Bandwidth Capacity Measurement in Small-Scale wireless IP Networks

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DECLARATION

I declare that this Research project is my original work and has not been previously published or submitted elsewhere for award of a degree. I also declare that this Research project contains no material written or published by other people except where due reference is made and author duly acknowledged.

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ABSTRACT

User applications on the internet cannot beget bandwidth guarantees from the network. Therefore, it is important to measure the available capacity bandwidth as well as link capacities so that the user applications may adopt these parameters to determine the applicability of the service.

For measurement of the available capacity bandwidth between devices in a wireless network, active capacity measurement methods are used. Data packets inform of packet probes are inferred into the network from the sending device. These data packets are stamped with time at the end node. The available bandwidth is analyzed from the separation with the time stamped packets as the input.

It is expected that measurement of bandwidth capacity in a low intrusive network, sender based probe would be equal to the theoretical capacities. The theoretical estimated capacities are done at the last hop node in a given network setup. In this dissertation work, bandwidth capacity measurement is done from the sender-node.

The results obtained indicate that the simulated network results in bandwidth capacity that is relatively indicative of wireless capacities that are known in theory as discussed in the research work. However, in real networks, these may not be realized as the practical networks will have cross traffic as a result of other devices in the network that are communicating and sending packets as well. These packets will cause an increase in the round trip time.

Key words: Path capacity estimation, path capacity measurement, packet pair probe, quality of service(QOS)

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DEDICATION

This research work is dedicated to my Children Michelle, Chloe and Gian.

LIST OF FIGURES and TABLES

ABBREVIATIONS

CSMA/CD	-	Carrier Sense Multiple Access with Collision Detection
DCF	-	Distributed coordination function
ETE	-	End-To-End
ICMP	-	Internet Control Message Protocol
IP	-	Internet Protocol
LAN	-	Local Area Network
MAC	-	Media Access Control
MTU	-	Maximum Transmission Unit
OWD	-	One-Way Delay
RTT	-	Round-Trip Time
TCP	-	Transmission Control Protocol
UDP	-	User Datagram Protocol
WLAN	-	Wireless Local Area Network

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TERMS AND DEFINITIONS

Available bandwidth - this is the maximum throughput that a path can provide to a data flow without causing significant degradation in service quality of other ongoing flows or to itself

CHAPTER ONE

1.1 - introduction

In today's networking environment, a Wireless Local Area Network (also known as WAN) is a wirelessly connected to the devices within the network which gives users an alternative to the more common wired Local Area Network, LAN. It utilizes air-borne signals in the place of wires for transmission of data packets between devices in a small area for example an office, school or home. Wireless Local Area Networks are network standards under the 802.11 family.

A small wireless local area network comprises of three to five devices connected to a central sever to enable sharing of information and resources among themselves. An example of a small wireless network is the home entertainment with the provision of Internet Protocol Television [IPTV], internet services and home telephone as a package. This form of entertainment is gaining popularity within the urban setup. An example of this setup is the Zuku Triple pay packages [http://www.zuku.co.ke/triple-play/triple-play-packages.html] which is offering an option of up to six devices in additional to the Television streaming and telephone.

The wireless devices used to access the internet services requires establishing the path capacity quality between itself, other devices to communicate to and the media server. The measurement of the path capacity therefore needs to be done from the sending device,

Internet Protocol has become the preferred protocol to transfer voice and data unlike the traditional use of wired network. Internet Protocol network can be used for real-time communication in both voice and data transfer. The transport layer through Transport Control protocol (TCP) provides reliability in data packet transmission while User Datagram Protocol (UDP) remains unreliable, unpredictable and inefficient in data delivery with no congestion control. For improvements to be recommended, available bandwidth in bytes/sec needs to be established, as well as the causes of delays. Most path capacity estimations in wireless are theoretical.

Wireless Local Area Networks are commonly setup to employ of remote data transmission system that uses magnetic attraction signals like radio waves, for the carrier and this implementation usually takes place at the physical level or "layer" of the network.

Wireless local area networks used when connecting to the internet or when several nodes want to inter-communicate in an improvised manner are becoming popular with the introduction of high power processing devices. Current small scale wireless IP connections are designed in a manner that gives the quality of service demanded by the devices in the network. This lack of Quality of services may be attributed to solutions that are available for wireless LAN where network management solutions are incorporated in the design. However, implementation of successful quality of service solutions in small scale wireless IP networks like home entertainment that requires being seamlessly compatible on the available quality of solutions in the methods employed and a different networking methodologies used throughout the wireless local area network. These qualities of service solutions administered requires to be supported and easily integration by devices in the network.

1.2. Causes of problems

Presently, in the field of small scale computer networks, many devices are easily integrated into an ad-hod network. It is observed that different devices are able to intercommunicate other the different network technologies like Personal Area network (PAN). To be able to provide user experience with quality of service services that is provided by these small scale networks, an uninterrupted quality of service needs to be provided the established networks. Presently small scale wireless networks were not meant to offer quality of service to the communicating devices. Most of the solutions available were either based on classification of the network or the prioritization of services provided. There are cases where network resource management solutions are incorporated in the design of the network [**White paper,1999**]. For successfully employing administration of quality of service solutions in a mixed network environment such as small scale IP network will require seamless integration given the different networking technologies applied within the mixed network architectures and design. These qualities of service solutions require the support of all the devices operating in the network. In addition, these parameter and their configurations are done with default settings for the by the end user to determine the specific uses, who mostly has no knowledge or is not willing to. To avoid these kinds of problems, an approach which has been recommended by Delphinanto et al***, 2008***is to incorporate the support of Quality of service in the small scale wireless networks by inclusion of a resource management with the resource manger located at the residential gateway in the design of the wireless network. This will be composed of additional device service discovery protocol for reservation of the required resource. The main resource manager within the wireless network dictates if the requested service will be guaranteed based on the network path quality assessment between the service provider and the device requesting. An open session for the service is terminated in an instance where the available bandwidth in the network path is not sufficient to guarantee delivery of the requested service. This request should be implemented and performed on the sending device with no specific support from the receiver device.

Currently, there is no tool that can measure the path capacity quality satisfactorily based on a single device, in a small scale wireless network, in low and fast intrusive way. The available capacity bandwidth is the main focus for the path capacity quality; we focus on an IP level bandwidth capacity estimation techniques. This research work try to answer on the questions on how to measure the available bandwidth in a network at the IP level in a small scale wireless IP network without modifying the existing client and devices. The end device that prays the part of the requesting, which at in the end receive of the service will determine the capacity. The main aim of this research work is to develop a model for path capacity measurement of the present capacity bandwidth between the two devices in small scale, wireless IP network. The model should be implemented at the requesting node without modification or installations of any extras in the primary nodes. The path capacity measurement should be fast, without disruption of the already existing packets in the network. The model should provide an operability of a real-time scenario with the measurement delays in seconds to guarantee efficiency.

1.3 - definition of key terms

Key terms

Path capacity estimation, path capacity measurement, packet pair probe, quality ofservice(QOS),

1.4 Problem statement

Bandwidth capacity measurement is an area which has been in focus in the domain of networks for some time and it is generating interest. There are a number of research areas that still needs to be studied and addressed more analytically.

Bandwidth capacity measurements in wired IP networks have attracted a lot of interests. New technological advances in networks have come into place and their adoptions are gaining momentum. Such technologies include 802.11 wirelesses, GPRS, Personal area networks, CDMA and 3G.The questions of whether current bandwidth capacity measurement methodologies can be applicable in these new network technologies are coming up. (*Andreas et al, 2005*)

It is prudent to measure the effects on the path quality in the process of cross-traffic and probe traffic interaction in a wireless network path. This will be achieved by studying this interaction by employing the packet pair probe in a scenario of the cross-traffic in the network and in a scenario with no cross-traffic. The question of how these two traffic packets affects each other and the overall effect on the quality of service on the wireless network by the presence of cross-traffic.

1.4.1 -The purpose/Aim of the research

The main purpose of this research work is to develop a bandwidth capacity measurement model for small-scale IP Networks. The application of the path capacity measurement tool should be sender based.
An evaluation of the existing bandwidth capacity measurement tools in wireless networks to identify whether their admissibility in wireless network will be carried out, and comparison of these tools.

1.4.2. Specific objectives

The objective of this research work is;

- To identify the existing problem in the area of bandwidth capacity measurement in small scale wireless IP networks.

- To define the requirements of implementing the model. This is achieved by carrying out an evaluation of the existing capacity measurement tools in wired network to determine if they can be used for IP wireless network.
- To design the model.
- To develop the model in the implementation design.
- To Test and validate the model.

1.4.3 - Research questions

How does the existing path capacity measurement methodologies and tool that are intended for wired networks perform in small scale wireless networks?

1.5 Justification of the research.

Path capacity measurements tools and methodologies in small scale IP networks are important for network error diagnosis, path quality assurance and performance improvements as well as a part of the adaptive mechanisms for assessing the guarantee of service for user applications such as streaming video as stated by Andreas Johnsson, 2005. This is in particular for research that has focused on path capacity measurement between two end-points in a wireless network. Active path quality measurements are achieved by inferring probe packets pairs that are time stamped at the receiving end into the network.

CHAPTER TWO

2.1 State of the art

The main goal of this dissertation is to design a model to be used by the devices to establish the quality of service in the network so the applications running on the device can interrogate the status of the network. These applications will then be in a position to decide whether the service is sufficient for uninterrupted transmission of information

Available bandwidth definition is adopted as

"The available bandwidth is the maximum throughput that a path can provide to a data flow without causing significant degradation in service quality of other ongoing flows or to itself"

Maximum available capacity bandwidth in a network, like the path capacity, will be affected by the path link with the lowest available bandwidth in the network path, also referred to as the 'tight-link'.

When more than one path links within a network utilize one medium, the resultant usable resources of the medium will be utilized by the two links.

2.2 State of practice

In capacity measurements involving IP networks, software network simulators are used. Network simulators are softwares that simulate these networked environments. In a scenario like this, the variables are known and are therefore suitable to use to test and verify the available bandwidth capacity measurement methodologies [*Manish Jain et al*]. Network designs that cannot be available or created by researchers can be easily simulated in these softwares. Models of these capacity measurement methods can be used to probe the simulated network path to evaluate the results to form a path bandwidth results. Verification of these results is simple, since the available link capacities and available network bandwidth are input characteristics to the simulation software. The cross-traffic in the network is generated and injected into the network by a cross-traffic generator device or by the traffic traces.

A simulation is a network model that tries to mimic the real world of networks. In this scenario, the simulation represents a network topology with all the software components and hardware

devices. Creating a network model of any topology requires simplification of the parameters to be made. This may result in variations between obtained results from the simulated networks and the theoretical results that are documented and achievable from the real networks.
Additionally, it may be hard to make realistic network simulations. As stated by Andreas Johnsson, it is a fact in the research community that it is hard to configure realistic cross-traffic mix network [Andreas Johnsson, 2005]

2.3 Technological advances in Network simulation

In the earlier years leading to the year 2004,many bandwidth capacity measurement tools developed were aimed at estimating the available bottle-neck capacities of bandwidth in paths. Jacobson presented a paper 1988 describing how congestion can be avoided in TCP [Jacobson]. This paper describes how to determine the min spacing effect between packet pair in the network path by the bottle-neck link. Bellovin in 1992 published his paper on the performance of a computer network model. He focuses on how the variable packet size probe can be used to determine the device packets capacity handling. This achieved by studying the relation between the size of the packet and transition cost. The transition cost comprises of a combination of packet forwarding delay and packet processing time. While the processing part is kept at a constant, the forwarding part is linearly dependent on the size of the packet. The rate of packet forwarding of the device is dictated by the interface of the link layer technology being used by the device to propagate or transmit the packets. Carter and Crovella presented a paper in 1996 on a path capacity measurement tool called ‘bprobe’. The bprobe tool utilizes bottle-neck spacing effect of the packet pair to get the bandwidth capacity estimate of the network path.

Crovella and Carter later offered a tool they called ‘cprobe’, that was meant for at estimating the congestion of a path in a network. Cprobe utilizes the probe-gap-model methodology to measure the path congestion on the bottleneck link. The packet-gap-method, ‘PGM’ is also used by the cprobe model. To obtain the maximum available capacity bandwidth in a network path, Crovella and Carter took the path capacity and subtracted the congestion from it. Another tool referred as Pathchar was presented Jacobson in the year 1997 [*Jacobson et al*] to measure hop by hop capacities in the link. This tool would measure successively the capacity of links in a network path by use of packet probes the network link by inferring different packet sizes. This is from the relationship between the packet sizes and the transmission time and the capacity of the link inferred. Several path capacity measurement tools followed that utilizes the bottleneck-spacing-effec t([Dovroliset al], [Kapoor et al], [Liet al],) or variable-packet-size probing techniques [Jacobson et al], which was the basis for inferring link or the path capacities. TOPP also known as Trains of Packet Pair was introduced in the year 2000. The Trains-of-Packet-Pair tool probes the network with the pairs of train packets at an ascending rate. The resultant available bandwidth of the narrow link is the delay rate of the pairs within the start of the pairs in the train. To determine the turning point of the delays of the increasing probe traffic rate, probe rate model ‘PRM’ is achieved.

The PGM as well as the PRM concepts and formed the main basis for several other bandwidth capacity measurement tools. The first path capacity estimation model that was based on a packet-pair-probing was*CapProbe* introduced *by* Kapoor et al in the year 2004. CapProbe was suitable for standardized paths. In the year 2004, another tool known s Probe-Gap was introduced for estimation and measuring of the available bandwidth capacity in the area of broad-band networks. Examples of Broad-band access networks are cable-modems and the 802.11 based wireless networks. The aims of Probe-Gap model determination of the utilization of bottle-neck links by estimating the relationships between delayed probe-packets and the non delayed probe packets caused by the network cross-traffic with a bottle-neck link. The resultant available bandwidth capacity is obtained by taking a share of the narrow link on the non-utilized capacity.

WBest and DietTOPP were introduced in the year 2006 to be used to measure the available capacity bandwidth in network paths including wireless mediums and links. The DietTOPP utilizes the probe rate model technology Wbest is a packet gap method tool. In 2008 a new tool a probe rate model based known as SLOT was introduced. This tool utilizes the active probing method for measuring available bandwidth capacity in ad-hoc small scale wireless networks.

Several tools were developed aimed at measuring bottle-neck bandwidth in ad-hoc small scale wireless networks. Majority of the tools developed utilizes MAC layer level details in order to acquire the information of the link-state. This result is used to obtaining the capacities or the available bandwidth capacity estimates. These MAC-layer level tools are not the best to use for the transport-layer-level bandwidth capacity measurement in mixed network environment.

2.4. Critique of the literature

Section 2.3 shows there are many existing tools designed for wireless network bandwidth measurements. The existing tools, however, do not comply with the requirements of this research work, which is being suitable for small scale wireless networks, should be low intrusive, utilizing a short convergence times and applied on the sender device. Most of previously developed bandwidth capacity measurement tools were where meant for measuring paths on the internet. Available information is really limited on these tools performance under the mentioned conditions.

CHAPTER THREE

METHODOLOGY

Capacity measurements in small scale Local Area Networks are significant for error detection and diagnosis in the network to optimize performance. This also helps in the adaptability of user applications like streaming video.

3.1 Existing methodology/techniques/tools

3.1.1 Methodologies used to measure bandwidths in paths

The main objective in this research work is to come up with a bandwidth capacity measurement model implemented at the source device node at any instance before transmission is commenced. That means that the only active measurement methodologies are highlighted in this research work. These are the tools or technologies that are active in sending probe packets within the network to obtain the required information from the packets on the network. The existing capacity measurement tool/methods are found to be based on the few measurement methodologies. The main link bandwidth capacity measurement technologies will be discussed.

3.1.2 Link idle-time measurement

If the minimum packet probes experienced on a path is higher than the one way delay (OWD), then the medium channel was presumed to be busy sending the probe traffic. The link idle time estimation ProbeGap model was based on this concept. [Lakshminarayanan, 2009]. The sending device transmits a stream of 'poisson spaced probe packets'. An average of 200 probe packets is streamed with an average size of about 20 byte with a time interval of about 50 seconds. An algorithm that performs a search for the turning point on the measured one way delays, OWDs. Those probe packets indicating delays below the expected turning points are identified as having on the idle link. Longer one way delay is a conclusion that the link has been busy. When there is no turning point identified, then the link is presumed to be 100 percent busy with no available bandwidth. The bandwidth capacity available is obtained by multiplying idle time faction by the link of the bandwidth capacity. To estimate the narrow link bandwidth should be known in advance so as use link idle-time measurement method for available bandwidth estimation.

3.1.3 Probe rate model

This model is also referred to as the ‘packet-rate-method’ or ‘packet-rate-model’. Probe rate model based tools are based on an observation that the average rate of inward probe traffic signals arriving at the end node will be equal to an average rate of the outward probes measured at the origin when the rate of probes is less than the overall available path bandwidth. If the probe rate is higher than the network path bandwidth available, it will lead to an increase of dispersion packets and delays of packets probes. The network path bandwidth available is obtained by establishing the point in the network where delays in packet probes or the dispersion start to show these different characteristics.

3.1.4 Probe gap model (PGM)

The probe gap model is also known as ‘probe rate method’, and is mainly used in measuring the narrow link cross-traffic in the network path. If probes in the path are transmitted at the rate of the bandwidth capacity of the path, then these packets will be queued back to back at the end of the narrow link. The cross-traffic packets that collide with the probed packets will result to increase of the dispersions between the probed packets. When the outward dispersion is double the inward dispersion, the rate of cross-traffic is equals to the rate of probe and subsequently equals to the capacity of the narrow-link. Therefore, the inferred amount of cross-traffic is obtained by adding the packets the probed in the network. An illustration of probe gap PGM concept is shown in Figure 3.1.

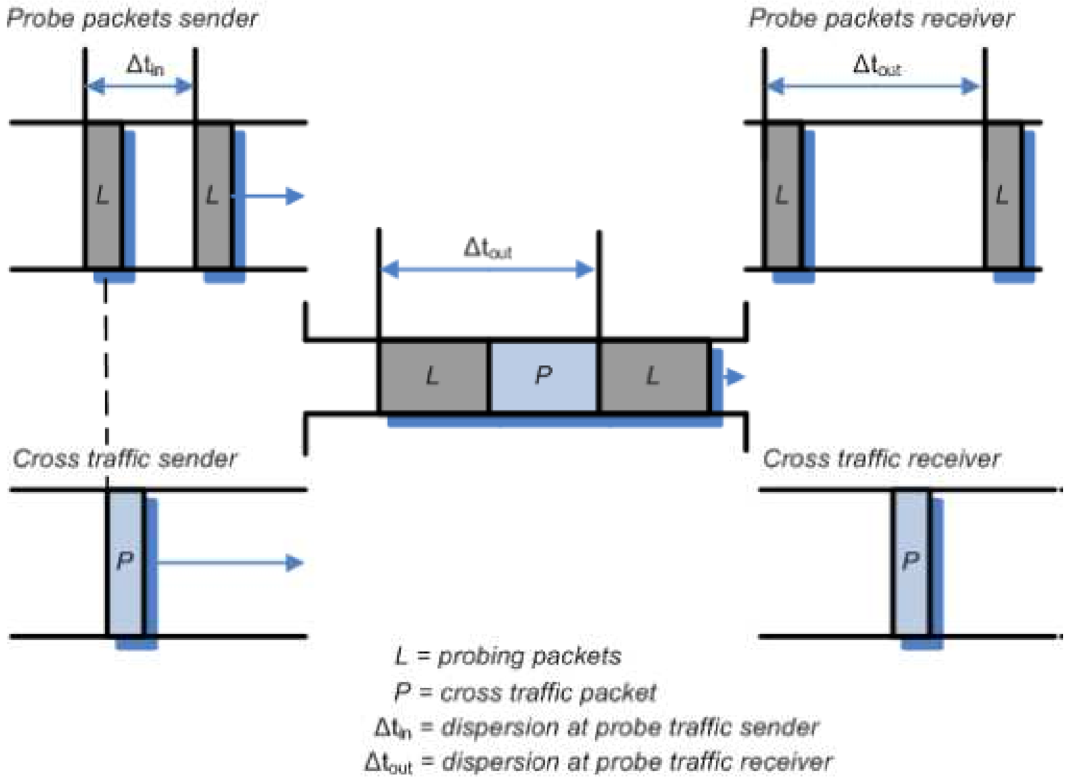


Figure3.1: The "probe gap model" illustration.

Figure 3.1shown three links that are consecutive. Probe packets are transmitted at the 'narrow-link' rate. When the cross-traffic is not introduced in the network X should not affect the 'narrow link' upwards it will handle the packets at the same rate. However, X increases as a result of the cross-traffic in the network which results more in delays between the two consecutive probe packets. In this analysis of dispersions measured at the receiving device, the cross-traffic amount can be predicted. Consequently, the rate of cross-traffic Rc is easily gotten by subtracting it from the capacity of the narrow link $C_{l\,,\,n}$ to get the available bandwidth in the narrow link.

For the probe gap model to be applicable an assumption is made that the narrow-link is the same as the tight-link, which is also referred to as the 'super-bottleneck-link'[Li, M, 2006]. In addition, the capacity of the narrow-link will be established or known in advance. It means then that it will be important to conduct a capacity measurement before the probe-gap-model based estimation of available bandwidth. The capacity measurements that are based on this model are not interactive; therefore this model is expected to achieve a fast convergence, less intrusive in comparison to the probe rate model. Probe gap model needs the network path probing to be at the rate of the narrow-link capacity, while the scan intrusiveness is kept low by use of short intervals of the probe packets. The disadvantage of this model is that it leads to erred measured results especially if the narrow-link is different from the tight-link. Wbest [Li, M, 2006] is also based on the probe gap model. This tool performs a simple path estimation of the capacity before the real estimation of available bandwidth. After the simple performance of capacity estimation, WBest then sends a stream of packet probes using the rate of the earlier measured path capacity to estimates the amount of cross-traffic from the measured dispersions at the receiving end device. Further, this tool is receiver-based and makes assumptions that the wireless-link is the ‘super-bottle-neck-link’ as well as the last-hop in the network path.

3.2.2. Measuring of capacity

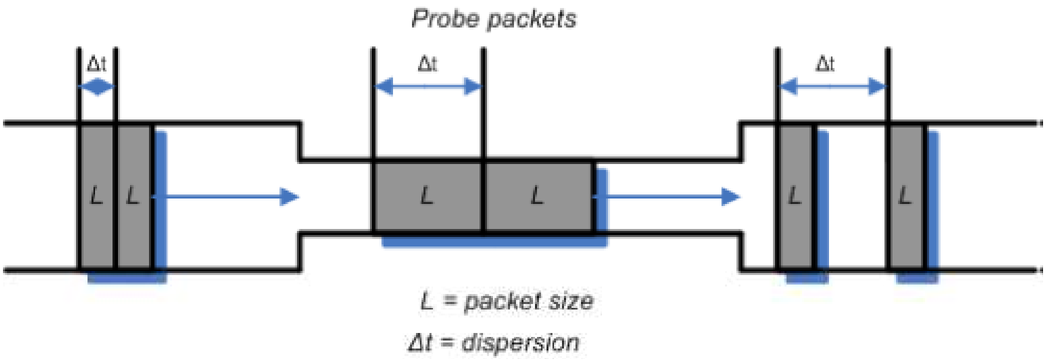
Variable packet-size probing

The time taken for the sent packet bits to propagate the link path in a network depends on the size of the packet as well as the operating physical layer on the link. This is an indication that the time of transmission as well as the packet sizes relate to one another on the physical layer link capacity.

Packet-pair or packet-train probing

Jacobson describes the bottle-neck spacing effect which is the basis for the packet-pair or the packet-train methodology path capacity measurement probing. This illustration is shown in Figure 3.2. The middle link in the illustration has the lowest capacity. This is referred to as narrow-link. The dispersion Δt is small as it initial speed of the link is higher. The packets in the middle link are transmitted at a relatively lower rate. This causes an increase in Δt. The probe packets are sent at a higher rate last link although this has no affect on Δt this illustration indicates that that narrow link in the path determines the minimum space between packets which is obtained after propagating the path. Now that the path capacity is defined by the narrow link, the minimum

Since path capacity is by definition determined by the narrow link, the obtained minimum dispersion between packets is an indication of the “path capacity”.



Using packet-pair or the train-train has an advantage in that it is believed that a single measurement of the dispersion taken correctly could be sufficient for obtaining the capacity of the path. However, attributable to cross-traffic and alternative processes which may interact the dispersion between the probe packets, inquiry with many packet pairs or packet trains are going to be important in practice to get a bottleneck link price for the dispersion. An assumption is that the cross-traffic has pre defined properties, and that if more probes are carried out, one of the pair will be lucky and has not been affected by cross-traffic. One of the disadvantages of packet pair probing is in that the 'post-narrow link' issues as outlined by Dovrolis et al, 2004. If a faster link is existing in the link following the narrow-link, the cross-traffic in the 'post-narrow-link' will cause the dispersions to decrease. When the initial pair packet is blocked by cross-traffic, these phenomena will be realized. This scenario will lead to the subsequent packets getting the chance to match with the earlier packets. Therefore, the dispersion can decrease and also the capabilities are going to be overestimated.
Due to this scenario, the minimum measured result of dispersion cannot be used. An illustration of 'post-narrow link problem' is shown in figure 3.3 below.

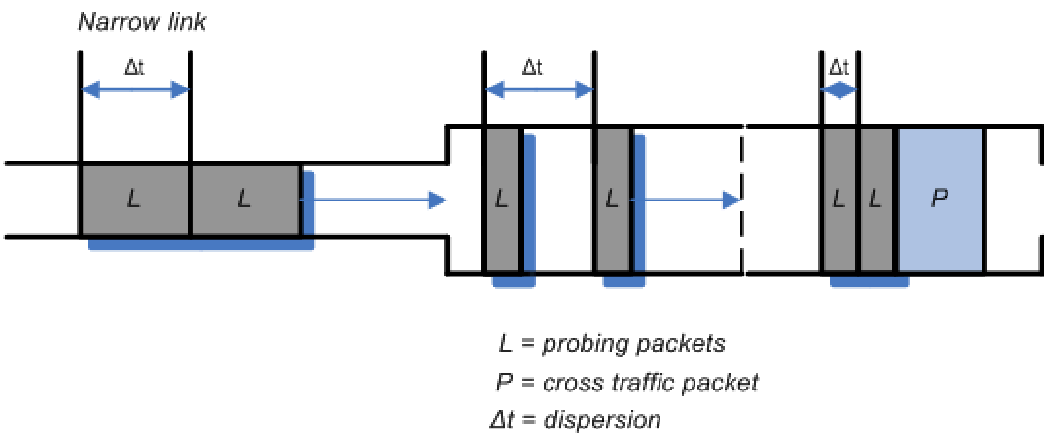


Figure3.3: post-narrow link problem'

Various different issues were also looked at in the literature relating to packet-pair probing as described by paxson et al.[Paxson, 1997]. A major issues that arose from non-first-in-first-out is the queuing in network nodes. Other related occurrences could be brought about by 'multi-channel' bottle-neck links [Paxson, 1997] for example two-line- integrated services digital network. When packet-pairs are transmitted using variant channels, the dispersion measured does not represent the combined of the channels. Other issues listed were limitations as a result of resolution of the clock and different bottle-neck capacity bandwidth. Packet-pair probing is the root for bandwidth capacity measurement in various tools that exist like *CapProbe* [Kapoor, 2004],*Adhoc* probe and *Wbest* [Li et al].these tools carry out bandwidth capacity measurements in wireless link path.

CapProbe is among the initial tools used to take measurement of paths that include wireless links. Capprobe utilize packet-pair probe to either conduct a sender-based probing that forces a reply from the end device using ICMP acknowledgement packets or based on the capacity measurements. If either packet of a try is delayed as a result of cross-traffic, then add the of the measured delays of each packets can increase. By "minimum delay sum" filtering, the tool aims to filter dispersion measurements that were distorted as a result of cross-traffic. Additionally a convergence take a look at is enforced that ought to improve the accuracy of the results.

AdHoc is a bandwidth capacity measurement tool that is based on the receiver and it utilizes the probing technique of is a receiver-based tool that utilizes the CapProbe's probing technique. The receiver-based version of the CapProbe searching methodology is employed as a result of theround-trip mode of CapProbe is insufficient in ad-hoc wireless networks. AdHoc Probe doesn't implement CapProbe's "convergence test". In similarity to CapProbe it uses "minimum delay sum" filtering to filtrate dispersion measurements that were distorted by cross-traffic. WBest is a receiver-based available bandwidth estimation tool based on the PGM. It aims to measure the available bandwidth in network paths with a wireless linked device as the last node. For this reason a packet train of at least six probe packets are propagated to the receiving node. The resultant capacity of the path of the narrow wireless link is estimated by use of the median method of dispersion measured on the last node in the network

3.3 The proposed methodology

Comparison of Simulation methodologies

OPNET Modeler

Optimized Network Engineering tool (OPNET) that is both an open source as well as commercial. The tool is popular in windows platforms but can also run on Linux systems. The OPNET network simulator is based on the discrete event approach that tracks packet transmission from origin to destination. (Bleslau et al,. 2000). The tool is under more active development. OPNET modeler uses a project and scenario approach to model networks. User interaction with the simulator model encompasses an interface with a visual, representation of the traffic patterns within the network. The model parameters can be changed and the impact of the changes observed.

GNS3 –

This is a synonym for Graphical Network Simulator that is used to emulate complex networks. GNS3 is open source software that graphically simulates complex networks and at the same time being close to the way real networks work and perform, without using dedicated network hardware such as switches and routers. GNS3 emulates networks by providing a virtual environment of networks in a computer will full functions of real networks components. The configured virtual network typically is configured on host computer hardware. This virtual network can be used on several different operating systems, such as Windows, Linux, and Mac OS X.

NS2

Computer network simulators for ns-2 is comprised of C++ code. They are used in modeling the characteristics of the simulated devices and oTcl scripts that takes control of the network simulation and give direction of more features in a network the network topology. This design choice was originally made to avoid unnecessary recompilations if changes are made to the simulation set-up

NS3

Network simulator -3 utilizes C++ architecture for the layout of the simulation models. Ideally, network simulator -3 does not use oTcl scripts to control the simulation, thus abandoning the problems which were introduced by the combination of C++ and oTcl in ns-2. Instead, network simulations inns-3 can be implemented in pure C++, while parts of the simulation optionally can be realized using Python as well. Moreover, ns-3 integrates architectural concepts and code from GTNetS

OMNET++

OMNeT++ is not ideally designed as a network simulator but is meant to be a general purpose discrete event based simulation framework. Although it is typically used in the field of computer network as a simulator, because of its INET module that provides a wide-ranging set of Internet protocol (IP) models. There are other packages in the model like as the OMNeT++ Mobility Framework for mobile and ad-hoc networks and Castalia used wireless sensor networks [*H. N. Pham et al*].

3.3.1 Comparison of different network simulation tools

Table 3.1: Comparison of network simulation tools

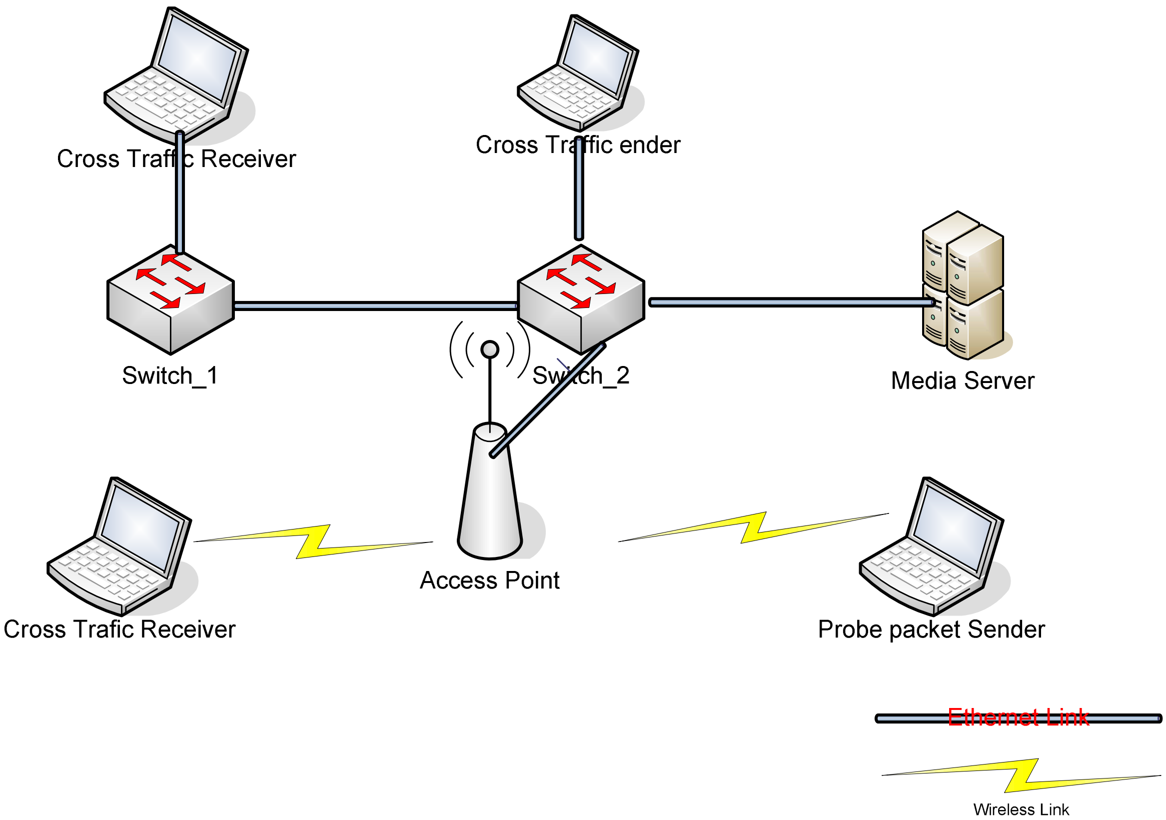
	Tools	**OMNET++**	OPNET	**NS3/NS3**	**GNS3**
No	**Features**				
1	**Graphical support**	Good visualization	Excellent graphical support	Limited	Good graphical support
2	**Model type**	Simulator	Simulator	Simulator	Emulator
3	**License**	Free academic and educational use	-Free academic edition for limited use	Open source	Open source
	Scalability	Excellent	Medium	Limited	Large
	Documentation & user support	Good	Excellent	Excellent	Good
	Interface	C++	C++ or C	C++	-

3.4 Characteristics of the methodology to be used

Simulation is an important modern technology of measurement acquisition. It can be applied to different disciplines of science, engineering, or other application fields for different purposes. Computer assisted simulation can prototype hypothetical and real-life objects or activities on a computer so that it can be studied to see how the system functions. Different variables can be used to predict the behavior of the system. Computer simulation can be used to assist the modeling and analysis in many natural systems. Common areas of application include physics, chemistry, biology, and human-involved systems in economics, finance or even social science. Other important applications are in the engineering such as civil engineering, structural engineering, mechanical engineering, and computer engineering. Application of simulation technology into networking area like network traffic simulation, however, is relatively new.

4.0 CHAPTER FOUR

4.0.1 Implementation Model



In the implementation model layout the probe-traffic-sender and the cross-traffic receiver nodes are inter-connected to each other using wireless links. The server is connected through an Ethernet link to switch_2 is also connected to the cross-traffic sender. Switch_1 is connected to switch_2 through an Ethernet link. The cross-traffic receiver is connected to Switch_1 by use of an Ethernet link. The probe traffic sender will infer the network by sending probe packets to the probe traffic receiver. This will be in two scenarios. In scenario 1 cross-traffic is not present in the network. In scenario 2 is whereby cross-traffic is present in the network. Cross-traffic is introduced in the network by the cross-traffic sender/generator and directed to the cross-traffic receiver. The amount of cross-traffic in the network is controlled by the media server. To measure the capacity the receiver is expected to responds with some reply packet.

4.1.1 Small scale wireless IP network link-layer technologies.

An analysis of the IP layer capacity of Ethernet and that of 802.11-b series is done. Several technologies are applicable in connecting the various devices in a small IP network. It is established that in current in today's small scale network, that a few link-layer technologies are in use and especially the twisted pair Ethernet used over the untwisted pair cables and the 802.11 wireless-links in small networks. This section gives a brief analysis on the effects of the MAC address layer as well as the physical layers on the input of data in the upper layer in the stack.

4.1.1. 10 BASE-Tandy100BASE TX Ethernet

The Ethernet has been designed to be used as a shared medium of data transmission with every node device in the network connected to other devices by a single coaxial cable (10-BASE-5). these coaxial cables were later replaced by introduction of the twisted pair cables and a carrier sense multiple accesses with collision detection scheme(CSMA/CD) has been added into the MAC to due to the shared nature of the network. The shared medium scheme and collision detection schemes would make an analysis of the higher layer throughput rather complicated. The Ethernet technologies used in today's networks utilize a fully switched technology by making use of duplex links thereby disregarding the Ethernet as a shared link anymore. This is the stand taken in this study, Ethernet is not considered as a shared link. Figure 4.1 below shows an illustration of an overhead. The overhead is introduced by the propagation of data using user data grams over IP and Ethernet. In addition to the payload (including IP and UDP headers) the Ethernet frame contains MAC layer header of 14 bytes and the payload that incorporates the UDP headers, the IP headers, a preamble of seven byte and a delimiter start frame of one byte. It also contains a 4 byte check sequence frame. After each frame, the Ethernet needs a 96 bit inter-frame gap .This makes a total of 34 bytes for the Ethernet MAC layer and a total of 272 bits in the IP layer frame

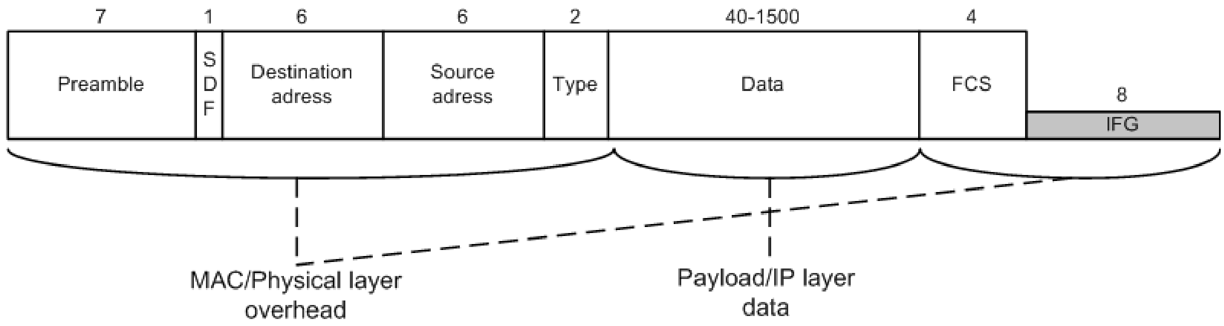


Figure4.1 : Ethernet overhead

4.1.2 Ethernet layer capacity analysis

Ethernet frame consist of a maximum payload of 1500 bytes, which is the maximum throughput that can be achieved. This throughput is calculated as follows:

$$C_1 = \frac{MACpayload}{MACpayload+overhead} x R_{ph}$$

Where Cl is the capacity of the link and Rph is the Ethernet link physical data rate. The MAC and physical overhead as a result of Ethernet has a total of 272 bits in each Ethernet frame therefore, the expected IP layer capacity of the 10.BASE-T and 100.BASE-T(X) Ethernet links are 9.78 Mbps and 97.88 Mbps respectively.

4.1.3 802.11b

802.11-b is a communication standard for wireless local area network(WLAN)and it works in a 2.4 GHz frequency band with a maximum data rate of 11 Megabits per seconds. When the conditions in the channels are changed, the data rates are lowered to attain data rates of 1,2 and 5.5 Mbps. These data rates can be used for improving the noise to signal ratio. This means the capacity of the channel may change over time. These mechanisms of adaptation are not specific in the 802.11standards.(Choiet al)

To calculate the overhead of physical and MAC and layer for802.11b is complicated than that of Ethernet. Because all the devices in the small scale network work on a single wireless channel, the wireless medium is considered as a shared media for transmission. Therefore the distributed and coordination function that is mostly used to control access to the media by use of the802.11

channels, it adds Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) method. This is as shown in Figure 4.2

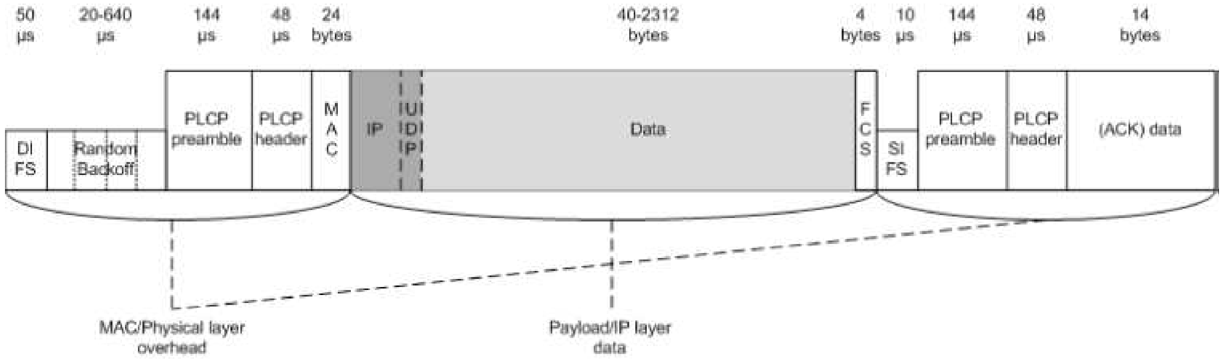


Figure4.2 : An illustration of Overhead of 802.11b

The payload on IP layer on 802.11-b frame consists of a MAC header, which is 24bytes long for communication between a station and an access point. A frame checks sequence field consisting of a 4 bytes long stream is present in the frame.

The frame also has a preamble of the physical layer convergence protocol comprising of 144 bits and a header that comprise of 48 bits. As a variation to the Ethernet communication, the frames comprising of 802.11-b are acknowledged by way of sending an acknowledgement frame. The acknowledgement frame follows a short inter-frame space. A preamble is also contained in this acknowledgement. This acknowledgement frame has a data 14 bytes.

This figure, 4.2 shows an overall overhead included by the physical and MAC layers of 802.11-b is bigger in overall in comparison to the Ethernet overhead. To limit the bandwidth utilization transmissions of 802.11 frames, the carrier sense multiple access/collision avoidance scheme is included in the media access control. In a carrier sense multiple access/collision avoidance scheme, a device will listen to the media for a period of DCF inter-frame space. When the medium is not transmitting in this period, the listening device will start transmission immediately once of the period comes to an end. If the channel was busy, the device will postpone the transmission. There is a possibility for more or several devices to start transmission at the same time especially after a busy period. After an idle period plus more back-off sessions, the devices can start the transmissions. In order to lower possibility of several devices to start sending data at the same time, back off period is added.

802.11b single hop throughput analysis

Single hop means that there exists a single wireless-link connecting the sending device to the destination device. The maximum throughput for the single hop link, the assumption is that the data packets will be transmitted in a continuous burst. This means therefore that the preceding packets will be buffered in readiness for transmission even before the previous packets have completed the transmission. Now that the next group of packets will be ready before of the previous packet is completed, a contention will arise between the subsequent transmissions of packets. Because there will be no other devices transmitting over the same channel, collisions will not occur making the back-off average time between successive packets to be half of the size of the contention window. The default contention window size in an 802.11-b wirelessis31 slots of time with a single time slot having a length of 20μs. To make the calculation we make an assumption of the use of long preamble header that consists of control information and the header that is sent at the rate of 1 mbps on the assumption that the link is operating at the maximum rate of data transmission of 11 mbps.

802.11-b two-hop analysis

The two-hop is a network path which has double wireless linking the receiving device to the sending device. Data packets are propagated from the sender to the receiver device and travel along the medium two times, during sending and receiving.

IP fragmentation

An IP fragmentation, as illustrated in figure 4.3gives the solution in an instant when the data packets propagated have a larger maximum transfer unit that cannot be supported by the medium’s link layer technology. The IP analysis is used in devices like network routers used for interconnection of the different link layer technologies. The maximum transfer unit of the router at one side can be different from the maximum transfer unit on the other side of the same device. The IP packet is fragmented into smaller IP packets if it is bigger on the receiving side than the maximum transfer unit of the outward side to reduce the payload. Figure4.3 shows this illustration. Additionally the initial IP header is divided into small fragments. A special bit is about within the flag field of the IP header to point that the fragments are separated components of a bigger IP packet.

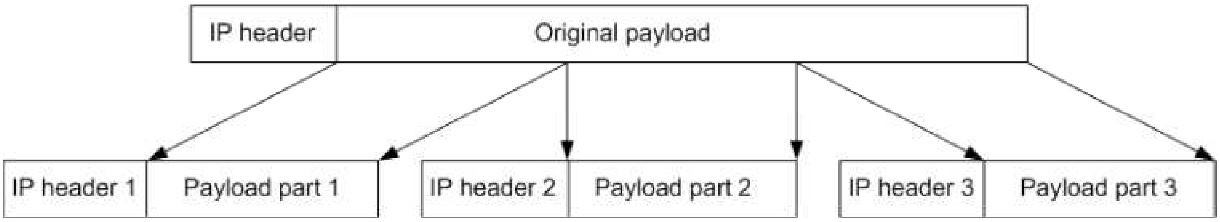


Figure4.3: Illustration of IP fragmentation

If any transitional nodes in the data path do not have the full support for fragmentation of IP, then packets bigger in size that the MTU-sized packets will not be forwarded but will otherwise be dropped and possibly error message response sent to the source node.

CHAPTER FIVE

Introduction

To implement the simulation of the networks we decide to use the most commonly available model and settings of the wireless. We make use of the standard Ethernet switch ethernet4-switch-adv and the standard access point wlan-ethernet-router-adv nodes. The cross-traffic sending device as well as the cross-traffic receiver to be used will be the standard workstation labeled as ‘ethernet-wkstn-adv’ and ‘wlan-wkstn-adv’. These modules are present on the wireless model in OPNET. The cross-traffic sender device to be used is as model using the available standard IP traffic configuration labeled as ‘ip-traffic-flow’ in the wireless model. All these devices in the simulated wireless network are interlinked by the standard available 10M Ethernet, 100-M Ethernet and 802.11-b wireless local area network links. The example of the simulation network is as given in Figure 5.1 below as is implemented in OPNET. The configuration object for the ‘IP-traffic-flow’ has been used to indicate the cross-traffic signal in the network.

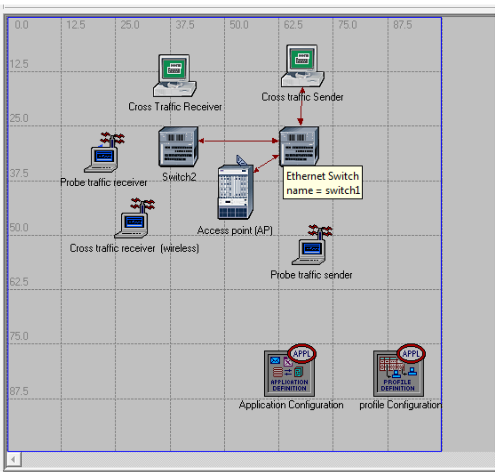


Figure 5.1: simulation of wireless in OPNET.

5.1. OPNET models

To implement the ‘probe-packet-sender’ and ‘probe-traffic-receiver’ the already available ‘Ethernet-wkstn-adv’ and ‘WLAN-wkstn-adv’ model also available on the OPNET wireless model are used. A single module is connected to the (User Datagram Protocol) modules captioned as probe in figure 5.2. UDP is a connectionless oriented protocol. The processing model of the ‘probe-traffic-sender’ that is specified for generation of the packets to propagate to the UDP node. The departure times as well as the sizes of the probe packets will be dictated through the node characteristics. We additionally enforced a method within which the probe packets sent by probe-traffic-sender will be received by probe-traffic receiver. Additionally the packets size of these reply will are sent using the attributes of the node. User datagram packets are used rather than the ICMP since ICMP protocols are not fully defined in this module.

The expectation is that very small UDP packets can perform just like ICMP destination unreachable packets and achieve similar delays.

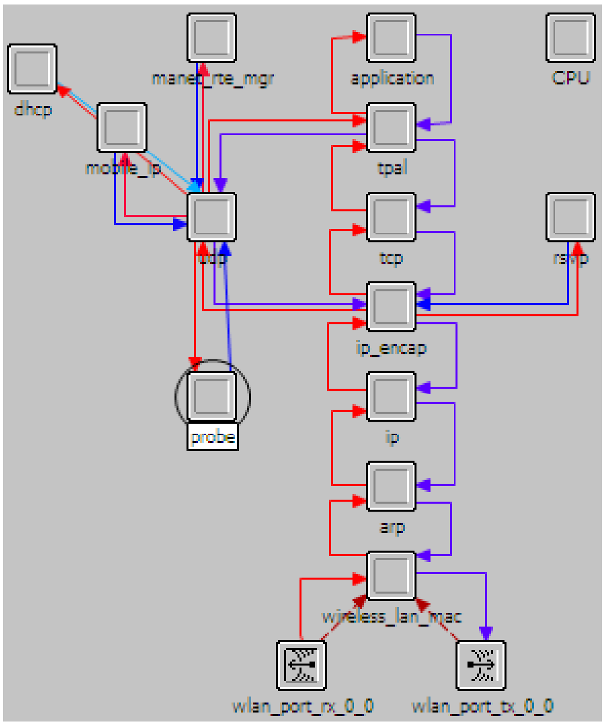


Figure 5.2:a node implementation in OPNET modeler

5.2. Simulated networks

5.2.1. Single-wireless-hop networks

A single wireless hop network comprises of 802.11-b interconnections and local area network Ethernet interconnections, as shown in figure 5.3. Each of the probe-traffic receiver and therefore the receiver are connected to the access point using 802.11-b wireless connections. The probe traffic sender and therefore the cross-traffic sender are connected to the AP or the wireless router using local area network links. The 802.11-b cable interconnecting the access point to the probe-traffic-receiver to comprise the ‘narrow-link’ within the path between the probe traffic sender and therefore the probe-traffic-receiver.

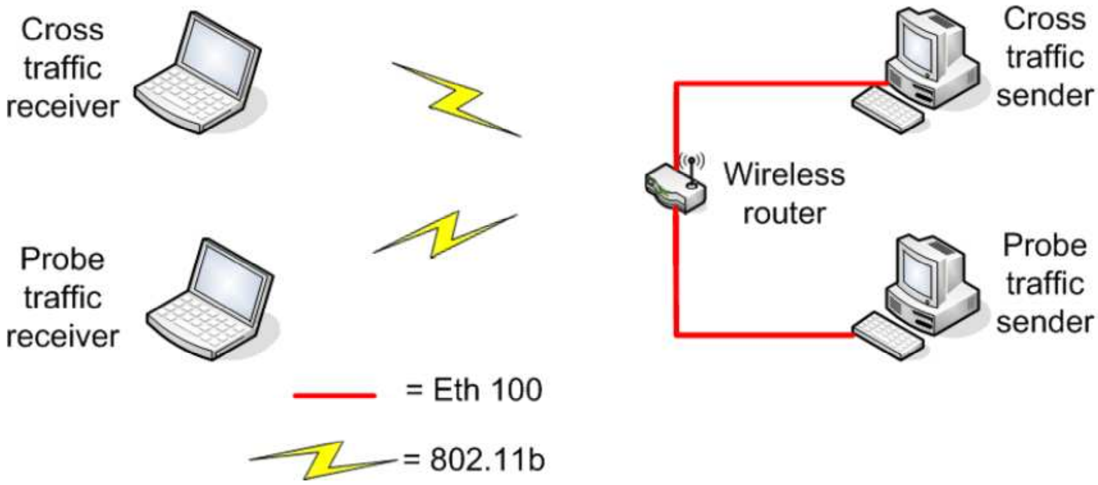


Figure 5.3: Simulated network with 802.11

Since the wireless link is shared by the 'probe-traffic-receiver' and the 'cross-traffic-receiver', the capacity of the media is shared as well.

5.2.2. Double-wireless networks

For the implementation of a 'double-wireless-network', two wireless interconnections are utilized within the network paths to connect the probe-traffic-sender and the probe-traffic-receiver as illustrated in figure5.4. Cross traffic sender is linked using the 100-M Ethernet cable to the wireless router operating as the access point.

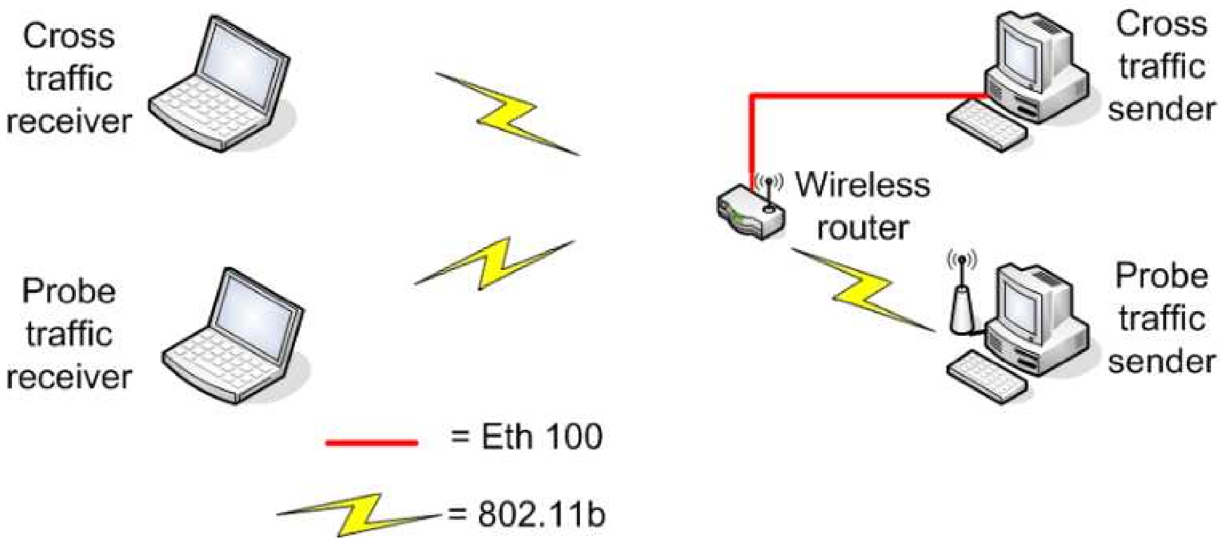


Figure 5.4: Simulated network with 802.11

5.3. Description of the probing concept

To establish the end-to-end maximum capacity bandwidth by use of the passive measurements is to carry out probing of the network path. To achieve this, we inject sets of probe-packets signals that contain some estimated separations. These dispersions are relatively proportional to the probing rate and the measurements are in bits-per-second. A higher probe-rate is equivalent to the small dispersion. While these probe-packets propagate in the network, the earlier defined spreading may result in different measurements. This is as a result of completion of the traffic in the network referred to as the bottle-neck-spacing-effect [*Chimento P et al*].

The most basic probing scheme is to divide the probe packets in pairs; each pair has a pre-defined dispersion that corresponds to the probe rate [*Chimento P et al*]. Each pair is sent through the network to the receiver where the packets are time stamped. The arrival-timestamps are used when the actual bandwidth estimate is calculated.

One of the best approached to estimate the available capacity bandwidth is to carry out some measurements that are based on the probe-gap-model. This approach is applicable as a fast convergence and is low intrusive. An alternative to this is the use if the ‘link-idle-time measurement’ method. For these two approaches, there is need to have prior knowledge about the bandwidth capacity of the path. Li [Li et al] obtained some good results by using the WBest modeling tool by use of the probe gap model with the measurement taken at the last node device on a wireless path. For this research, narrow link is not assumed to be at the last hop node on the network. For this research work the intention is to model the measurement to be taken from the sending device. This will utilize the roundtrip measurement of packets probed into the network. This research work idea of probing the path capacity bandwidth is more the same as that of CapProbe’s probing scheme. *CapProbe*d evelopers had proposed to use ICMP probe packets if installation on the destination node is not possible. With the use of ICMP packets it is possible to measure RTTs.

If installation on each sender and receiver is feasible, then the utilization of UDP inquiring packets is usually recommended. The utilization of UDP inquiring packets is most popular as a result of the information measure essential applications area unit typically supported UDP flows. In distinction to CapProbe, we have a tendency to propose a sender primarily based technique supported UDP inquiring packets. To live RTTs it's necessary that the receiver quickly responds with some reply packet. So we propose ending UDP inquiring packets to a (UDP) port variety that's unlikely to be used. In distinction to ICMP echo packets, the “ICMP port unreachable” messages area unit typically a lot of smaller in size than the first UDP packet. as a result of some ICMP implementations seem to use somewhat larger ICMP port destination unreached packets than per (larger ICMP error messages area unit allowed per RFC1112 we've used a packet size of ninety two computer memory unit (20 computer memory unit scientific discipline header, eight computer memory unit UDP header and sixty four computer memory unit payload) using simulations.

This definition indicates that capability is that most accomplishable turnout victimization most sized packets. so we advise inquiring the trail of packets with a size up to the path's most unit of transmission If a sender is unaware of the trail MTU, then it should begin the measure with the MTU for the link through that it's connected to. The path most MTU will usually be speedily determined victimization path MTU [Mogul et al, Deerings et al]

5.4. **Path with a single wireless link (802.11b)**

A network diagram of a 'single wireless link' was shown in section 5.2.1. We tend to begin the investigation of the inquisitor technique by causing packet pairssent to the probe traffic receiver by the probe-traffic-sender without cross-traffic with unit of 1500 computer in size including the IP header. The figure 5.5 indicates the results.

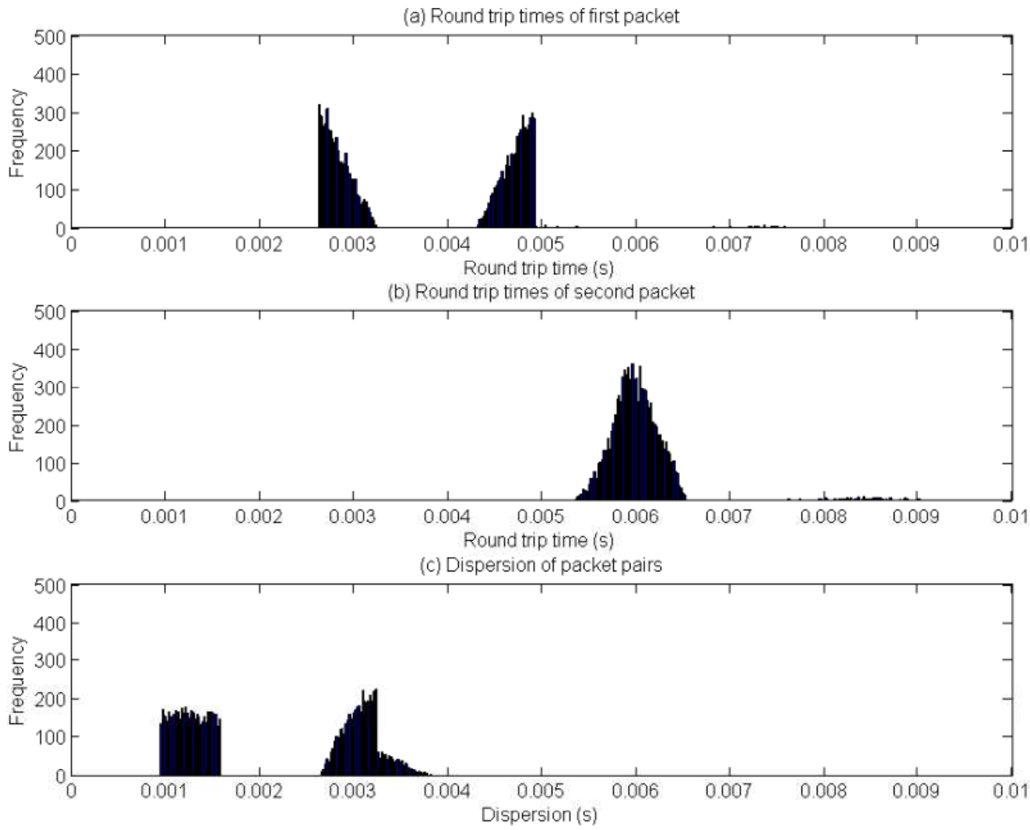


Figure5.5:RTTs and dispersion of packet pairs in a "single wireless"

The bar chart shows the primary packets RTTs measurements. There square measure two separate portions wherever there is RTTs concentration. These square measure bins after0.05 MS that have terribly low frequency. This is often caused by packets that require to be resent because of a collision and therefore expertise for much longer delays. in addition it's noticeable that the peaks don't seem to be sharp peaks however square measure cover multiple bins of the bar chart.(b)Shows the bar chart of the RTTs. There one region wherever the RTTs concentrate. The lower half shows a bar chart of the measurements. These measurements are divided into two different areas. The primary region indicates a regular distribution of the dispersions. The calculable capacities that square measure obtained victimization the 3 completely different filtering ways square measure shown in figure 5.6.

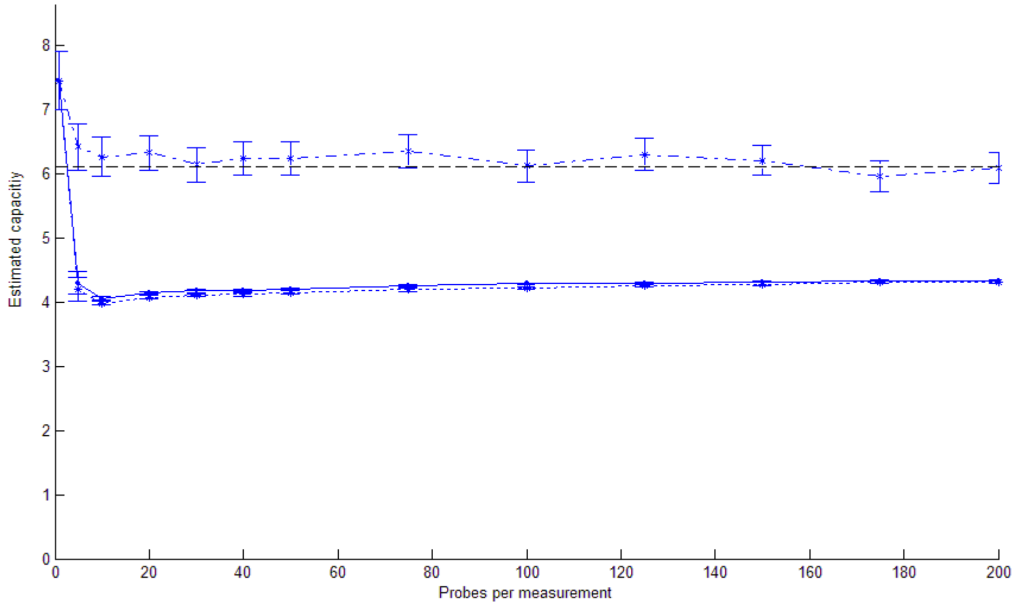


Figure 5.6 : Estimated path capacities vs ppm for the "single wireless" scenario

The figure 5.6 illustrates the capacities measured in treatments the three different strategies, median, mean, and easy lay for the RTTs measured. This indicates dotted black line indicates the already known capacities as shown in section 4.1.2 with the median approaching a capacity of about 6.3 Mbps. though the median technique shows slightly inconsistent with the next variance within the results; the mean values area unit nearer to the worth expected from the capability analysis in part 4.1.2.

Figure5.7 is an illustration of capacity estimation of the path resulting to 2 Mbps in presence of cross-traffic in the path. The cross-traffic packet size is lineally distributed ranging from 40 to 1500bytes while its inter-arrival duration of signals is exponentially distributed.

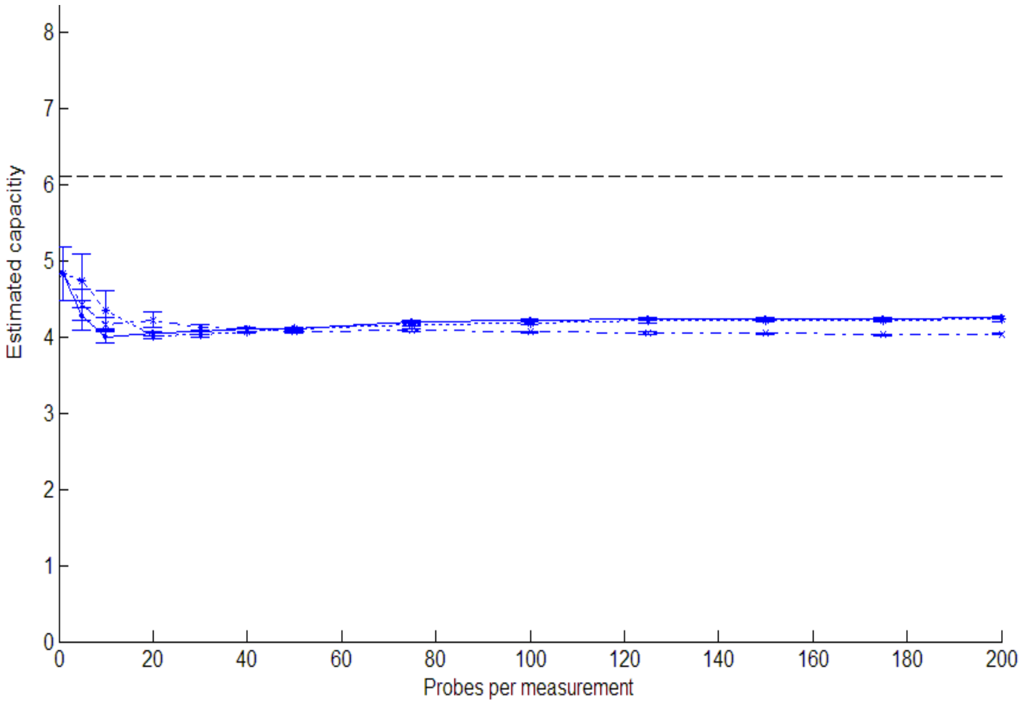


Figure 5.7illustrates the' single wireless' capacities of the network path using three related methods for filtering the measured RTTs. The probe method nearing path capacities of 4.2 Mbps. These are estimations are dependent on the amount cross-traffic in the link.

This path capacity is estimated when the ETE is measured at the 'probe-traffic-receiver' as shown in the figure below.

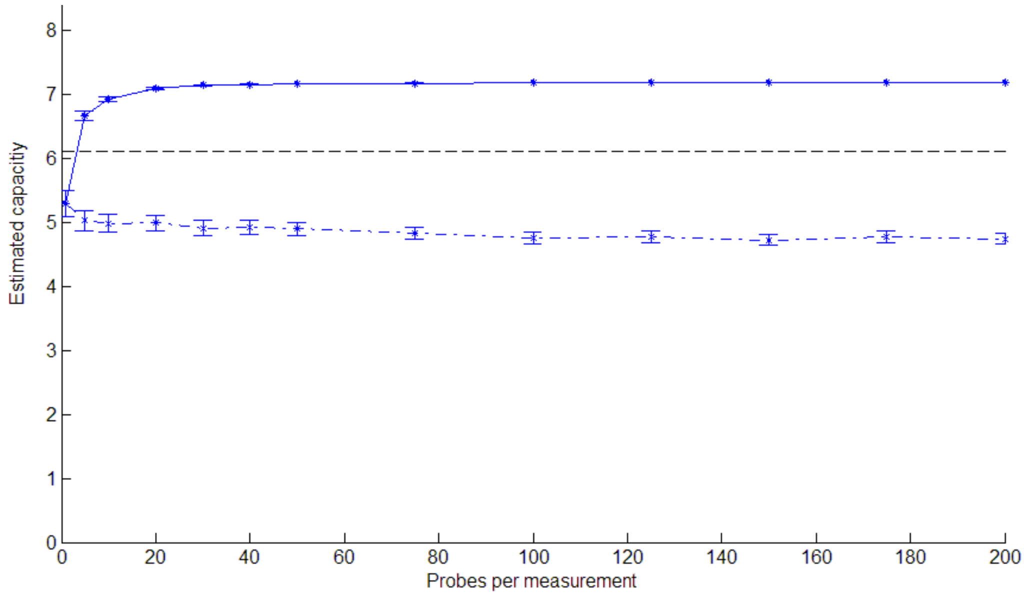


Figure 5.8: Single wireless path capacities estimation

The graphs show the measured path capacities for the ‘single wirelesses. The graph approachan capacity of cross to 7.1 Mbps. This median approachnearsthe capacity of cross to 5.0 Mbps.

CHAPTER SIX

6.1 Discussion of results

It is observed that the initial packets of the probing pairs have similar end to end. This is an indication that all the packets originate from the access point without having to experience the random back off period. In this illustration of the successive packets we make an observation that delays are distributed over multiple bins. This can be attributed to the random-back-off period which is inserted prior to propagation of the consecutive probe packets immediately preceding the initial probe-packet. Even though the random back-off times are evenly distributed, as seen in the diagram there is an observation that there are two different portions. Initial portion showing a uniformly decrease in frequency and the second portion showing frequencies increase linearly. This is as a result of the reply packet from the very first packets of probe. Once the first packet was received by the receiver, it will respond by sending packet the sender. When the access point tries to send the consecutive packet following the first one, it will be directly received by the receiver.

When the probe traffic receiver is in control of the network, the response probe packet will be sent first. Any consecutive packets will have to wait for completion of transmission of the reply packets. After this wait period, this second packet will now be sent in the network path. This results to the longer portions of ETEs.

6.2 Conclusions

From the analysis we arrive to a conclusion that the packet probing scheme and the technique adopted in this research work has not lead to the accurate or near optimal bandwidth capacity measurements in wireless networks with paths that have both wired devices and wireless links. When the network is free of cross traffic, the capacities of the networks are seen to be closer to actual values. It is very rare case in real networks to have networks without the cross traffic which is as a result of the noise in the network. When cross-traffic is added to simulate a scenario when the other devices in the network are already transmitting and/or receiving data packets in the network, the measured capacity underestimate the network capability. Therefore the dispersions of the packets measured between the packets at the probe traffic sender and the receiver will have propagated the network twice and thus it is half the round-trip.

However, resultant network bandwidth capacities in these measurements relatively close to the theoretical figures as analyzed in section 4.1.2. Use of average RTTs will lead to accurate time instead of using the minimum RTTs for dispersion estimation. In real situations, cross-traffic will always be present mostly. The cross-traffic will cause the average RTTs of the packets to increase. By use of average RTTs for capacity estimation of the capacity probed in a computer network in the presence of cross-traffic leads to incorrect results

In a situation where UDP traffic is sent in the single direction from sender to receiver, then there will be no reply packets that cause a longer dispersion between subsequent packets. For correct capacity estimation we need a value for the dispersion that is not increased due to reply packets.

6.3 - Recommendations

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If the capacity measurement in wireless is conducted with more spaces in the probed packets, and with more random back-off phases, the resulting round trip delay of the probes will probably be lower in comparison to less spaced probing. This scenario would be a benefit to the devices as it would most likely reduce the distribution of the packets caused by the cross traffic present in the network. This is recommended for more research.

Measuring available bandwidth from a single node is dependent on the technologies of the link layers present in the path thereby creating the need to employ more links measurement methods so as to attain a realistic status and nature of the network. The relationship between the different methods of capacity bandwidth measurement needs to be studied further. This will lead to the best combination of technologies for path capacity bandwidth measurement tools that employs the link capacities as well

6.4. Future research

There is needed to be come up with a methodology for determination of the precise of the measured results from a single measurement in wireless especially where there is cross-traffic. Cross-traffic is that traffic that intervenes between two consecutive packets of a significant flow.

There is need to carry out several capacity measurements of path capacity of a bandwidth on a network rather than a single measurement per probe and using these estimate to calculate the applicability of an application on these measurements. This will lead to longer periods of measurement being adopted. Further research on continuous measurement using the model deployed in this research work is needed.

There is need to incorporate bandwidth measurement research results into real applications by identifying the types of application that needs to use these results.

References

1.HAVi organization, "HAVi, the A/V digital network revolution", White paper, (1999)

2. Delphinanto, A., Koonen, A.M.J. and den Hartog, F.T.H., "Improving Quality of Experience by Adding Device Resource Reservation to Service Discovery Protocols", IEEE ICC'08 International Conference on Communications, Beijing, (May 2008)

3. Kapoor, R., Chen, L.J., Lao, L., Gerla, M. and Sanadidi, M.Y., "CapProbe: a simple and accurate capacity estimation technique", ACM SIGCOMM Computer Communication Review, (October 2004)

4. Kapoor, R., Chen, L.J., Lao, L., Gerla, M. and Sanadidi, M.Y., "CapProbe: a simple and accurate capacity estimation technique for wired and wireless environments", ACM SIGMETRICS Performance Evaluation Review, (June 2004)

5.Lakshminarayanan, K., Padmanabhan, V.N. and Padhye, J., "Bandwidth Estimation in Broadband Access Networks", ACM, Taormina, Sicily, Italy, (2004)

6. Li, M., "*Using Bandwidth Estimation to Optimize Buffer and Rate Selection for Streaming Multimedia over 802.11 Wireless Networks*", Ph. D. Thesis, (2006)

7. Jacobson, V., "*Congestion Avoidance and Control*", SIGCOMM'88 Symposium on Communication Architectures and Protocols, Stanford, CA, USA, (August 1988)

8. Bellovin, S.M., "*A Best-Case Network Performance Model*", (1992)

9. Dovrolis, C., Parameswaran, R. and Moore, D., "*What do Packet DispersionTechniques Measure?*", IEEE INFOCOM'01, Anchorage, AK, USA, (2004)

10. Paxson, V, "Measurements and Analysis of End-to-End Internet Dynamics", Technical Report, (1997)

11. Kapoor, R., Chen, L.J., Lao, L., Gerla, M. and Sanadidi, M.Y., "CapProbe: a simple and accurate capacity estimation technique", ACM SIGCOMM Computer Communication Review, (October 2004)

12. Kapoor, R., Chen, L.J., Lao, L., Gerla, M. and Sanadidi, M.Y., "CapProbe: a simple and accurate capacity estimation technique for wired and wireless environments", ACM SIGMETRICS Performance Evaluation Review, (June 2004)

13. Carter, R.L. and Crovella, M.E., "Dynamic Server Selection using Bandwidth Probingin Wide-Area Networks", Technical Report, (March 1996)

14. Bellovin, S.M., "A Best-Case Network Performance Model", (1992)

15. IEEE Std 802.11-1999, "Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications", (1999)

16. Choi, S., Del Prado, J. and Sherman, M., doc. IEEE 802.11-01/055: "802.11a and 802.11b Maximum Throughput for Simulation Model Conformance", (January 2001)