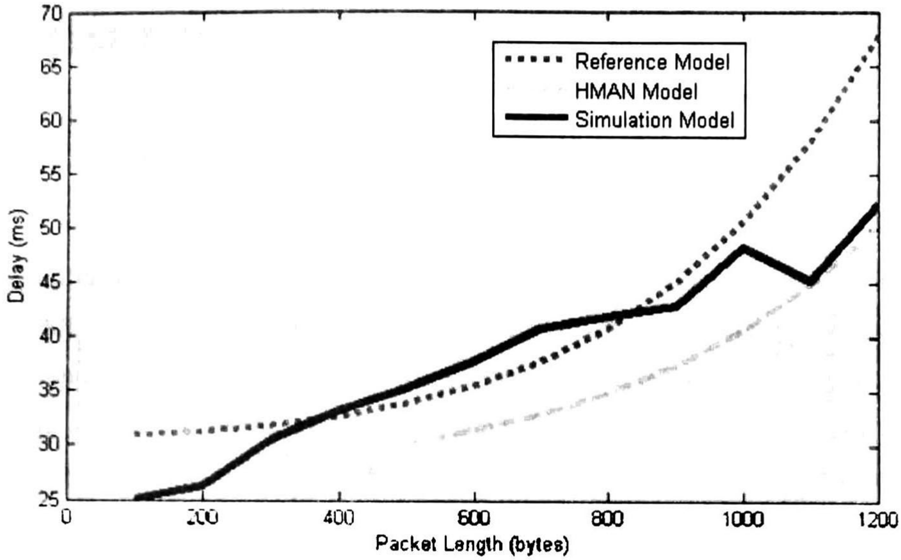


Figure 4.18 End to end delay (ms) versus Packet Length (bytes) in connection *c*

Optimal Packet Length

Optimal Packet Length was analyzed in both scenarios. There is a packet size that maximizes the throughput in error-prone channel. We used the Packet Error Rate obtained from the second scenario. Figure 4.19 shows the OPL which brings it near to 135 bytes vs PER from 0.1 to 0.6 in connection *a*. Figure 4.20 shows the OPL vs PER which brings it near to 293 bytes in connection *b*.

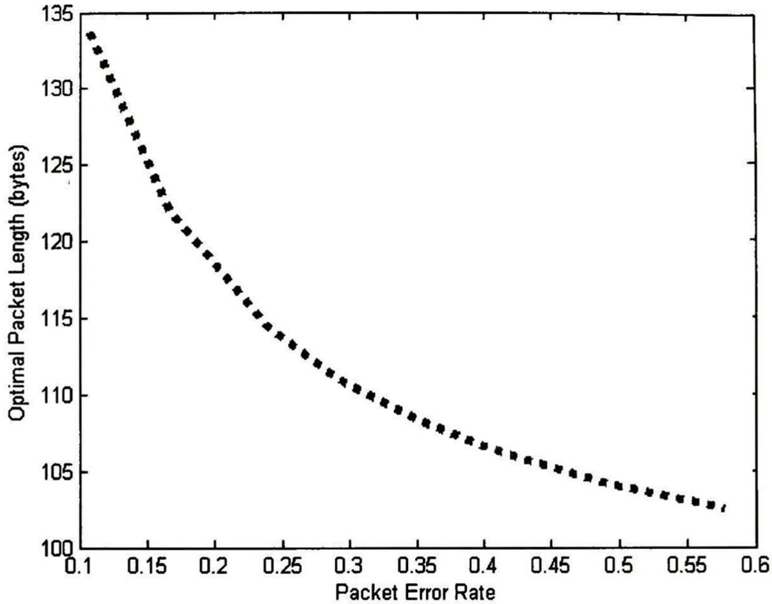


Figure 4.19 Optimal Packet Length (ms) versus Packet Error Rate in connection *a*

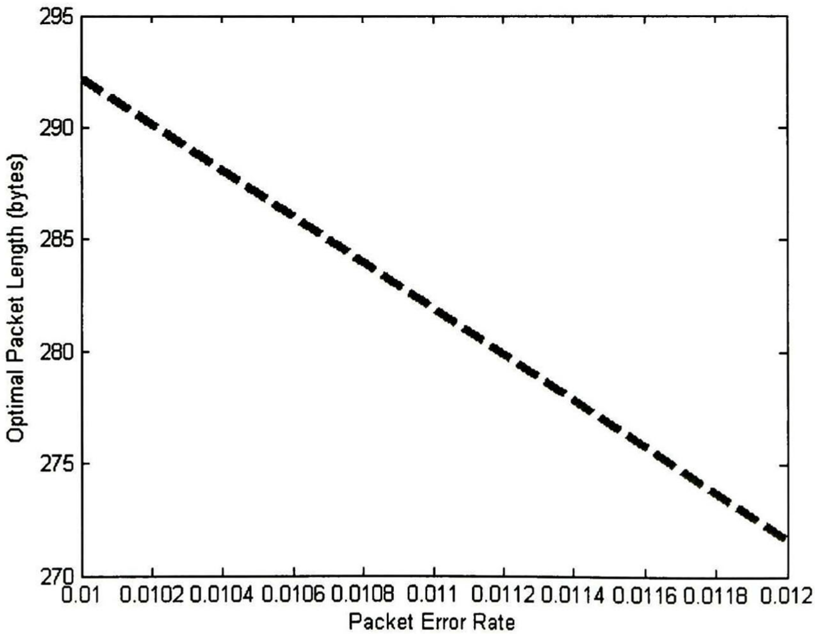


Figure 4.20 Optimal Packet Length (ms) versus Packet Error Rate in connection *b*

Chapter 5

Conclusions and Future Work

We analyzed a heterogeneous system composed of WiMAX cell and an Ad-Hoc network. The WiMAX technology and architecture form a complex, but feature-rich environment for supplying end user mobility. It shares many characteristics of cellular networks, such as architecture support of billing, mobility, and QoS. However, it also scales down with the technology being used for bridging other networks while Ad-Hoc is a simpler type of technology and easier to connect to.

The main contribution in this research is to study the end to end throughput and delay in a heterogeneous MAN by introducing the impact of different layers with the CLD (Layer 2 and Layer 1 of OSI Model) which was defined in Chapter 3. Also, we concluded that BER and OPL are important factors for network performance. Another important issue is packet success rate that is affected by NSR. We added the PER and the Optimal Packet Length to model both IEEE802.11 and IEEE802.16 protocols. Further, numerical and simulation results validate the utility of our HMAN model.

The HMAN model seems to be reasonable and comprehensive compared with the Reference Model in performance analysis and optimization of throughput and delay. Simulation results also indicate that the proposed analytical model is fairly accurate. This research could be of great interest for the future of wireless network when multiple wireless technologies are inter-operating between them.

FUTURE WORK

From the research presented on this thesis a number of issues could be extend or required further investigation:

- The HMAN could be interconnected to other protocols such as: CAN, Zigbee, LIN, etc.
- The network scenario could be extended by using the Internet or WAN (wide area network) Networks.
- We could consider different study cases for example: WiMAX Network with more than two modulations in different nodes or a big nodes amount per each technology.
- The CLD could employ other OSI layers and be analyzed if the throughput is better.
- We could consider other performance metrics such as Jitter, QoS, frame segmentation, etc.
- We observed that NS3 is still developing in some classes so we could support the WiMAX module.

Appendix A

The attempt rate is given by [6] (from equation 3.4):

$$P = \frac{2(1-2P_c)}{(1-2P_c)(CW_{min}) + P_c CW_{min}(1-(2P_c)^m)} \qquad (A.1)$$

Let the stationary distribution defined as:

$b_{i,k} = \lim_{t\to\infty} P\{\, s(t) = i, b(t) = k \,\}, i \in (0, m), k \in (0, W_i - 1)$

Note that: $b_{i-1,0} \cdot p = b_{i,0} \rightarrow b_{i,0} = p^i b_{0,0} \quad 0 < i < m$

$$b_{m-1,0} \cdot p = (1-p) b_{m,0} \rightarrow b_{m,0} = \frac{p^m}{1-p} b_{0,0} \quad (A.2)$$

Due to the chain regularities, for each $k \in (1, W_i - 1)$, it is

$$b_{i,k} = \frac{W_i - k}{W_i} \begin{cases} (1-p)\sum_{j=0}^{m} b_{j,0} & i = 0 \\ p \cdot b_{i-1,0} & 0 < i < m \\ p \cdot (b_{m-1,0} + b_{m,0}) & i = m \end{cases} \qquad (A.3)$$

By relation of (equation A.2) and using the fact of $\sum_{i=0}^{m} b_{i,0} = \frac{b_{0,0}}{1-p}$ the equation A.3 is rewritten as:

$$b_{i,k} = \frac{W_i - k}{W_i} b_{i,0} \qquad i \in (0, m), \quad k \in (0, W_i - 1) \qquad (A.4)$$

Equation A.2 and A.4 are expressed in terms of $b_{0,0}$, hence $b_{0,0}$ is determined imposing the normalization condition:

$$1 = \sum_{i=0}^{m} \sum_{k=0}^{W_i - 1} b_{i,k} \qquad (A.5)$$

In equation A.6, the first sum indicates that backoff stage goes from zero to m (maximum stage) represented by subscript i whilst the other sum indicates the backoff counter goes from $k = 0$ to contention window maximum size less one.

$$1 = \sum_{i=0}^{m} b_{i,0} \sum_{k=0}^{W_i - k} W_i - k / W_i \qquad (A.6)$$

$b_{i,k}$ is replaced by:

$$\frac{W_i - k}{W_i} b_{i,0} \qquad (A.7)$$

Using the following arithmetic series:

$$\sum_{i=0}^{n-1} (a + id) = \frac{n}{2}(a + l)$$

where $l = a + (n-1)d$ considering $d = -\frac{1}{W_i}$ so,

$$l = 1 + (W_i - 1)\left(-\frac{1}{W_i}\right) = 1 - 1 + \frac{1}{W_i} = \frac{1}{W_i}$$

Thus,

$$\sum_{k=0}^{W_i - 1} \frac{W_i - k}{W_i} = \sum_{k=0}^{W_i} 1 + (-k/W_i) = \frac{W_i}{2}(1 + l) = \frac{W_i}{2}\left(1 + \frac{1}{W_i}\right) = \frac{W_i}{2} + \frac{1}{2} = \frac{W_i + 1}{2}$$

Then this term is substituted in the equation A.6:

$$1 = \sum_{i=0}^{m} b_{i,0} \frac{W_i + 1}{2} = \sum_{i=0}^{m} \frac{b_{i,0} W_i + b_{i,0}}{2} = \sum_{i=0}^{m-1} \frac{b_{i,0} W_i + b_{i,0}}{2} + \frac{b_{m,0} W_m + b_{m,0}}{2}$$

Substituting $W_i = 2^i W$ leads to

$$1 = \frac{1}{2}\left[\sum_{i=0}^{m-1} \left[b_{i,0} 2^i W + b_{i,0}\right] + b_{m,0} 2^m W + b_{m,0}\right]$$

Now, substituting $b_{i,0} = p^i b_{0,0}$

$$1 = \frac{1}{2}\left[\sum_{i=0}^{m-1}\left[p^i b_{0,0} 2^i W + p^i b_{0,0}\right] + b_{m,0} 2^m W + b_{m,0}\right] \qquad (A.8)$$

The equation A.2 is used in the equation A.8 as follows:

$$1 = \frac{1}{2}\left[\sum_{i=0}^{m-1}\left[p^i 2^i W b_{0,0} + p^i b_{0,0}\right] + \frac{p^m}{1-p} b_{0,0} 2^m W + \frac{p^m}{1-p} b_{0,0}\right]$$

$$= \frac{b_{0,0}}{2}\left[\sum_{i=0}^{m-1}\left[(2p)^i W + p^i\right] + \frac{(2p)^m}{1-p} W + \frac{p^m}{1-p}\right]$$

$$= \frac{b_{0,0}}{2}\left[\sum_{i=0}^{m-1}(2p)^i W \sum_{i=0}^{m-1} p^i + \frac{(2p)^m}{1-p} W + \frac{p^m}{1-p}\right] \qquad (A.9)$$

Then the sum $\sum_{i=0}^{m-1} p^i = \frac{1}{1-p} - \frac{p^m}{1-p}$ is used in the equation A.9:

$$1 = \frac{b_{0,0}}{2}\left[\sum_{i=0}^{m-1}(2p)^i W + \frac{1}{1-p} - \frac{p^m}{1-p} + \frac{(2p)^m}{1-p} W + \frac{p^m}{1-p}\right]$$

$$= \frac{b_{0,0}}{2}\left[W\left(\sum_{i=0}^{m-1}(2p)^i + \frac{(2p)^m}{1-p}\right) + \frac{1}{1-p}\right] \qquad (A.10)$$

From which $b_{0,0}$ is got from equation A.10:

$$b_{0,0} = \frac{2}{\left[W\left(\sum_{i=0}^{m-1}(2p)^i + \frac{(2p)^m}{1-p}\right) + \frac{1}{1-p}\right]} = \frac{2}{\left[W\left(\frac{1-(2p)^m}{1-2p} + \frac{(2p)^m}{1-p}\right) + \frac{1}{1-p}\right]}$$

$$= \frac{2}{\left[W\left(\frac{1-(2p)^m}{1-2p}\right) + W\frac{(2p)^m}{1-p} + \frac{1}{1-p}\right]} = \frac{2}{\frac{(1-p)W\left(\frac{1-(2p)^m}{1-2p}\right) + W\frac{(2p)^m}{1-p} + \frac{1}{1-p}}{(1-p)}}$$

$$= \frac{2(1-p)}{(W-Wp)\left(\frac{1-(2p)^m}{1-2p}\right) + W(2p)^m + 1}$$

$$= \frac{2(1-p)}{\frac{W-W(2p)^m}{1-2p} + \frac{-Wp+Wp(2p)^m}{1-2p} + W(2p)^m + 1}$$

$$= \frac{2(1-p)}{\frac{W-W(2p)^m - Wp + Wp(2p)^m + W(2p)^m(1-2p) + (1-2p)}{1-2p}}$$

$$= \frac{2(1-p)(1-2p)}{W-W(2p)^m - Wp + Wp(2p)^m + W(2p)^m - 2pW(2p)^m + (1-2p)}$$

$$= \frac{2(1-p)(1-2p)}{W - Wp + Wp(2p)^m - 2pW(2p)^m + (1-2p)}$$

$$= \frac{2(1-p)(1-2p)}{W - Wp + Wp(2p)^m - 2pW(2p)^m + (1-2p)} = \frac{2(1-p)(1-2p)}{W - Wp - pW(2p)^m + (1-2p)}$$

Equivalence $-pW = -2pW + pW$

$$b_{0,0} = \frac{2(1-p)(1-2p)}{W - 2pW + pW - pW(2p)^m + (1-2p)}$$

$$= \frac{2(1-p)(1-2p)}{W + 1 - 2pW - 2p + pW - pW(2p)^m}$$

$$= \frac{2(1-p)(1-2p)}{W(1-2p) + 1(1-2p) + pW(1-(2p)^m)} = \frac{2(1-p)(1-2p)}{(1-2p)(W+1) + pW(1-(2p)^m)}$$

Now, the probability τ is expressed such as one station transmits in one time slot chosen randomly. Any transmission occurs when the time backoff counter is equal to zero without taking the backoff stage, we have:

$$\tau = \sum_{i=0}^{m} b_{i,0} = \frac{b_{0,0}}{1-p} = \frac{2(1-p)(1-2p)}{(1-p)(1-2p)(W+1) + pW(1-(2p)^m)}$$

$$= \frac{2(1-2p)}{(1-2p)(W+1) + pW(1-(2p)^m)}$$

Proposition 1

1) We can observe a node $i \in S_g$ gateway for $S_{i,t}$ cycles.

Let $S_{i,t}^{a}$ is the cycles number ad hoc till t^{th}slot, $S_{i,t}^{w}$ is the cycles number for WiMAX traffic. S_t^a is the total number of transmission slots using for Ad Hoc connections till t^{th}slot. The authors in [9] describe the proportion of cycles WiMAX as:

$$x_i = \frac{S_{i,t}^{w}}{S_{i,t}} = \frac{S_{i,t}^{w,Q} + S_{i,t}^{w,F}}{S_{i,t}}$$

where $S_{i,t}^{w,Q}$ is the probability to chose a WiMAX packet from Q_i, have:

$$\frac{S_{i,t}^{w,Q}}{S_{i,t}} = \frac{S_{i,t}^{w,Q}}{S_{i,t}^{Q}} \cdot \frac{S_{i,t}^{Q}}{S_{i,t}} = P_{i,B}(1 - \pi_i f_i)$$

On the other hand have:

$$\frac{S_{i,t}^{w,F}}{S_{i,t}} = \frac{S_{i,t}^{F}}{T_{i,t}^{a}} \cdot \frac{T_{i,t}^{a}}{S_{i,t}} \cdot \frac{S_{i,t}^{w,F}}{S_{i,t}^{F}} = f_i \pi_i \sum_{s} \frac{\pi_{i,s,d}}{\pi_i} = f_i \sum_{s} \pi_{i,s,d}$$

where $T_{i,t}^{a}$ is the cycles number that have an ad hoc packet till slot t. The proportion of WiMAX cycles will be:

$$x_i = P_{i,B}(1 - \pi_i f_i) + f_i \sum_{s} \pi_{i,s,B}$$

2) The attempt rate is:

$$\bar{P}_i = \lim_{t\to\infty} \frac{T_t^a}{t} = \lim_{t\to\infty} \frac{T_t^a}{S_{i,t}^{a}} \cdot \frac{S_{i,t}^{a}}{S_{i,t}} \cdot \frac{S_{i,t}}{t}$$

where

$\lim_{t\to\infty} \frac{T_t^a}{S_{i,t}^a} = \bar{L}_i$ is exactly the average number of slots per cycle (WiMAX or Ad hoc)

$\lim_{t\to\infty} \frac{S_{i,t}^a}{S_{i,t}} = (1 - x_i)$ the proportion of Ad hoc cycles between $S_{i,t}$

$$\lim_{t\to\infty} \frac{t}{S_{i,t}} = \frac{S_{i,t}^a \frac{\bar{L}_i}{P_i} + S_{i,t}^w \cdot \tau_i^w}{S_{i,t}} = \frac{\bar{L}_i}{P_i}(1 - x_i) + \tau_i^w\, x_i = \frac{\bar{L}_i(1 - x_i) + \tau_i^w\, x_i P_i}{P_i}$$

Having that

$$\lim_{t\to\infty} \frac{t}{S_{i,t}} = \frac{\bar{L}_i(1 - x_i) + \tau_i^w\, x_i P_i}{P_i}$$

Omitting limit for practical purposes, now

$$t = \frac{\bar{L}_i(1 - x_i) + \tau_i^w\, x_i P_i}{P_i} S_{i,t}$$

$$P_i t = \bar{L}_i(1 - x_i) + \tau_i^w\, x_i P_i S_{i,t}$$

$$\frac{P_i}{\bar{L}_i(1 - x_i) + \tau_i^w\, x_i P_i} = \frac{S_{i,t}}{t}$$

Add the limit,

$$\lim_{t\to\infty} \frac{S_{i,t}}{t} = \frac{P_i}{\bar{L}_i(1 - x_i) + \tau_i^w\, x_i P_i}$$

Substituting the three limits on $\bar{P}_i$,

$$\bar{P}_i = \frac{\bar{L}_i(1 - x_i)}{\bar{L}_i(1 - x_i) + \tau_i^w x_i P_i} P_i$$

Prove $E[V] \equiv \tilde{n}_i^Q \approx \sum_{k=0}^{\infty} k(1 - f_i)^k f_i = \frac{1-f_i}{f_i}$

$E[V] = \sum_{k=0}^{\infty} k(1-p)^k p = p\sum_{k=0}^{\infty} k(1-p)^k = p\left[\frac{d}{dp}(-\sum_{k=0}^{\infty}(1-p)^k)\right](1-p) =$

$-p(1-p)\frac{d}{dp}\frac{1}{p} = \frac{1-p}{p}$

Proof of $\bar{W}_i$ is:

$$\bar{W}_i = \bar{B}_i + \bar{R}_i$$

$$\bar{B}_i = \bar{W}_i - \bar{R}_i = a_i\bar{W}_i\tau_i^F + (a_i\bar{W}_i + 1)(\frac{1-f_i}{f_i})\tau_i^Q$$

$$\bar{W}_i = a_i\bar{W}_i\tau_i^F + a_i\bar{W}_i\tau_i^Q\left(\frac{1-f_i}{f_i}\right) + \tau_i^Q\frac{1-f_i}{f_i} + \bar{R}_i$$

$$\bar{W}_i - a_i\bar{W}_i\tau_i^F - a_i\bar{W}_i\tau_i^Q\left(\frac{1-f_i}{f_i}\right) = \tau_i^Q\frac{1-f_i}{f_i} + \bar{R}_i$$

$$\bar{W}_i(1 - a_i\tau_i^F - a_i\tau_i^Q\frac{1-f_i}{f_i}) = \tau_i^Q\frac{1-f_i}{f_i} + \bar{R}_i$$

$$\bar{W}_i\left(1 - a_i\left(\tau_i^F - \tau_i^Q\frac{1-f_i}{f_i}\right)\right) = \bar{R}_i + \tau_i^Q\frac{1-f_i}{f_i}$$

$$\bar{W}_i = \frac{\bar{R}_i + \tau_i^Q\frac{1-f_i}{f_i}}{1 - a_i\left(\tau_i^F - \tau_i^Q\frac{1-f_i}{f_i}\right)}$$

Appendix B

Heterogeneous Networks.- A Heterogeneous Networks is a set of devices interconnecting such as networks with different Operating System, protocols &/or hardware way.

Metropolitan Area Network (MAN).- "A MAN is a large computer network that spans a metropolitan area or campus. Its geographic scope falls between a WAN and LAN. MANs provide Internet connectivity for LANs in a metropolitan region, and connect them to wider area networks like the Internet".

	802.11	802.16
Scalability	Fixed wide channels (20MHz)	Adaptative channel bandwidth (sectorization)
		Scalable bandwidth from 1.5 MHz to 20 MHz. MAC independent of the channel bandwidth
	MAC designed to support tens of users	MAC designed to support hundreds of users
QoS	Contention-based MAC (CSMA/CA).	Grant-request MAC
	No guaranteed QoS.	Designed to support Voice and Video
	Standard cannot currently guarantee latency for Voice, Video (PCF not implemented)	
	Standard does not allow for differentiated service levels for each user	Supports differentiated service levels: T1 for business customers, best effort for residential
	TDD only asymmetric	TDD/FDD/HFDD symmetric or asymmetric

	802.11e (proposed) QoS is prioritization only	Centrally-enforced QoS
Range	Optimization for ~100 meters No distance compensation Designed to handle indoor multi-path (delay spread of 0.8μs) Optimization centers around PHY and MAC layer for 100m range Range can be extended by cranking up the power but MAC may be nonstandard	Optimized for up to 50Km Designed to handle many users spread out over kilometers Designed to tolerate greater multi-path delay spread (signal reflections) up to 10.0μs PHY and MAC designed with multi-mile range in mind Standard MAC
Cover	Optimized for indoor performance	Optimized for outdoor NLOS performance Standard supports mesh network topology Standard supports advanced antenna techniques
Security	Existing standard is WPA + WEP 802.11 in process of addressing security	Triple-DES (128-bit) and RSA (1024-bit)

Table B.1 Differences between 802.11 and 802.16 standards [44, 46]

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Martha Maria HERNÁNDEZ OCHOA

el día 21 de Enero de 2011.

Dr. Félix Francisco Ramos Corchado
Investigador CINVESTAV 3A
CINVESTAV Unidad Guadalajara

Dr. Mario Angel Siller González Pico
Investigador CINVESTAV 2A
CINVESTAV Unidad Guadalajara

Dr. Héctor Alejandro Durán Limón
Profesor-Investigador
Universidad de Guadalajara