# A Simulator for analyzing the throughput of IEEE 802.11b Wireless LAN Systems

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# A Simulator for analyzing the throughput of IEEE 802.11b Wireless LAN Systems

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## (Abstract)

Wireless Local Area Networks (WLAN) have proliferated in the last 5 years. The IEEE 802.11b products have become commonplace both in the residential and business places for untethered Internet access. However the end user experience has often been less satisfactory than what the technology can offer. The degradation in the performance of the system is mainly attributed to the poor network design. The current network design is primarily RF centric. There are two factors that need to be in the incorporated in the design. Firstly a clear understanding of the traffic sources in the network such as the peak load of the system is necessary. Secondly the design should account for the limitations of the indoor propagation such as interference and multipath.

The goal of this thesis is to develop a simulator which will predict the performance (throughput) of an end user. The throughput is predicted for a given topology and traffic source. The simulator is built on object oriented design. To validate the simulator a measurement campaign was conducted. The campaign was conducted in two different channel conditions, office space and open hall. The channel measurements were also performed at these locations to understand the multipath.

Comparative studies indicate that the choice of the rate adaptation algorithm hugely influences the predicted throughput. The simulator results match very well with the measurement results for the open space scenario. For the office space scenario the simulator varied by roughly 20% from the measurement results. This was due to existence of multipath leading to Inter Symbol Interference.

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# 1. Introduction

## 1.0 Motivation

Wireless Local Area Networks (WLAN) have proliferated in the last 5 years. This was possible due to the low cost of the Access points (AP) and PC cards and also due to the ease of installation of the network. However utilizing the capabilities of the system in providing a better service to the end user has been a huge concern. Improper network planning, security concerns, higher bandwidth requirements are some of the areas that are being worked on in both the academia and the industry.

The maximum data rate available in an 802.11b system is 11 Mbps. However the theoretical maximum throughput for a CSMA/CA based system is 6.1Mbps[Jangeun03]. The throughput decreases further with more number of users and in the presence of multipath. When deploying wireless LANs, most installers ensure that there are enough access points to provide adequate signal coverage. This enables users to roam throughout the facility; however, it does not completely address capacity requirements.

## 1.1 Problem Description

Due to the growing users and the variety of applications there is a need to provide better Quality of Service (QoS) to the end users. The current network design is primarily RF centric. There are other factors that need to be considered in designing better systems.

1) A clear understanding of the traffic sources in the network such as the peak load of the system
2) The design should account for the limitations of the indoor propagation such as interference and multipath

The traffic generated in the system can be understood by studying the application needs of the users in the system. The applications can vary from simple web browsing, file transfer or inventory management involving database interactions.

The deployment should take in to consideration the limitations of indoor propagation. Radio propagation in the indoor office environment is subject to interference, multipath and excess losses, making it behave poorer than the predicted performance. The propagation path is rarely direct in indoor wireless local area networks. Moreover the 2.4GHz ISM band is used by other devices such as microwave ovens, cordless phones and Bluetooth. The WLAN deployment should consider the impairments induced by these devices.

The goal of this work is to develop a simulator which will predict the performance of an end user. This tool attempts to simulate a real world scenario of multiple users accessing a shared AP, which connects to the wired network infrastructure.

## 1.2 Wireless LAN simulator

A wireless simulator based on the IEEE 802.11b standard has been developed as a part of this thesis. Following are some of the features of the simulator.

1) The location of the WLAN node can be specified. Cartesian coordinates are used to locate the users with the access point at the origin.
2) The traffic of individual users can be modeled in the system. The packet arrival rate and packet length distributions of the traffic can be specified in the model.
3) The throughput calculation is dependent on the path loss and partition losses in the channel.
4) The simulator is provided with the information about the building materials between the line of sight of the access point and WLAN node. Also the distance between the WLAN node and Access Point (AP).

Currently the floor plan information is fed manually. In future the simulator can be extended to work with CAD tools in gathering such information.

## 1.3 Contributions and Thesis Overview

One of the contributions of this work is the WLAN simulator, developed using object oriented programming. The simulator is an open framework for building wireless networks. This open framework was used to build the IEEE802.11b system. The simulator provides flexibility to add independent traffic sources to each user in the system. Also the simulator is scalable to add required number of users in the system.

A measurement campaign was also conducted as a part of this work. The campaign was carried out at two different buildings with different channel characteristics and building materials. The channel measurements were also conducted alongside to understand the multipath characteristics of the channel. The simulator was validated from the measurement campaign.

The experimental results were mostly congruent with the simulated results for cases in which the packet length used was higher (1000B). The rate adaptation algorithm is a critical part of the multi-rate WLAN systems and is vendor specific. Two rate adaptation algorithms are discussed in this work. The experimental results were compared with results from both algorithms. It was established that a good understanding of the algorithm used in commercial systems is critical in predicting the throughput. This will be possible with more extensive and controlled measurement campaign.

Chapter 2 gives a detailed overview of the IEEE802.11b standard. Emphasis is given to the Infrastructure mode of operation of the WLAN system since this investigation pertains to this mode. The DCF algorithm used in the MAC layer is discussed in length. The physical layer of the system – spectrum allocation, modulation scheme, and physical layer headers are discussed.

The performance of WLAN systems is a major research interest to both the academia and industry. Several measurement campaigns have been performed to understand the factors that influence the performance of the WLAN system. Chapter 3 discusses these previous research works.

Chapter 4 starts with an overview of this simulator and later discusses in detail all the key classes and functions in the simulator. The chapter concludes with a discussion on the salient features of the simulator.

The results of the simulator are validated with an experimental campaign. The throughout of the simulator for a single node scenario was used for comparing the results. The experimental campaign was conducted in two different building providing different channel conditions. For every location in the campaign, the channel characteristic (power delay profile) was recorded using a software defined measurement receiver. Chapter 5 discusses the hardware and software required for the throughput and the channel measurement campaign.

Chapter 6 tabulates the results from the experimental campaign and simulator for each building. The results from the channel measurement are also presented for each building. Impact of the multipath on the performance of the system is discussed. Chapter 7 summarizes the measurement campaign, contributions of this research and suggests future research areas.

# 2. Background

## 2.0 Overview

This chapter provides the overview of the WLAN technology as standardized by the IEEE 802.11 committee. The technical detailzs of the MAC (Medium Access Control) and the physical layer of the standard are discussed.

MAC introduces the concept of collision avoidance to mitigate frame collision in the wireless medium. There are additional procedures such as Virtual carrier sensing, which provides enhance protection to frame collision. The standard also provides flexibility to adapt the rate of transmission to mitigate bad channel conditions. A good understanding of these procedures is crucial in developing a real world simulator.

This chapter begins with an overview of the standard providing a top bottom view of the protocol stack. Section 2.2 discusses the operational modes of the WLAN system – Ad hoc versus Infrastructure. The medium access in the standard is of two types – the Point Coordinated Function (PCF) and the Distributed Coordination Function (DCF). The simulator is based on DCF. Section 2.3 discusses the details of the DCF procedure. Section 2.4 discusses the physical layer information such as channel allocation, modulation schemes and the services it offers to the MAC layer. The final section discusses the format of the IEEE 802.11 frames, which includes information bits pertaining to the physical layer and the MAC procedures.

## 2.1 IEEE 802.11b WLAN system

WLAN systems are available in different flavors. The initial version of 802.11 standards provided data rates of 1 and 2Mbps and operated at 2.4GHz. IEEE802.11b provides enhanced data rates, providing a peak data rate of 11Mbps with fall back rates of 5.5, 2 and 1Mpbs. IEEE 802.11b also operate at 2.4GHz. The higher data rates are achieved using complementary code keying (CCK) modulation. The next generation of systems namely IEEE802.11a and IEEE801.11g are based on OFDM modulation providing a peak data rate of 54Mbps. The 802.11a operates at 5GHz while the 802.11g operates at the same 2.4GHz ISM band. In this work the WLAN system investigated is IEEE 802.11b.

The scope of the IEEE 802.11 standard is to develop medium access control (MAC) and physical layer (PHY) specification for wireless connectivity for fixed, portable, and moving stations within a local area [802.11 standard]. Some of the key features of the standard are:

- The 802.11 presents the same interface to the upper layer protocols as other IEEE 802 standards.
- The standard supports two operational modes: Infrastructure and Ad hoc mode.

- At the PHY layer, IEEE 802.11b defines three physical characteristics for wireless local area networks: diffused infrared, direct sequence spread spectrum (DSSS), and frequency hopping spread spectrum (FHSS).
- The MAC sub layer includes the distributed coordination function (DCF), the point coordination function (PCF), and their coexistence in an IEEE 802.11 LAN. DCF is based on Carrier sense multiple access with collision avoidance (CSMA/CA). PCF is based on polling with the access point controlling the polling mechanism.
- The standard provides an optional Ready-To-Send (RTS) and Clear-To-Send (CTS) extension to the DCF to deal with the hidden terminal problem in a wireless network.
- WLAN nodes can operate in power save mode. The nodes inform the AP by using the power management bits within the frame control field of the transmitted frames.

## 2.2 Operation Modes

IEEE 802.11b defines two pieces of equipment, a wireless station (or node), which is usually a PC or a laptop with a wireless network interface card (NIC), and an AP, which acts as a bridge between the wireless stations and Distribution System (DS) or wired networks. A group of WLAN node controlled by a single coordination function is called as a Basic Service Set (BSS). There are two operation modes in IEEE 802.11b, Infrastructure Mode and Ad Hoc Mode.

### 2.2.1 Ad hoc Mode

The independent BSS is the most basic type of WLAN configuration and is referred as an Ad hoc network. Figure 2.1 shows two Ad hoc networks. This mode is possible when the nodes are able to communicate with each other directly.

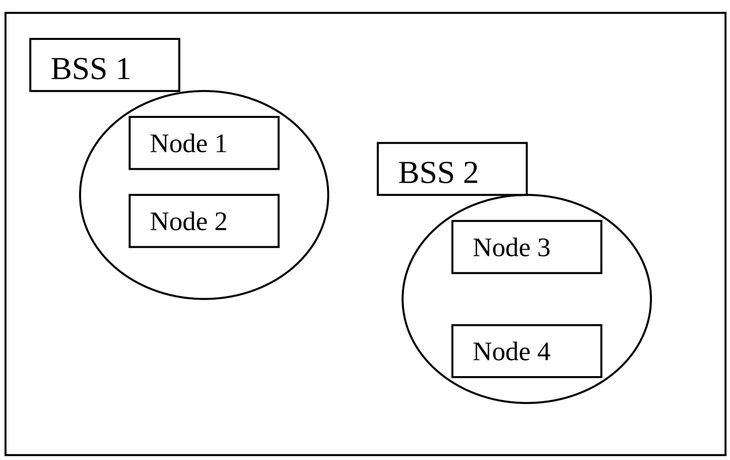



***Figure 2.1: Basic Service Sets***

### 2.2.2 Infrastructure mode

The independent BSS is limited in the coverage. In order to achieve an increase in coverage, multiple BSS are interconnected using the distribution system. Alternatively an Infrastructure Mode consists of at least one Access Point connected to the Distribution System. The access point performs the dual operation of being a WLAN node and also providing access to the DS using the distribution services. ***This thesis focuses on Infrastructure based wireless networks.***

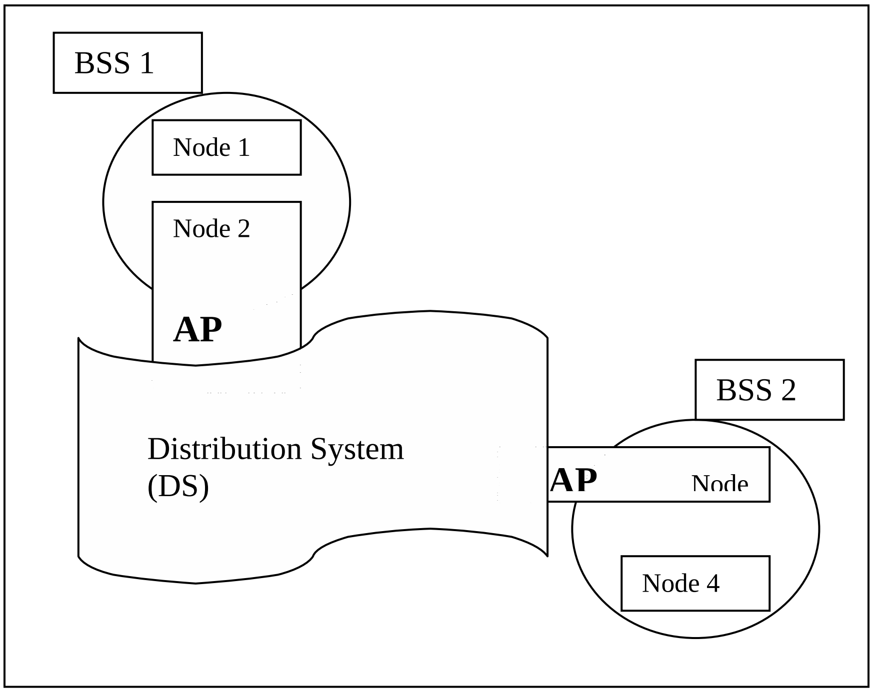



***Figure 2.2: WLAN Infrastructure***

Distribution services primarily deals with transporting the MAC Protocol Data Units (MPDU) from the nodes within a BSS to other nodes outside of the BSS. The outside nodes could either be within another BSS or could be a portal. The distribution services could also involve the transport of MPDU between stations in the same BSS in cases where the MPDU has a multicast or broad-cast destination address or where the destination is an individual address, but the station sending the MSDU chooses to involve DSS.

## 2.3 DCF

Distributed Coordination Function (DCF) is the primary access method in the IEEE802.11 MAC. The DCF is implemented as a *carrier sense multiple access with collision avoidance* (CSMA/CA). This access method is applicable to both Infrastructure and Ad hoc networks. The WLAN nodes communicate with each other using the CSMA/CA protocol. The MAC proposes the usage of RTS/CTS packets to avoid the hidden terminal problem. The MAC layer of the sender communicates with the peer MAC using the MPDU. The MPDU carries control, management or service data information. The frames can be fragmented to create smaller MPDU with an intention to increase the probability of successful frame transmission. In such cases the frame will contain the fragmentation information. The following sections elaborate the DCF MAC mechanism.

### 2.3.1 Physical carrier sense

The DCF enables the sharing of the medium between active WLAN nodes in a BSS based on physical sensing of the medium. In a DCF all directed packets are positively acknowledged (ACK). Retransmission occurs if there is a failure to receive an ACK.

The IEEE proposes the collision avoidance method rather than the collision detection. This is because the standard employs half-duplex radios—radios capable of transmission or reception but not both simultaneously. The CSMA/CA protocol is designed to reduce the collision probability between multiple WLAN nodes accessing the medium at the instant when the probability of collision is highest. The maximum probability is when the medium becomes idle following a busy medium. This necessitates the use of random backoff procedure to resolve the contention conflicts.

The basic unit of time for which the physical layer can access the medium is defined as 'aSlotTime' duration. This is the time needed by the PHY circuitry to tune to the working frequency, sense the medium successfully (inclusive of the MAC processing delay). There are different intervals between frames transmission during which the WLAN node accesses the medium for physical carrier sensing. They are short Interframe Space (SIFS), PCF Interframe Space (PIFS), DCF Interframe Space (DIFS), extended Interframe Space (EIFS) in the increasing order of the duration.

The working of the DCF follows the below procedure as shown in the Figure 2.3.

Each node that has a packet to send senses the medium for the DIFS period. If the medium is idle after the DIFS period, the MAC PDU is transmitted.

When multiple nodes try to access the medium, the probability of medium being occupied is higher. Also the probability of collision once the medium becomes idle is higher. Hence there is a need to spread out the transmission among different nodes.

Once the medium is found busy during the carrier sense, the WLAN node back offs the transmission. The backoff time is random and is a multiple of the slot duration. Backoff time = Random Number * aSlotTime. The random number is uniformly distributed over the interval [0, CW]. CW assumes the initial value of CWmin and is incremented for every retransmission (by square of the previous CW minus 1) until it reaches CWmax.

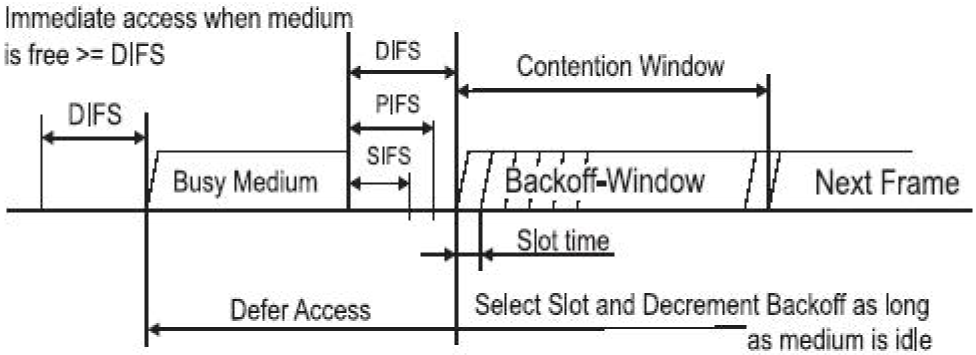



***Figure 2.3: DCF medium access method [IEEE 802.11]***

The node waits until the medium becomes idle. Once the medium becomes idle, the nodes waits for an additional Inter Frame Space (IFS, see section below) time before it starts the backoff timer. ***The nodes can only transmit when the backoff timer expires***. The backoff timer is stopped once the medium is found busy. This mechanism ensures that nodes that have been waiting longer do not get starved. The node waits for the medium to become idle and follows the same procedure as explained above until the backoff timer expires.

*2.3.1.1 Inter Frame Spacing (IFS)*

There are four IFS that are defined in the standard, SIFS, PIFS, DIFS and EIFS in the increasing order of time**.**

Short Inter-Frame Spacing (SIFS) is the shortest additional time the node waits once the medium become idle. This is used while transmitting the acknowledgements for data packets.

PIFS is used only for the WLAN system which uses the Point Coordinated Function (PCF) version of the MAC. In this system the AP polls the nodes to transmit. The nodes wait for PIFS duration before transmission.

DCF Inter-Frame spacing (DIFS) is used for the DCF function of the WLAN MAC (the system that is addressed in this work). The nodes wait for DIFS duration once the medium becomes Idle before accessing the medium. If the nodes are under backoff, then the backoff timer is decremented after this duration.

Extended Inter-Frame Spacing (EIFS) is used in DCF. EIFS is used when the node is attempting to transmit a frame, which has been previously detected as unsuccessful due to FCS failure.

### 2.3.2 Virtual carrier sense

The contention resolution mechanism of DCF is limited by the 'physical' carrier sensing range of the WLAN radio. Hence this mechanism suffers from hidden terminal problem. Hidden terminal is a common problem in contention prone wireless networks. Assume a WLAN Node close to the receiver but far away from the sender. The Node will sense the medium to be idle as it is hidden from the transmission range of the sender. This could lead to collision in the medium if the hidden Node attempts to transmit any MPDU to the common receiver.

To supplement the DCF in addressing this problem, the IEEE has proposed an optional 'virtual' sense mechanism. The virtual carrier sense is performed in addition to the physical carrier sense. The virtual carrier sense is achieved by reserving the medium for the transmission of a MPDU and distributing this reservation information to the other WLAN nodes to avoid collision. This is accomplished by the use of Read to Send (RTS) and Clear to Send (CTS) frames.

The sender WLAN node sends a RTS frame that contains the address of the sender and recipient. The RTS frame contains a duration field that forewarns other nodes, the time the medium will be occupied for the following MPDU exchange. This includes the overheads like CTS frame, ACK frame and three SIFS duration. Any WLAN Node close to the sender should update its NAV to this duration field. The NAV indicates the earliest point in time the Node can attempt to use the medium without any contention.

On receiving the RTS frame, the recipient WLAN node sends a CTS frame that again includes the sender and recipient address and the time duration to send the pending MPDU. This duration field is calculated from the duration field in the RTS packet after subtracting the time needed to transmit the CTS frame and its SIFS duration. Any WLAN node close to the receiver should update its net allocation vector (NAV) to this duration field.

Thus nodes close to both the sender and the receiver are made aware of the upcoming MPDU transaction; eliminating the threat of collision from the hidden terminal. Finally when the sender receives the CTS frame successfully it starts the transmission of the pending MPDU.

The virtual carrier sense adds additional overheads by introducing the RTS and CTS frames. This overhead will decrease the throughput if smaller MAC Protocol Data Units (MPDU) is being transmitted. Hence only those MPDUs which are greater than 'RTS threshold' will use this mechanism. This threshold can be set per individual WLAN nodes.

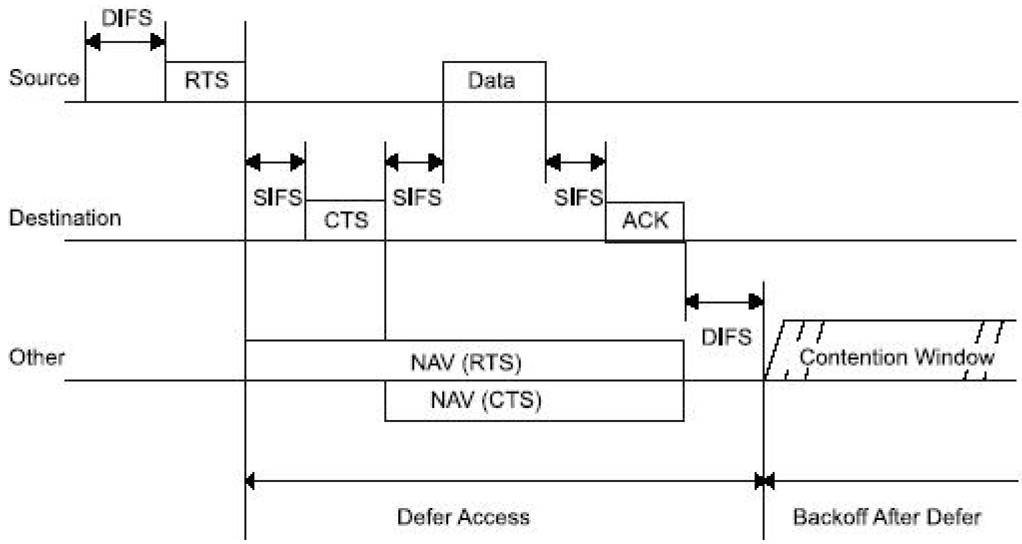



***Figure 2.4: Virtual carrier sense [IEEE 802.11]***

## 2.4 PHY Layer

The IEEE 802.11b supports three physical layers: Infrared, direct sequence spread spectrum (DSSS), and frequency hoping spread spectrum (FHSS). The 802.11 physical layer supports data rate of 1Mbps and 2 Mbps. The IEEE 802.11b standard (clause 15 in IEEE Std 802.11- 1999) extends the physical layer of DSSS system. The new physical layer is known as High Rate PHY and supports additional data rates of 5.5 and 11 Mbps in additional to 1 and 2 Mbps. The thesis work is based on this High Rate PHY.

The DSSS is primarily aimed for deployment in the 2.4 GHz ISM band. See Table 2.1 below for the frequency allocation in various geographical regions.

The available spectrum is divided in to 20 MHz channels with 5 MHz separation between them. This creates a spectral overlap between adjacent channels, restricting the network planning. The IEEE recommends at least 25 MHz of separation between adjacent channels. Thus only 3 non-overlapping channels can be deployed within the 83.5 MHz (as in US).

| Regions | Allocated Spectrum |
|---|---|
| US | 2.4000 – 2.4835GHz |
| Europe | 2.4000 – 2.4835GHz |
| Japan | 2.4710 – 2.4970GHz |
| France | 2.4465 – 2.4835GHz |
| Spain | 2.4450 – 2.4750GHz |

***Table 2.1 Spectrum Allocation***

### 2.4.1 Modulation schemes

*2.4.1.1 Basic access rates (1 & 2Mbps)*

Each bit is spread using an 11 bit Barker Sequence. The following is the sequence used for spreading.
+1, –1, +1, +1, –1, +1, +1, +1, –1, –1, –1

The chip rate of the Barker symbol is 11Mcps, thus the symbol rate is 1MSps.
For 1 Mbps data rate the chips are modulated using DBPSK and for 2 Mbps DQPSK is used.

*2.4.1.2 Higher data rates (5.5 & 11Mbps)*

Higher data rates namely 5.5Mbps and 11 Mbps are achieved using CCK Modulation Scheme. This scheme was proposed by Intersil and Lucent and was later adopted by the IEEE 802.11.

CCK is a form of M-ary code word modulation where one of set of M unique signal codeword is chosen for transmission. The spread function for CCK is chosen from a set of M nearly orthogonal vectors by the data word [Andren]. CCK Modulation uses 8 bit long symbol. CCK codes have the same chip rate of 11Mcps as that of Barker sequence. This makes it preferable in interoperating with the 1 and 2 Mbps data rate schemes.

The bits/symbol for the 5.5 and 11 Mbps is 4 and 8 respectively as shown below.
Bits per symbol = bit rate / symbol rate = 5.5 Mbps / (11 Mcps / 8 chips/symbol) = 4. Similarly for the 11 Mbps data, the bits per symbol can be calculated as 8

### 2.4.2 Physical Layer Services

The physical layer provides many services to the higher MAC layer. The services are related to Clear Channel Assessment (CCA) and data transmission and reception etc. These services are provided through two functions of the Physical layer, the Physical Layer Convergence function and the Physical Medium Dependent functions.

The Physical Layer convergence function takes care of mapping the PDU from MAC layer to the format compatible with the PHY format. This is achieved using the Physical Layer Convergence Protocol (PLCP).

The physical medium dependent as the name suggests provides methods for transmitting and receiving data through the wireless medium between two or more WLAN nodes.

## 2.5 Frame format

The format of the WLAN frame sent over the air can be seen below in Figure 2.5. The frame consists of physical information from PHY, MAC headers and the payload. The number of bits used to code the individual fields can also be seen in the Figure. The details of the fields in the frame and its types are discussed in this section.

| Sync | SFD | Signal | Service | Length | CRC | MPDU |
|---|---|---|---|---|---|---|
| 128 | 16 | 8 | 8 | 16 | 16 | (Variable size) |

**PLCP Preamble** **PLCP Header**

| Frame Control | Duration/ ID | Addr1 | Addr2 | Addr3 | Sequence Control | Addr4 | Frame Body | CRC |
|---|---|---|---|---|---|---|---|---|
| 16 | 16 | 48 | 48 | 48 | 16 | 48 | 0-18496 | 32 |

***Figure 2.5: MAC Frame Format***

*PHY Fields*

The physical channel information can be classified in to PLCP preamble and PLCP header. These bits are always transmitted at 1 Mbps to provide maximum robustness.

The SYNC field aids the PHY circuitry of the receiver in reaching steady state frequency offset and synchronization with respect to the packet timing. While the Start Frame Delimiter provides frame timing.

The Signal Field codes the rate at which the MPDU is transmitted. It is an 8 bit field and the value is in multiple of 100 Kbps. The Service Field is reserved for future use. The length field uses unsigned 16 bit to represent the time needed (in microseconds) to transmit the MPDU. These fields are very critical in the proper reception of the radio frame and hence they are protected using a 16 bit CRC algorithm. The CRC field contains this information.

***<u>MAC Fields</u>***

***Frame Control:*** The frame control field is a collection of information as seen in the below in Figure 2.6.

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Protocol Version | Type | Subtype | To DS | From DS | More Frag | Retry | Pwr Mgt | More Data | WEP | Order |

***Figure 2.6 MAC Frame Control Fields***

The protocol version specifies the version of the standard that governs the frame exchange.

The type and the subtype identify the frame type that is being transmitted. These are basically three main types of frames: Data, Management and Control. The frame subtype identifies the message that is being exchanged under each category. The Table below tabulated some commonly used frames with its type and subtypes.

| **Type** | **Subtype** |
|---|---|
| Management | Association Request/Response |
| Management | Reassociation Request/Response |
| Control | Ready to Send (RTS) |
| Control | Clear to Send (CTS) |
| Data | Data |

***Table 2.2 MAC frame types***

The rest of the fields in the frame control are 1 bit in length and act as a boolean. The 'To DS' and 'From DS' identify whether the data is destined or originating from the distribution system. The More Fragments field indicates if any fragments are left for the current MPDU. The Retry indicates if the frame is a retransmission of the previous frame. Power Management notifies the receiver, whether the transmitter will get in to power-save mode or will remain active. If the WLAN node is in power-save mode, the more data will specify is there is more data available for the node. The WEP indicates if the frame body is processed by the WEP algorithm. Finally the order field is applicable to frames which are transferred using high priority service class.

***Duration Field:*** The Duration Field is mainly used for the control frames during the contention resolution phase – RTS and CTS frames. It carries the duration the medium will be occupied for the upcoming MPDU transfer. All stations receiving this update their Network Allocation Vector (NAV) accordingly.

***Address Fields:*** There are four address fields in the MAC header. The four addresses are source address, destination address, transmitter address and the receiver address. Since the source and the destination can be separated by more than one hop, the message is relayed using intermediate nodes. These nodes are identified by the transmitting and the receiving station addresses. The addresses refer to the IEEE MAC address of the WLAN node.

***Sequence Control:*** The sequence control field has two parts: the sequence number and the fragment number. Each MAC PDU has a unique sequence number ranging from 0 to 4095 (modulo 4096). The receiving station uses the sequence number to identify missing MPDU, triggering retransmissions. If the MPDU is fragmented, each fragment is uniquely identified by the combination of sequence number and the fragment number within the MPDU.

***Frame body:*** The frame body carries the payload specific to the all frame type and subtype.

***CRC:*** The frame check sequence is calculated over the MAC headers and the payload using a 32 degree polynomial.

# 3. Related Work

## 3.0 Overview

A good understanding of the limitations of indoor propagation is necessary to achieve good system performance. The system performance can be improved by careful site analysis, planning, and installation utilizing the knowledge of the indoor propagation and user traffic patterns. On the contrary bad design can lead to poor user experience. Throughput is a good measure of the end user's quality of service.

The degradation of throughput in a wireless LAN system has drawn interest. Along the lines, the impact of applications based on classical transport protocols such as User Datagram Protocol (UDP) and Transport Control Protocol (TCP) have also been researched.

The simulator provides a framework through which such open problems in the academia can be explored. Since the simulator is built on open framework, it can be extended to develop any interfering systems such as Bluetooth.

The research also helps understand factors that are difficult to model while building a WLAN simulator for performance analysis.

The following are some of the areas that have been researched in the areas of WLAN performance.

1) Impact of application over wireless link, including the transport layers - TCP and UDP Performance over Wireless LAN
2) Multipath characterization at 2.4GHz and its impact on the performance of the WLAN system
3) Impact of interferer systems such as Bluetooth, microwave and Cordless phone on the performance of the WLAN system.

Sections 3.1, 3,2 and 3.3 discusses the above three problems respectively.

## 3.1 Application and hardware

There are many hardware factors that can influence the performance of the application throughput even under good signal conditions. Host processing speed, WLAN drivers, network implementation in the operating system are some of the reasons which causes performance bottle necks. Results from prior research [Xylomenos99] indicate that the use of PCIMCIA over ISA reduces the performance.

Industry Standard Architecture (ISA) is a 16 bit expansion slot that can be used by Network adapters to read and write from the PCs memory. It is a slower bus and is capable of transferring at the rate of 2MBps. Personal Computer Memory Card International Association (PCIMCIA) is a special socket that enables plugging in removable devices in the size of a credit-card. It is mostly used in laptops. PCIMCIA devices have short single buffer whereas the ISA cards have multiple buffers. The ISA cards gained throughputs around 1.8Mbps for UDP traffic whereas PICMCIA attained 1.28Mbps. The peak performance is also influenced by the host processing power but reaches a peak with a 166 MHz Pentium host.

The choice of the transport protocols used in a network application influences the performance of the wireless link. There are two popular protocols that are used as a transport layer, namely TCP and UDP. Both these protocols were developed primarily to work on wired networks. Most network applications use TCP as the transport layer. TCP is favored due to its error recovery and congestion control mechanisms. TCP at the sender senses packet loss and adaptively changes its transmission rate. This is very advantageous in wired networks where the packet loss is primarily due to congestion at intermediate routers. In wireless networks the packet loss can be due to momentarily signal degradation arising out of multipath fading or blockage (affecting path loss). However TCP is transparent to this phenomenon and readily reacts to the frame loss by adapting its transmission rate. This can adversely affect the overall performance. Several versions of TCP have been proposed to tackle this problem such as Reno, Tahoe, etc.

UDP is a transparent transport layer and does not provide any error recovery mechanism. Hence the error recovery has to be taken care at the application layer. For this reason UDP is primarily used in applications which in intolerant to retransmissions such as streaming audio. Moreover UDP provides the upper limit to the performance of the link; hence it is commonly used for throughput analysis of the wireless links. Using smaller UDP packets (100 bytes ) for testing might result in lower throughputs than expected. This could be due to buffer shortage at the UDP interface as the UDP packets get created at a faster rate [Arranz01].

The transport layer data (TCP or UDP) is packed within an IP datagram. The IP datagram is passed on to the MAC layer and are transmitted as MAC frames after fragmentation (if applicable). Thus the IP datagram loss is strictly governed by the error recovery mechanism at the WLAN MAC layer. MAC layer ensures recovery using ARQ. It is seen that for a low SNR scenario (<10 dB) [Arranz01], the frame error rate (FER) increases for higher WLAN data rates and payload size. For some radio conditions the true throughput performance for lower data rates (2 Mbps) is seen to be more than that of 11 Mbps. This is because the FER for 11 Mbps is higher which causes more retransmissions. This necessitates the need for good link adaptation. In this work it was proposed that a proxy layer be placed between the IP and the MAC layers. This layer will assure good frame transmission performance when transmitting over a bad channel. This will be achieved by dynamically adjusting parameters such as fragmentation threshold and FEC correction capability.

## 3.2 Multipath Analysis

Multipath channels are those whose power delay characteristics reveal energy in more than one instant of time. This occurs when a signal arrives at the receiver via different propagation paths with various delays.

In a multipath environment, the delay of the reflected paths is measured in terms of delay spread. Delay spread ($\sigma$) is a measure of the power of the individual components and its time delay with respect to the first arriving multipath component.

Measured in nanoseconds, delay spread introduces a phenomenon known as intersymbol interference (ISI) to the receiver. ISI is introduced if the symbol period is shorter than the delay spread of the channel. Delay spread and number of significant paths increase gradually with distance in indoor environments [Dobkins02]

The arriving signals can destructively add, leading to signal fading. Fading can cause variations as much as 40 dB [Stein01]. Fading can be categorized in two ways, namely based on time delay spread and Doppler spread [Rappaport02].

If the delay spread of the channel is greater than the symbol period then the channel is called as frequency selective. Alternatively if the delay spread is less than the symbol period then the channel is considered flat fading.

The channel can also be defined based on the rate of change of the channel due to motion. Coherence time is a quantity that measures the time duration over which a channel is invariant. If the coherence time of the channel is less than the symbol duration then the channel is considered a fast fading channel else it is considered a slow fading channel.

An Equalizer is used to adapt and compensate for changing channel. In an experiment, it was seen that the performance was degraded considerably for typical indoor delay spreads. The mobile channel places stress on the channel estimation and equalization functions of most WLAN implementations (D-Link and Orinoco) [Steger03].

To design a WLAN system that can reliably decode the transmitted data from the received waveform, the design has to account for the multipath characteristics of the most typical channel. There have been many channel models proposed for indoor channel. Most of the channel models have the following common characteristics.

1) The average received power of the individual multipath is an exponential decaying function of the time delay.
2) The amplitudes of the individual multipath components are Rayleigh distributed about the average value.
3) The individual components are spaced equally along the time delay axis.

The IEEE802.11 channel model is based on the above characteristics[Fakatselis98]. However it assumes the existence of large number of multipath components, thus favoring systems which employ antenna diversity.

Some models consider the existence of line of sight component (strongest component) between the transmitter and receiver. In such models the amplitude is considered Rician distributed.

The delay spread is proportional with the size of the particular indoor area. Detailed measurement and study have been performed to measure the mean delay spreads and maximum delay spread for common indoor environments [Table 3.1]. These statistics were provided as guidelines [Fakatselis99] in designing the complex physical layer.

| **Median Delay Spread (ns)** | **Maximum Delay Spread (ns)** | **Channel Type** |
|---|---|---|
| 40 | 120 | Large building |
| 40 | 95 | Office building |
| 105 | 200 | Shopping center |
| 106 | 270 | Large Laboratory |

***Table 3.1: Delay spread in Indoor Environments***

## 3.3 Interferers in the 2.4GHz Band

Bluetooth (BT) is one of the main interferer for WLAN operation in the 2.4GHz ISM band. Bluetooth is a short-range, cable replacement technology with transmit powers in the range of 1mw. It hops between the available 79 channels (2.402 –2.480 GHz) at the rate of 1600 hops/second. Bluetooth supports data rate up to 1Mbps.

The presence of BT near the WLAN system affects the performance of both the systems. This has been studied both quantitatively and experimentally by many researchers for typical network topologies.

Analytical Approach

The Bluetooth devices in a piconet are synchronized in time with each other. Whereas the Bluetooth and 802.11 systems are not synchronized, therefore the number of Bluetooth packet overlapping on an 802.11 packet depends on the following factors.

- Packet length of 802.11
- Packet length of Bluetooth
- Time offset between the Bluetooth and the 802.11

To understand the above-mentioned scenario, the following mathematical model was developed by Greg Ennis (submitted to the IEEE 802.15 WPAN Task group 2, reference)[Ennis98].

If $H$ is the duration of a Bluetooth hop and $L$ is the duration an 802.11 packet, then the minimum number of hops for which the 802.11 packet overlaps with the BT radio is given by $\lceil L/H \rceil$. The maximum number of hops overlapped is $\lceil L/H \rceil + 1$, where $\lceil x \rceil$ is the least integer greater than or equal to x.

The actual number of hops that the packet overlaps depends upon the relative timing of the start of the packet and the hop. Let d be the "delta" between the last Bluetooth hop and the start of the packet as indicated in the following timing figure.

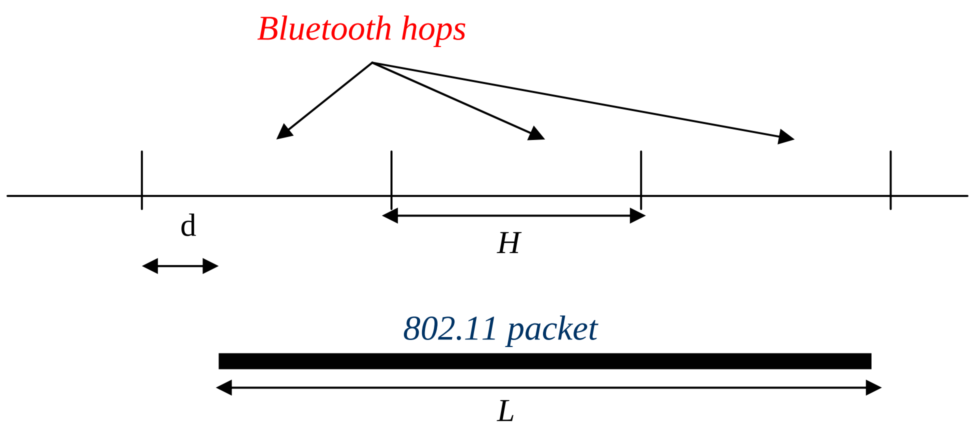



***Figure 3.1: Bluetooth and WLAN frame Collision***

Note that $0 < d \leq H$. If d is zero, then the 802.11 overlaps with its minimum number of Bluetooth dwell periods, namely $\lceil L/H \rceil$. If d is greater than $\lceil L/H \rceil * H - L$ then the 802.11 packet overlaps with $\lceil L/H \rceil$+1Bluetooth hops. Consequently, an 802.11 packet will overlap $\lceil L/H \rceil$ Bluetooth dwell periods whenever

$$0 < d \leq \lceil L/H \rceil * H - L$$

and will overlap $\lceil L/H \rceil + 1$ dwell periods whenever

$$\lceil L/H \rceil * H - L < d \leq H.$$

This translates into probabilities by expressing these intervals as fractions of the interval [0, H], yielding the following:

The probability that an 802.11 packet of duration L will overlap in time with $\lceil L/H \rceil$ Bluetooth dwell periods of duration H is $\lceil L/H \rceil - L/H$. The probability that it overlaps with $\lceil L/H \rceil + 1$ dwell periods is $1 - \lceil L/H \rceil + L/H$. Similarly the probability that 802.11 packet will overlap in frequency with a Bluetooth packet is either (2/3)^(L/H) or (2/3)^(L/H + 1). Therefore the total probability of collision is given by the sum of the product of the two probabilities.

$$(2/3)^{\lceil L/H \rceil}(\lceil L/H \rceil - L/H) + (2/3)^{(\lceil L/H \rceil+1)}(1 - \lceil L/H \rceil + L/H)$$

<u>Experimental Study</u>

Prior to the development of this simulator some experiments were conducted to understand the impact of Bluetooth on WLAN performance. Throughput was used as a metric in studying the impact of interference from Bluetooth radios. This work was carried out with help from Mobile & Portable Radio Research Group (MPRG) and Communications and Network Services (CNS) of Virginia Tech.

It was found that the WLAN performance is affected in the following three ways.

1) The clear channel assessment helps the WLAN MAC in resolving the contention in the medium.
2) The presence of BT radios affects the contention resolution.
3) The BT radios induces packet collisions in the medium causing WLAN frame retransmissions

Details about the experimental setup and complete results are available in Appendix A

# 4. SOFTWARE DESIGN AND DEVELOPMENT

## 4.0 Objectives

The chapter describes the software design and implementation of the WLAN simulator. An open Wireless simulator was built at the Mobile and Portable Research lab at Virginia Tech (Max Robert and Jody Neel). This work provided generic functionalities such as packet generation; transceiver functionalities and wireless node functionalities. This thesis work extended this simulator for building the IEE802.11b system.

The simulator is one of the key contributions of this thesis. The features of the simulator such as scalability and open framework arise out of the object oriented design of the simulator.

Section 4.1 outlines the objectives of the simulator. Section 4.2 provides a brief overview of the simulator and introduces the individual components such as WLAN node, Channel and WLAN Packet. Section 4.3 provides a detailed description of the components. The implementation details and the execution of the simulator are outlined in Section 4.4 and 4.5. The features of the simulator are presented in section 4.6.

## 4.1 Objectives of the simulator

The development of a wireless LAN simulator based on the IEEE 802.11b standard is the focus of the thesis. The WLAN simulator is used for analyzing the throughput performance of the system and hence only the essential functionality has been implemented namely the basic service set (BSS) mode of the system. The DCF (distributed coordination function) access method of the MAC has been employed.

## 4.2 Overview of the WLAN system

The WLAN system has be envisaged with the following components

- WLAN elements
- Propagation medium

The WLAN elements comprises of WLAN nodes and the AP. The nodes transmit data frames to the AP using the DCF of the underlying MAC layer. The AP acts as a sink for the frames and is responsible for sending the acknowledgement frame upon reception of frames from the WLAN node. The two main functions of a WLAN element are MAC specific functionality and channel interface functionality [Figure 4.1]. The MAC functionality is implemented as per the IEEE 802.11 standard. The channel interface (transceiver) module is used for exchange of frames between the elements. It is also responsible for reporting events such as collision of frames in the channel.

The propagation medium (channel) introduces signal attenuation and degradation to the transmitted signal. The obstacles between the WLAN radios cause signal attenuation. The attenuation value depends on the material the obstacle is made of and it can vary from one building to another building. The typical obstacles in a building are bricks, concrete, dry wall, and glass. The transmitted signal can arrive at the receiver in multiple paths due to reflections off the obstacles. These multi-paths can destructively add to each other leading to signal degradations.

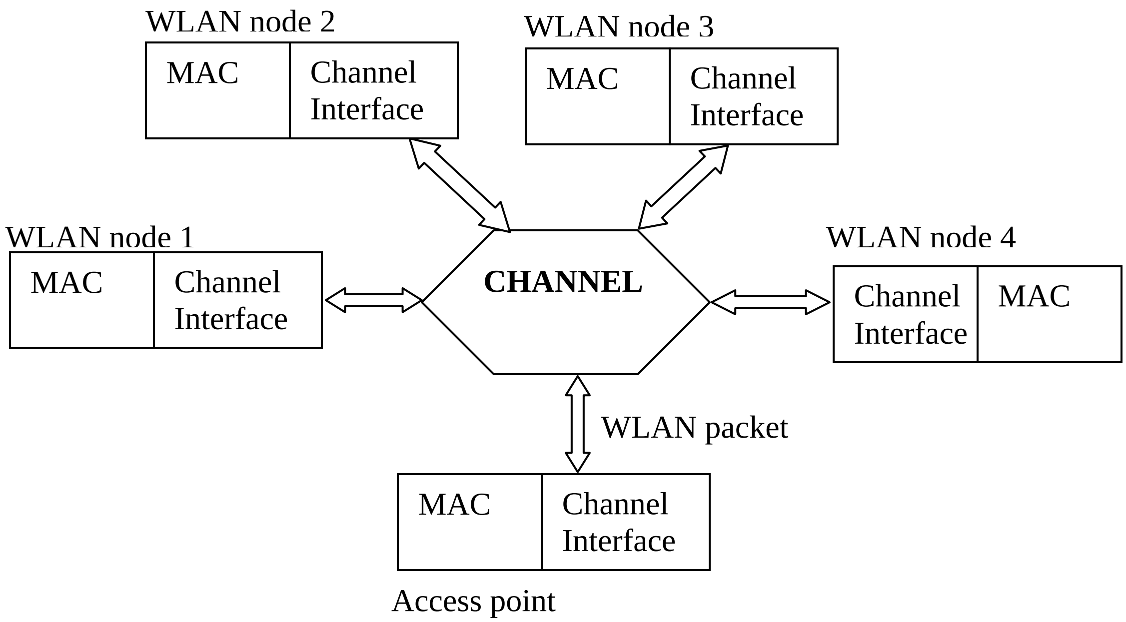



***Figure 4.1: Overview of the simulator***

## 4.3 Simulator Design - Object Oriented

A generic wireless system can be conceived as individual components interacting with each other. Typical components include wireless nodes, packets, channel etc. Every component encapsulates its behavior acting as a self contained unit exhibiting a well defined functionality. The IEEE 802.11 WLAN system is constructed from the generic wireless system elements.

The object oriented paradigm is well suited for characterizing real world objects. The object oriented concept of class is a template encapsulating the methods (functions) and variables characterizing the behavior of the object. In the WLAN system, the individual components (such as packet, WLAN nodes) can be considered as classes. The object oriented concept of inheritance can be employed in building specific classes for a WLAN system from a generic wireless system. Extensibility for developing other wireless technologies has been the fundamental motivation for the development of generic wireless components (classes). Thus the object oriented paradigm lends itself well the development of the system in focus.

The key functionality of the individual classes in the IEEE 802.11 simulator and their interaction with the objects of the other classes are detailed below.

### 4.3.1 WLAN node class

The WLAN node class is derived from a generic wireless node class. The attributes and methods of the WLAN node class are specific to the functionality of a WLAN node. The attributes of a WLAN node class can be classified into 3 different categories.

#### *4.3.1.1 Application specific attributes*

WLAN nodes have different applications running on them such as browser, ftp applications etc. The arrival rate and length of the packets from the applications are modeled with known distributions. The packets are stored in an application stack. Other variables of interest in the WLAN node are total number of frames transmitted, frames retransmitted, frames lost due to collision and frames lost due to stack overflow.

#### *4.3.1.2 MAC specific attributes*

The MAC layer is the central part of the WLAN system concerned with the transmission of frames. The MAC is based on DCF and collision avoidance (CSMA/CA) mechanism. Due to the many details involved its implementation is complex. The DCF mechanism is detailed in Section 2.3

A successful frame transmission spans from the arrival of frame from the application layer to the transmission of the frame. The transmission process involves several intermediate states. The WLAN node can be in any one of the following states.

- Idle state: The WLAN node waits in this state until the application layer sends any frame that needs to be transmitted. After receiving the frame, the node waits for DIFS (defined in the standard) period of time. After the DIFS time if the channel is found idle, the frame is transmitted otherwise the node enters the defer state.

- Defer state: The nodes defer their transmission in such a way that two competing nodes do not transmit at the same time. In order to achieve this every node waits for a DIFS time plus a random time. This random time is known as backoff window and the state is called as backoff state.

- Backoff state: During this state the frame waits in the channel for an additional time represented as backoff slots. The backoff slots is a random number and is based on uniform distribution. The uniform distribution ranges from 0 to $C_{max}$, where $C_{max}$ depends on the number of retransmission of the frame and is calculated using a binary exponential scheme.

- Transmit state: After every backoff Slot the MAC senses the channel. If the channel is found idle the backoff slots are decremented otherwise the backoff time is halted until the channel becomes idle. The frame is transmitted after the expiration of all the backoff slots, irrespective of whether the channel is busy or not. This scenario leads to the possibility of collision among frames from different WLAN nodes.

- Wait for Response state: Upon successful reception of the data frame, the destination WLAN node sends an ACK frame. The transmitter does not transmit any other frame until it receives the ACK frame. If either the transmitted frame or the ACK frame is lost due to collision, the transmitter is blocked on waiting. To avoid the infinite blocking of the transmitter a timer is started after sending every frame to indicate the time for the next attempt.

  The duration of the timer is based on the data frame length, ACK frame length, the delay due to the DCF mechanism and the propagation delay. If the ACK frame does not arrive before the timer expires, the transmitter assumes that the frame was lost due to collision and retransmits the frame by entering the Defer state. If the ACK frame arrives before the timer expires then the node goes back to the Idle state.

#### *4.3.1.3 Node specific attributes*

The WLAN node class provides interfaces for specifying the channel interface, interface number, initial channel that the node would use upon booting. The class also provides an interface to set the location of the node in the Cartesian format. The access point is assumed to be located in the (0,0) coordinate.

#### *4.3.1.4 Data Member & functions*

The functionalities and the attributes of the WLAN node are contained within multiple member functions (or methods). The key methods of the WLAN node class are tabulated in Table 4.1.

| Members | Function |
|---|---|
| Packet Arrival | Checks for packet from the application layer. The packet arrival distribution can be varied (exponential, uniform). The fields of the frame are set using the member functions in WLAN packet class. |
| Check Transceiver | Interacts with the channel interface object in receiving the frames in the channel. The node scans through the frame and performs one of the operations: updates the NAV, responds with a frame based on the errors in the frames or discard the frame |
| Set Position | Specifies the location of the node using cartesian coordinates |
| Iterate | Handles all the MAC functionalities discussed in Chapter 2 |
| Link Statistics | Displays performance statistics of the node such as total number of transmitted frames, retransmitted frames, frames lost due to collision. |
| Transceiver | Object of the channel interface class |
| Spacket | Object of the WLAN packet class |

***Table 4.1: Member functions of the WLAN node class***

### 4.3.2 Access point

The access point being a special type of WLAN node performs all of the WLAN node functions in addition to the distribution services. The access point maintains an array which stores the address of all the WLAN nodes.

The access point responds with an acknowledgement frame whenever it receives a successful data frame.

### 4.3.3 WLAN packet class

The WLAN packet class is derived from the generic packet class. The packet class provides access to the payload, source and the destination address of the packet, power level etc.

The main functionality of the WLAN packet class is to provide interfaces for setting the fields in a WLAN frame. The class also facilitates the storage of information pertaining to collision between the transmitted frame and another frame in the channel.

#### *4.3.3.1 WLAN Packet fields*

The WLAN packet contains MAC headers, frame body and a 32 bit CRC (refer to Section 2.5). The fields that are supported in the implementation WLAN packet class are discussed below.

<u>Type and Subtype field:</u>
The IEEE standard defines three broad types of frames - Data, Control and Management frames. Each type has different subtypes that are used based on the state of the WLAN node. There are totally 27 different frame categories. The implementation uses only four frame type (or subtypes) namely, Data, Request-To-Send (RTS), Clear-To-Send (CTS) and acknowledgement (ACK) frames.

<u>Sequence Control field:</u>
The Sequence Control field consists of two sub-fields, the Sequence Number and the Fragment Number [IEEE 802.11]. Every transmitted MSDU (MAC Service Data Unit) is assigned a unique sequence number. This number is based on modulo 4096 counter, starting at 0 and incremented by 1 for every MSDU transmitted.

The MSDU is fragmented if the size of the MSDU exceeds the fragmentation threshold. Each fragment is assigned a unique number (starting from 0) so that the fragments can be reassembled at the receiver. If the fragment is retransmitted, the fragment number remains unchanged. Moreover, the *More Fragments* field is set to 1 in all frames that have another fragment of the current MSDU to follow. It is set to 0 in all other frames.

Retry Field:
The Retry field is set to 1 in any frame that is a retransmission of an earlier frame. It is set to 0 in all other frames. A receiving station uses this indication to aid the process of eliminating duplicate frames.

Duration field:
The duration field aids in preventing collision between frames from multiple WLAN nodes. When a frame is transmitted, it is sensed by the nodes along the transmission path of the frame. These nodes try to avoid collision by updating their network allocation vector (NAV) with the value in the duration field of the transmitted frame.

Address field:
The four address fields are used for situations, in which the frame exchange is between nodes from different BSS. In this thesis, the frame exchange is always within a single BSS, hence only two address fields (the address of the receiving and the transmitting node) are used.

#### *4.3.3.2 Collision Information*

As outlined earlier in section 3.3, the channel object monitors the collision between various frames in the channel and updates the colliding frames with the collision information. Every transmitted frame object contains a structure to hold collision information. The structure contains the following information

- Number of nodes involved in collision,
- The address of the nodes, and
- The received power of the all frames involved in the collision.

The WLAN packet class provides methods to update the collision structure for every iteration of the simulator and methods to estimate the error in the frame based on the Signal to Interference Noise Ratio (SINR). The frame is discarded even if it has a single bit error. The bit error calculation depends on the rate of transmission of the frame. Table 4.2 lists the symbol and bit error for the different data rates in terms of the error function Q( ). The channel is assumed to be AWGN. The modulation schemes for 1, 2, 5.5 and 11 Mbps are DBPSK, DQPSK, CCK and CCK respectively. It is also assumed using the differential modulation schemes doubles the effective noise power at the receiver [Lansford03].

| Data Rate | Symbol Error | Bit Error |
|---|---|---|
| 1 Mbps | $Q\left(\sqrt{11\times SNIR}\right)$ | $Q\left(\sqrt{11\times SNIR}\right)$ |
| 2 Mbps | $Q\left(\sqrt{5.5\times SNIR}\right)$ | $Q\left(\sqrt{5.5\times SNIR}\right)$ |
| 5.5 Mbps | $14\times Q\left(\sqrt{8\times SNIR}\right)+Q\left(\sqrt{16\times SNIR}\right)$ | $\left(\frac{2^{4-1}}{2^4-1}\right)SER$ |
| 11 Mbps | $24\times Q\left(\sqrt{4\times SNIR}\right)+16\times Q\left(\sqrt{6\times SNIR}\right)+174\times Q\left(\sqrt{8\times SNIR}\right)+16\times Q\left(\sqrt{10\times SNIR}\right)+24\times Q\left(\sqrt{12\times SNIR}\right)+Q\left(\sqrt{16\times SNIR}\right)$ | $\left(\frac{2^{8-1}}{2^8-1}\right)SER$ |

***Table 4.2: Symbol & Bit error calculation for various data rates***

*4.3.3.3 Member functions*

Table 4.3 lists the member functions that sets the fields of the MSDU and updates the collision information of the frames.

| Function Name | Role of the function |
|---|---|
| Update Collision | Updates the each bit of the packet with the SNR value obtained from the channel |
| Estimate Collision | Checks whether the a given packet has any bit errors based on the SNR and the modulation used. |
| Set_type | Sets the type of packet being transmitted. The packet can be one of the following: Data, ACK, RTS, CTS. |

***Table 4.3: Member functions of WLAN packet class***

### 4.3.4 Channel interface class

The channel interface acts as a bridge between the WLAN node and the channel. Whenever the WLAN node has a frame for transmission, the ‘send packet’ function of the transceiver is triggered. The function internally stacks the frame in the channel object based on the channel number of the frame. The sequence of interaction is shown in red lines in Figure 4.2. On the reverse link, the channel invokes the ‘receive packet’ method of the channel interface object. The method stacks the frame in a packet stack. The sequence of interaction for the reverse link is shown in green in Figure 4.2.

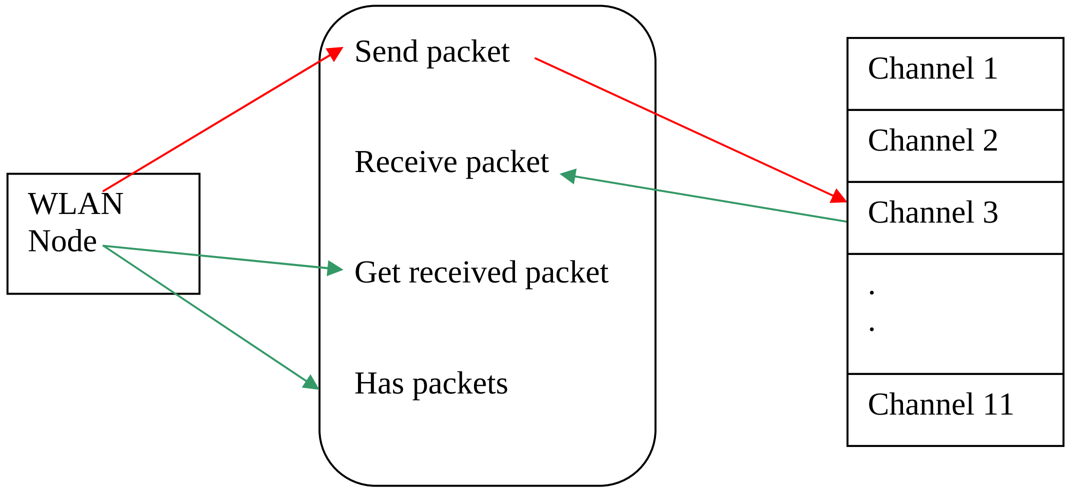
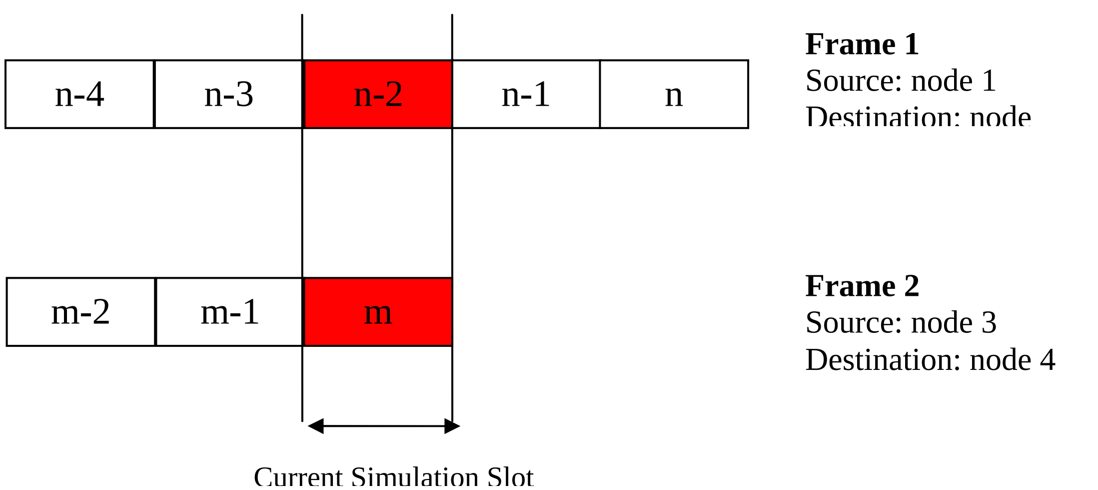



***Figure 4.2: Interaction of Channel Interface class***

### 4.3.5 Channel class

IEEE 802.11b standard defines 14 channels (spaced 5MHz apart) in the ISM band (2.4 to 2.4835 GHz) for the deployment of WLAN in North America. Each 802.11b DSSS channel typically occupies 22 MHz of bandwidth. To avoid any interference between adjacent channels, a minimum of 25 MHz spacing is required. This allows up to three 802.11b access points, each programmed with one of three non-interfering channels to be located adjacent to each other.

The main role of the channel class is to identify frame collision for every iteration of the simulator. It also checks whether the propagation time of the frame has elapsed and accordingly transfers the frame from the channel to the corresponding channel interface object. Figure 4.3 reveals a collision scenario in which the red boxes represent the current simulation slot. Frame 1 and Frame 2 occupy the channel for n and m simulation slots respectively. Moreover the two frames overlap in time. The Figure also explains the actions taken by the channel class for this scenario.



**Actions taken by Channel class**

Frame1.update_collision(SNIR1)
Where, SNIR1 = Power of Frame 1/ Power of Frame 2

Frame2.update_collsion( SNIR2)
Where, SNIR2 = Power of Frame2/ Power of Frame 1
Channel interface of node 4. Receive_packet(Frame 2)

***Figure 4.3: Collision between frames***

#### 4.3.6 Additional Classes

The simulator contains other additional classes that are specific to the implementation such as 1) Stacks and linked lists and 2) Simulation clock.

Stacks (or link list) are useful in storing objects of similar type. They can be used for selecting the objects, traversing the list, inserting new objects etc. Packet stack class and user stack class are two examples of stack in the simulator. The packet stack stores the packets from the application layer before they are transmitted using the 802.11 radio. The user stack contains all the WLAN elements that are currently active in the network.

The simulator is based on an internal clock. The clock is implemented as a class which provides methods to retrieve the current time, to set the current time, to change the timer increment value etc.

### 4.4 Implementation

The simulator was implemented using the C++ programming language in the Visual C++ environment. The implementation consists of class definitions and class declarations. The class definition is a prototype of the object being implemented, whereas the declaration contains the actual functionality. The definition file is called as the header file (.h extension) and the declaration is called as the source file (.cpp extension). The objects are instantiated in a main source file (Figure 4.4). The main file is responsible for generating the statistics by invoking functional calls to other objects.

```
void main( )
{
        network n;
        system_clock *network_clock;
        network_clock = n.get_clock();
        user_stack u;
        access_point ap1;
        ap1.set_interface_number(1);
        ap1.set_channel(1);
        ap1.set_position(0.0,0.0);
        wlan_node w1;
        w1.set_interface_number(2);
        w1.set_position(dist,0);
        ap1.add_to_BSS(&w1);
        u.new_item(&ap1);
        u.new_item(&w1);
        u.connect_network(&n);
        double total_iterations = SIMULATION_LENGTH;
        for(double i=0; i < total_iterations; i++)
        {
                u.iterate();
                n.iterate();
                network_clock->increment();

        }
        w1.link_stats( );
}
```

Initializing the Access point

Initializing the WLAN node

User List

The WLAN elements, channel is iterated for the simulation time

***Figure 4.4: Main source file***

## 4.5 The Simulator Execution

The simulation involves cooperation of all the objects that comprise the WLAN system. The simulator is based on discrete time model. The simulation runs for a specified number of slots (iterations), where each slot represents a finite time. For every simulation slot the following events occur in order

1. The link list is traversed and every WLAN element is triggered to execute based on its current MAC state.
2. The individual channel objects are triggered to execute in the ascending order (channel 1 to channel 14). Each channel object performs the following operations
    a. Finds the number of frames present in the channel
    b. Calculates the index of each frame based on the current time, start time of the frame and the simulation step size. The current time is obtained from the global clock and the start time is obtained from the frame object.
    c. Checks if two or more frames overlap in the current simulation slot
        i. If so it calculates the Signal to Interference ratio of the each frame and updates the collision structure of the frame based on the index.

d. If the propagation time of the frame is exhausted, the frame is placed in the channel interface object corresponding to the destination of the frame

3. The global clock increments by the simulation step size

## 4.6 Features of the Simulator

The object oriented nature and the generic design of the simulator provides the simulator some added advantages and the same is discussed in the following sections.

### 4.6.1 Open Framework

The wireless simulator has been built as an object oriented framework. It provides the fundamental classes such as channel class, channel interface class, packet class, wireless node class and the like. The basic set of classes can be extended or additional classes can be built in for building any wireless system. Such a framework will facilitate the technical community in building wireless systems without having to start from the scratch.

### 4.6.2 Scalability

One of the principal advantages of object-oriented programming techniques over procedural programming techniques is that they enable programmers to create modules that need not change when a new type of object is added. A programmer can simply create a new object that inherits many of its features from existing objects. This makes object-oriented programs easier to modify.

The open framework facilitates the co-existence analysis of competing wireless technologies. For example the interference between WLAN and Bluetooth devices can be analyzed by adding their MAC and PHY software components to the framework. This is possible because the framework provides all the other classes like the channel class, the channel interface class which can be used by the nodes from both technologies.

## 4.7 Conclusion

This chapter explains the entire software development process involved in the creation of the simulator. The simulator is designed in an object oriented paradigm. The functionalities of the individual objects of the simulator like the WLAN node and packet are explained in detail along with the overall working of the simulator. Finally the merits of the simulator are described.

# 5. Measurement Campaign

## 5.0 Objectives

The aim of the measurement campaign is to measure the experimental throughout of wireless LAN system for various channel conditions. The experimental results are compared with the throughput results from the simulator for the same scenario. The experiment was repeated in 12 locations in two different buildings.

Along side the throughput measurement, channel estimation (multipath) measurement was also performed. The mean excess delay of the channel was measured to characterize the channel.

The chapter is divides in to three main sections. Section 5.1 provides details about the hardware and Section 5.2 provides details about the software used in the measurement campaign. Section 5.3 provides description of the two environments where the campaign was conducted. Section 5.4 details the procedure used in obtaining the measurement results.

## 5.1 Hardware

### 5.1.1 Throughput setup

The access points (AP) from ‘RoamAbout’ was used for the experimental setup. The access point was configured with default factory settings. The setup included two laptops, one acting as WLAN node and the other acting as wired server. The throughput of the WLAN system depends on the received signal strength of the user and the amount of loading (number of users) in the system. In this work the emphasis is on understanding the impact of channel on the performance. Hence the throughput measurements were conducted with a single WLAN node in the system.

Both the Laptops (Dell Inspiron 5000) used had the same processing power and operating system. The WLAN PC card for the node was also from ‘RoamAbout’ to maintain homogeneity.

The AP was connected to the Server through a high speed (100 Mbps) switch from Cisco (Figure 5.1). The high speed ensures that the delay in packet transmission over the wired path is negligible.

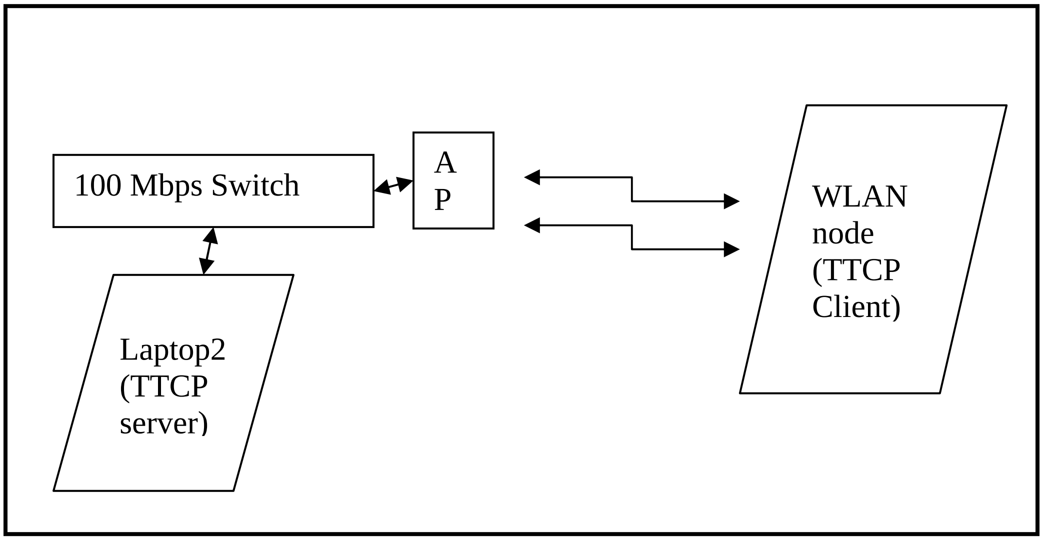



***Figure 5.1: Throughput measurement setup***

### 5.1.2 Channel Measurement Setup

A software defined measurement receiver [Newhall03] was used to perform channel measurement. The setup consists of a RF front end, Sampling unit and processing unit. The RF consists of 4 channels. Each channel is passed through a band pass filter which passes only 100 MHz centered around 2.45 GHz. The signal is down converted to 150 MHz IF center frequency using a local oscillator (figure 5.2).

The sampling unit consists of a Tektronix TDS 580 digital oscilloscope. The oscilloscope converts the signal from all 4 channels in to digital samples at 1 gigasamples/second rate. The samples are later acquired by the PC. The PC later processes the raw IF samples (figure 5.3)

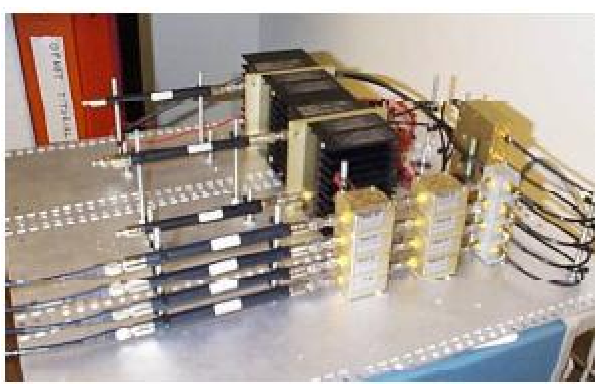


***Figure 5.2: Channel measurement setup***

***Figure 5.3: Measurement campaign***

## 5.2 Software

The data source for the WLAN clients was generated using a test TCP application called as TTCP. Test TCP (TTCP) is a command-line sockets-based benchmarking tool for measuring TCP and UDP performance between two systems. TTCP was used to generate the WLAN traffic between the WLAN node and the server. TTCP utility provides many options for throughput testing.

1) Data Acknowledgement: TTCP can be used to send data in two modes – TCP and UDP.
2) Size of the Data: The length of the data packet to be transmitted for the testing can be specified.

Two instances of TTCP are required - one instance is started in “receive” mode, and the other in “transmit” mode. The transmitter is provided the address of the receiver and the amount of data to be sent. The transmitter contacts the receiver, generates and transmits the specified volume of data. At the end of the transmission it reports the throughput based on the time taken to send the data. The receiver accepts the incoming data and based on the mode of operation either acknowledges it or sinks it upon reception.

TTCP was operated in UDP mode as UDP does not have any inherent retransmission mechanism. Hence the delay in receiving the packets can be a directly attributed to WLAN protocol. However the application adds overheads at the IP and the UDP layers (20 and 8 bytes respectively).

## 5.3 Environment

Two different building floors were chosen for the experiment. The building floors were chosen to provide different channel conditions for the signal propagation such as office space and large open spaces.

The building floors used different building materials such as concrete, dry walls, glass exteriors, etc. Table below shows the typical attenuation values of commonly used building materials at 2.4 GHz. These values are obtained using Siteplanner®. SitePlanner is a commercial tool which aids in the RF design of wireless networks like WLAN, LMDS etc. Siteplanner helps in the layout of the system based on the propagation parameters within the building. The propagation parameter values are optimized based on RF measurements performed inside the building.

| **Building Material** | **Attenuation value (in dB)** |
|---|---|
| Elevator - metal partitions | 5 |
| External Wall | 10 |
| Basement Walls | 20 |
| Dry walls | 3 |
| Concrete | 10 |
| 1 Floor Separation Loss | 13 |
| 2 floor Separation Loss | 18 |

***Table 5.1: Partition loss at 2.4 GHz***

At every location the received signal strength at the receiver is calculated as below
Received signal = Tx power – path loss - partition loss. Equation 5.1

Path loss is calculated as in Table 5.2[Kamerman00]. Path loss follows free-space propagation (coefficient is 2) up to 8m and then attenuates more rapidly (with a coefficient of 3.3).

$$\text{Path Loss} = 40.2 + 20\log(d), \quad d < 8\text{m}$$
$$\text{Path Loss} = 58.5 + 33\log(d/8), \quad d > 8\text{m}$$

***Table 5.2: Path Loss versus distance (m)***

Partition losses are calculated by adding the attenuation values of building materials between the line of sight of the transmitter and receiver. The attenuation values from Table 5.1 are used for this calculation.

### 5.3.1 Building 1 (CNS)

The experiment was conducted on the $2^{nd}$ floor of the CNS building. Figure 5.1 shows the floor plan of a large office space in the $2^{nd}$ floor. The floor consists of several offices of varying sizes. Some of the offices were further divided using wooden partitions. The offices were made of concrete with glass exteriors.

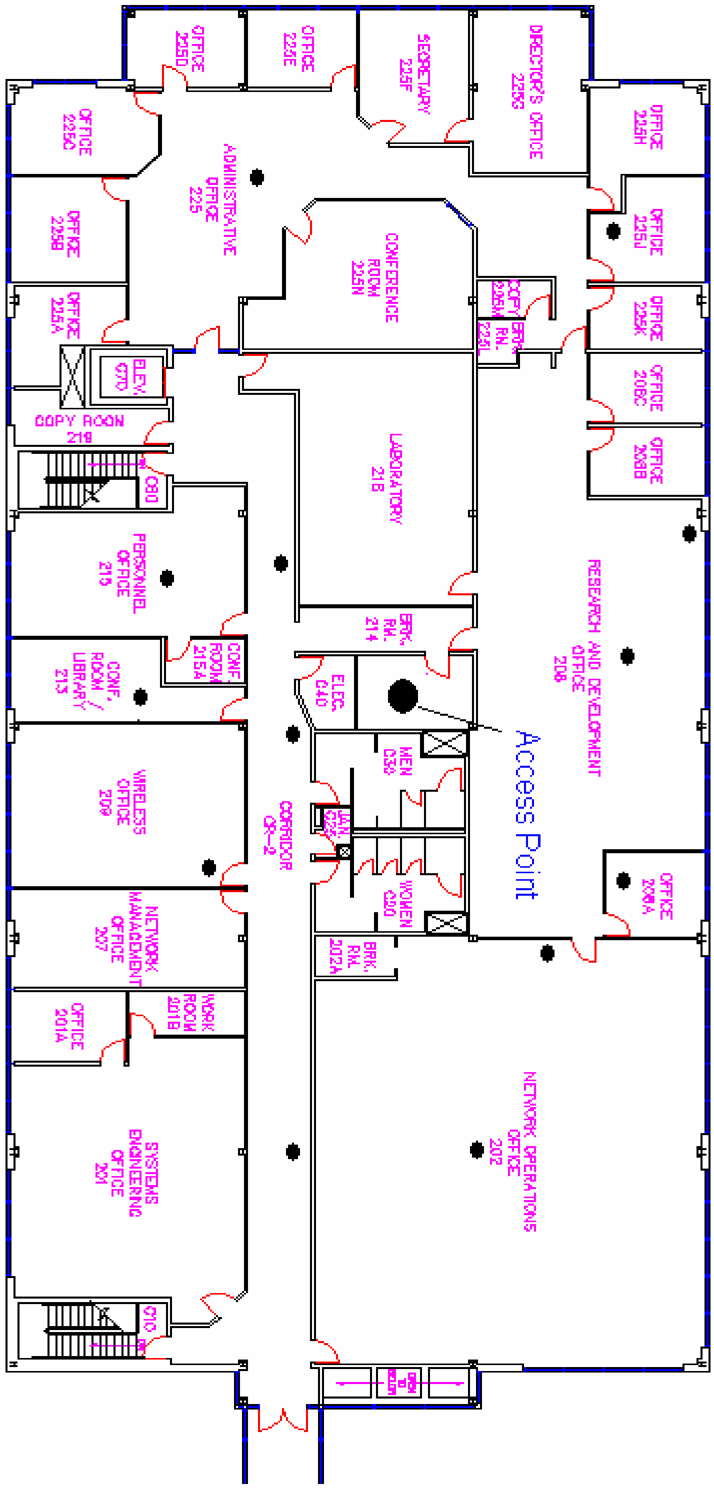


*Figure 5.4: Floor plan of the large office space*

The Access point is marked by a big circle and the measurement locations are shown as small black dots. Figure 5.2 and 5.3 shows the variation of the received signal strength and the path loss between the AP and the WLAN node as the distance between them increases. The values are calculated based on Equation 5.1

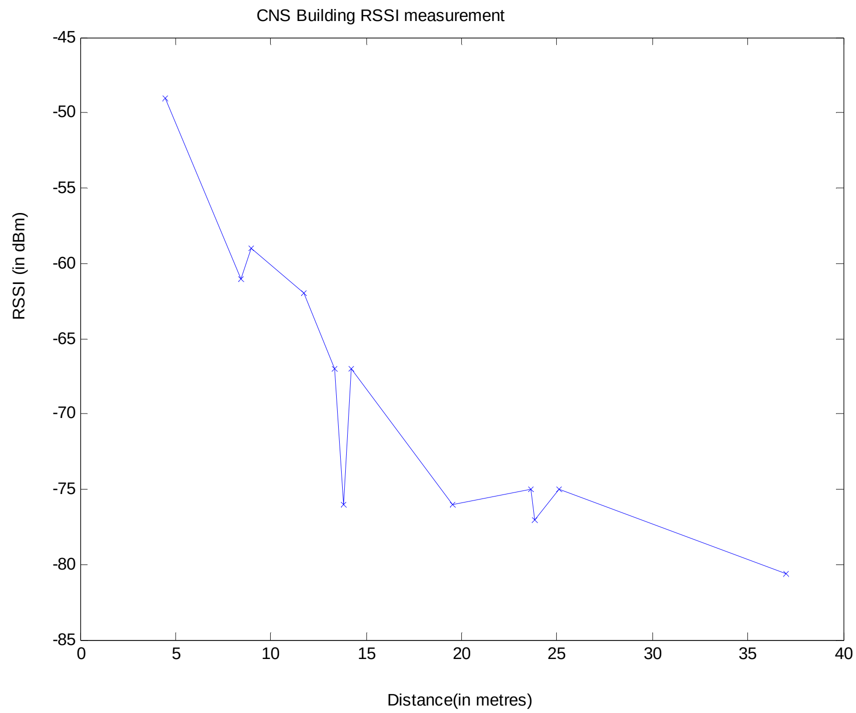



***Figure 5.5: Signal Strength at CNS Building***

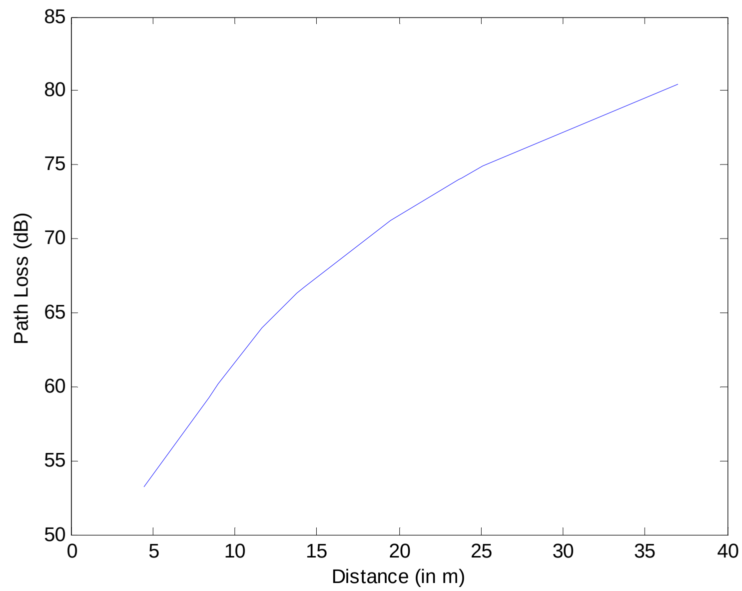



***Figure 5.6: Path Loss at CNS Building***

The channel impact on the performance was statistically averaged by taking measurements in multiple locations (about 8-12) in each building floor.

The locations were chosen keeping two things in mind. One, the line of sight distance between the Access point and the WLAN node was varied to get a wide range of transmitter- receiver separation. Secondly the locations were chosen around different building materials.

**5.3.2 Building 2 (Wallace Hall)**

The second experiment was conducted in the Atrium of Wallace Hall (figure 5.7). The access point was placed in the second floor just above the open space. The measurements were conducted mainly in the only space. Hence t**he major attenuation was due to the floor-floor attenuation (**~13dB loss) as the TX and Rx were in different floors.

***Figure 5.7: Wallace Hall***

The locations for experiment were selected to cover wide range of separation between the WLAN node and the AP. The simulation results were obtained by feeding the path loss and partition loss information between the WLAN node and the AP. The partition losses are calculated using Table 5.1.

## 5.4 Throughput measurement procedure

The following procedure is followed at every location for measuring the throughput.

1) The WLAN node (laptop) is placed on a table in such a way that the base of the laptop is aligned to the 0 degree line of the table as shown in figure 5.8.
2) The TTCP transmitter is instantiated at the WLAN node and the TTCP receiver at the wired node.

3) The transmitter was configured to transmit packets of length 100 bytes. The transmitter is started and the throughput for transmitting 2048 packets is noted down.
4) Step 3 is repeated five times for statistical averaging.
5) Steps 2 ,3 & 4 are repeated after rotating the WLAN node 120 degrees clockwise from the 0 degree position
6) Steps 2, 3 & 4 are again repeated after rotating the WLAN node 240 degrees clockwise from the 0 degree position

7) The entire test (steps 1 through 6) is repeated by changing the packet length to 1000 bytes instead of 100 bytes. Two packet sizes were selected to understand the relation between frame loss and frame size.

It can be seen that the measurement campaign spans 30 iterations (3 orientations each repeated 5 times for two different packet lengths) at any given location.

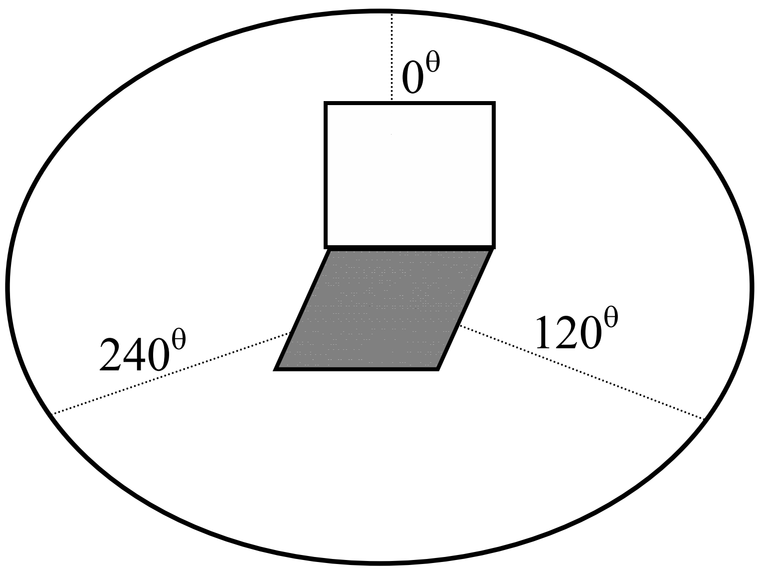



***Figure 5.8: Orientation of the WLAN node***

## 5.5 Summary

The chapter provides details about the hardware and software used in the measurement campaign. It also provides details about the two buildings used for the campaign. An UDP based application was used to provide transparency to the access layer (MAC). The buildings were chosen to provide different channel conditions, one with large office space and the other predominantly open space. The experiment was repeated with different orientation of the WLAN node to account for any antenna diversity.

# 6. Simulator Results

## 6.0 Objectives

The results obtained through the simulator are presented in this chapter. The results are divided in to two sections – performance analysis and comparative study. The performance analysis section helps understand the scope of the simulator towards system studies. The comparative study compares the results of the measurement campaign with the simulator results. It provides a quantitative measure of the simulator in replicating real world implementations, thus providing feedback for future work. Rate adaptation is a MAC algorithm by which the rate of transmission is changed based on the history of previous transmissions. Since this is a proprietary algorithm, the simulator introduces two algorithms for rate adaptation.

Section 6.1 briefs the details of the simulator such as features implemented and assumptions made in the simulator design. Section 6.2 explains how the simulator can be used for analyzing the performance of the WLAN system. It introduces throughput as a metric for performance studies. Section 6.3 shows the impact of throughput as a function of the received signal strength (RSSI) with one active user in the system. Section 6.4 shows the impact of throughput as a function of number of active users in the system.

Section 6.5 outlines the need for rate adaptation algorithms and introduces two new algorithms namely Reduce-First and Reduce-Second Auto-reduction algorithms. Section 6.6 discusses the measurement campaign and how it is used to validate the simulator. Sections 6.7 and 6.8 shows and analyses the results from CNS and Wallace hall respectively.

## 6.1 Simulator Model

The following entities are implemented in the simulator to study the throughput of a WLAN system under varying signal and loading conditions.

1) Packet source that generates packets based on specified distribution for packet arrival rate and packet length
2) WLAN nodes, which transmits the packets based on the MAC mechanisms as described in IEEE 802.11 standard
3) Access point that acts as a sink for the packets
4) Channel that holds the packet for the propagation duration and delivers it to appropriate WLAN node. It also detects if there is any collision during transmission and updates the packet with SNR information.

Moreover, various types of data (such as total time taken for transmissions, number of collision) are collected in the various functions of the simulation program to compute statistics such as the effective data throughput.

The following assumptions were made in this simulation model

- The IEEE 802.11 DCF (Distributed Co-ordination Function) MAC is used
- In the physical layer the long preamble PLCP PDU format is used
- Independent BSS, Ad hoc operation is used
- Upper layer protocols are not considered.
- The traffic is assumed to a UDP data

## 6.2 Performance Analysis of WLAN using the Simulator

Wireless network performance depends mainly on the end to end throughput and average delay. Different applications place different requirements on the network. Real time applications such as voice over IP are highly sensitive to delay but function satisfactorily with little bandwidth. At the other hand data transfer applications like FTP are insensitive to delay but require as much bandwidth as possible.

In order to determine the throughput of the system it is necessary to analyze the MAC layer of the IEEE 802.11b system. An 802.11b compliant data packet consists of preamble, header and the actual data (or payload). The payload in turn consists of data from the application plus the overhead added at transport and IP layer. The transport mechanism can either be TCP or UDP. TCP adds more overhead as compared to UDP and also has inherent retransmission and flow control mechanisms. Hence it is not an ideal choice for analyzing the performance of the lower layers (in this case the MAC of 802.11b).

Throughput depends on the time taken to transmit the packet. In a WLAN system the time taken to transmit a packet is determined by the MAC mechanism (known as DCF). DCF enables the sharing of the medium between active WLAN nodes based on physical sensing of the medium. In a DCF all directed packets are positively acknowledged (ACK). Retransmission occurs if there is a failure to receive an ACK.

Thus the time taken to transmit a packet (including MAC acknowledgement) in a WLAN system can be shown below.

T = DIFS + (Preamble+Header) (bits) + [Data(bits) / Rate (bits/sec)] + SIFS + ACK_Time + Backoff_time (in μs)

Where,
- ‘DIFS’ is the minimum duration for which a node senses the medium before transmitting any data frame even in the absence of contention in the medium.
- ‘SIFS’ is a short version of DIFS and it is used while sending an ACK frame.
- ‘Backoff_time’ depends on the amount of contention in the network. It is always a multiple of slot duration. The slot duration is 12 μs.
- ‘ACK_Time’ refers to the time taken to receive a positive acknowledgement from the

receiver. The ACK frame might not reach the other end either due to frame error on the ACK frame or the data frame. In either case the MAC layer on the other side gets timed out and retransmits the data frame.

From the above equation, it can be seen that throughput depends on two factors - the load in the network and received signal strength. Below sections analyze the performance of the WLAN system based on the throughput of the UDP data transmitted.

## 6.3 Single user Scenario (RSSI versus throughput)

In this scenario, a single user is assumed to be present in the network. The user transmits with an exponential arrival rate. The user moves within the coverage of the access point. As the user moves, the building partitions along the virtual line between the access point and the user changes. The change in partition loss affects the received signal strength. Figure 6.1 explains the change in throughput for varying RSSI, as the user moves within the network coverage.

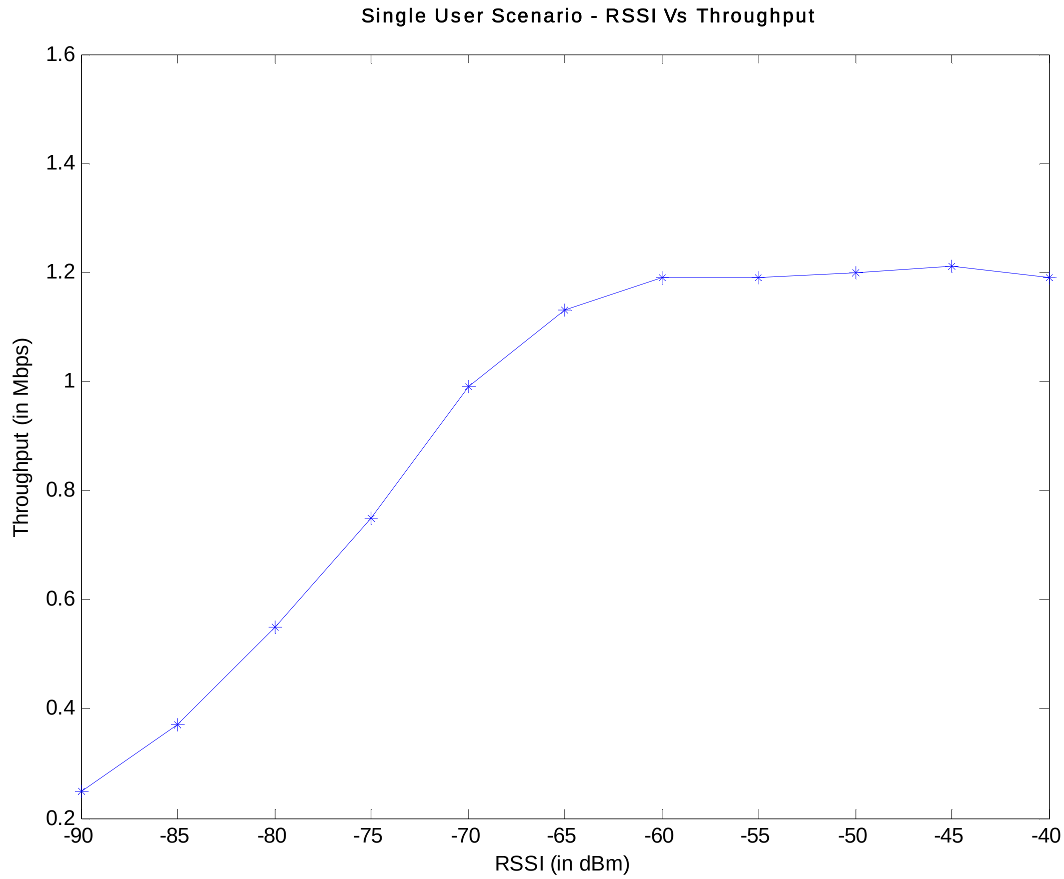



***Figure 6.1: Simulated results for RSSI Vs Throughput (Single user; packet length = 100B)***

In the single user scenario the performance of the system is directly dependent on the performance of the underlying physical layer. The above results

In a single user scenario, packet length is one of the main factors that influence the throughput. Every packet transmitted contains overhead from various layers such as UDP, IP, MAC, PHY etc.

The length of the overheads remains constant. Hence for smaller packets the percentage of useful information contained is low. This decreases the throughput of the system. The throughout increases with increase in packet length as long as the packet length is less than the fragmentation threshold.

## 6.4 Multiple-User Scenario: (Load versus throughput)

The number of users attempting to transmit defines the load on the system. The load on the system affects throughput and is studied in this section.

Load (G) was increased by keeping the packet arrival rate of individual users constant (1000 packets/second) but by increasing the number of stations. The mean packet size was fixed at 1000 bytes. Figure 6.2 shows the plot for offered load (G) versus total throughput ($T_{all}$). Total throughput indicated the additive throughput of individual users in the network. It can be seen from the graph that for the given scenario, as the number of users increases the throughput decreases proportionately. From the plot it can be seen that a single user achieves up to 8Mbps (1000 packets * 1000 * 8 bits per second) throughput in the system. If more user are introduced in to the network, the cumulative rate at which data is generated exceeds the maximum bandwidth (11Mbps) supported by the system. Hence the throughput of a user decreases as contention dominates in the network leading to backoffs and collisions

It should be noted that the throughput is related to medium utilization. It is possible that when the number of stations is lower the load on the system is very low i.e. lesser number of stations transmits data and hence the channel idle time is more. As medium utilization is low the throughout is also correspondingly low.

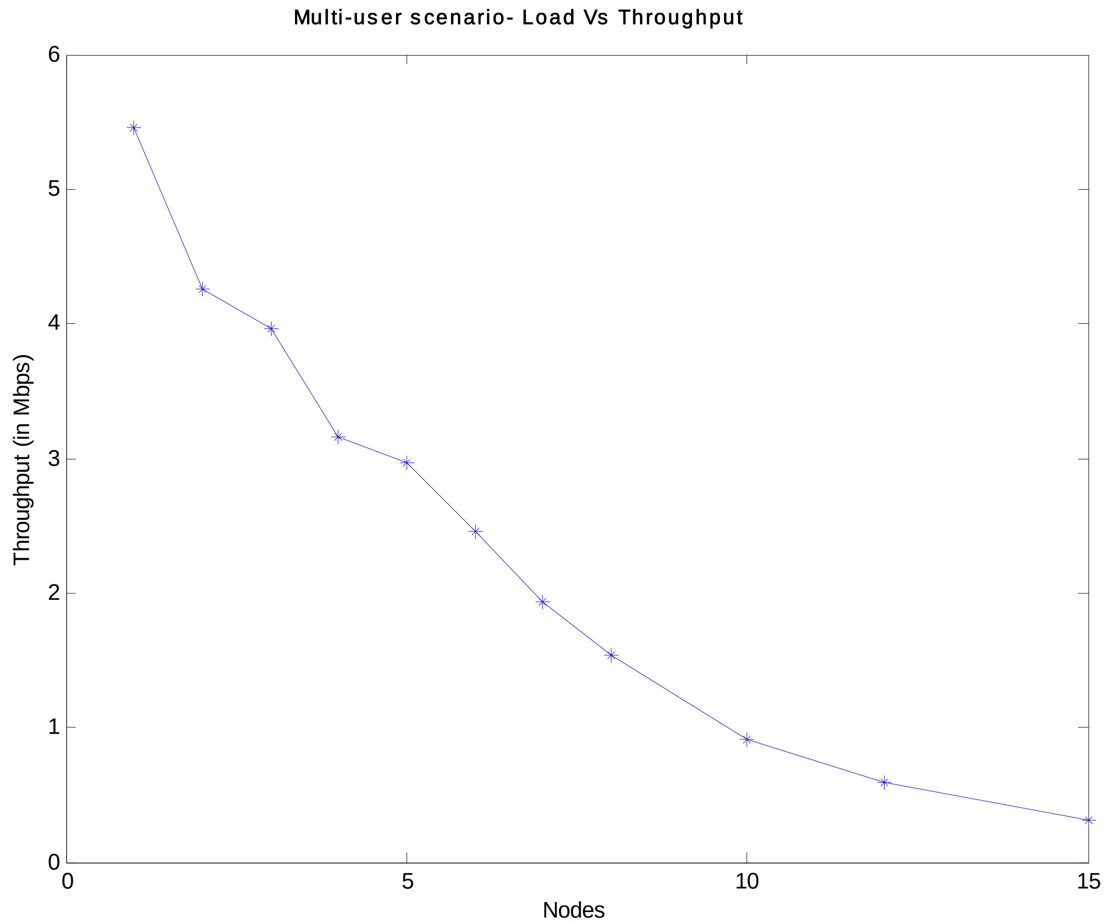



***Figure 6.2: Simulated Results for Load Vs Throughput (Packet size = 1000B, arrival rate = 1000 packets/sec)***

## 6.5 Rate Adaptation Algorithm

Following are some of the radio management parameters that can significantly influence the performance of the wireless link.

1) Rate Adaptation
2) Fragmentation threshold

WLAN MAC uses retransmission to overcome frame loss. The frame loss can be due to collision in the medium or interference in the channel. The probability of collision in the medium is dependent on the time the frame stays in the medium; which is related to the fragmentation threshold at the sender. Similarly the bit error in the channel is dependent on the modulation scheme used for transmission and the quality of signal. Typically retransmission involves changing the one of both of these parameters. Both these parameters are vendor specific.

The approach taken to adapt rate can influence the performance significantly. In general decreasing the transmission rate helps while operating at bad signal strength, but it also increases the time the frame stays in the channel. This can increase the probability of frame loss due to collision especially when there are multiple (greater than 3; there can only be three non-overlapping channels) access points in a single building. Vendor algorithms can work on optimizing this collision avoidance and at the same time reduce the data rate to decrease the probability of bit error.

For these reasons the simulated results are compared with a 90% confidence interval with the experimental results.

Two Rate reduction algorithms Reduce-First and Reduce-Second are proposed below. Both the algorithms are based on auto rate selection where the node tries the fastest rate and falls back to lower rate during next retransmission. This is usually very efficient to overcome attenuation and pretty good with fading.

Reduce-First readily reacts to frame retransmission by reducing the rate whereas Reduce-Second is slightly tolerant to frame retransmission. In theory the rate reduction algorithm should not only take in to account packet failure but also received signal strength. There can be several algorithms that can be devised based on above discussions. The choice of the two algorithms is to understand how much of a performance impact even a slight change in the algorithms (Reduce-Second versus Reduce-First) could contribute.

The simulation results are obtained for both the algorithms. In both the algorithm the fragmentation threshold is fixed at 1024 byte. This is acceptable as the experimental setup consists of one node and hence no possibility of collision.

**Algorithm 1:** Reduce-First Auto-reduction Algorithm

Whenever there is data to send, MAC attempts to send the data at the highest possible rate (11Mbps). If it does not receive the acknowledgement either due to loss of the data frame or the ACK frame, it backs off the transmission. During its second re-transmission opportunity it sends the same data at the next highest rate (5.5 Mbps). For any subsequent re-transmissions it further reduces the data rate until the least possible rate (1 Mbps) is reached. Upon reaching the least rate MAC re-transmits at this rate until the “max retry counter” is reached. MAC then drops the packet and starts with the transmission of the next frame.

**Algorithm 2:** Reduce-Second Auto-reduction Algorithm

Though the above algorithm works fine for most radio conditions, this is not always the best strategy, because decreasing the rate increases the transmission time. If the packet was lost because of an interferer, increasing the transmission time will increase the probability of collision [Tourrilhes01].

In this scheme MAC attempts to send the data at the highest rate (11 Mbps). If it does not receive any ACK it re-transmits the frame with the same rate (11Mbps). For any further retransmission it reduces the rate to the next highest rate until the least rate (1 Mbps) is reached.

## 6.6 Measurement Campaign

The aim of the measurement campaign is to compare the throughput of the simulator with the experimental throughout for two different indoor channel conditions. Chapter 5 discusses in detail the hardware and the software required for the experimental campaign and the experimental procedures. The measurement campaign is an effort to validate the simulator. More measurements and better controlled setups will be required to gain more confidence with the experimental results.

The below sections provide the results from the campaigns performed in two different buildings along with the simulated results. The simulated results are compared for both the Rate reduction algorithms. The key motivations for the comparative studies are as follows.

1) The realism of the simulator in replicating real world WLAN systems. The comparative studies will help answer questions such as
    a. what is the quantitative difference in throughput between the simulated and the experimental result
    b. Factors that could contribute to the deviation. This will help in guiding the future work for the simulator.
2) Understand the impact of multipath on the performance of WLAN systems
3) Compare the relative performance of the rate reduction algorithms against the experimental data

The x-axis of the graph displays the RSSI (in dBm) in increasing order with a scale of 5 dBm per unit. The y-axis of the graph displays the throughput measured at the WLAN node in Mega bits per second. The scale of the y-axis is 500 kbps per unit.

It is to be noted that the maximum and the minimum values of the y-axis are dependent on the maximum and the minimum values of the experimental data. Thus the difference between the experimental and the simulated values will be blown out in proportion to the range of the coordinates.

## 6.7 Building 1 (CNS)

### 6.7.1 1000 Bytes Scenario

Figures 6.3 & 6.4 show the comparison between simulated (for both the rate adaptation algorithms) and experimental throughput for packet length = 1000. The simulated results are plotted for 90% confidence interval.

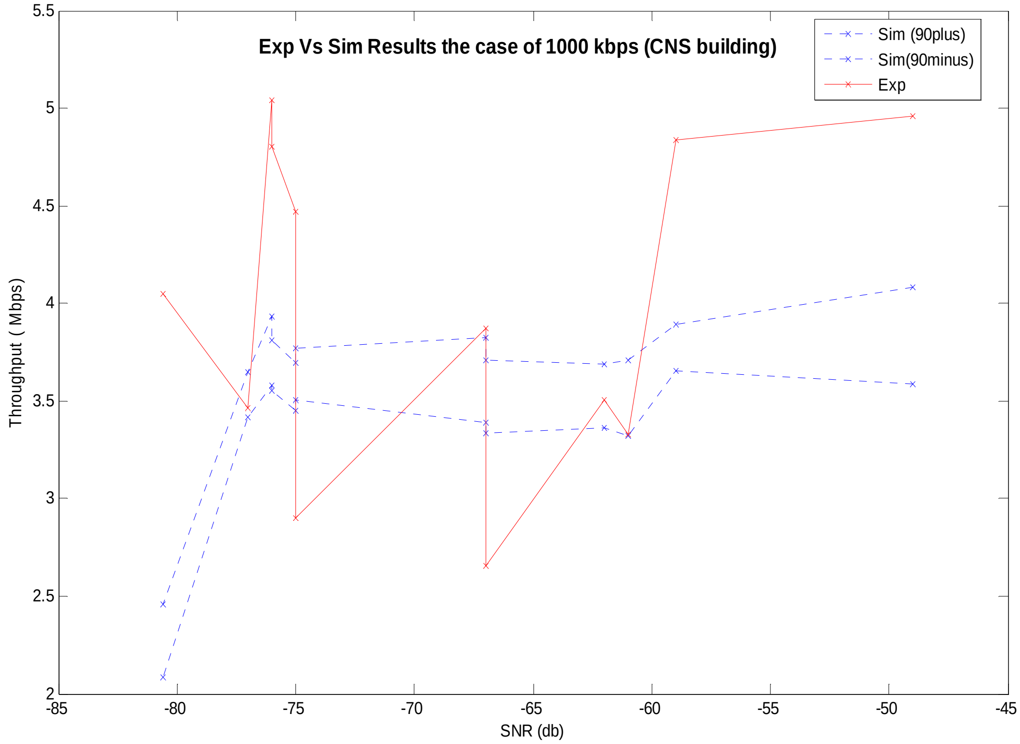



***Figure 6.3: Simulated Vs Experimental Results (for packet size = 1000; Reduce First Auto-reduction Algorithm; CNS Building)***

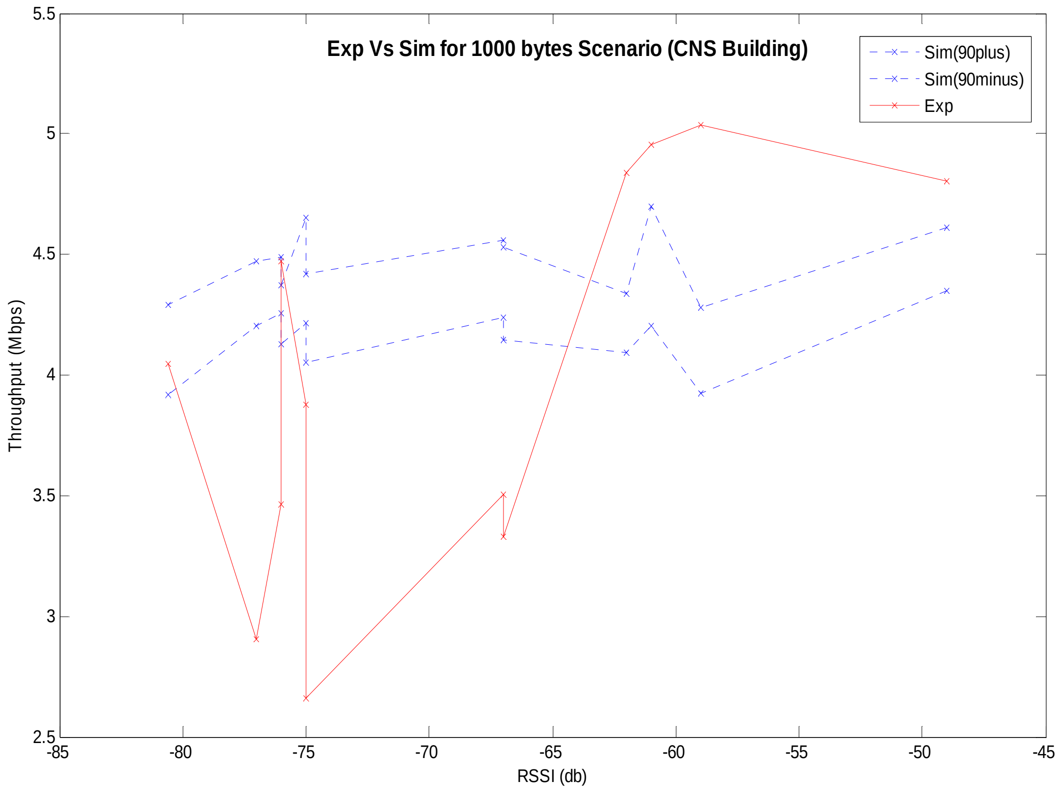



***Figure 6.4: Simulated Vs Experimental Results (for packet size = 1000; Reduce Second Auto-reduction Algorithm; CNS Building)***

The mean excess delay defined above is the temporal or spatial average of consecutive impulse response measurements collected and averaged over a local area. Ten power delay profiles are used to calculate the average.

Figure 6.5 shows the mean excess delay as a function of RSSI found at various locations in the building.

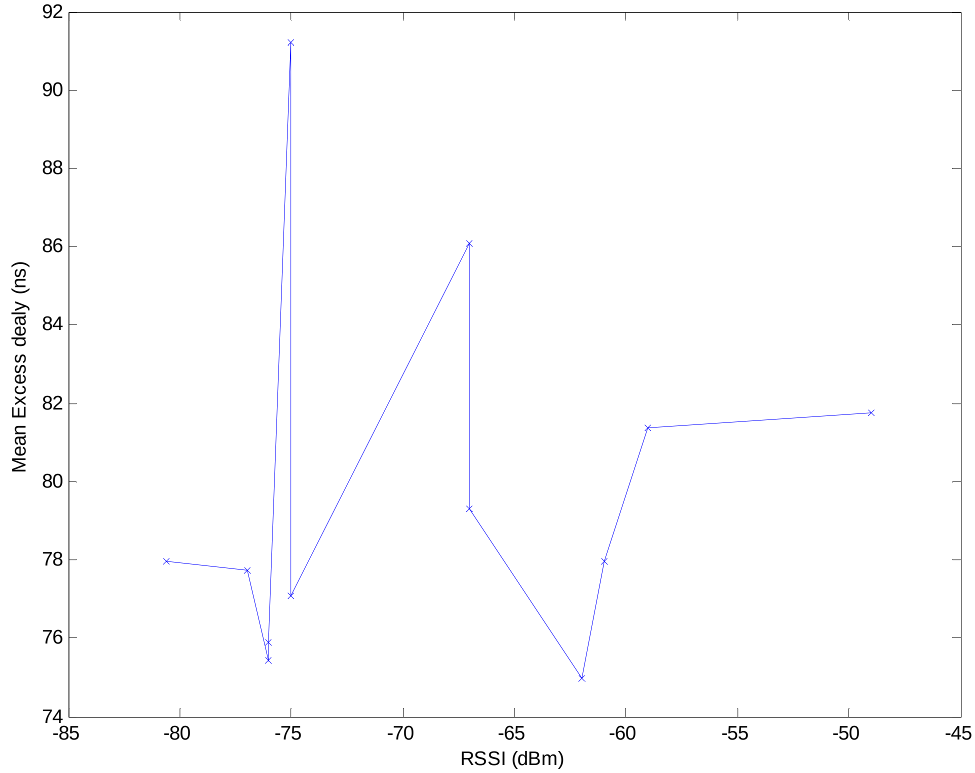
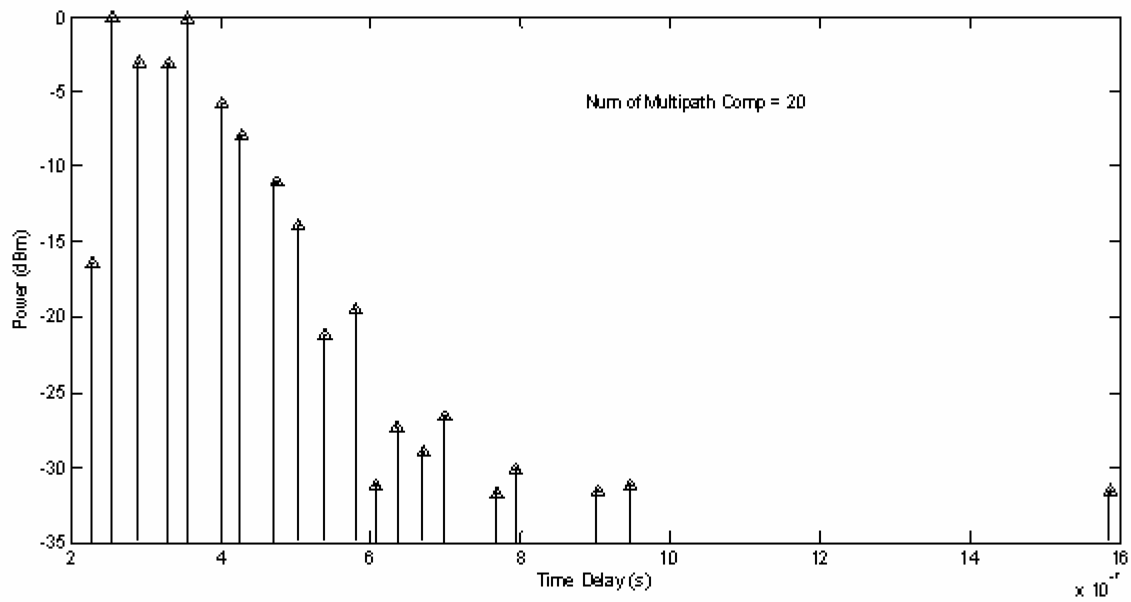
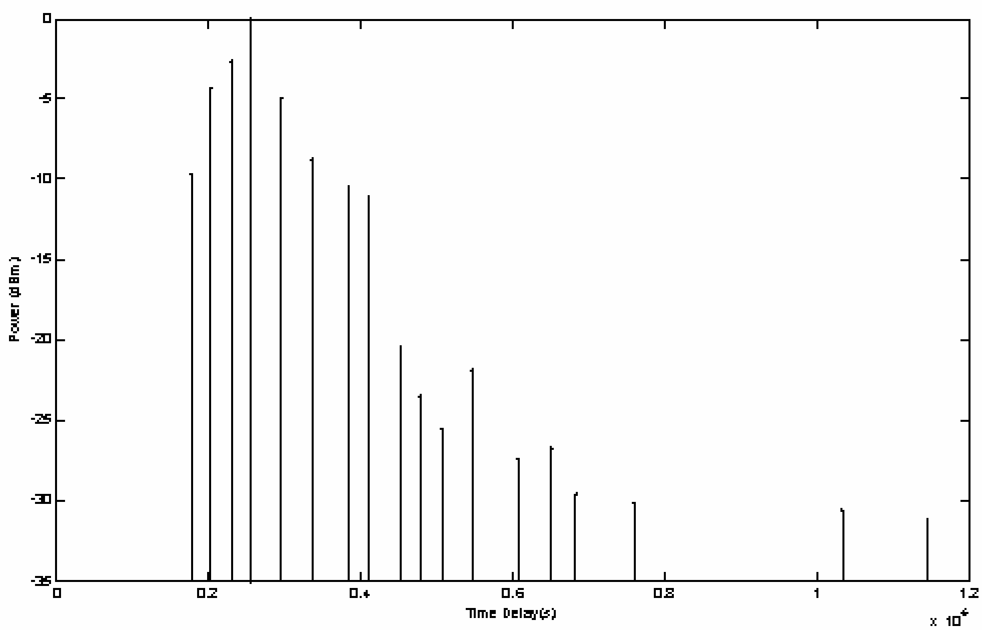



***Figure 6.5: Effect of Multipath (RSSI vs. Mean Excess delay)***

Around -75dBm, there are five measurement locations. From Figure 6.5 it can be seen that the mean excess delays at these points were sharply changing. The power delay profile of two locations in this region (location 6 & 7) can be seen below in Figure 6.6.




Location 6 ; RSSI = -75dBm




Location 7 ; RSSI = -77dBm

***Figure 6.6: Power delay profile (CNS Building)***

### 6.7.2 100 Bytes Scenario

Figure 6.6 shows the comparison between simulated and experimental throughput for packet length = 100B.

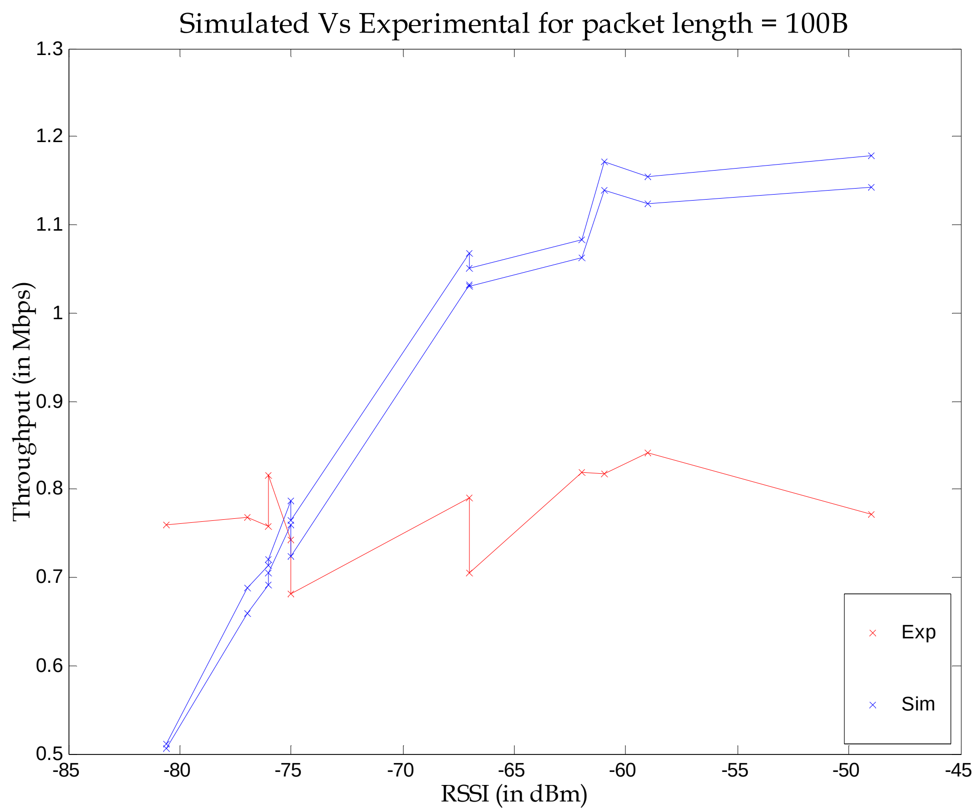



***Figure 6.7: Simulated Vs Experimental results (CNS building; packet size = 100B)***

### 6.7.3 Discussion of Results

The following inferences can be made from the graph.

- The reduce-first algorithm fares better than reduce-second for the CNS building. More points in the Reduce-First algorithm results are within the 90% confidence interval of the experimental value. Reduce first deviates from the experiemental results by 19% whereas reduce-second does by 21.6%.

- It can be seen that the simulated results follows the same pattern (curve) as that of the experimental results until the -75dB threshold.

- Around -75dBm, there are five measurement locations. The experimental throughput shows high variance in this region. From Figure 6.5 it can be seen that the mean excess delays at these points were sharply changing. One of the locations in this region had the maximum mean excess delay (91ns). Also from figure 6.6 it can be seen that the time delay of some of the multipath component in this region extend beyond the symbol duration (even for 1Mbps rate). This will lead to Inter Symbol Interference (ISI). Since the simulator does not model the effects of multipath, it fails to track the experimental result in this region.

- Difficulty in deriving a *degradation factor* (based on mean excess delay) in describing the effect of multipath on the throughput of the system, due to less number of measurement sample data.

- It can be seen that in locations (-67, -62 and -78) where the experimental results and the mean excess delay rises sharply, the Reduce-Second algorithms tracks better. This is because Reduce-Second is more tolerant to frame retransmission and maximizes the highest data rate as much as possible.

- From the above discussions it appears that a combination of Reduce-First and Reduce-Second might fare better while comparing with the experimental results.

- The simulator seems to work poorly for lower packet lengths. This is due to the fact that as packet length decreases the ratio of payload to overhead carried in a WLAN frame decreases. Therefore any small difference in throughput creates disproportionately large changes.

## 6.8 Building 2 (Wallace Hall)

### 6.8.1 1000 Bytes Scenario

Figure 6.7 & 6.8 shows the comparison between simulated (for both the algorithms ) and experimental throughput for packet length = 1000. The simulated results are plotted for 90% confidence interval.

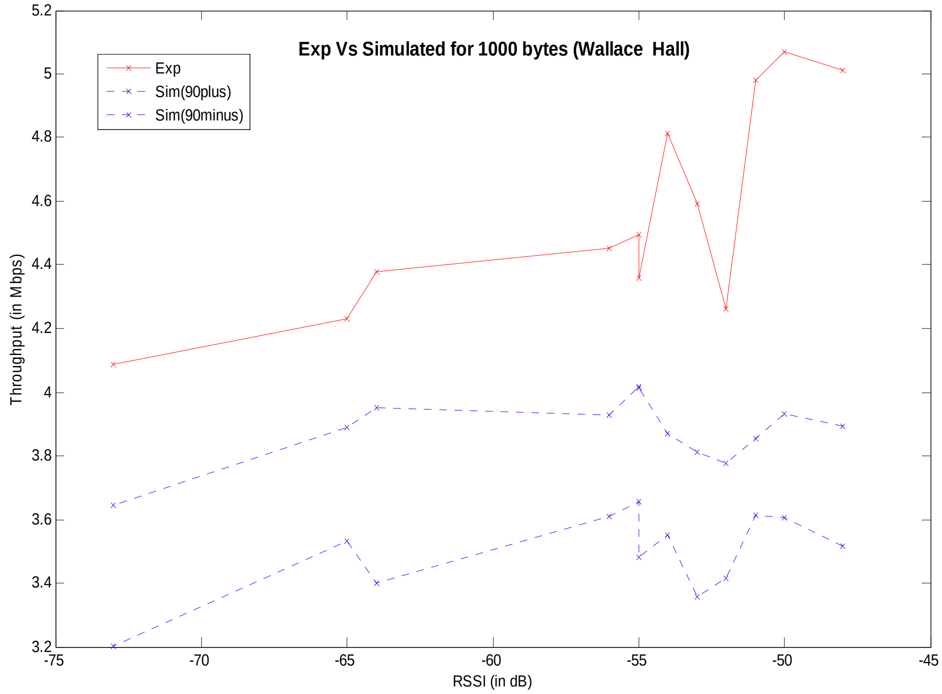



*Figure 6.8: Simulated Vs Experimental Results (for packet size = 1000; Reduce First Auto-reduction Algorithm; Wallace Building)*

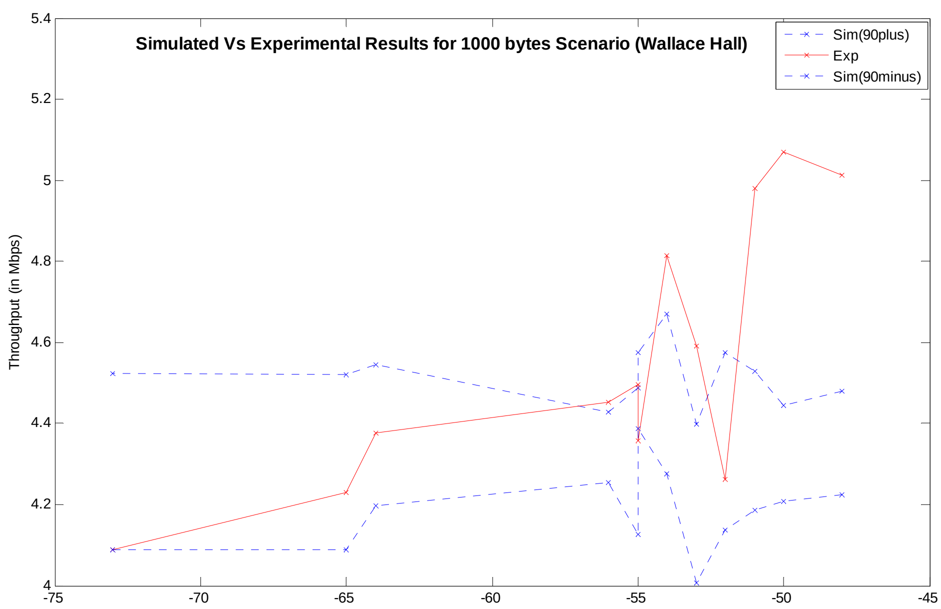



*Figure 6.9: Simulated Vs Experimental Results (for packet size = 1000; Reduce Second Auto-reduction Algorithm; Wallace Building)*

### 6.8.2 100 Bytes Scenario

Figure 6.9 shows the comparison of the simulated results with the experimental results for the 100bytes scenario and Figure 6.10 shows the mean excess delay variations in the building.

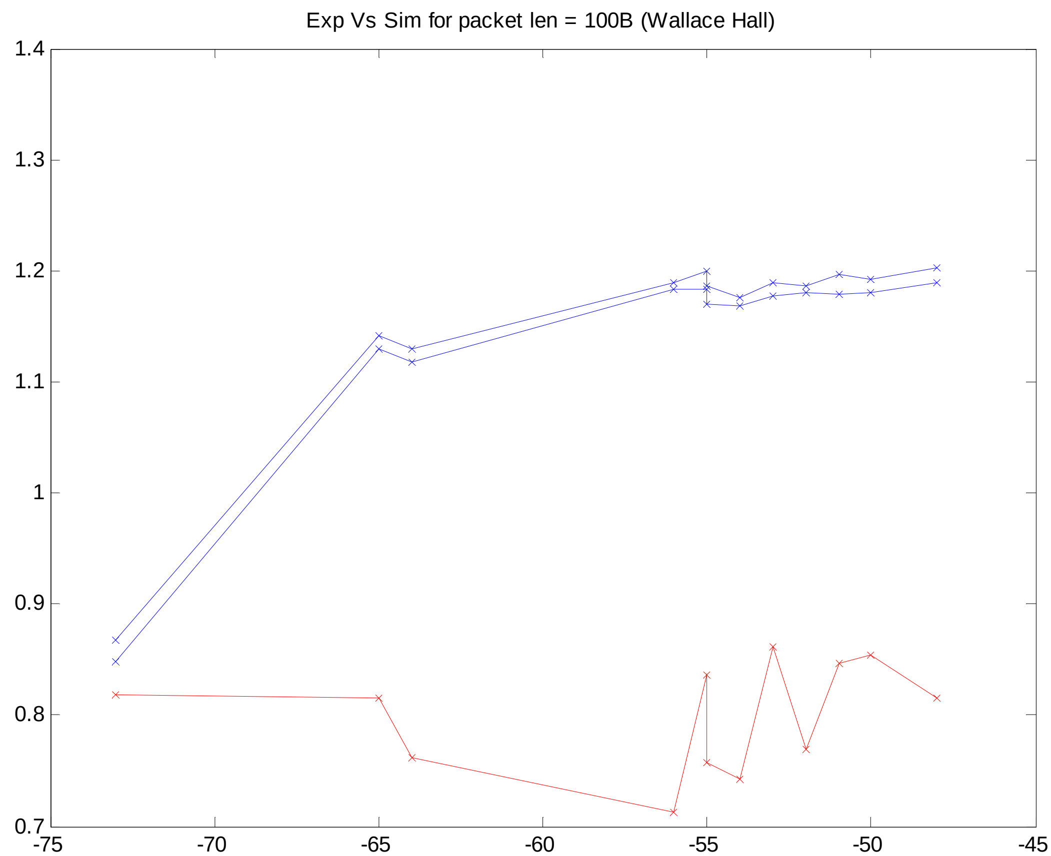



***Figure 6.10: Simulated Vs Experimental results (Wallace building; packet size = 100B)***

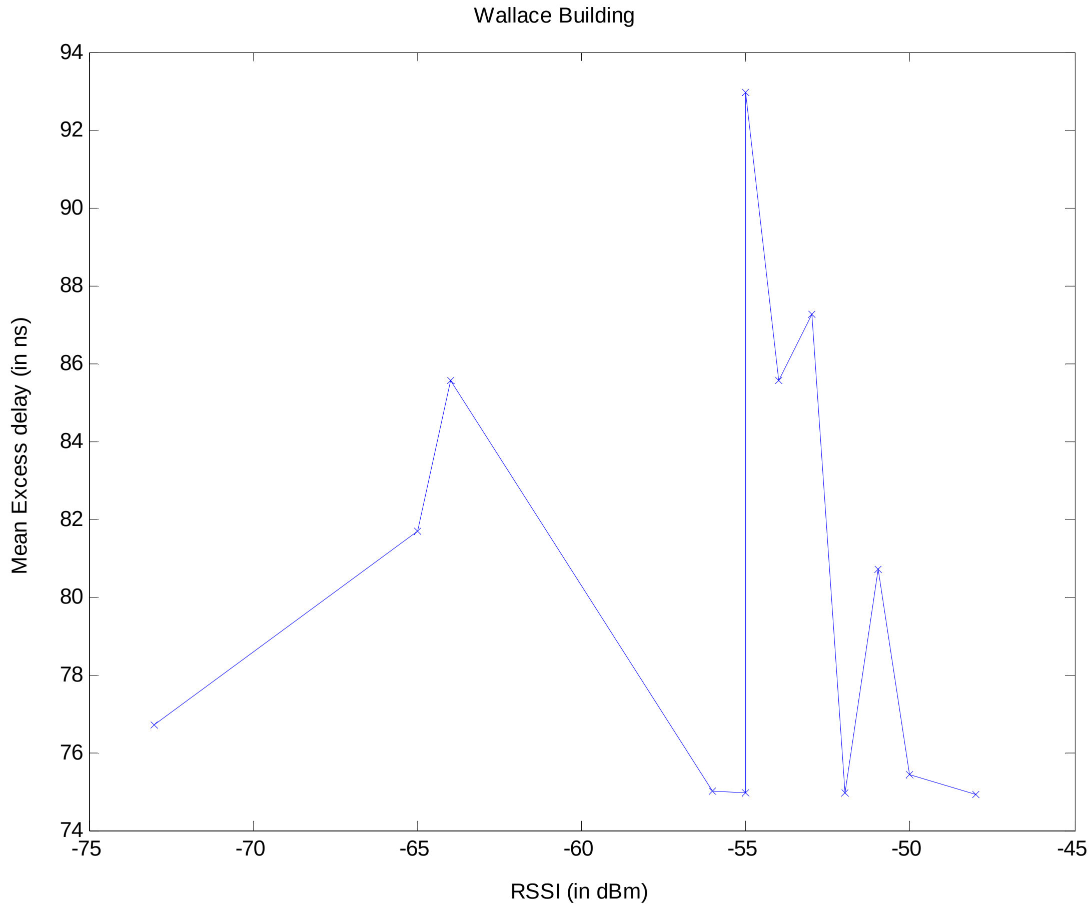
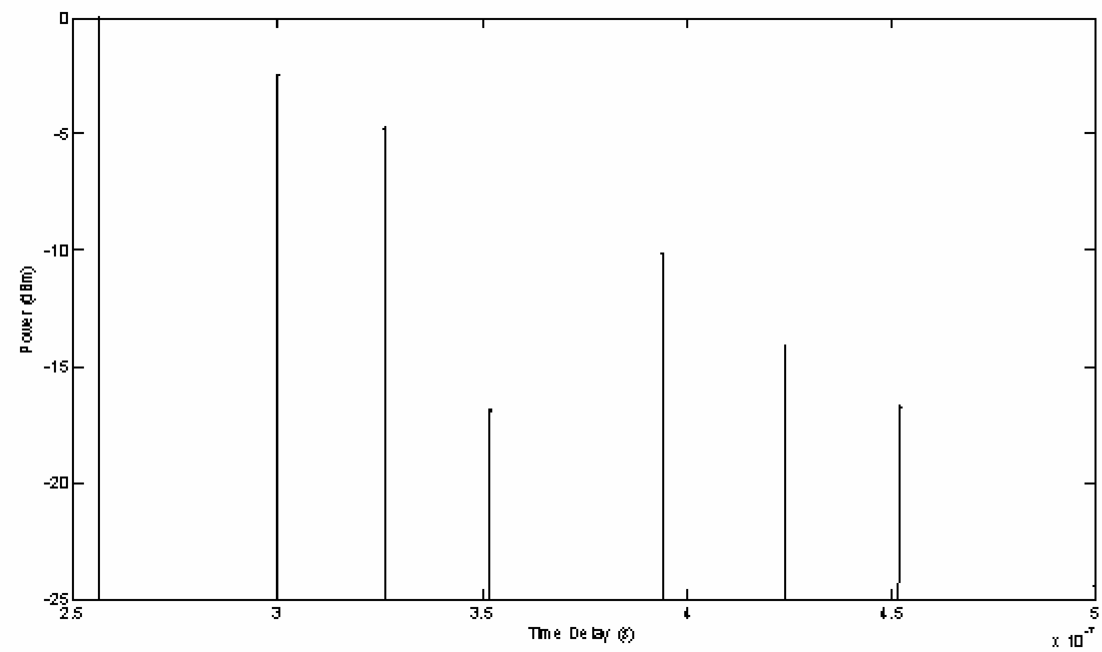
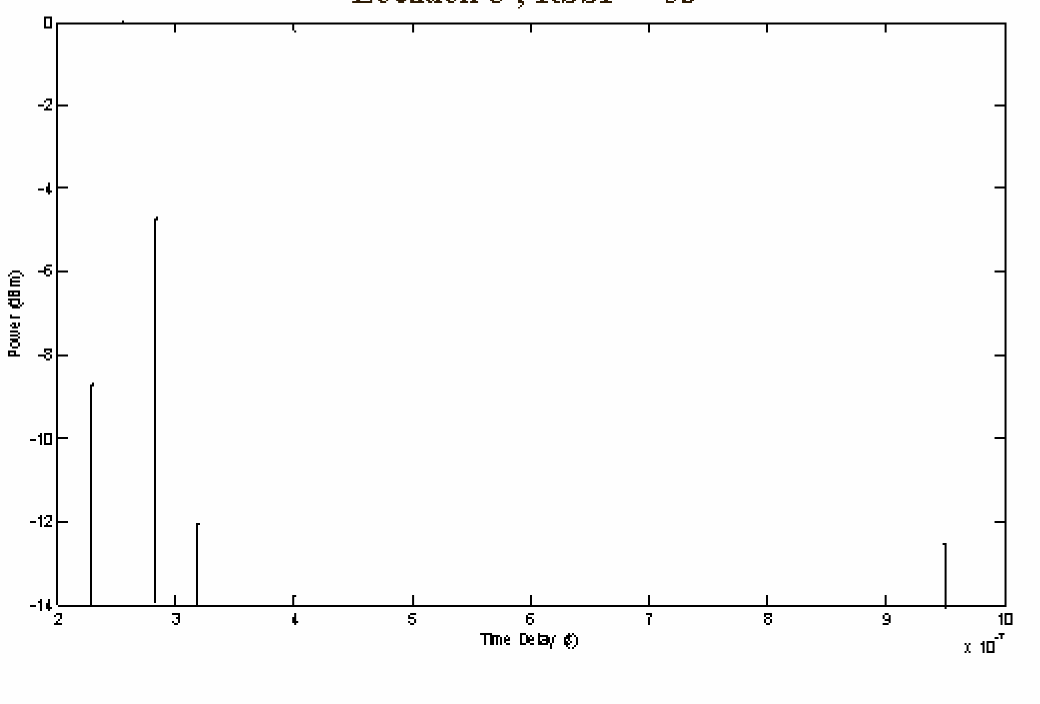



***Figure 6.11: Effect of Multipath (RSSI vs. Mean Excess delay)***

Figure 6.12 shows the power delay of some of the locations. It can be seen that the number of multipath is less compared to CNS building as expected for an open space.




Location 8 ; RSSI = -53




Location 12 ; RSSI = -48dBm

***Figure 6.12: Power delay profile (Wallace Hall)***

### 6.8.3 Discussion of Results

- For Wallace hall building, the reduce-second results fare better than reduce-first as most of the simulated results are within the 90% confidence interval. The simulator results vary only by 6% from the experimental results.
- The simulated results track the experimental results reasonably well for most of the points. As discussed before for building 1, at low signal areas the multipath of the channel influences the performance of the system. This results in big difference (30-40 %) between the simulated and the experimental results.

## 6.9 Limitation of the comparative study

The following are some of the factors that need to be kept in mind while comparing the results.

1) It is to be noted that the traffic source used for the measurement campaign is based on a third party tool (TTCP). The simulator attempts to implement this tool as closely as possible.
2) The throughput prediction of the simulator is based on RSSI. The RSSI calculation is dependent on the attenuation losses contributed by various building material. These attenuation values are obtained after optimizing the RF layout through Siteplanner®

***Resolution***
The simulation results for the 100 bytes scenario does not match very well with the experimental results. This is mainly due to the limitation of the TTCP tool used for the experimental campaign. TTCP has a resolution of 1/100 sec or 1000 μs for reporting the time taken to transfer the UDP packets. This resolution is not fine to capture a single successful frame transaction for the 100 byte scenario. As seen below it takes 580 μs to transmit a 100 byte frame and receive a positive acknowledgement.

Time taken (no contention and good SNR)
= DIFS + propagation time for 100bytes + SIFS + propagation time for WLAN ACK frame
= 50 + 300 + 10 + 220 = 580 μs

***Host processing delays***
TTCP reports the amount of data transferred the transfer time, and the approximate throughput. The reported rate is approximate because many factors can cause variations. For example, other traffic on the network or other programs using the computers' CPUs or memory can slow down transmission.

***Vendor specific Algorithms***
As discussed before in section 6.4, the rate adaptation algorithms can influence the throughput results especially in low signal strength areas.

# 7. Contributions and Future Work

## 7.0 Contributions

The following are the key contributions of this thesis

1) One of the main efforts of the thesis was in developing a generic wireless simulator. The tool was extended to simulate an IEEE 802.11b WLAN Network.
    - The simulator provides the flexibility to change the Load (number of users in the network), traffic distributions (packet length, packet arrival rate), topology of the WLAN network, etc.
    - The impact of these parameters on the throughput was also studied in this thesis.

2) A wireless LAN measurement campaign was conducted with an intention to validate the simulator.
    - The experiment was conducted in two different channel conditions.
    - Multipath statistics of the channel was also measured at every point using a wideband vector channel measurement system.
    - Mean excess delay was used as the metric in characterizing the multipath of the channel

3) The simulator results for two buildings were compared with the experimental results. The effect of multipath on the performance of the WLAN system was studied.
    - The throughput results from the simulator for most occasions with the experimented for higher packet lengths.
    - Multipath was found to greatly influence the performance of the system at low signal areas.
    - The simulator adds value to the design of WLAN systems by considering the throughput experienced by each user.
    - It was established that the rate adaptation algorithm used in multi-rate LAN system is critical in accurately predicting the throughput.

## 7.1 Limitation and Future work

This thesis work is just a start in analyzing the throughput in a real world WLAN system. The usability of this simulator as a standalone tool toward this goal requires work on the following areas.

**<u>Interface with CAD tools</u>**

The tool requires information for calculating the path losses such as

- The different building materials between the line of sight of the transmitter and receiver,
- The distance of separation between the nodes, etc.

Currently these values are manually feed to the simulator. In future the simulator can be extended to work with CAD tools in gathering this information.

**Additional measurement campaign**

The measurement campaign established reasonable confidence of the simulator, but it was not enough to completely validate the tool. Following are some of the questions that can be addressed by performing more measurement in more controlled test setup.

1) Identify any relationship between multipath metrics (such as delay spread, mean excess delay) and throughput. To avoid the influence of multi-rate adaptation, the test setup can be controlled to operate in one fixed rate (say 2 Mbps). The experiment can be repeated in multiple locations covering both diverse signal coverage regions and diverse building materials
2) Perform more extensive comparative studies to characterize the rate adaptation algorithms used in commercial products. The experiment can be repeated with multiple vendors to understand the differences.

# Appendix A: Experimental Analysis of Interference between Wireless LAN and Bluetooth

## A.0 Abstract

The 2.4 GHz Industrial, Scientific and Medical Band (ISM) is used by two technologies namely Bluetooth and the IEEE 802.11b Wireless LANs. Since both the technologies use the 2.4 GHz ISM band, there is a potential for interference between them. The inference issue can be seen separately as interference of Bluetooth on 802.11b and the interference of 802.11b on Bluetooth. A mathematical treatment of the situation was done followed by experimental verification. TTCP software was used for the throughput estimation. The throughput suffered in the presence of Bluetooth at SNR around –70-dBm .The reduction in throughput is due to the failure of the ACK frames from the Access point and due to the failure of Clear Channel Assessment (CCA). This work was supported by Mobile & Portable Radio Research Group (MPRG) and Communications and Network Services (CNS) of Virginia Tech.

## A.1 Motivation for IEEE 802.11b and Bluetooth

The 2.4 GHz Industrial, Scientific and Medical Band (ISM) is seeing the emergence of two technologies: Wireless Personal Area Networks (WPAN) led by Bluetooth and the Wireless Local Area Networks (WLAN) led by the IEEE 802.11b. Bluetooth is a short-range, cable replacement technology with transmit powers in the range of 1mw. It hops between the available 79 channels (2.402 –2.480 GHz) at the rate of 1600 hops/second. Bluetooth supports data rate up to 1Mbps.

IEEE 802.11 is a standard set by the IEEE to be used for wireless network connections. The initial standard supported only two data rates: 1Mbps and 2Mbps. The new standard IEEE 802.11b supports two additional data rates: 5.5 Mbps and 11Mbps. The changes in the data rates were possible by changing the modulation techniques and the coding schemes. This is the standard that has reached the present market and finds place inside buildings such as offices, hospitals, banks, shops, and other commercial or residential buildings. There are also outdoor uses like parking lots, campuses, and large building complexes. There are 14 available channels for 802.11b deployments with inter channel spacing of 5Mhz and channel width of 22Mhz.

## A.2 Interference Scenario

WPAN and WLAN are complimentary rather than competing technologies. Therefore Coexistence has become a significant topic of analysis in the industry. Because both the technologies use the 2.4 GHz ISM band, there is a potential for interference between them. The inference issue can be seen separately as *interference of Bluetooth on 802.11b* and the *interference of 802.11b on Bluetooth*. The interference occurs when a packet from a neighboring *piconet* overlaps in frequency and time with a packet from an 802.11b network. As we know bluetooth channel (1Mbps) hops at a faster rate and therefore, the probability that a packet from a neighboring piconet runs in to the pass band of the fixed channel (22Mbps) increases the chance of a collision. Such collisions will result in bit error at the destination and depending upon the locations of the errors in the packet (different portions of the packet have different coding schemes) will result in packet loss, thereby affecting the throughput of the network. For a collision to occur the packets should be in the same frequency and time. Since the bandwidth of 802.11 packets is 22MHz and the total number of hoping channel for bluetooth is 79, the probability that a given narrowband channel (Bluetooth) overlaps with a given wideband channel (802.11) is one-third. Therefore the probability that of a given pair of consecutive Bluetooth hops, at least one of the channels overlaps with a given wideband 802.11 channel is given by 1-(2/3)^2 or 56%.

## A.3. Mathematical Treatment

The Bluetooth devices in a piconet are synchronized in time with each other. Whereas the Bluetooth and 802.11 systems are not synchronized, therefore the number of Bluetooth packets overlapping on an 802.11 packet depends on the following

- Packet length of 802.11
- Packet length of Bluetooth
- Time offset between the Bluetooth and the 802.11

To understand the above-mentioned situation, the following mathematical model was developed by Greg Ennis (submitted to the IEEE 802.15 WPAN Task group 2).
Let H be the duration of a Bluetooth hop (typically 366 microseconds for a DM1 packet) and L be the duration an 802.11 packet (typically 727 microseconds assuming a 1000 byte packet). Then the minimum number of hops in which the 802.11 packet overlaps is

$$\lceil L/H \rceil$$

and the maximum number of hops overlapped is

$$\lceil L/H \rceil + 1$$

where $\lceil x \rceil$ is the least integer greater than or equal to x. The actual number of hops that the packet overlaps depends upon the relative timing of the start of the packet and the hop.

Let d be the “delta” between the last Bluetooth hop and the start of the packet as indicated in the following timing Figure:

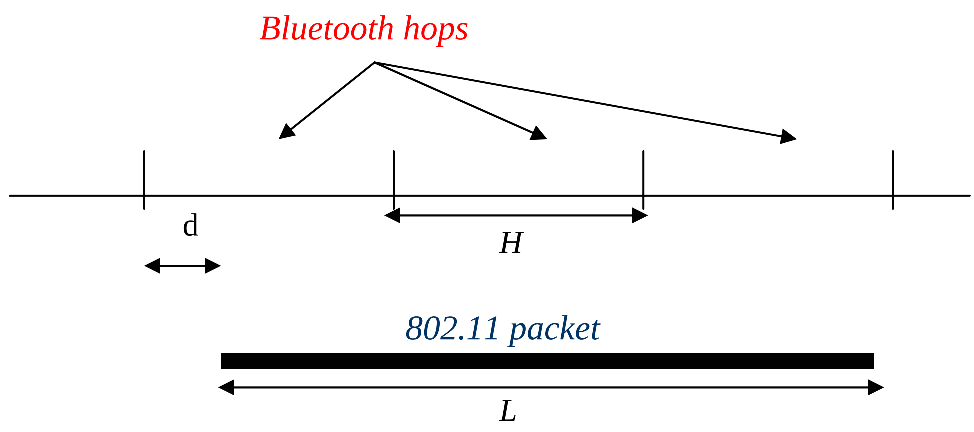



***Fig A.1: Collision scenario***

Note that $0 < d \leq H$. If d is zero, then the 802.11 overlaps with its minimum number of Bluetooth dwell periods, namely $\lceil L/H \rceil$. If d is greater than $\lceil L/H \rceil * H - L$ then the 802.11 packet overlaps with $\lceil L/H \rceil + 1$Bluetooth hops. Consequently, an 802.11 packet will overlap $\lceil L/H \rceil$ Bluetooth dwell periods whenever

$$0 < d \leq \lceil L/H \rceil * H - L$$

and will overlap $\lceil L/H \rceil + 1$ dwell periods whenever

$$\lceil L/H \rceil * H - L < d \leq H.$$

This translates into probabilities by expressing these intervals as fractions of the interval [0, H], yielding the following:

The probability that an 802.11 packet of duration L will overlap in time with $\lceil L/H \rceil$ Bluetooth dwell periods of duration H is $\lceil L/H \rceil - L/H$. The probability that it overlaps with $\lceil L/H \rceil + 1$ dwell periods is $1 - \lceil L/H \rceil + L/H$. Similarly the probability that 802.11 packet will overlap in frequency with a bluetooth packet is either (2/3)^(L/H) or (2/3)^(L/H + 1). Therefore the total probability of collision is given by the sum of the product of the two probabilities.

$$(2/3)^{\lceil L/H \rceil}(\lceil L/H \rceil - L/H) + (2/3)^{(\lceil L/H \rceil + 1)}(1 - \lceil L/H \rceil + L/H)$$

## A.4 Experimental Setup

The goal of the experimental setup was to study the performance (throughput) of a WLAN system as a function of RSSI in a co-existent scenario (Bluetooth and WLAN device in a single laptop). The interference was Bluetooth was kept constant by keeping the distance between the radios constant. The Bluetooth radios were constantly kept active by engaging them in a huge file transfer. The RSSI at the WLAN node was measured from the driver software.

The experimental setup consists of the following devices:

1) Laptop, DV1, which has co-located bluetooth (BT) and 802.11b PC cards (Cabletron PC cards were used). (Separated by 10cm).
2) DV1 is connected to the Wireless LAN network using an Access Point (AP).
3) Laptop (DV2) with a BT PC card (IBM PC cards were used) that communicates with the Bluetooth radio in DV1.
4) Laptop, DV3 that is connected to the same wired network as that of AP.

The Access point (Roamabout) and DV3 were connected to a catalyst 1900 series Switch to create an isolated network (198.82.245.0). The AP was configured to be in a secured mode and was set to channel 6. DV1 and DV2 were kept in a trolley with fixed distance of separation between them. The experiment was conducted in the 4th floor of Durham Hall. The network was placed in the atrium

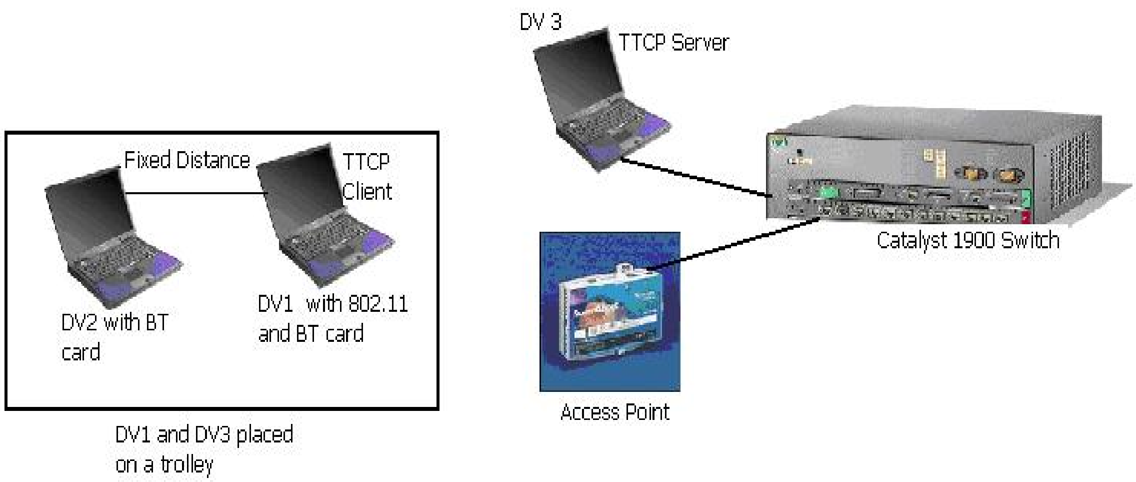



***Fig A.2: Experimental setup***

## A.5 Experimental results

Test TCP (TTCP), a command-line sockets-based benchmarking tool for measuring TCP and UDP performance between two systems, is used for generating the WLAN traffic between DV1 and DV3. The metric of the experiment is the variation of throughput with SNR (signal to noise ratio). The experiment is repeated by varying the distance between DV1 and AP, keeping the distance between DV1 and DV2 fixed. Bluetooth traffic is generated by having a very long file transfer (using DH5 packets) occurring between DV1 and DV2 at the same time as that of a TTCP session.

The TTCP server was run in DV3 and the TTCP client in DV1. The experiment was conducted for varying distance of separation between the AP and DV1 (hence varying SNR) and each time the TTCP server is run to get the throughput. For every measurement run, the BT traffic was shut off and the throughput without BT was found. The trolley was moved along the lobby and then in to the offices and labs around the AP. The results are shown below. The X-axis is the signal strength received from the AP. The signal strength was read in DV1, using the link test monitor in the PC card. The Y-axis is the throughput variation in kilobytes/second.

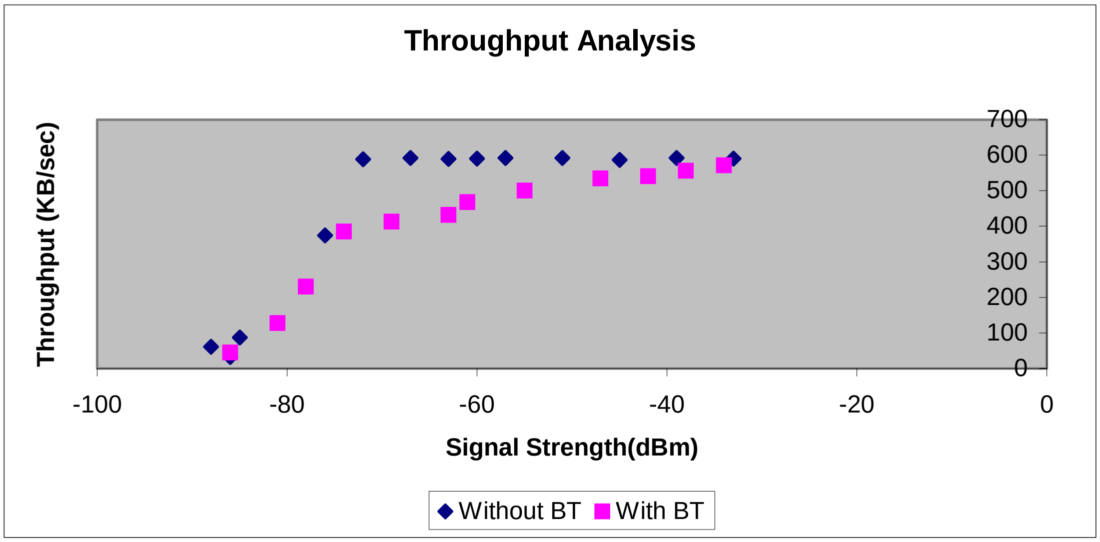



*Fig A.3: Throughput results for WLAN*

## A.6 Analysis

The following points can be drawn using the above results.

1) The throughput of 802.11b in the presence of BT suffers greatly for fair signal strength (-60 to –75). The reduction in throughput is because of the following mechanisms.
   a) Collision of the ACK packets originating from DV1 with the BT packets.
   b) Failure of the CCA (clear channel assessment) mechanism at DV1.

2) Under extremely good signal strength conditions the effect of BT is not predominant. The Signal to Interference ratio is large enough to drive the throughput.

3) At low signal strength (<-80dBm) noise dominates and the performance of the WLAN system gets worse.

4) The use of RTS by the AP may help some, as the station will not respond with a CTS if the RTS collides with a Bluetooth transmission. However, the success of an RTS/CTS exchange is not a good indicator of success for the data transfer, since during the data frame transmission a Bluetooth transmitter might hop into the channel and cause a collision.

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# Resume

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**Education**

**M.S., Electrical Engineering,** May 2005, Virginia Tech, USA **GPA:** 3.68/4.0
**B.E., Electronics and Communication Engineering,** May 2000, University of Madras, India

**Work Experience**

Engineer, QCT systems Test, **Qualcomm, Incorporated** *(03/03/03 – Present)*

- Worked with the GSM/GPRS performance team. Responsibilities include creating dynamic RF test scenarios, protocol analysis, throughput testing, system studies
- Worked with the UMTS Inter RAT team, testing the mobiles performance while transitioning between GSM/GPRS and UMTS systems.
- Worked with various test equipment vendors in achieving our technology needs.

Wireless Network Researcher, **Communications and Network Services**, Virginia Tech *(07/01 05/02)*

- Design of on-campus *Wireless LAN* Network at Virginia Tech
- Coverage of WLAN using *Site Planner* (software from Wireless Valley Inc)
- RF testing using Locust & Grasshopper 802.11b Receivers from Berkeley Varitronics Systems

Research Assistant under Dr.J.H.Reed**, Mobile & Portable Research Group** *(05/ 01 –present)*
*Thesis work*: Analyzing the interference between *Bluetooth* and *IEEE 802.11b WLAN***.** Involves the implementation (development in C++) of a PHY-MAC layer simulator.

Graduate Teaching Assistan**t**, **Bradley Dept of Electrical Engineering**, Virginia Tech

- Course: Embedded Systems *(Spring 2001)*
- Course: Pattern Recognition and artificial intelligence Survey *(Fall 2000)*

**Academic Projects**

**Network Applications using WINSOCK version of Client-server programming**
The projects were done in VC++ 1) HTTP 1.1 Server using Multithreaded design 2) HTTP 1.1 Server using asynchronous and overlapped I/O design 3) Application Gateway 4) Multicast chat Application

**Dynamic web page development to analyze the utilization of the DHCP sever**
Dynamic Graphs were created to analyze the utilization of the DHCP server at Virginia tech using TCL scripting language. The data were archived and the graphs were plotted using the RRD package.

**Implementation Of Embedded Digital Communication sub-systems Using TMS320c30 DSP**
1) Generation of a BPSK Signal 2) Implementation of FIR & IIR filters 3) Carrier Recovery 4) Code & symbol synchronization 5) Equalization 6) DPCM & ADPCM systems

**Multi-user Detection Techniques for Adhoc Networks**
To implement successive and parallel interference cancellation techniques and study their performance in an Adhoc network for a CDMA system.

**Performance Evaluation and Comparison of Packet Discard Algorithms for Congestion control (EPD Vs FPD) -** *OPNET was used for modeling this system*
Evaluated and compared the performance of these two schemes in terms of their effectiveness in handling the badput and managing the queue through simulation experiments

**Quality of Service Issues in Mobile Networking**
Study the various aspects of Quality of Service issues in Mobile systems and to develop a comprehensive web resource. **http://www.ari.vt.edu/ece5516/QoS/index.htm**

**Design of Digital Communication System**
Design a digital communication system for transmitting security information from the manufacturing plant to its headquarters. Design involves optimizing the cost and the bandwidth of the system.

**Skills**

**LANGUAGES -** VC++, Visual Basic, C, C++, HTML, Java, TCL/TK, PERL, SCOTTY-TCL, SQL
**COMMUNICATION TOOLS -** EVM of TMS320C30 DSP, MATLAB, SITEPLANNER, SITESPY
**NETWORK TOOLS -** NetID, Rrdtool, Rrdgraph, MRTG, OPNET, ROAMABOUT AP MANAGER

**Acadameic Courses**

Stochastic Signals and Systems • Digital communications • DSP Implementation of communication Systems • Digital Signal processing • Computer Networks and Architecture • Network Performance, Design, and Management • Network Application Design • Cellular Communications

**Professional Courses**

• GPRS – Signalling and Protocol Analysis (Week long course Conducted by CETECOM, completed on 04/04/03)

**Activities & Honor**

Finished 3rd in the VT table tennis league during fall 2001 • Active participant at group discussion forums •Best Under-graduate project award