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# **A Quality of Service Architecture for WLAN-Wired Networks to Enhance Multimedia Support**

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As the candidate's supervisor, I have approved this dissertation for submission.

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## Declaration

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Name: Samuel Senkindu

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To my dear parents Samuel Sentongo and Domitilla Sentongo, and to my beloved wife Caroline Agonzibwa and lovely son Ssali Kigunddu.

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## Abstract

From the turn of the 21<sup>st</sup> century, multimedia services over IP networks experienced a tremendous growth due to the increasing use of voice over the Internet Protocol (VoIP) and streaming video over the Internet. This ongoing growth is further fuelled by the continued evolution of legacy telecommunication networks towards the Next Generation Network (NGN). Internet Protocol (IP) multimedia services are increasingly delivered over wireless local area network (WLAN) access networks because WLAN access networks are cheap and easy to deploy. However the use of WLAN for the provision of IP multimedia services faces a number of challenges which include quality of service (QoS). Because WLAN users access multimedia services usually over a wired backbone, attention must be paid to QoS over the integrated WLAN-wired network. This research focuses on the provision of QoS to WLAN users accessing multimedia services over a wired backbone.

In this thesis, the IEEE 802.11-2007 enhanced data channel access (EDCA) mechanism is used to provide prioritized QoS on the WLAN media access control (MAC) layer, while weighted round robin (WRR) queue scheduling is used to provide prioritized QoS at the IP layer. The inter-working of the EDCA scheme in the WLAN and the WRR scheduling scheme in the wired network provides end-to-end QoS on a WLAN-wired IP network. A mapping module is introduced to enable the inter-working of the EDCA and WRR mechanisms. This mapping module is located in the WLAN QoS-enabled access point (QAP), at the boundary between the WLAN and the wired network.

The proposed module maps EDCA AC traffic classes to IP layer QoS traffic classes, enabling uniform and seamless prioritized QoS to be accorded to the traffic classes by the EDCA and WRR schemes.

The mapping module is evaluated using the NS2 network simulator. It is found that the WLAN-wired network, with the integrated mapping module, performs better than that without the integrated mapping module.

However because of the fact that a WRR scheduling mechanism is used to implement

QoS in the wired network, the lower priority traffic receives much less network resources when compared to the higher priority traffic. Nevertheless the lower priority traffic is not starved of traffic in network congestion periods.

Further research with regard to the proposed scheme needs to be conducted. This includes the use of admission control and rate-limiting.

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## Glossary

**Access Category (AC):** An identifier for a common set of enhanced distributed channel access (EDCA) parameters. They are used by a quality of service (QoS) enhanced station (QSTA) to contend for the wireless local area network (WLAN) channel, in order to transmit wireless frames.

**Access Point (AP):** A WLAN station that bridges a WLAN and wired network, in the infrastructure mode of operation.

**Alternate Priority:** A queue scheduling mechanism that services packets in the priority queue, after servicing one due queue in the queue scheduling mechanism.

**Average Delay:** The average of the one-way end-to-end delay experienced by all transmitted packets belonging to a particular flow. The end-to-end delay is measured from a transmitted station to a received station.

**Constant Bit Rate (CBR) traffic:** Traffic that is generated and transmitted at a constant rate by a network station.

**Differentiated Services (Diffserv):** An IETF specified QoS architecture that provides prioritized service differentiation to different IP traffic classes.

**Diffserv Code Point (DSCP):** A value in the IP header that is used to identify the per hop behaviour (PHB) service treatment that an IP traffic flow receives.

**Dropped Packets:** Packets that are discarded by network devices due to congestion experienced

in the network.

**Enhanced Data Channel Access (EDCA):** A prioritized carrier sense multiple access with collision avoidance (CSMA/CA) channel access mechanism that uses AC to contend for the WLAN channel.

**Flow label:** A value in the IP header that is used to identify data packets belonging to a particular flow. The flow might be distinguished by any combination of source address, destination address, transport layer protocol, or application.

**Institute of Electrical and Electronic Engineers (IEEE):** A professional organization that issues networking standards among other services.

**Integrated Services (IntServ):** An IETF defined QoS architecture that provides for the reservation of network resources before a traffic flow is admitted into the network. Intserv makes a provision for a traffic class that can provide guaranteed QoS.

**Internet Engineering Task Force (IETF):** An organization that issues Internet standards.

**Internet Protocol (IP):** A network layer protocol used to route packets over a data network.

**IP Flow:** A distinguishable traffic flow over an IP network.

**Medium Access Control (MAC):** Logical entity that is part of layer 2 of the open systems interconnection (OSI). The MAC layer is responsible for the scheduling of access to the transmission channel by the network stations.

**MAC Service Data Unit (MSDU):** A discrete MAC layer data package that carries the IP layer

packets and higher layer transport and application headers.

**Next Generation Network (NGN):** An International Telecommunications Union – Telecommunications sector (ITU-T) defined set of layered-logical functions and protocols that define the future structure of telecommunication networks. The NGN is composed of a common transport core based on IP.

**Open Systems Interconnection (OSI):** An ITU-T specified layered logical structure that defines the interaction of software, hardware, and protocols in network devices.

**Quality of Service (QoS):** The provision of differentiated access to network resources to different network traffic classes.

**QoS enhanced AP (QAP):** A WLAN AP that supports QoS in an IEEE 802.11-2007 hybrid channel access enabled network.

**QoS enhanced station (QSTA):** A WLAN non-AP station that supports QoS in an IEEE 802.11-2007 hybrid channel access enabled network.

**Station (STA):** A WLAN network end-station that transmits WLAN MSDU.

**Throughput:** The rate of successful transmission of packets in a network.

**Traffic Stream (TS):** A group of MSDU that are transmitted subject to a set of QoS traffic parameters defined by an associated traffic specification.

**Traffic Specification:** A set of QoS characteristics such as data rate and delay bound.

**Transmission Control Protocol (TCP):** An OSI transport layer protocol that provides a

connection oriented service over the IP network layer. TCP provides flow control, congestion control and reliable data delivery.

**Transmission Opportunity (TXOP):** An opportunity to transmit that is given to a QSTA that has successfully accessed the WLAN channel. The TXOP is defined by a time limit.

**User Datagram Protocol (UDP):** An OSI transport layer protocol that provides a connectionless oriented service over the IP network layer. UDP does not provide reliable data delivery.

**User Priority:** A value assigned to MSDU that indicates the priority of the MSDU, and how it is to be prioritized in relation to other MSDU.

**Voice over IP (VOIP):** The transmission of voice traffic over an IP network in the form of IP packets.

**Wi-Fi:** A term that stands for Wireless Fidelity, but is used to describe a wireless local area network.

**Wireless local area network (WLAN):** A network composed of wireless stations that communicate with each other through data broadcasts over the wireless medium.

**Weighted Round Robin:** A router queue scheduling mechanism that schedules packets for transmission based on the weights assigned to each queue during each service cycle.

# Chapter 1 Introduction

From the mid 1990s to date telecommunication networks are undergoing rapid growth and change in terms of infrastructure, services and customers. The nature of services is evolving from simple time division multiplexing (TDM) voice calls, email and web services to enhanced multimedia services such as video conferencing, mobile presence management and IP television (IPTV) [1].

In-Stat, a telecommunications market research organization, estimated that the total number of VoIP users worldwide increased by 34 million in 2006 and that the global market for VoIP services will reach \$44 billion in 2011 [2]. Gartner, another telecommunications industry research organization, estimates the IPTV market to have 48.8 million subscribers and total revenues of US\$13.2 billion by 2010 [3].

The drivers for this change include:

- the increasing demand for more sophisticated services anytime and at anyplace,
- the increasing use of the Internet as a medium for multimedia communication,
- the increase in innovation and introduction of rich multimedia services over the Internet,
- the use of disparate access network technologies such as digital subscriber line (DSL), Cable TV, wireless microwave access (WiMAX), wireless local area network (WLAN), universal mobile telecommunications system (UMTS), and Ethernet,
- and the increasing use of open standardized protocols in the development of new multimedia services.

These new rich multimedia services are delivered over the Internet and IP based Next Generation Networks (NGN).

The NGN is an evolution of the legacy telecommunication network that seeks to address

the delivery needs of these new enhanced multimedia services. The NGN model was introduced by the International Telecommunications Union - Telecommunications Standardization Sector (ITU-T). The NGN delivers services over a host of different broadband access network technologies such as DSL, UMTS, WiMAX, Cable TV and WLAN [1].

However, the full adoption of NGN faces a number of challenges which include; security, billing and uniform user management, seamless roaming and mobility, and quality of service (QoS) [4].

## 1.1 WLAN Access Networks

WLANs are a critical access network technology in NGN. They are playing an increasingly important role in Internet and data access, in homes, offices and as WLAN hotspots. WLAN popularity is due to their low cost, ease of deployment, high bandwidth, and ubiquitous worldwide presence [5].

However, among the common broadband access network technologies, WLAN suffer most from QoS problems. This is due to:

- the presence of interference, channel fading and multipath propagation which are characteristic of wireless media.
- contention-based nature of the wireless medium.
- the presence of many uncontrolled users since the WLAN frequency band of operation does not require users to be licensed.

The Institution of Electrical and Electronic Engineers (IEEE) 802.11-2007 standard [6] enables QoS on a WLAN, but this still does not address the issue of lack of end-to-end QoS for a WLAN inter-working with a wired IP network. The enabling of end-to-end QoS on an integrated WLAN-wired network will help in establishing WLAN as a telecom grade access network.

## **1.2 Problem with QoS in WLAN Access to Multimedia Services on a Wired Network**

In many cases WLAN users access multimedia services hosted on the provider core network by traversing a wired network that could be an Ethernet link or wide area network (WAN) link, such as a synchronous digital hierarchy (SDH)/ synchronous optical network (SONET) transmission link running over copper or fiber optic cables [7]. In most of the cases both the WLAN and wired network have limited bandwidth and there is a need for QoS schemes on the WLAN and wired portions of the network.

QoS in packet data networks is generally implemented using two approaches and these are parameterized and prioritization methods. Parameterized QoS uses network resources, such as router queues, to provide measurable performance guarantees to traffic flows [8]. The performance guarantees are defined in terms of parameters such as bandwidth, end-to-end delay, jitter, and packet losses, and they are negotiated with the traffic flow prior to the start of the traffic flow. Prioritized QoS uses network resources to provide a required service level, in terms of low delay, high throughput, and high reliability, to data packets on a preferential basis [9]. The desired service levels are indicated on the packet headers and each the preferential treatment is based on the category that the packet is placed into. The higher priority category packets will be more likely to receive their desired service level.

QoS management in a network is achieved in a hierarchical manner with a high-level QoS control based on network resource and admission control, and low-level QoS control based on traffic conditioning [10], [11]. Resource and admission control is the process by which a network decides whether to admit a new traffic flow based on the availability of adequate resources to support the flow's QoS demands [11]. Traffic conditioning involves controlling the rate of flow of a packet in order to meet bandwidth, delay and reliability requirements [12].

Network standards organizations such as the IETF and the third generation partnership project (3GPP) have specified high-level QoS policy-based management mechanisms for IP networks [13], [14]. Many other QoS policy-based control schemes have also been proposed by researchers and implemented by vendors [15], [16], [17], [18].

In addition to resource and admission control, high-level QoS management involves resource reservation [11]. Resource reservation is carried out by protocols such as the resource reservation protocol (RSVP) and session initiation protocol (SIP), while admission control is performed by policy decision points (PDP) and policy enforcement points (PEP) functions.

To enable QoS on WLAN the IEEE released the IEEE Standard 802.11e in 2005 [19], which is then incorporated into the IEEE Standard 802.11-2007 [6]. The standard specifies two schemes, which are enhanced data channel access (EDCA) and hybrid coordination function (HCF) controlled channel access (HCCA) [6]. EDCA implements separate transmission queues for different classes of traffic, with the highest-precedence class being transmitted before the lowest-precedence one. Hence EDCA provides prioritized QoS. HCCA provides transmission opportunities for WLAN stations based on their requested traffic service needs such as data rate and maximum delay. Hence HCCA provides parameterized QoS.

QoS on the wired network is enabled on the MAC and IP layers. QoS on the MAC layer is specific to the network technology with integrated services digital network (ISDN), digital subscriber line (DSL) and cable modem technologies having different medium access control (MAC) layer QoS mechanisms. Ethernet utilizes the IEEE 802.1D standard for enabling QoS at the MAC layer.

IP layer service differentiation is nonetheless a more common way of enabling QoS on a wired network. IP layer QoS is enabled by a combination of fundamental utilities known as traffic conditioning functions which include traffic scheduling, policing and rate limiting. The Internet Engineering Task Force (IETF) specified two architectures based on traffic conditioning functions for providing QoS at the IP layer and they are differentiated services (Diffserv) for prioritized QoS and integrated services (Intserv) for parameterized QoS [12].

Despite the existence of adequate service differentiation mechanisms on the WLAN and wired networks, there is no guarantee that a user on an IEEE 802.11-2007 WLAN inter-working with an IP-layer QoS-enabled wired network will also experience a similar level of service differentiation. To enable uniform end-to-end service differentiation on a WLAN inter-working with a wired network there is a need to ensure that similar traffic classes are defined on the

WLAN and wired network, and that they experience consistent service differentiation.

### **1.3 Thesis Objectives**

The aims of this research are:

- to present the IEEE 802.11-2007 EDCA QoS scheme and its service differentiation mechanism.
- to present various QoS schemes for providing prioritized QoS treatment to traffic flows at the IP layer.
- to design a mapping scheme between wireless IEEE 802.11-2007 QoS and wired IP layer QoS mechanisms.
- to design a module for mapping IEEE 802.11-2007 QoS classifications to IP layer QoS classifications. The module will be located in the AP.
- to integrate the mapping module into an architecture for enabling end-to-end QoS in a mixed WLAN-wired network.
- to evaluate the performance of the designed scheme using simulation.
- to draw conclusions arising from the simulation studies.
- to make relevant recommendations on the suitability of the scheme in meeting the QoS needs of different traffic flows.
- to make recommendations on any further research work to be carried out on the designed scheme.

### **1.4 Scope and Limitations of this Research**

There are many QoS architectures in IP networks. However, this research focuses on WLAN IEEE 802.11-2007 EDCA and IP layer QoS on the wired network.

Admission control, service guarantees and rate limiting for the network traffic are not considered in this research. The focus is on differentiated treatment for different traffic classes.

QoS on the wired network is implemented using weighted round robin (WRR) scheduling on the router.

This research will not consider the effect of interference, frame collisions and number of transmitting stations on the WLAN.

## **1.5 Research Methodology**

If WLAN traffic classes are mapped onto corresponding wired network traffic classes, end-to-end prioritized QoS can be seamlessly prioritized in a WLAN-wired network. The research methodology involves identifying the QoS schemes to implement in the WLAN and wired networks. The QoS schemes identified are WLAN IEEE 802.11-2007 EDCA and the WRR scheduling mechanism for wired networks [20]. The WLAN EDCA traffic classes are mapped onto corresponding wired network traffic classes in order to achieve seamless end-to-end QoS. The performance of the WLAN-wired network with an integrated QoS scheme is compared to that of a non-integrated one.

The Network Simulator software (NS2) version 2.28 is used to carry out the performance verification of the scheme [21]. The designed scheme is evaluated by measuring network performance parameters such as throughput, delay, jitter, and dropped packets.

## **1.6 Contributions of the Research**

The contributions of this research are:

- the proposal of a mapping scheme between WLAN IEEE 802.11-2007 EDCA traffic classes and IP layer traffic classes.
- the introduction of a mapping module in a QoS-enabled AP (QAP) to enable the transparent inter-operation of WLAN EDCA and wired IP layer QoS schemes. The mapping module can easily be plugged into an existing network without any hardware

or software changes to other network devices.

- the proposed mapping scheme does not introduce any changes or deviations to any of the relevant standards used in the specification of WLAN-wired network devices. A QAP enhanced with the mapping module is easy to produce and interoperable with different vendor equipment.
- the demonstration of how enabling end-to-end QoS in a WLAN-wired network improves performance of service differentiation between different traffic classes.
- the proposed mapping module facilitates the use of the enhanced QAP as a PEP in a QoS policy-based network management scheme. It provides the higher layer PDP with a uniform end-to-end traffic classification scheme that can be transparently managed. This is useful in an NGN network with a WLAN access network
- the presentation of a new experimental framework in NS2 that can be used to evaluate end-to-end QoS schemes.

## 1.7 Thesis Outline

The remainder of this thesis document is organized as follows:

Chapter 2 discusses end-to-end QoS in an all-IP network. The approaches of research, industry and standards bodies to traffic control, QoS policy control, and resource and admission control are reviewed briefly. Network layer QoS is also reviewed in chapter 2, with a focus on provision of QoS on wired IP networks. This includes traffic classification and conditioning mechanisms, such as marking, policing and scheduling. The IETF IntServ and Diffserv architectures are also mentioned in chapter 2.

The later part of Chapter 2 presents a review of WLAN technology with an emphasis on the layer 2 MAC medium access mechanism. The IEEE 802.11-2007 standard for enabling MAC layer QoS is introduced, with a focus on the EDCA scheme for providing prioritized medium access.

Chapter 3 introduces the proposed end-to-end QoS solution for integrated WLAN-wired networks, utilizing the EDCA QoS mechanism inter-operating with the Diffserv QoS architecture. The inter-operation is enabled by mapping WLAN EDCA traffic classes onto Diffserv traffic classes on the wired network.

Chapter 4 presents the software evaluation framework. The software framework consists of a number of WLAN modules, which enable the simulation of an IEEE 802.11-2007 enabled WLAN inter-working with a wired network. Some modifications are carried out on the software to enable WRR queue scheduling, for service differentiation, on the wired network. The topological layout of the network that is evaluated is presented in this chapter. The implemented scheme is compared to a baseline network in which there is no mapping between IEEE 802.11-2007 EDCA traffic classes and Diffserv traffic classes on the wired network.

The results of the simulation study are presented in Chapter 5. The performance parameters measured are throughput, end-to-end delay, jitter, and packet loss. An analysis of the results is carried out in this chapter.

Based on the experimental results, conclusions are drawn on the performance of the proposed architecture and presented in Chapter 6. Recommendations based on the above conclusions are made. The recommendations are about the applicability of the scheme in a practical scenario. Later in the chapter, recommendations on further research and evaluation of the design are given.

## **Chapter 2      End-to-End QoS in an All-IP Network**

The use of IP as the transport protocol of choice enables the use of a common transport core in the next generation wired and wireless networks. It also enables the easy interoperation of telecommunications networks, especially the NGN, and the Internet.

The delivery of multimedia services over the IP network was also boosted by the release of the third generation partnership project (3GPP) defined IP multimedia subsystem (IMS). The (IMS) is a set of related functions and protocols, originally intended to deliver IP multimedia services to mobile phones over a universal mobile telecommunications system (UMTS) network [22].

However the use of the IP network for the delivery of multimedia services is still facing a challenge of providing adequate QoS guarantees.

### **2.1 QoS in the All-IP Network**

The widespread acceptance of IP-based multimedia services depends on the quality of user experience (QoE), among other factors [23]. QoE is a subjective user opinion on the consumed service, and it is mostly dependant on service reliability, availability and speed of responsiveness. The QoS and the infrastructure and engineering design of the network affect QoE. QoS refers to the ability of a network to provide certain types of traffic with a better service than others [23].

QoS in wired and wireless IP networks is based on four principles; which are [12]:

- the need for classification of traffic flows,
- the need for different treatment of different classes of traffic flows,
- the need for optimal use of network resources such as bandwidth and packet queues,
- the need for traffic flow admission control.

In an IP network traffic classification is needed in order for the QoS scheme to provide service differentiation to the different traffic classes. The traffic classes are then subjected to:

- high level admission control and resource reservation based on user subscription information and available resources,
- and/or traffic control using packet marking, shaping, policing and gate control at the IP and MAC layer [7], [12], [13].

## **2.2 QoS versus Bandwidth**

Some sections of the Internet industry believe that QoS is not necessary in the presence of adequate bandwidth [24]. They cite the example of the widespread use of VoIP over instant messaging (IM) applications, such as Microsoft Network (MSN) IM, Google Talk, Yahoo! Voice and Skype. The shortcoming in this argument is that although voice over IP (VoIP) has low bandwidth requirements (typically 10kbps to 64kbps), other multimedia traffic such as video require a much higher bandwidth than VoIP (typically 5 to 10, or even more times as much) [25]. It must also be noted that other types of traffic can also cause congestion in the network, and this congestion will affect the VoIP traffic. Despite the increasing availability of cheap bandwidth regions such as Africa are still having low Internet bandwidth due to their underdeveloped telecommunications infrastructure.

From the brief discourse above, it is apparent that there is still need to implement QoS on IP networks to enable the efficient delivery of IP multimedia services. QoS is more critical in error and congestion prone media such as wireless links.

## **2.3 Current Trends in Inter-Worked WLAN-Wired IP Networks**

Some instances of QoS in an integrated WLAN and wired IP network environment are implemented by network equipment vendors such as SpectraLink, Symbol Technologies, Meru Networks, and Cisco Systems, especially for voice over WLAN (VoWLAN) [26].

The most visible player on the VoWLAN QoS scene is SpectraLink which implements

QoS by varying the required backoff time for the different traffic classes, with voice having the least backoff time [27].

Most vendors implement closely guarded pre-IEEE 802.11-2007 proprietary WLAN QoS technology. From the scant information on the website of a vendor such as Symbol Technologies, it can be concluded that certain classes of traffic (usually voice) are prioritized on the outgoing wireless interface queue [28]. If any QoS is enabled on the wired network, it is implemented using the IEEE 802.1D/Q virtual local area network (VLAN) priority tagging mechanism. It is not clear if there is any specific mapping between the IEEE 802.11-2007 priority values and the IEEE 802.1D/Q tags. Cisco's implementation, which is quite open to the public, uses the layer 2 IEEE 802.1D/Q VLAN priority-tagging mechanism to separate and mark traffic flows over the WLAN [29]. The Cisco implementation involves mapping the IEEE 802.1D/Q traffic classes onto IP layer QoS classes at the AP for differentiated treatment on the wired part of the network, for differentiated treatment. The service differentiation is provided based solely on IP layer QoS classes. The drawbacks of this scheme are the increased administrative overhead due to the use of VLANs, and the implementation of WLAN QoS on the IP layer rather than on the MAC layer. WLAN QoS performs more effectively on the MAC layer.

## 2.4 Previous Research

Skyrianoglu *et. al.* introduced a wireless adaptation layer (WAL), located between the link and IP layer in the wireless station [30]. The WAL intercepts the outgoing IP packet header and extracts the QoS classification. Using the extracted QoS classification the WAL places the IP packet into an appropriate queue. A QoS module in the WAL uses scheduling to achieve service differentiation for different traffic classes. For packets received from the wired network, the WAL in the access point (AP) extracts the QoS classification and places the packet in the corresponding outgoing queue, before onward transmission on the wireless medium. The disadvantage of this scheme is that the modification of the WLAN MAC layer results in a new MAC layer which is outside the specifications of the relevant IEEE 802 standards. The proposed WAL approach is also complex in its implementation due to the extra headers and packet processing operations introduced. Skyrianoglou *et. al.* did not publish any performance

verification of this scheme.

Park *et. al.* proposed a scheme of mapping IP layer QoS classes, which are IETF defined differentiated services code point (DSCP) values, to MAC layer IEEE 802.11-2007 traffic categories (TC) in a direct or hierarchical manner [31]. The direct manner involves reading the DSCP value of a packet from the wired network and placing it in the appropriate IEEE 802.11 traffic queue. The hierarchical manner involves classifying, marking and shaping the packet, and then encapsulating it in an IEEE 802.11-2007 MAC header with the appropriate traffic class identification (TCID), and placing the packet onto the appropriate IEEE 802.11-2007 queue. One shortcoming of this architecture is that all the WLAN stations are required to support the Diffserv architecture, hence the need to modify all the user stations through software upgrades. It is rare to encounter end-user stations which have Diffserv functionality. Another disadvantage is that the QoS over the wireless interface is driven from the IP layer, yet it is generally agreed that wireless QoS is best managed at the MAC layer. Park *et. al.* did not publish any performance verification of their proposed scheme.

Selvig *et. al.* proposed a scheme that introduces a mapping module in the AP, which maps DSCP values to EDCA ACs [32]. The scheme offers a lot of promise in enabling end-to-end QoS across wireless-wired networks. However their experiments evaluate whether the EDCA traffic classes match the performance of the Diffserv traffic classes in a WLAN, which is not an indicator of the scheme's suitability for enabling end-to-end QoS on an integrated WLAN-wired network. This is because EDCA cannot be used on a wired network.

A scheme known as IROISE for inter-working IEEE 802.16 wireless microwave access (WiMAX) and IEEE 802.11-2007 WLAN networks is proposed by Gakhar *et. al.* [33]. The scheme maps QoS traffic classes' parameters in the WLAN to corresponding ones in the WiMAX. The mapping module is contained in the co-located QAP and base station. The mapping module maps both parameterized and prioritized QoS classifications between the two access networks. Although it deals with wireless heterogeneous networks, it is worth noting due to the fact that it provides useful design ideas.

## **2.5 QoS in the Wired Network**

Most wired IP networks implement QoS on the IP (network) layer of the open systems interconnection (OSI) stack. The fundamental network layer-based traffic control mechanisms, such as marking, policing and scheduling are used individually or collectively to achieve QoS on the network layer.

The effectiveness of a network layer QoS scheme in the delivery of multimedia traffic to end-users is determined by performance characteristics that include [34]:

- the throughput of the traffic flow which is the number of successfully delivered packets per second. Another closely related characteristic is goodput, which is the number of uncorrupted successfully delivered packets within an acceptable period.
- the end-to-end packet delay.
- the jitter, also known as the variation in end-to-end packet delay.
- the percentage of dropped packets.
- the packet arrival sequence.

All the performance characteristics mentioned above are affected by:

- the state of the physical layer media over which the network runs. Wired links do not generally experience link errors because the end systems are physically connected to each other, and the physical links have effective shielding techniques to counter electromagnetic interference from other information carrying signals. On the other hand, wireless links experience a significant number of errors due to the propagation of signals through the air, which increases the chance of interference from obstacles, and wireless signals from other sources.
- the network load. A highly loaded network will experience waiting delays at the router queues, which leads to a delay in packet transmission.
- router queue buffers. During periods of increasing network congestion, the router buffer queues fill up and new incoming or already queued packets are dropped. This

affects the throughput and the rate of dropped packets. Full queue-buffers increase end-to-end packet delay.

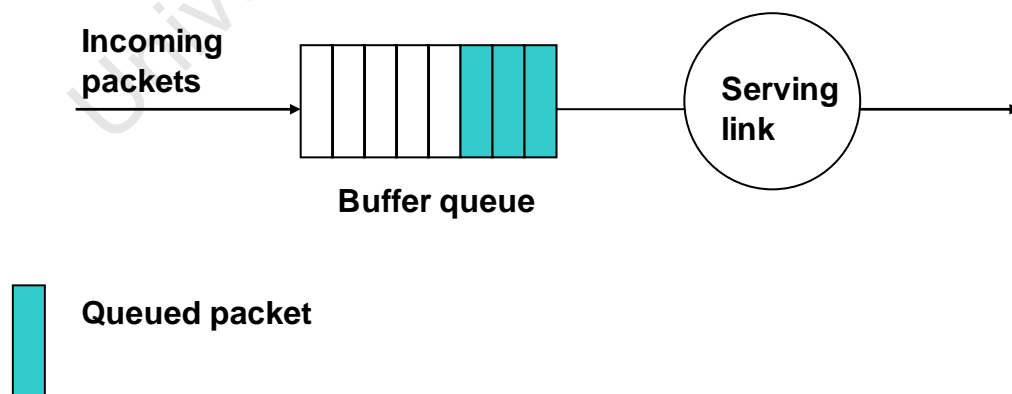
## 2.5.1 Packet Scheduling

When packets arrive at a router and find the outgoing link in use they are queued at the router in order to await transmission. Packet scheduling describes the method used to select queued packets for transmission on the network link. It affects the allocation of bandwidth and buffer queues (or drop probability), as well as the delay experienced by the packet [35]. The various scheduling mechanisms commonly in use are first-in-first-out (FIFO), round robin (RR) queuing, weighted round robin (WRR) queuing or priority queuing (PQ) [12].

When a packet arrives at a network device with a busy outgoing link and full buffer queues, the incoming packet is discarded in accordance with a packet dropping policy. The packet dropping policy may drop the new incoming packets, or drop existing packets in the queue so as to make room for an incoming packet. An example of a common packet dropping algorithm is random early detect (RED) [36].

### 2.5.1.1 First-In-First-Out

The FIFO mechanism selects packets to be transmitted based on the order of their arrival in the queue as shown in Figure 2.1 [37].



**Figure 2.1: FIFO Queue Scheduling**

FIFO does not provide bandwidth or end-to-end delay guarantees, nor does it protect

light traffic flows against heavier traffic flows. Hence FIFO does not provide any QoS [35], [38].

### 2.5.1.2 Priority Queuing

In the priority queuing mechanism different queues in a router are assigned different priorities. Incoming packets are assigned to different priority queues based on the markings in their IP headers. The packet to be transmitted is selected from the highest priority non-empty queue. Packets in a particular queue are transmitted using FIFO until the queue is empty [39]. The operation of priority queuing is shown in Figure 2.2.

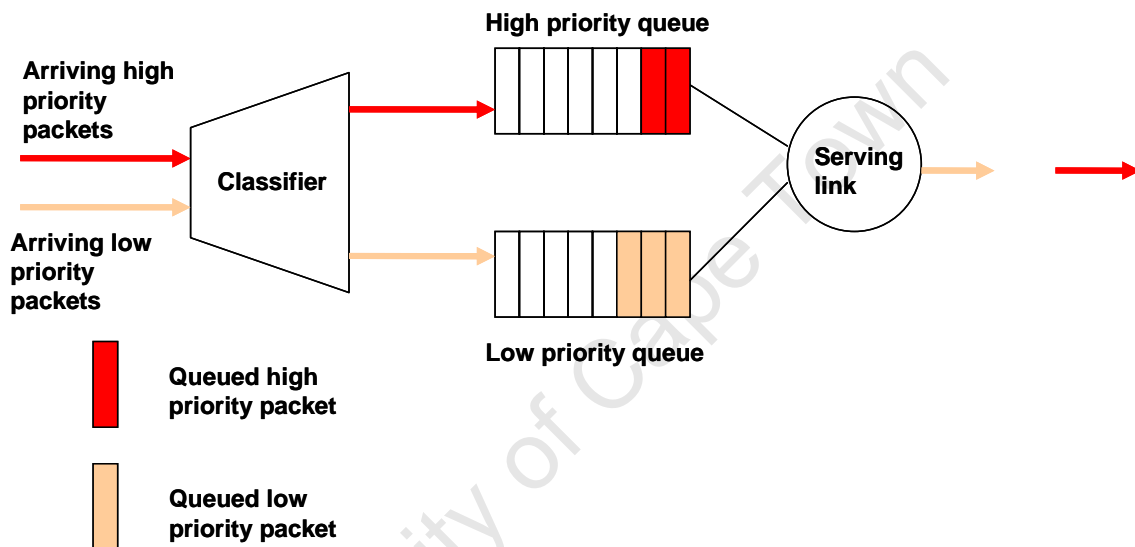


Figure 2.2: Priority Queue Scheduling Mechanism

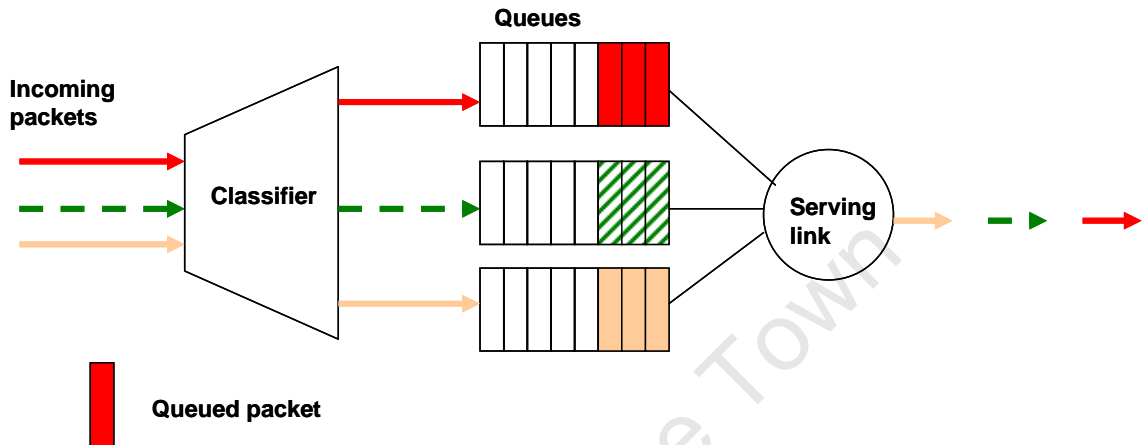
PQ is good for providing preferred service to critical traffic but it can lead to lower priority queues being starved of service.

A variation of PQ is strict priority queuing whereby one queue is designated as the priority queue and all packets in the queue are serviced before other queues are serviced, at any time interval.

Alternate priority queuing is another variation of PQ that alternately serves high and low priority queues [40]. The low priority queues are serviced by a different queue scheduling mechanism.

### 2.5.1.3 Round Robin Queuing

In the round robin (RR) queuing mechanism, incoming packets are classified and put in different queues at the router. One queue packet is then transmitted in turn, as shown in Figure 2.3 below [12].

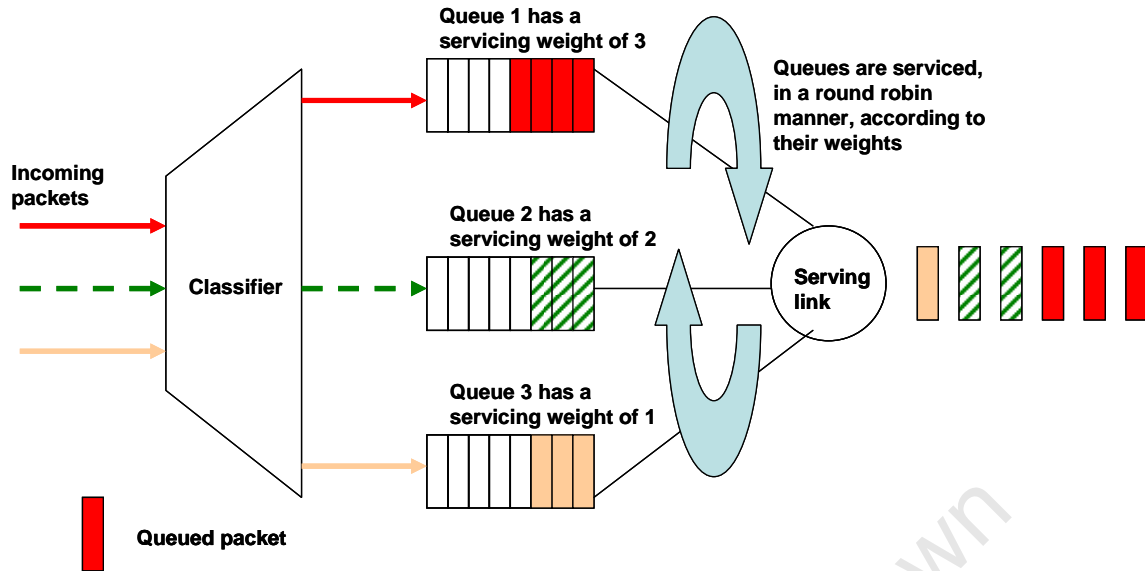


**Figure 2.3: Round Robin Queue Scheduling**

There exist a number of analytical treatments of round robin (RR) scheduling, which analyze the efficiency and fairness of RR scheduling [41]. However it is apparent that in RR scheduling larger packets benefit from more resource allocations, such as bandwidth, than smaller packets.

### 2.5.1.4 Weighted Round Robin

Weighted round robin (WRR) is a modification of round robin queuing in which different router queues are assigned different servicing weights [12]. The WRR queues servicing weight is a number that denotes how many packets in that queue will be serviced during each queue-servicing interval. Incoming packets are classified and queued to wait for transmission scheduling. WRR is a work conserving scheduling mechanism which skips any empty queues and services the next due non-empty queue. The WRR scheduling mechanism is illustrated in Figure 2.4.



**Figure 2.4: Weighted Round Robin Queue Scheduling**

If a router has  $n$  queues with each queue supposed to services class  $i$  packets and each individual queue  $i$  is assigned a weight  $w_i$ , then in any interval of time class  $i$  packets are guaranteed to receive a proportion of total service given by [12], [20]:

$$\frac{w_i}{\sum_{i=1}^n w_i} \quad (1)$$

In equation 1, the denominator sum is given by all packets with non-empty queues.

Thus if a link has a transmission rate of  $R$ , class  $i$  packets will be guaranteed a sending throughput given by [12], [20]:

$$\frac{w_i}{\sum_{i=1}^n w_i} R \quad (2)$$

Weighted fair queuing (WFQ) is a more complex implementation of WRR that is based on the packet-based generalized processor sharing (PGPS) algorithm [35], [39]. PGPS is a resource servicing algorithm that seeks to fairly, flexibly, and efficiently allocate capacity on congested network links. PGPS was first proposed and analyzed by Demers *et. al.* [35]. WFQ

has been extensively studied and shown to provide good performance guarantees for different traffic flows [20]. However it is quite complex to implement due to the assumption of a fluid packet flow which in practice is hard to realize due to the discrete nature of the data packets [42]. Hence WRR is more commonly used due to its simpler implementation [39].

## 2.5.2 Traffic Policing

Traffic policing is the control of the packet forwarding rate of a traffic flow [12]. There are three parameters that are used to characterize the packet rate of a traffic flow and these are:

- average rate, which is considered over a long duration and is in per second or per minute units.
- peak rate, which is considered over a short duration and is usually denoted in per second units. Peak rate describes the upper limit of the packet flow rate during a high burst of traffic flow. If the average rate is specified in per minute units, the peak rate can be taken in per second units. As an illustration, consider a traffic flow with an average rate of 100 packets per minute and a peak rate of 10 packets per second. Assuming a steady packet flow rate, an average rate of 100 packets per minute would be an average rate of  $5/3$  packets per second. However if the peak rate of the flow is specified as 10 packets per second, a sudden increased packet flow rate of up to 10 packets per second is permissible as long as it does not occur for more than 10 seconds (in which case the 100 packets per minute average rate would be exceeded) [8].
- burst size, which is the maximum number of packets that can be transmitted on a network link over an extremely short interval of time. In the limit, as the time interval approaches zero, the burst size is the upper limit of the number of packets that can be instantaneously transmitted over the network link. Due to limitations on link-interface rates, the simultaneous transmission of a number of packets equal to the burst size is hardly realizable in practice. However, burst size is a useful abstraction that is helpful in modelling traffic policing mechanisms [8]. Burst size is usually specified in bytes.

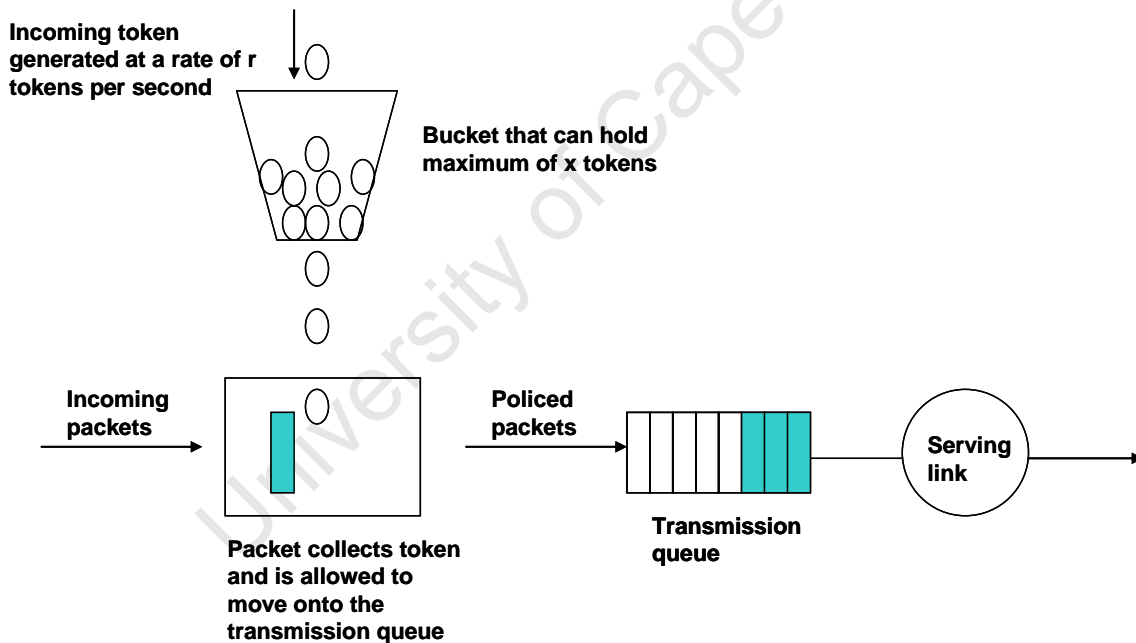
Traffic policing involves measuring the traffic flow rate and if the flow exceeds an

agreed rate it is dropped, delayed or reclassified, to bring it into conformity with the required rate. Traffic shaping refers to the delaying and reclassification process undertaken to ensure the traffic flow rate is within the necessary limits.

There are various traffic policing mechanisms such as token bucket, time sliding window two colour marker (TSW2CM), and single rate three colour marker (srTCM) [43], [44]. However, the token bucket is the most widely used and it forms the basis for the implementation of other policers such as srTCM.

### 2.5.2.1 Token Bucket

The token bucket traffic policer mechanism uses the concept of a bucket to represent the desired traffic characteristics [20], [45]. The operation of the token bucket is shown in Figure 2.5.



**Figure 2.5: Token Bucket Operation**

An incoming packet has to collect a token from the bucket before it can be forwarded to the link transmission queue for subsequent transmission over the link. If the token bucket is empty when a packet arrives at the policer, the packet is delayed until a token is generated and put in the bucket. The packet could also be dropped if there are no tokens in the bucket.

The mathematical expressions for the rate of packet transfer and the delay experienced by the packet flows are derived in the following paragraphs [20].

If the rate of token generation is given by  $r$  and the maximum number of tokens that the bucket can hold is given by  $b$ , and  $P(t)$  is the number of packets that enter the router transmission queue at time  $t$ , then:

$$P(t) - P(u) \leq r(t - u) + b, \text{ for all } 0 \leq u \leq t \quad (3)$$

The maximum number of packets that can be served by the link during the time interval  $[u, 0]$  is  $r(t - u) + b$ .  $b$  represents the burst size of a traffic flow policed by the token bucket in Figure 2.5, while  $r$  represents the maximum average rate of the traffic flow served by the token bucket.

To derive expressions for the delay experienced by packets served by the token bucket mechanism in Figure 2.5, consider a time  $t > 0$ , and a value for number of packets given by  $K(t) > 0$ . Assuming that  $u$  is the last time that  $K(u) = 0$ , and that:

$$K(w) > 0 \text{ for } w \in (u, t) \quad (4)$$

Let  $Q(t)$  be the number of packets that leave the router transmission queue in a time interval given by:

$$[0, t] \text{ for } t \geq 0 \quad (5)$$

Assuming that  $s$  is the rate at which packets from a non-empty queue are transferred from the transmission queue and out of the link interface, then during the time interval  $[u, t]$ , the number of packets that leave the transmission queue and out of the link interface are given by:

$$Q(t) - Q(u) \geq s(t - u) \quad (6)$$

Hence using equation 3 and considering the fact that  $K(u) = 0$ , and since the rate  $s$  is at least equal to  $r$  in a non-empty token bucket, we derive the following expression:

$$K(t) = P(t) - PQ(u) - [Q(t) - Q(u)] \leq r(t - u) + b - s(t - u) \leq b \quad (7)$$

$K(t)$  refers to the number of packets in the queue that are waiting to be transmitted out on to the network, through the link interface.  $K(t)$  is also referred to as the queue backlog. Since  $s$  is the minimum rate at which packets leave the transmission queue out on to the link interface, the queuing delay of a packet that arrives at the transmission queue at a time  $t$ , when the queue backlog is  $K(t)$ , is less than  $K(t)/s$ . From Equation 7,  $K(t)$  is always less than  $b$ , hence the queuing delay experienced by a packet is always less than  $b/s$ .

## 2.6 IP QoS Architectures

Packet classification, marking, scheduling, policing and admission control are the basic building blocks of the IntServ and DiffServ architecture [12].

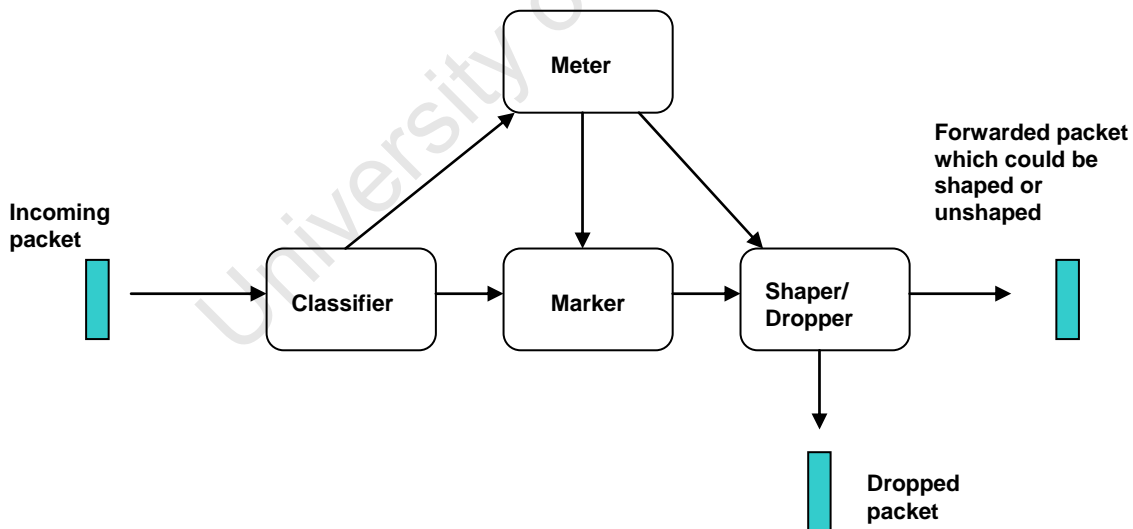
Integrated Services (IntServ) provides service guarantees to individual application flows, by reserving network resources for the application flows [46]. IntServ uses the RSVP protocol to reserve network resources in the form of bandwidth [47]. The two main service specifications in IntServ are guaranteed QoS and controlled-load network service. IntServ guaranteed QoS provides quantified bandwidth and delay bound [8]. The guarantees are specified using token bucket parameters ( $r$  and  $b$ , as defined previously), and a requested packet transmission rate. The controlled-load network service specifies that a traffic flow will receive network service equivalent to what that particular network would give it, in the event that it was not servicing any traffic at all [45]. This means that the packet drop would be minimal and approximately equal to that due to errors in the link's physical media. It also implies that the end-to-end delay of the transmitted packets would be almost equal to zero, and should be equivalent to the sum of the propagation delay and router processing times. This definition of the controlled-load network service is ambiguous. It is meant to be used with current multimedia services delivered over the Internet, such as streaming video and audio.

IntServ faces a number of challenges due to the need to reserve router resources and maintain traffic flow state information along the traffic path. Another drawback of Intserv is that the existence of only two main service specifications, which are the guaranteed and a controlled-load network service, limit the service options available for admitted traffic flows. The above challenges faced by IntServ led to limitations on its scalability and flexibility.

In response to the shortcomings posed by IntServ, the IETF released the Differentiated Services (Diffserv) architecture which is composed of two mechanisms and they are [48]:

- packet marking where the six most significant bits of the former IPv4 type of service (ToS) or IPV6 traffic class (TClass) eight bit header are used to contain the traffic class identifier that the packet belongs to. The class identifier is known as the differentiated services code point (DSCP) [49].
- per hop behaviour (PHB). PHB is the externally discernible forwarding action applied to a combined traffic class flow at a Diffserv compliant router [49]. The PHB is denoted by the DSCP. There can be up to 26 PHBs, but the Diffserv architecture defines four standard PHBs, which are default PHB, expedited forwarding (EF), assured forwarding (AF), and class selector PHB (CS).

The Diffserv architecture utilizes classification, metering, marking, and policing mechanisms to attain the PHBs. The mechanisms used are illustrated in Figure 2.5 [48].



**Figure 2.6: Diffserv Traffic Conditioning Functions**

Edge routers which are located at the boundary of a Diffserv enabled network (or domain) carry out traffic conditioning while core routers which are located within the Diffserv domain implement packet forwarding based on the traffic flow's PHB [50].

Although the Diffserv architecture is flexible and scalable, it has not been widely implemented in the Internet because most network operators consider it to be complex to administer [24]. Therefore most network operators prefer to implement priority queuing and weighted round robin which are much simpler to administer. Diffserv's application across multi-provider networks is limited by the issues of whether providers can trust each others policies and how differentiated services should be billed across different provider's networks [50].

During periods of low load network conditions, high priority users in Diffserv domain experience the same level of service as low priority users, hence negating the effect of the applied Diffserv QoS [12].

## **2.7 QoS in the WLAN**

WLANs are based on the IEEE 802.11 MAC layer standard [51]. There are many constituent IEEE 802.11 based standards dealing with issues such as the physical layer technology, security, and QoS [51]. Some of the commonly used standards are given in Table 2.1.

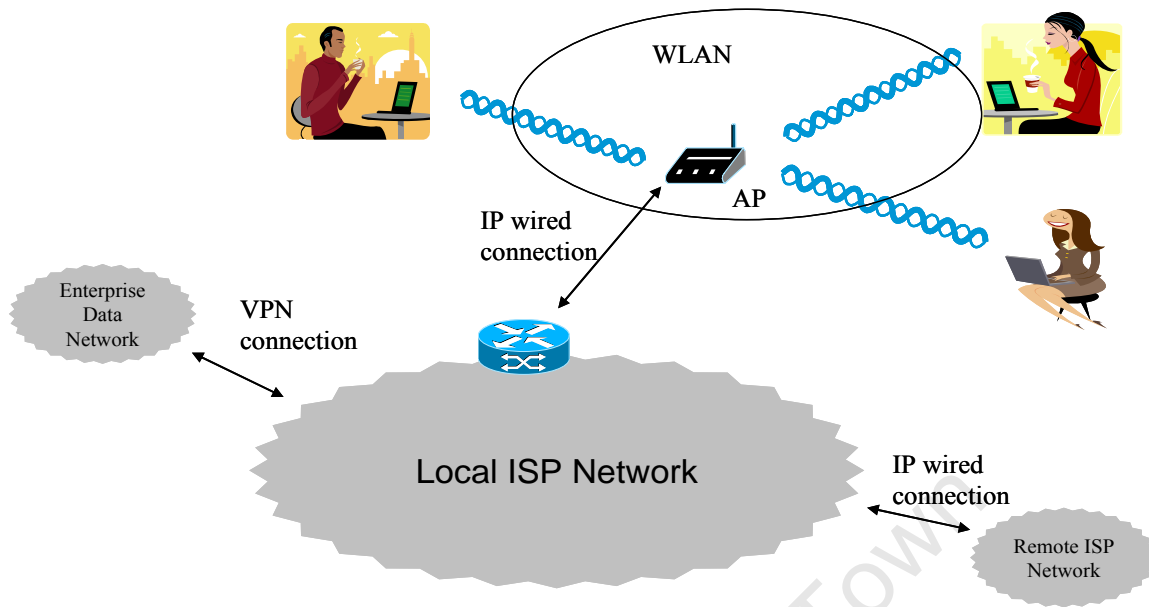
**Table 2.1: Common IEEE 802.11 Standards**

<b>Standard</b>	<b>Operating frequency</b>	<b>Throughput</b>	<b>Range</b>	<b>Modulation scheme</b>
IEEE 802.11a	5 GHZ	54 Mbps	20 metres	Orthogonal frequency division multiplexing (OFDM)
IEEE 802.11b	2.4 GHZ	11 Mbps	100 metres	Direct sequence spread spectrum (DSSS)
IEEE 802.11g	2.4 GHZ	54 Mbps	100 metres	Orthogonal frequency division multiplexing (OFDM)

A WLAN is composed of end-user stations (STAs), access points (APs), the wireless medium, and an optional backbone network for connection to external networks. A WLAN can operate in infrastructure mode where all STAs communicate through the AP, or adhoc mode where the STAs communicate directly with each other [51].

WLANs are commonly used as data networks for the provision of IP services such as Internet access, enterprise networking, home networking, and remote network access in the form of virtual private networks. However WLANs offer a limited range of coverage, typically 100m for an IEEE 802.11b WLAN, with an omni-directional antenna.

A typical WLAN hotspot illustrating connections to data networks such as the Internet and virtual private networks (VPNs) is shown in Figure 2.6.



**Figure 2.7: Illustration of a Typical WLAN Hotspot**

Some cellular network operators, such as T-Mobile, use WLANs to supplement their Internet and data access services [52]. This entails the co-location of WLANs and cellular data networks, such as UMTS or GPRS. Users equipped with dual-mode handsets can choose which network to use depending on availability and user preferences. In the presence of both WLAN and cellular network coverage, users tend to prefer the higher bandwidth WLAN.

WLAN access networks are specified as one of the key NGN access networks by TISPAN and 3GPP [53], [54]. WLANs are also identified as one the key technologies for fourth generation (4G) wireless networks [55]. However issues such as seamless vertical handover, roaming, user authentication and management, and QoS still remain to be resolved, before WLANs can be successfully deployed in NGN or 4G wireless networks.

### 2.7.1 Medium Access in WLAN

WLAN uses the carrier sense multiple access with collision avoidance (CSMA/CA) scheme to transmit wireless frames known as MAC service data units (MSDUs). CSMA/CA involves an STA checking the medium and ensuring it is free of signal from other STAs before it can transmit an MSDU. The collision avoidance component of CSMA/CA ensures that MSDUs

from different STAs do not collide by initiating a timed random backoff in the event of the STA detecting an ongoing transmission from another STA [56].

The basic WLAN MAC protocol is the distributed coordination function (DCF) which uses the CSMA/CA scheme. To increase the robustness of DCF a request to send (RTS) MSDU control frame is used to request the AP for channel access and if the channel is clear the requesting STA receives a clear to send (CTS) broadcast MSDU from the AP. All other STAs desist from attempting to use the channel during the requesting STA's transmission [6]. STAs transmit acknowledgement (ACK) frames when MSDUs have been received successfully.

DCF implements two kinds of carrier sensing mechanisms; physical carrier sensing and virtual carrier sensing. Physical carrier sensing involves the STA physical layer sensing the wireless medium and updating the MAC layer. The complex and expensive transceivers needed for physical carrier sensing and the unpredictability of hidden nodes make virtual carrier sensing more popular among WLAN vendors [51]. Virtual carrier sense is essentially implemented by a timer which is contained in the MAC header duration field of MSDUs such as the RTS and CTS. The duration field value indicates the length of time that the sending STA will use the channel for. All stations use the value of the duration field in the broadcast RTS, CTS, and other MSDUs to update their network allocation vector (NAV). As long as the NAV of any STA is a non-zero value, the STA will consider the channel to be in use. The period during which the DCF is active in a WLAN is known as the contention period (CP).

A WLAN STA can also operate in a contention free mode using the point coordination function (PCF) [56]. In this mode a point coordinator (PC), commonly located in the AP, is used to poll and allocate STAs a transmission time during the contention free period (CFP). Functionally, PCF is implemented upon the DCF scheme and can only operate in an infrastructure mode. A WLAN can operate with PCF and DCF schemes at the same time (with each scheme being used at certain intervals of time), or with only one of them. PCF was meant to introduce QoS and its implementation is rather complex, which has led to its limited deployment. DCF-only WLANs are the most widely deployed type.

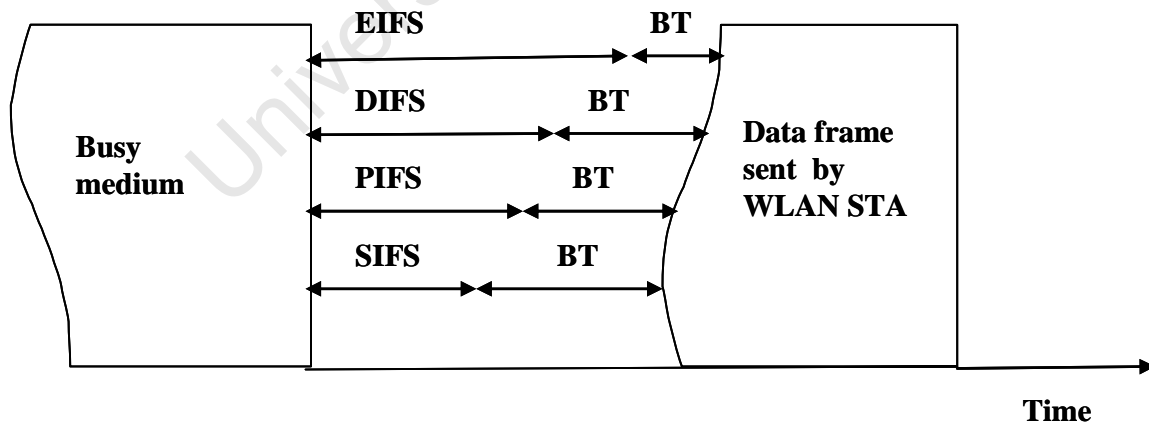
WLANs use a variety of timers to mediate between STAs wishing to transmit data. The

timers are generally known as interframe spaces (IFS) and they represent the minimum time the channel can be free before transmission of the next MSDU. There are four types [51]:

- Short interframe space (SIFS). This is the shortest duration timer, and after its expiry, high priority frames such as RTS, CTS, and ACK are transmitted.
- DCF interframe space (DIFS). This is the timer interval used for DCF channel access.
- PCF interframe space (PIFS). This is the timer interval used for PCF channel access and it is shorter than DIFS. PIFS allows an AP priority access to the medium.
- Extended interframe space (EIFS). This is a timer activated during DCF mode of operation and it is used after the detection of a frame error during the transmission of MSDU.

Another critical timer used in DCF mode is the random backoff timer (BT). After the lapse of any IFS, an STA increases its medium access waiting time by a value equal to BT. After the lapse of the BT time interval, the station can transmit an MSDU.

The operation of these timers is illustrated in Figure 2.7 [6].



**Figure 2.8: WLAN Medium Access Timers**

The BT time interval is a random value given by:

$$BT = \text{randomSlotNumber}() \times \text{slotTime} \quad (8)$$

Where  $\text{randomSlotNumber}()$  is a pseudorandom integer selected from the uniform distribution given by  $[0, \text{contention window (CW)}]$ . The range  $[0, \text{CW}]$  is divided into integer slots and each slot has a duration denoted by  $\text{slotTime}$ .  $\text{CW}$  is an integer that is determined by the particular IEEE 802.11 physical layer characteristics.  $\text{CW}$  can take on a value within the range given by  $[\text{CW}_{\min}, \text{CW}_{\max}]$ .

### 2.7.2 IEEE 802.11-2007

Section 9 of IEEE 802.11-2007 standard introduced a number of QoS functions in the IEEE 802.11 MAC layer. The most important ones in relation to this research are the channel access and traffic specification (TSPEC) management [6]. Other new MAC sub-layer functions introduced by the IEEE 802.11-2007 standard are:

- no acknowledgements which removes the need for a QoS-enabled STA (QSTA) to acknowledge received packets.
- direct link setup that allows QSTAs operating in infrastructure mode to send data directly to each other.
- automatic power save delivery which introduces a more efficient power saving scheme during periods of QSTA inactivity.
- block acknowledgement which allows multiple frames to be acknowledged in a single transmitted frame.

The IEEE 802.11-2007 standard defines a new channel access management function known as the hybrid coordination function (HCF). HCF introduced two channel access methods known as the enhanced data channel access (EDCA) mode and the HCF controlled channel access (HCCA) mode. EDCA is based on the legacy DCF, while HCCA is based on PCF. EDCA and HCCA can operate together (but not in the same interval of time) or individually in a QoS-enabled WLAN. The IEEE 802.11-2007 standard designates two periods of operation which are the contention period (CP) during which EDCA operates, and the contention free period (CFP)

during which HCCA operates.

The channel access function grants a transmission opportunity (TXOP) to QSTAs that wish to transmit or receive MSDUs. A TXOP is a defined time interval during which a station can transmit as many frames as it wishes, as long as all the frames can be sent within the TXOP duration.

A TSPEC, which is used in both EDCA and HCCA mode, defines a traffic flow in terms of its QoS characteristics such as transmission rate, packet size and delay bound. TSPECs aid in admission control decisions, TXOP scheduling, and the setup and teardown of traffic flows. Although admission control and TXOP scheduling is important in WLAN due to the limited bandwidth, the IEEE 802.11-2007 standard does not mandate the existence of admission control and TXOP scheduling mechanisms. The implementation of these is left to the vendor's discretion [32].

The TSPEC function provides the link between the higher layer QoS mechanisms such as IntServ and Diffserv, and the MAC layer. The higher layer applications can signal their QoS resource requests in the form of TSPECs to the MAC layer management entity (MLME) service access point (SAP), through the layer-independent station management entity (SME) [6]. The MLME uses these TSPECs to negotiate with the QAP for the necessary TXOP.

The IEEE 802.11-2007 standard introduced a priority parameter in the MSDU header. The priority value can be any integer from 0 to 15. The first eight integers in the priority parameter field define the individual higher layer (application) user priority (UP) values of the MSDU. UP values are passed to the MSDU through the MAC service access point (MAC\_SAP). The UP value defines the traffic category (TC) the MSDU belongs to and the UP value is equal to the TC number. UP classifications are similar to IEEE 802.1D user priority values.

The remaining priority parameter values (8 to 15), define QSTA traffic classes known as traffic streams (TS). Each TS is identified by a TS identifier (TSID). Manufacturers can define standard traffic flows and associate them with a specific TSPEC. An MSDU can also use the TSID to associate itself with a specific UP [6]. The IEEE 802.11-2007 standard is vague in its definition of the use of TS.

### **2.7.2.1 EDCA**

EDCA operates during the CP and it enables different priority access to the medium using TCs, which are grouped into a maximum of four access category (AC) queues. Each AC is characterized by a group of common timing parameters that are used to contend for access to the channel within a QSTA. A typical UP/TC to AC mapping is shown in Table 2.2 below [6]. The mapping is similar to the wireless fidelity (Wi-Fi) Alliance's Wi-Fi Multimedia (WMM) guidelines [54].

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**Table 2.2: EDCA QoS Classification Mappings**

IEEE 802.1D classification/ UP/ TC	IEEE 802.1D traffic designation	IEEE 802.11e traffic classification	AC (AC Index)
0	Best effort (BE)	Best effort	00
1	Background (BK)	Best effort	00
2	Not defined	Best effort	00
3	Excellent effort (EE)	Video probe	01
4	Controlled load (CL)	Video	10
5	Video - less than 100ms latency and jitter (VI)	Video	10
6	Video - less than 10ms latency and jitter (VI)	Voice	11
7	Network control (NC)	Voice	11

Channel access contention is mediated by the individual AC's arbitrary interframe space values (AIFS) instead of DIFS [31]. The expression for the AIFS of individual ACs, which is denoted as AIFS(AC), is [6]:

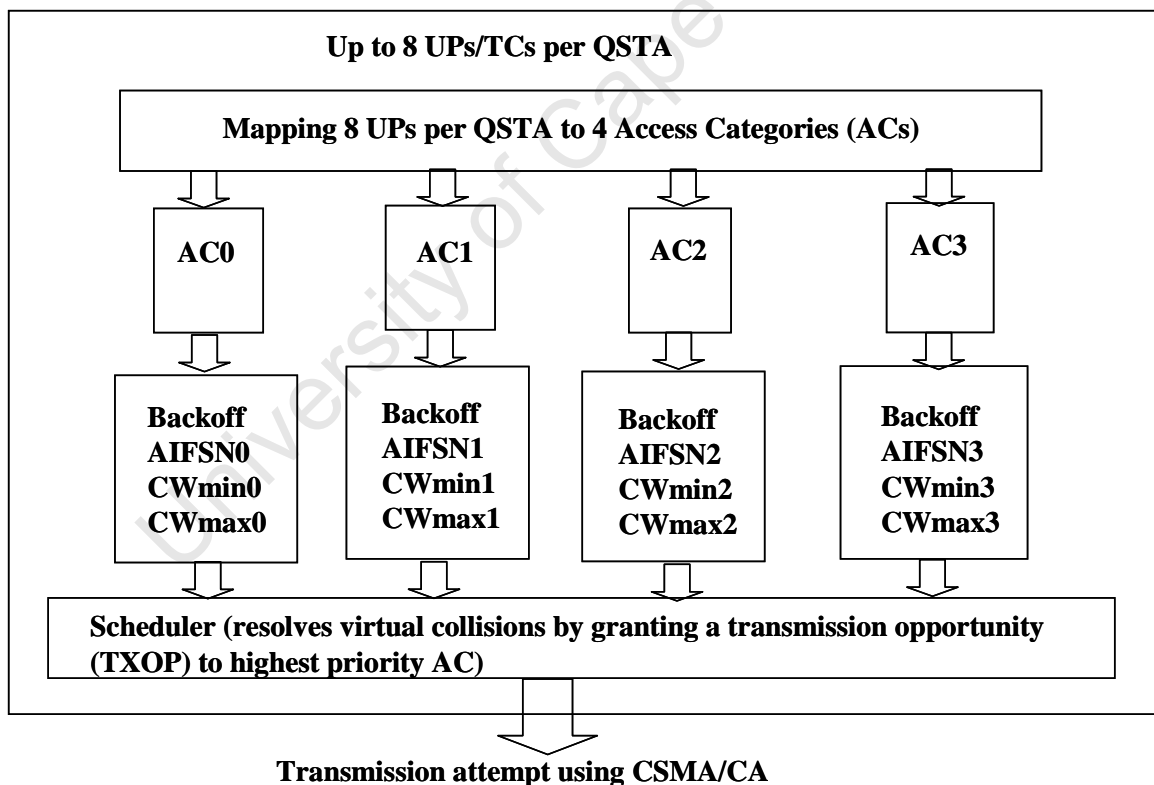
$$\text{AIFS(AC)} = \text{SIFS} + \text{AIFSN(AC)} \times \text{slotTime} \quad (9)$$

The AIFS is made up of many equal duration slots with the slot duration denoted by

slotTime. AIFSN(AC) is an integer that determines how long the AIFS of a particular AC will be and the higher the AC priority the lower the AIFSN value and hence the AC will have a higher chance of accessing the channel.

The values for AIFSN(AC) and slotTime are obtained from the beacon frames transmitted by the QOS-enabled AP (QAP). This is to maintain fairness in channel access for all QSTAs. Central control of these parameters is also useful in view of the fact that the downlink traffic from the QAP is much more than the uplink traffic to the QAP. To make up for this asymmetry the AC parameters for the QAP are different from those of the other non-QAP QSTAs [57].

The differentiated channel access mechanism of EDCA is illustrated in Figure 2.8 below [6].



**Figure 2.9: EDCA Channel Access Mechanism**

After expiry of a time equal to AIFS(AC), the individual contending ACs start counting

down their backoff counters,  $BT_x$  (where  $x$  can be 0, 1, 2 or 3) regardless of whether the channel is idle or not [31]. Upon expiry of  $BT_x$ , the MSDU in the AC that is due to transmit starts contending with other for channel access using DCF. On successfully accessing the channel the AC is granted a TXOP and the maximum number of MSDUs it can transmit in this TXOP is given by a value denoted as  $TXOP_{limit}$ .

The backoff time,  $BT_x$ , can take on any value in the range  $[CW_{minx}, CW_{maxx}]$  (where  $x$  can be 0, 1, 2 or 3). In the case of an unsuccessful transmission attempt, the  $CW_{min}$  value is increased by a multiplicative factor known as the persistence factor (PF) [58].

Various studies have shown that the EDCA scheme is suitable for service differentiation of multimedia traffic, and is an improvement to the legacy IEEE 802.11 medium access scheme [56], [59], [60], [61].

Kong *et. al.* showed that with an increase in the number of stations, the higher priority traffic class AC experiences a constant performance level while the lower priority traffic class AC experiences a decline in performance, in terms of throughput [61]. This is as expected since an increase in stations means there is more traffic contending for the same amount of bandwidth and the higher priority traffic get the bigger amount of service.

Qiang *et. al.* demonstrated that EDCA experiences a drop in throughput in the saturation region (when the offered network load is higher than the effective data bandwidth of the WLAN) [62].

Hui *et. al.* demonstrated that the service differentiation abilities, in terms of throughput, of the EDCA scheme are mostly influenced by a combination of the AIFS and CW parameters, followed by the AIFS parameter alone, and least by the CW parameter [63].

Due to the fact that EDCA does not provide performance guarantees, various schemes incorporating admission control have been proposed to improve the QoS performance of EDCA [64], [65], [66]. The schemes assume that if the amount of traffic into the network is controlled, the performance guaranteeing capabilities of the EDCA scheme will improve, which premise has been proved by the simulations, albeit not very strongly.

Another issue that still remains to be resolved is the inter-operation of EDCA with the legacy IEEE 802.11 medium access mechanisms [56].

### **2.7.2.2 HCCA**

The HCCA scheme consists of a hybrid coordinator (HC) that is usually located in the AP. QSTAs with data to transmit send TSPECs which consist of their required data rate, maximum service interval, nominal frame size and delay bound. The HC will then determine if the TSPEC can be accommodated using an admission control algorithm, and if it can then a traffic stream is established between the QSTA and QAP.

The HC will then use a traffic scheduling algorithm to assign the QSTA a TXOP [67]. The IEEE 802.11-2007 standard does not specify the type of traffic scheduler or admission control algorithms to use, but leaves the implementation specifics to the equipment manufacturer. The IEEE 802.11-2007 standard does however give an example of a simple round robin scheduler and admission control unit [6].

HCCA has been found to provide good QoS to constant bit rate (CBR) traffic [68]. However HCCA needs to be coupled with an adaptive traffic scheduling mechanism to handle variable bit rate (VBR) traffic well, as demonstrated by Qiang [68].

Cicconetti *et. al.* and van der Schaar *et. al.* have incorporated cross-layer designs into the HCCA scheme in a bid to improve the fairness of the traffic scheduling mechanism and to minimize the wastage of bandwidth [69], [70]. Both schemes utilize information from the application layer to provide better service guarantees to multimedia traffic flows.

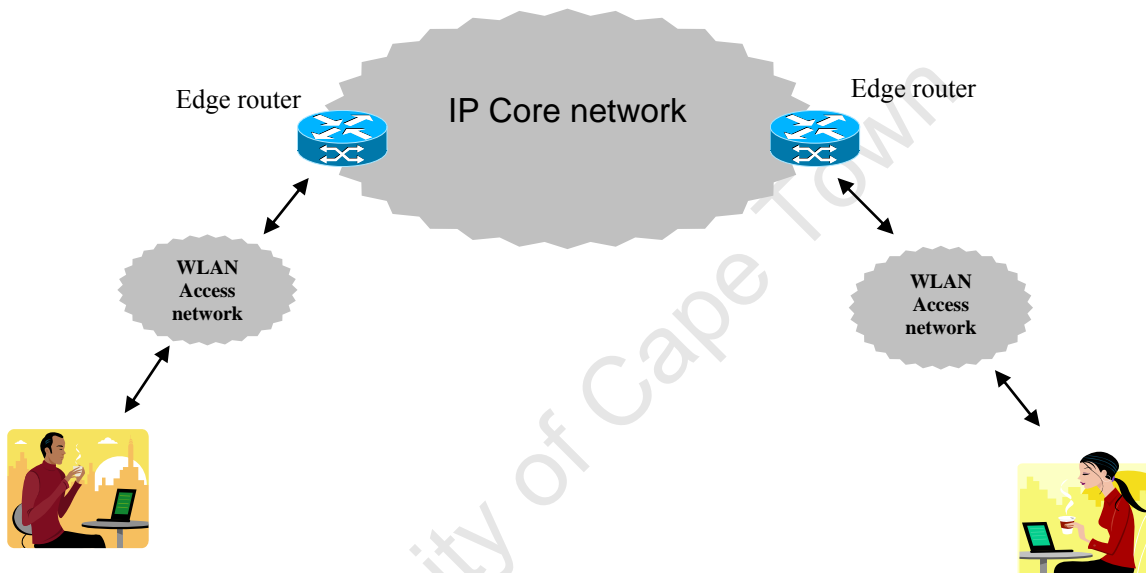
### **2.7.3 Effect of Varying Channel Conditions**

The WLAN channel can experience varying levels of interference from other wireless sources, multi-path propagation effects, and physical obstacles which affects the error rate of the transmitted wireless bits, and subsequently the ability of the WLAN to provide QoS is compromised. Various authors have suggested enhancements to the IEEE 802.11-2007 standard to accommodate these varying channel conditions [67], [69]. However, the effect of varying channel conditions will not be considered in this research.

## Chapter 3 Design of a QoS Enabling Scheme for a WLAN-Wired Network

In this chapter, a design for enabling end-to-end QoS in a WLAN-wired network is presented.

The topology of a typical WLAN-wired network is illustrated in Figure 3.1.



**Figure 3.1: Illustration of End-to-End WLAN-wired network**

The IEEE 802.11-2007 EDCA scheme is used to provide MAC layer QoS in the WLAN while WRR queue scheduling at the IP layer provides QoS in the wired core network.

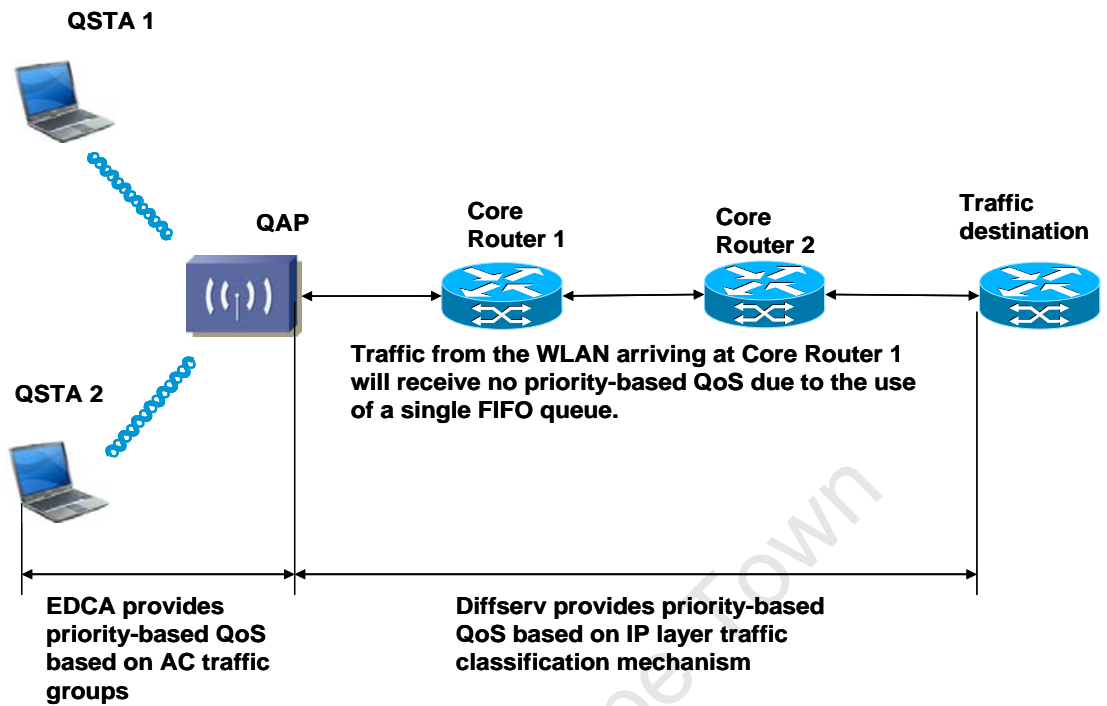
QoS is a critical part of access networks such as UMTS and WLAN, which unlike DSL, WiMAX and Cable TV access, have relatively small bandwidth. Conversely, QoS is less of a concern in the core network than in the access network because the core is composed of high bandwidth and low error-rate wired or optical networks. Examples of core network links are Ethernet and ATM which experience very low transmission errors, typically less than  $10^{-9}$ , and their traffic flows do not experience as much delay and packet drop problems as in the access networks, where bandwidth is more limited [71].

However, bandwidth-limited networks are common in under-developed regions such as Africa, with distant links to telecom points-of-presence (POP) run over microwave, satellite, or even E1/T1 copper lines. The research focuses on networks with bandwidth-limited core network links between the access and service networks. Service networks are the networks that host multimedia services. Examples include VOIP gateways, multimedia conferencing servers, and multimedia streaming servers. The core network is composed of wide area network (WAN) transmission links that carry the aggregated access network traffic to the service network. If WLAN can effectively support multimedia traffic over these bandwidth-limited WAN links, they will prove useful for the provision of telecommunication access to previously un-served areas.

The research introduces a scheme to enable the seamless inter-working of the IEEE 802.11-2007 WLAN EDCA mechanism and the wired IP layer QoS which is WRR queue scheduling.

### **3.1 Limitations of QoS Provisioning in a WLAN-Wired Network**

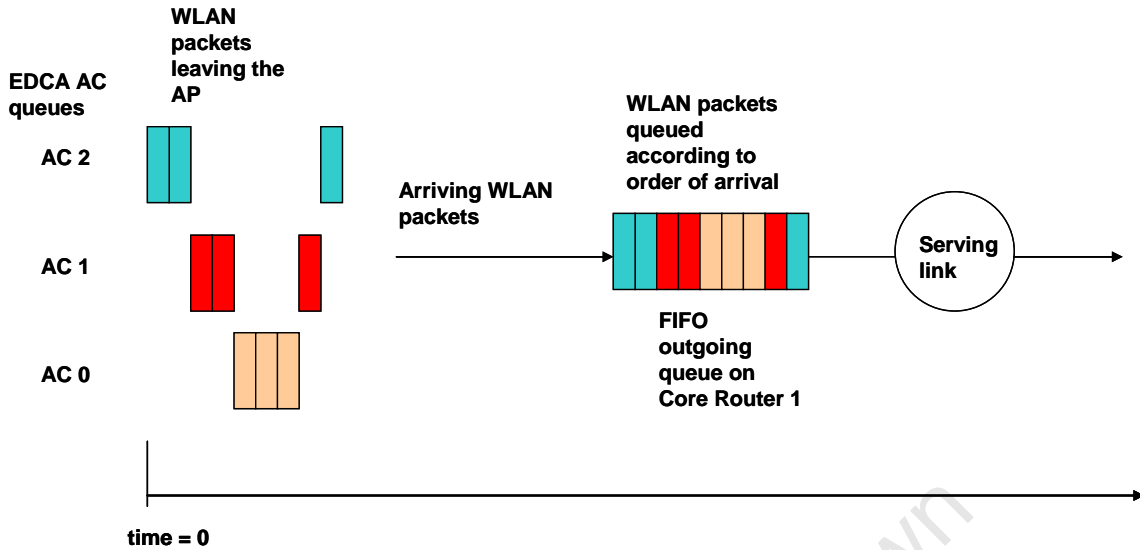
Figure 3.2 below will help in illustrating the limitation of a WLAN-wired network which does not have end-to-end QoS enabled.



**Figure 3.2: Limitation of Disparate QoS Schemes on WLAN-Wired Networks**

From Figure 3.2 above, it can be seen that there is no guarantee that the wired network will provide better QoS to high priority WLAN traffic as opposed to lower priority WLAN traffic.

The above scenario can be further illustrated by considering the application of a single FIFO queue on the outgoing interface of core router 1 in Figure 3.2. All the EDCA traffic from AC 0, 1 and 2 will queue at the router according to their order of arrival, as illustrated in figure 3.3.

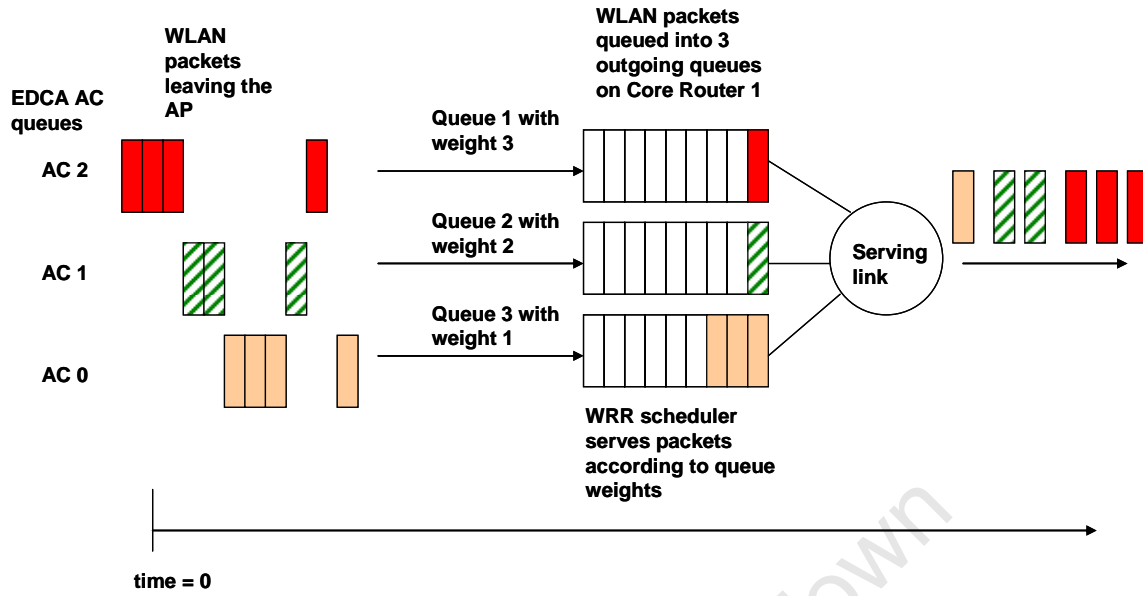


**Figure 3.3: Core Routers with FIFO Queuing**

Traffic from AC 2 is the highest priority traffic and traffic from AC 0 is the lowest priority traffic. As can be seen all three lowest priority packets will be transmitted out of the router link before the last two highest priority packets. The highest priority traffic does not receive any special treatment compared to the lower priority traffic. This shows that FIFO does not provide QoS. If the network experiences a high flow of lower priority packets, the highest priority traffic would be starved of service.

### 3.2 Improvements due to the Enabling of End-to-End QoS

In considering a WLAN-wired network with end-to-end QoS enabled, the network layout is similar to that of Figure 3.2, but all the core routers have three WRR scheduled queues on the outgoing interface. The traffic arrival and queuing process in a core router are illustrated in figure 3.4 below.



**Figure 3.4: Core Routers with WRR Queue Scheduling**

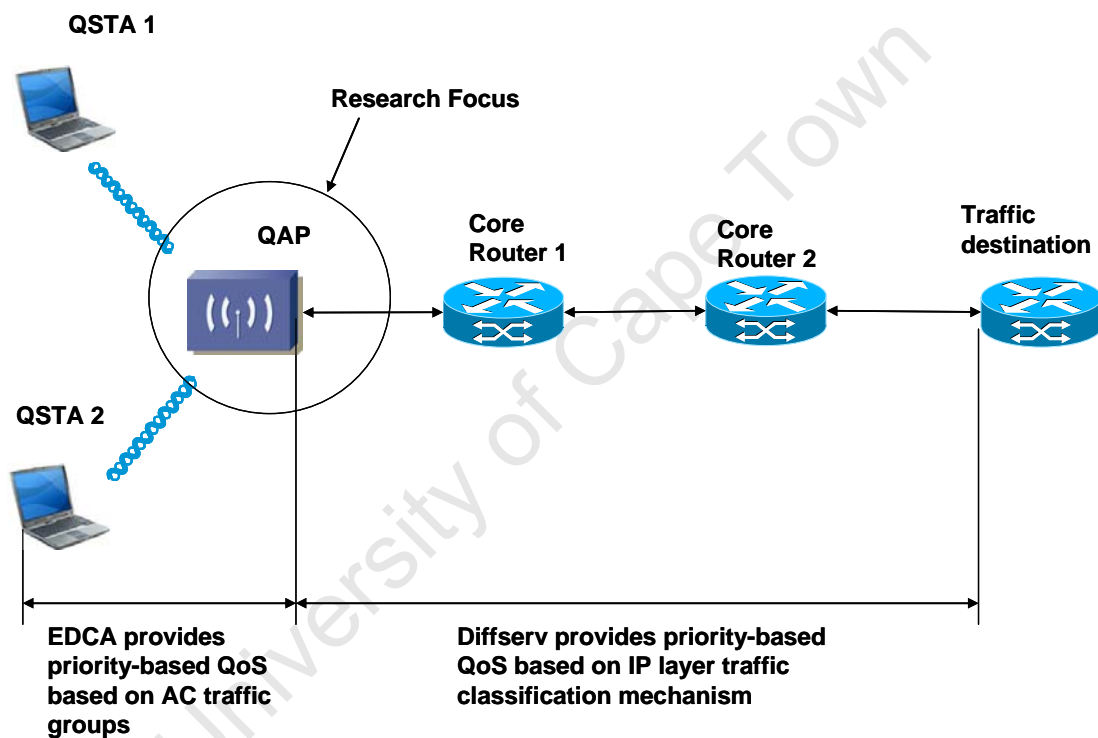
As can be seen from Figure 3.4 above the highest priority AC 2 packets obtain the highest priority transmission on the WLAN as well as the wired network. This is consistent with what is required from an end-to-end QoS scheme.

### 3.3 Proposed Scheme

The aim of this research is to enable seamless end-to-end QoS on a WLAN-wired network, using a scheme that maps traffic classification mechanisms across the WLAN-wired interface.

The proposed scheme is based on priority differentiation of different traffic flows. The traffic flows can be identified according to source IP, source port, destination IP, destination port, or transport layer protocol. The traffic flows are identified and classified into different traffic groups, and the QoS mechanism will apply different treatment to each group according to its classifier marking. To provide QoS to the different traffic classes, the EDCA scheme will be used in the WLAN and WRR in the wired network. Traffic conditioning mechanisms such as rate-limiting, traffic policing, and algorithmic droppers will not be considered in the wired network.

Since the QoS schemes are different and operate on different layers it is desirable to maintain the two schemes functioning separately on the two networks. However, there must be a mapping of the traffic classes between the two networks which will maintain the classifications and relative traffic class priority across the two networks. The mapping is carried out in a module located on the boundary between the WLAN and wired network, in the QAP. Figure 3.6 below illustrates the research focus area. The links to the two core routers are Ethernet links and the QAP has two interfaces, one for connection to the WLAN and the other to the wired Ethernet network.



**Figure 3.5: Research Focus**

The WLAN and wired QoS schemes use the same traffic classification mechanisms which include source identifiers, destination identifiers and application traffic in order to uniformly prioritize different traffic flows.

### 3.3.1 Logical Design of the WLAN-Wired QoS Inter-working Scheme

The QAP has a mapping table that maps AC values from the WLAN to traffic classes on the wired network. The mapping is carried out in the AP and applies to traffic in either direction. The mapping scheme read and writ to and from the appropriate fields in the MAC and IP headers.

The general frame format of the MSDU as well as the number of octets that make up each field are shown in Figure 3.6 below [6]. The last field is used for error checking and is known as the frame check sequence (FCS).

<b>Number of bits</b>	16	16	48	48	48	48	16	16	0-18432	4
	Frame Control	Duration/ID	Address 1	Address 2	Address 3	Sequence Control	Address 4	<b>QoS Control</b>	Frame Body	FCS

**Figure 3.6: General Frame Format of the IEEE 802.11-2007 MSDU**

The 16-bit QoS control field contains the value of the TS or TC that the MSDU belongs to [67]. The QoS control field also identifies the type of data the MSDU contains and the duration of the TXOP.

There are two types of IP packets and they are; IP version 4 (IPv4) and IP version 6 (IPv6). IPv4 was the original IP packet type used in the Internet.

Figure 3.7 illustrates the general header format of an IPv4 packet with the field sizes indicated in brackets [72].

32 bits length			
Version (4 bits)	Header Length (4 bits)	Type of Service (8 bits)	Datagram Length in bytes (16 bits)
Fragmentation Identifier (16 bits)		Fragmentation Flags (3 bits)	Fragmentation Offset (13 bits)
Time-to-live (8 bits)	Transport Layer Protocol Identifier (8 bits)	Header Checksum (16 bits)	
Source Header (32 bits)			
Destination Header (32 bits)			
Options (not commonly used)			
Data Payload			

**Figure 3.7: IPv4 Header Format**

The type of service field (ToS) was originally meant to enable an IP packet to request specialized treatment such as minimal delay and maximum throughput [9]. The field is now used to contain the DSCP value in the six left-most bits while the two remaining bits are unused [49].

IPv4 provides a limited number of addresses, and this led to a fear that the explosive growth of the Internet would exhaust the entire IPv4 address space. In response to this concern, the IETF released the IPv6 protocol standard [73].

The general packet format of an IPv6 packet is shown in Figure 3.8 with the field sizes in brackets [72].

32 bits length			
Version (4 bits)	Traffic Class (8 bits)	Flow Label (20 bits)	
Payload Length (16 bits)		Next Header which identifies the Transport Layer Protocol (8 bits)	Hop Limit (8 bits)
Source Header (128 bits)			
Destination Header (128 bits)			
Data Payload			

**Figure 3.8: IPv6 Header Format**

The traffic class field was envisaged to provide the same functionality as the ToS field in the IPv4 packet header. It is currently used to contain the DSCP value in the six left-most bits with the two remaining bits not in use.

The IPv6 flow label field is used to identify packets belonging to a particular traffic flow so that they can receive special treatment such as minimum delay and maximum throughput [74]. Network devices use the flow label, source address, and destination address to identify a particular traffic flow.

### **3.3.2 Mapping MAC layer AC to IP Layer Traffic Markings**

There are two possible ways to map the WLAN MAC layer AC to wired IP layer traffic classification markings and they are:

- mapping WLAN AC to IPv4 or IPv6 DSCP values. This is the preferred approach, since the Diffserv QoS scheme is standardized and the most popular choice for the implementation of QoS in wired IP networks. In this research, any further reference to mapping WLAN AC to DSCP values will encompass both IPv4 and IPv6.
- mapping WLAN AC to the IPv6 flow label field. This is an alternative mapping scheme that could be used in a network with flow label aware devices such as routers [74]. It is a simpler implementation in terms of the mapping scheme. The routers could then provide differentiated services to different IP flows in the network.

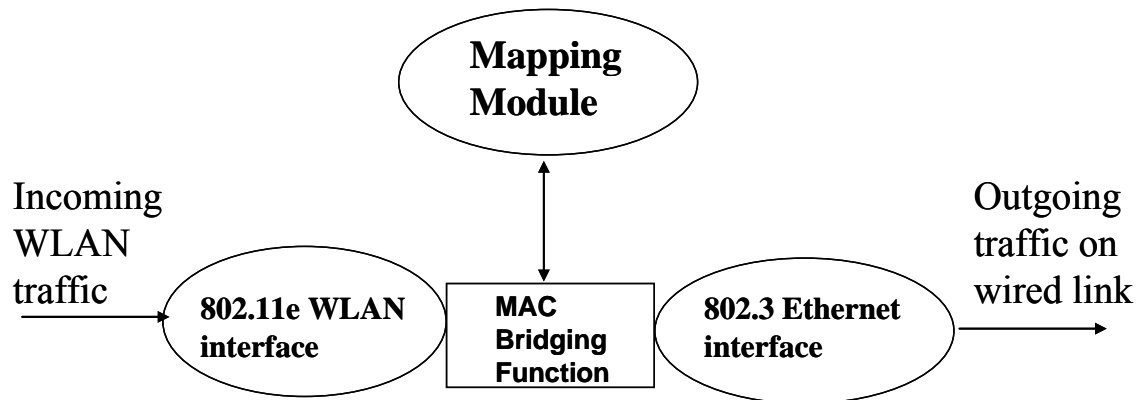
A proposed mapping table with is shown in Table 3.1 [6], [31].

**Table 3.1: Proposed Mapping Table**

Traffic class	Type of traffic	IEEE 802.11e AC (AC Index)	DSCP	Flow Label
Class 1	Voice	AC_VO (11)	101110 (EF)	3
Class 2	Video	AC_VI (10)	100xxx (AF4x)	2
Class 3	Signaling traffic	AC_BK (01)	010xxx (AF2x)	1
Class 4	Normal data traffic (web, email)	AC_BE (00)	000000 (default best effort)	0

The AF4x and AF2x values in Table 3.1 can take on the values 0 or 1 depending on the drop precedence levels assigned to them [50]. These values are at the operator's discretion. Further details will not be presented, since this research is only concerned with differentiated priority service.

The mapping module will consist of a software program and its logical operation is illustrated in Figure 3.9 below. The QAP containing the mapping module will have multilayer processing capabilities to enable it to manipulate the data packets at the MAC and IP layers.



**Figure 3.9: Logical Layout of Mapping Module in AP**

The QAP is a wireless to wired bridge that receives WLAN frames, looks up the destination MAC address in the WLAN MAC header, strips the wireless MAC header, encapsulates the resulting IP packet with an Ethernet MAC header and places it into the appropriate Ethernet link outgoing queue. Ethernet to WLAN frames passing through the AP are bridged in a reverse order.

With the introduction of the mapping module in the QAP the bridging function will alter slightly. When a WLAN frame arrives at the AP WLAN interface, the mapping will be carried out as follows:

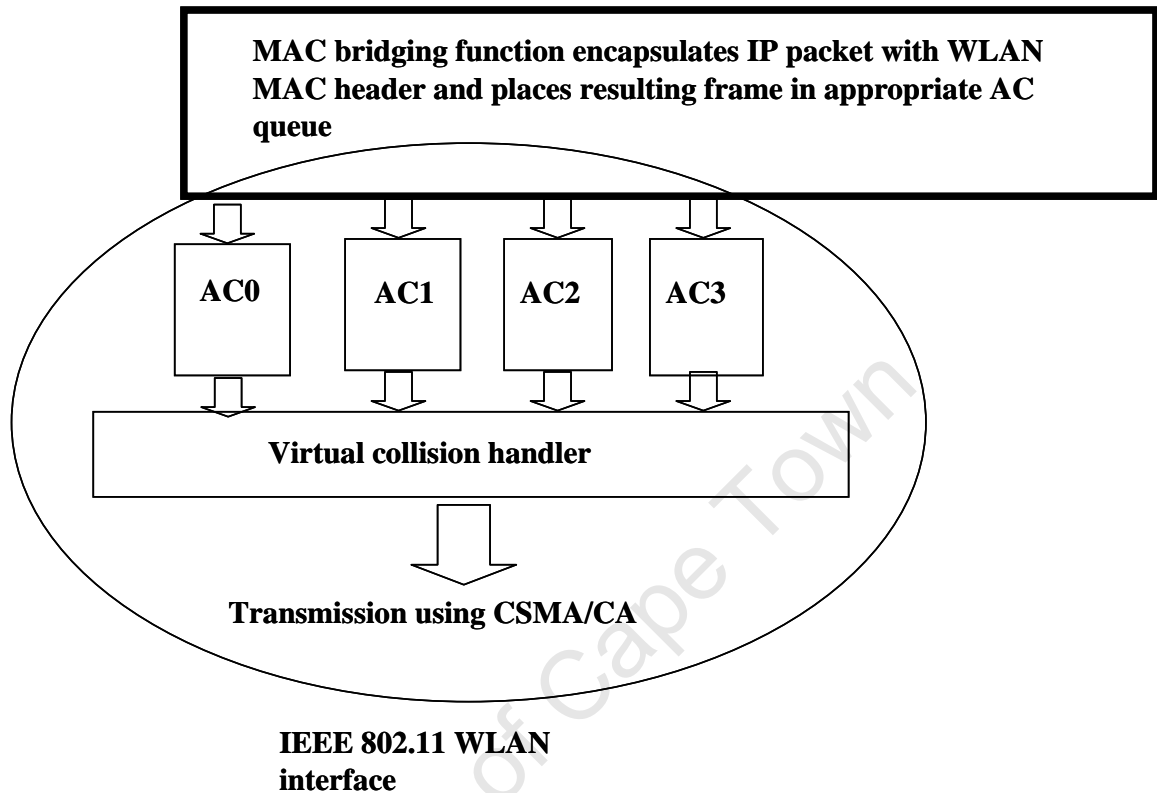
- the WLAN frame will be passed onto the MAC bridging function,
- the MAC bridging function will extract the AC value in the WLAN MAC header and store it,
- the MAC bridging function will strip the WLAN MAC header from the frame and forward the resulting IP packet together with the frame's AC value to the mapping module,
- the mapping module will use the received AC value to lookup the corresponding DSCP value (or IP flow label) for the arriving IP packet,

- the mapping module will write the corresponding priority value in the DSCP (or IP flow label) field of the packet,
- the mapping module will then pass the modified IP packet back to the MAC bridge,
- the MAC bridge will encapsulate the modified IP packet with an Ethernet MAC header and pass it on to the Ethernet interface for transmission on the wired network.

The Ethernet frames transmitted onto the network will then have DSCP (or IP flow label) values in their IP packets which will enable them to receive QoS from the wired network.

Traffic from the wired to the WLAN network will have its DSCP (or IP flow label) values mapped to corresponding AC values, although the process will differ slightly from the one used for traffic from the WLAN to the wired network. The process is detailed below.

- the arriving Ethernet frame will be passed onto the MAC bridging function,
- the MAC bridging function will remove the Ethernet MAC header and pass the resulting IP packet to the mapping module,
- the mapping module will read the DSCP (or IP flow label) value of the received IP packet and lookup the corresponding AC value for the IP packet it received,
- the mapping module will send the read AC value and IP packet back to the MAC bridging function,
- the MAC bridging function will encapsulate the received IP packet with a WLAN MAC header and place it in the appropriate AC queue. This is illustrated in Figure 3.10.



**Figure 3.10: Treatment of Packets from the Wired to the WLAN Network**

The WLAN frames placed in the AC queues will receive prioritized QoS from the EDCA scheme operating in the WLAN.

In the following chapter, an experimental framework to investigate the performance of the proposed scheme will be presented.

## **Chapter 4 Experimental Evaluation of WLAN-Wired QoS Scheme**

A proposed mapping scheme to enable the inter-working of WLAN and wired QoS scheme was described in the previous chapter. In this chapter, an experimental framework for investigating the performance of the proposed design is presented.

The experimental evaluation is a simulation study using the Network Simulator 2 (NS2) simulation software. The software implementation is described first, then the network topology is presented and finally the data collection process is explained.

### **4.1 NS2 Experimental Framework**

NS2 is a discrete event simulator that is used to perform wired and wireless network experiments [21]. It was developed by the Defense Advanced Research Projects Agency (DARPA) of the United States Department of Defense (DoD) as part of the Virtual InterNetwork Testbed (VINT) project. NS2 is written in the C++ programming language and utilizes the Object Tool Command Language (OTcl) to run Tel simulation command scripts. NS2 is a widely used open source software that has support for many network protocols through user supported modules.

In these research experiments the NS2 version 2.28 base software and a few additional modules were used. The additional modules are described in the following sub-sections.

#### **4.1.1 The TKN EDCA Module**

The TKN EDCA model provides IEEE 802.11-2007 EDCA functionality without the HCCA scheme [58]. The EDCA only module is sufficient for the experiments to be conducted since the design does not utilize the HCCA scheme.

The TKN EDCA model is the only IEEE 802.11-2007 implementation that can carry out wired-cum-wireless simulations in NS2. Its performance was verified by Wiethoelter *et. al.* and

researchers such as Selvig *et. al.* have used the TKN EDCA model [75].

The TKN EDCA model implements up to four interface queues between the MAC and network layer. The interface queues represent relative priority queues, with the priority values of 0 to 3 indicated in the prio field of the IP packet header. The highest priority field is indicated by 0 and the lowest priority by 3. The TKN EDCA software's priority value ordering is at odds with the AC priority values, as indicated in Table 2.2 and Table 3.1, and this is inherent in the software design [58]. However as long as the relative priority of the queues is maintained there will be no effect on the experiments.

The TKN EDCA model implements the contention free bursting (CFB) scheme which allows for the transmission of multiple MSDU in a single TXOP as long as the TXOP limit is not exceeded [58].

The TKN EDCA model implements a backoff algorithm modeled on the IEEE 802.11-2007 EDCA backoff algorithm, but modified to make it less complex in the software implementation [58].

Three priority levels were implemented in the experiments hence three AC queues were used. The timer values used in the experiments are shown in table 4.1 below.

**Table 4.1: TKN EDCA Timer Parameter Values**

<b>Parameter</b>	<b>High Priority</b>	<b>Medium Priority</b>	<b>Low Priority</b>
PF	2	2	2
AIFSN	2	4	7
CWmax	7	10	15
CWmin	7	31	255

The TKN EDCA model is incorporated into the NS2 base software through the use a software patch. Some modifications to the NS2 WLAN implementation must be carried out as described in the following sub-section.

### 4.1.2 Modifications to the NS2 WLAN Implementation

The existing legacy IEEE 802.11 NS2 MAC implementation has a number of limitations, which are [76]:

- When a WLAN STA begins to countdown its DIFS timer before data transmission, the timer is supposed to stop in the event of another station beginning its transmission. However, in the NS2 IEEE 802.11 legacy implementation, the DIFS timer will countdown completely and subsequently a backoff timer will be started.
- After a successful data transmission and acknowledgement, a backoff timer is started in the event of an idle medium and its duration is determined by the prior remaining backoff time. The backoff timer should instead have a duration equal to the remaining backoff time plus the DIFS duration.
- The calculation of the backoff time is not done properly and always leads to a value less than the selected `randomSlotNumber()` multiplied by the slot time (as given by equation 3 in sub-section 2.7.1). This is not a problem in the legacy IEEE 802.11 implementation, but with the IEEE 802.11-2007 EDCA differentiated service queues it is a critical issue.
- The NAV that is a sum of a number of timers includes the DIFS timer, which should not be the case. The NAV should also be reset on the reception of a valid frame, which is not the case in the existing NS2 implementation.
- There is no separate SIFS timer implemented in the legacy IEEE 802.11 implementation.

An WLAN patch by Wiethoelter *et. al.* was applied to the NS2 software to address the shortcomings detailed above [75].

### 4.1.3 WRR Implementation

A software patch by Sayenko *et. al.* was added to the NS2 software to provide WRR

functionality [77]. The WRR module implements up to three different queues on an outgoing router queue. Each queue is assigned a weight that reflects its proportional access to link resources. The link resources in this case are bandwidth and minimal queuing delay. The weights reflect the number of packets that are de-queued for transmission during a single service cycle. The module implements a work conserving WRR scheduling algorithm which jumps empty queues and services the next non-empty queue.

The module also implements an optional alternate priority queue scheduler. A single queue is designated as the priority queue. The priority queue is serviced alternately during each service cycle of the WRR scheduling scheme. This means that in between servicing the normal weighted queues the priority queue is serviced until no packets remain in the queue.

#### 4.1.4 Mapping Module Implementation

The mapping module was implemented in the Tcl simulation script. In our experiments the WLAN EDCA AC markings were mapped to the IP flow label identifiers (ID). The routers in the network will use the flow label markings to distinguish traffic flows and implement QoS using WRR.

The mapping scheme was implemented as shown in Table 4.2 below. As mentioned in section 4.1.1, the priority value ordering is at odds with the AC priority values. This is a consequence of the software implementation, but as long as the relative priority of the queues is maintained there will be no effect on the experiments.

**Table 4.2: Mapping Scheme Implemented**

Priority	AC Queue Number	IP Flow Label
High	0	0
Medium	1	1
Low	2	2

It should be noted that the flow label number ordering used in the WRR module are at odds with those indicated in Table 3.1. This is because the WRR module has to be integrated with the TKN EDCA module and as explained in section 4.1.1, the TKN EDCA software model

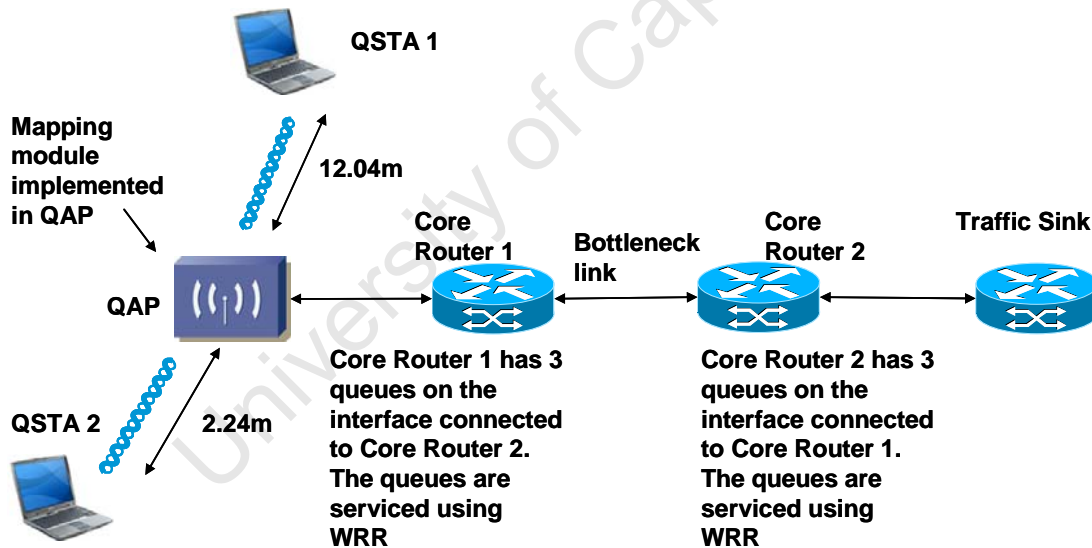
has AC number 0 as the highest priority queue, which is not the convention used in the proposed mapping scheme presented in Table 3.1.

### 4.1.5 NOAH Routing Protocol

The No Ad-Hoc Routing Agent (NOAH) routing protocol is used to route packets between the WLAN and wired networks [78]. It only supports communication between directly linked wireless and/or wired nodes on a per hop basis. The NOAH routing protocol does not use routing updates to set up its routes but it relies on static routing information that is learned from the topology setup, prior to the start of the simulation.

## 4.2 Network Topology Used in Experiments

The network consisted of a heterogeneous WLAN-wired network as shown in Figure 4.1.



**Figure 4.1: Network Topology used in Experiments**

QSTA1, QAP, and QSTA2 are aligned in a straight line. QSTA1 was not disadvantaged by its longer distance from QAP in terms of accessing the wireless channel. The distances from the QAP were selected arbitrarily. The QSTAs were stationary and there was no hidden node

problem. The WLAN implements the EDCA-only QoS scheme. The wireless interface queues can each contain up to 50 packets.

The experimental WLAN was based on the IEEE 802.11b standard which operates in the 2.4 GHz band. The WLAN bandwidth used throughout the experiments was 2Mbps because only two QSTAs were used, so the bandwidth had to be lowered from the standard 11Mbps to enable the link to be easily saturated and a bottleneck to be created at the QAP. The presence of a constraint at the QAP enables the examination of the QoS effectiveness of the EDCA scheme.

It has been shown that a WLAN with a data rate  $BW$ , has an effective bandwidth less than  $BW$  [57], [79]. In the presence of two transmitting QSTAs and a QAP that does not originate traffic the effective bandwidth is approximately  $BW/2$ . Since the bandwidth in all the experiments is 2Mbps, the effective bandwidth will be approximately 1Mbps and it is expected that the WLAN link will become saturated with traffic at an offered load of 1Mbps. At this point the WLAN will be operating in its saturation region.

Assuming an almost fair distribution of  $BW$  bandwidth between  $N$  QSTAs, each QSTA will have a bandwidth given by:

$$\frac{BW/2}{N} \quad (5)$$

The QAP will receive and transmit traffic with a bandwidth given by:

$$\frac{BW/2}{N} \times N \quad (6)$$

In a network topology with two QSTAs and uplink traffic only, the QAP will receive and transmit traffic with a bandwidth given by  $BW/2$ . This value of bandwidth assumes that the QAP will not drop any frames due to buffer overflows. It must be noted that this is an estimation of the bandwidth value.

The wired link has the same bandwidth at all segments except the bottleneck link. The

bottleneck link is used to introduce a constraint that can better demonstrate the presence of QoS among contending traffic in the wired network.

All the wired router links, apart from the bottleneck link, have single incoming and outgoing FIFO queues with drop-tail queues. Drop-tail queues discard newly arriving or tail-end packets during periods of congestion. The bottleneck link implements three WRR serviced queues at either end of the link. All the queues in the wired router links can contain up to 50 packets.

All the experiments were conducted with two QSTAs. Since each QSTA generates three different types of application traffic, two QSTAs were sufficient for the experiment.

### 4.3 General Simulation Parameters

The general simulation parameters for all the experiment are shown in Table 4.3.

**Table 4.3: General Simulation Parameters**

Parameter	Value
Channel data rate	2Mbps
Traffic type	UDP/CBR
Packet size of priority 0 traffic	160
Packet size of priority 1 traffic	500
Packet size of priority 2 traffic	500
Wired link delay	6ms
Queue length	50 packets
Simulation duration	110 seconds

### 4.4 Type of Traffic Used in Experiments

The traffic used in the simulation is of high, medium and low priority.

High priority traffic is simulated by CBR traffic with a 160-byte user datagram protocol (UDP) data payload and a 20-byte IP header. This is representative of VoIP traffic which is a low bandwidth but delay sensitive application. The bandwidth of the high priority traffic ranges

from 32kbps to 128 kbps. This represents a range of voice codecs which use up to 64kbps bandwidth. The 128kbps bandwidth represents two simultaneous voice calls, each using 64kbps bandwidth.

Medium priority traffic is simulated by CBR traffic with a 500-byte UDP data payload and a 20-byte IP header. This is representative of video traffic which could be streaming or non-streaming video. The bandwidth of the medium priority traffic ranges from 32kbps to 512 kbps.

Although there are very few examples of common high-bandwidth normal data traffic, CBR traffic with a 500-byte UDP data payload and a 20-byte IP header is still used to simulate low priority traffic. The overall results obtained from the experiments are useful due to the use of high-bandwidth consuming low priority traffic. A few examples of normal UDP data traffic are trivial file transfer protocol (tftp), database queries and responses, and domain name system (DNS) queries and responses. The bandwidth of low priority traffic ranges from 64kbps to 768kbps.

The experiment is conducted by varying the offered load in the network. The configuration of the different priority traffic is shown in Table 4.4 below. The traffic configuration remains constant throughout the experiments conducted.

**Table 4.4: Data Rates for the Different Priority Traffic**

Traffic (kbps)	Load	Priority 0 traffic (kbps)	Priority 1 traffic (kbps)	Priority 2 traffic (kbps)
256		32	32	64
320		32	64	64
448		32	64	128
832		32	128	256
1408		64	256	384
2048		128	384	512
2304		128	512	512
2816		128	512	768

The transmission control protocol (TCP) is not used in the experiments because TCP is an elastic protocol that adjusts to congestion and delay in the network, hence it would not be

appropriate for use in the experiments, which are dealing with congested networks.

The experiments are conducted with uplink traffic only because of the experimental software limitations. The uplink traffic originates from the WLAN. The TKN EDCA model does not provide the functionality needed to configure downlink traffic from the QAP to ensure the required QoS implementation [75]. The implementation of downlink traffic in a wired-cum-wireless scenario would require modification to the TKN EDCA software. However experiments in the downlink direction would provide similar results since the WLAN EDCA and wired WRR QoS schemes work in both the uplink and downlink directions.

The experimental results and analysis are provided in the following chapter.

## **4.5 Performance Objectives**

The desired outcomes of the proposed scheme are:

- to ensure different categories of application traffic receive end-to-end differentiated services.
- to ensure higher priority traffic receives better treatment than lower priority traffic.
- to ensure lower priority traffic is not starved of service.

The service requirements of the application traffic will be the performance parameters that will be used to determine the effectiveness of the proposed scheme. The performance parameters that will be investigated are throughput, delay, and lost packets.

## **4.6 Scope of the Simulation Experiment**

A number of restrictions that have a bearing on the simulation experiment are:

- although admission control is not implemented in the wireless network, the network will not be flooded by a high amount of traffic, which would make it completely unusable.

- rate limiting and traffic shaping mechanisms are not present in the network and will not be considered in the experiment.
- there is no resource reservation in the wired network.

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## Chapter 5 Experimental Results and Analysis

This chapter presents results obtained from experiments conducted on a WLAN-wired network with our proposed end-to-end QoS scheme enabled and a baseline network (as presented in sub-section 3.1) without end-to-end QoS enabled. The first part of the experiment consists of analyzing the effect of the wired bottleneck link on the performance of the network, in order to set the wired bottleneck-link bandwidth. The second part compares the performance of the network with WRR scheduling enabled, to WRR with alternate priority scheduling enabled, in the wired part of the network. The third part evaluates the proposed end-to-end QoS WLAN-wired network design using the preferred WRR mechanism against the baseline network.

In the presented results, the high priority traffic is labeled flow0, the medium priority flow1, and the low priority flow 2.

### 5.1 Setting the Bottleneck Link Bandwidth

Since the bandwidth of the data traffic coming out of the QAP cannot be accurately determined, the wired bottleneck link (Core Router1 – Core Router 2) bandwidth has to be set using experimental investigation.

A baseline experiment is run with the link between Core Router 1 and Core Router 2 set at 2Mbps, which is equal to the bandwidth on the other wired links. The wired bottleneck link is then set to 1Mbps, and the experimental results compared to the baseline experiment results to determine if the link indeed acts as a bottleneck.

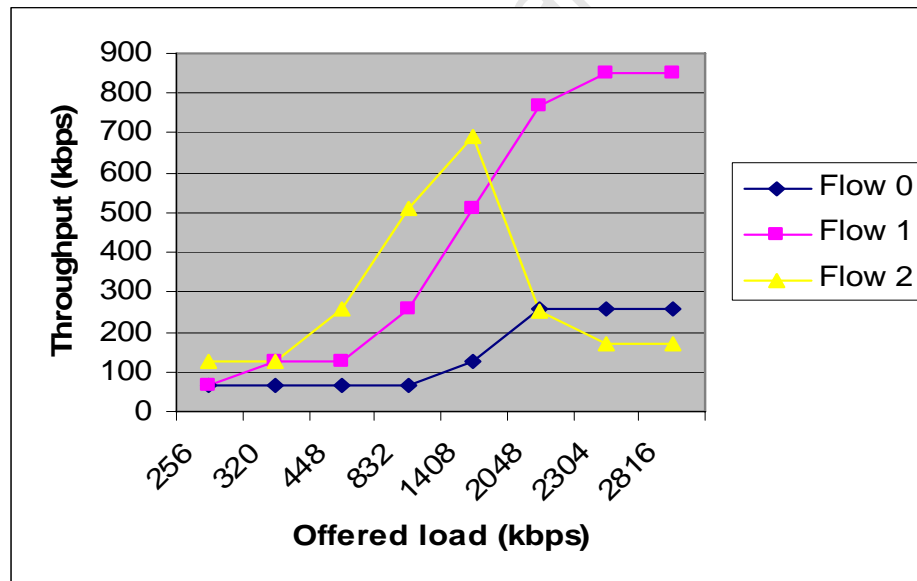
The bandwidth values for the wired link segments are given in Table 7.1.

**Table 5.1: Wired Link Segment Values**

Wired link segment	Data Rate in baseline experiment for setting wired bottleneck link	Data Rate in second experiment for setting wired bottleneck link
Between QAP and Core Router 1	2 Mbps	2 Mbps
Between Core Router 1 and Core Router 2 (Bottleneck Link)	2 Mbps	1 Mbps
Between Core Router 2 and Sink	2 Mbps	2 Mbps

### 5.1.1 Results from Experiment

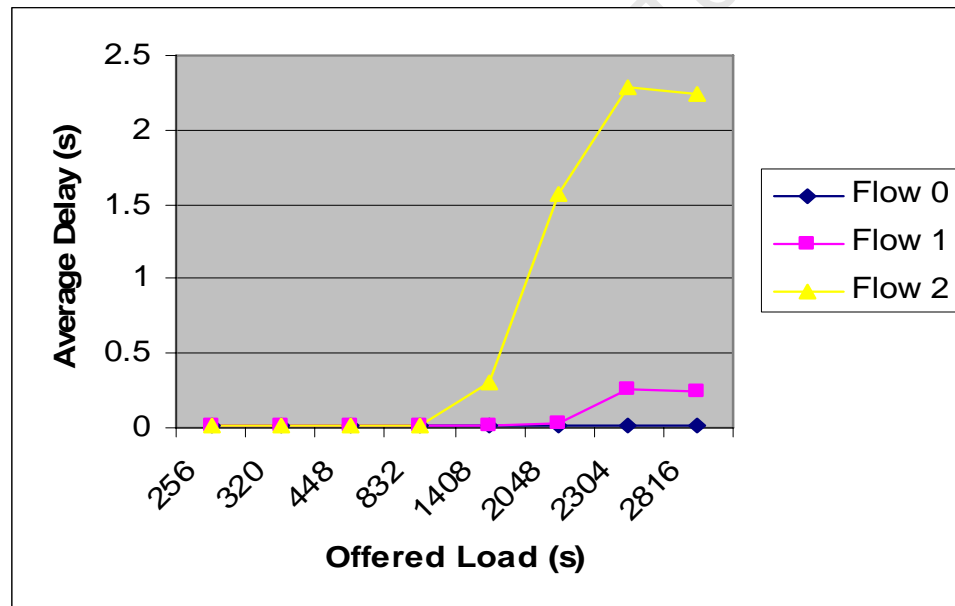
The throughput and average delay obtained after setting the wired bottleneck link to 2 Mbps is illustrated by the graphs in Figure 5.1 and 5.2.



**Figure 5.1: Throughput after Setting Wired Bottleneck Link to 2Mbps**

Considering the values of offered load in Table 4.4 and the graph in Figure 5.1, it can be seen that up to an offered load of 832kbps, the total throughput of all the flows is equal to the offered load. Beyond an offered load of 832kbps, the throughput of flow 2, which is the lowest priority flow, is less than the offered load, while the other flows do not drop any packets. This is

because at an offered load of 832kbps, the WLAN is approaching its saturation region of operation. The WLAN saturation point occurs at an offered load of approximately 1Mbps. In the saturation region of operation the WLAN effective bandwidth is less than the offered load, and the some packets have to be dropped. In an EDCA WLAN the lowest priority flow, will take longer to access the WLAN, hence they will be dropped when still in the WLAN STA buffer queues. At an offered load of 2304kbps and beyond, the throughput of flow 1, which is the medium priority, is less than the offered load, because the increased offered load causes it to suffer packet drops too. Flow 0, which is the highest priority flow, is unaffected by the operation of the WLAN in the saturation region because of its best preference QoS, and the fact that it has a low bandwidth compared to the other flows.

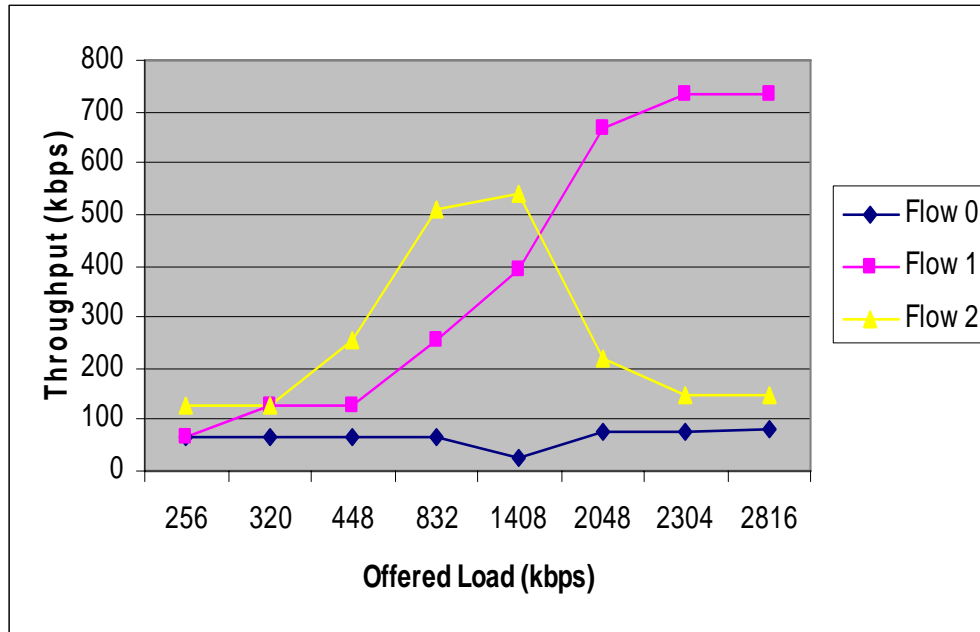


**Figure 5.2: Average Delay after Setting Wired Bottleneck Link to 2Mbps**

From the average delay graph in Figure 5.2 and the offered load values in Table 4.4, it can be seen that up to an offered load of approximately 832kbps, the average delay of all flows is close to 0 seconds (the experimental data indicates a value in the region of 10ms). Beyond an offered load of 832kbps, flow 2, which is the lowest priority flow, has an increased average delay due to the WLAN's operation in its saturation mode. Beyond an offered load of approximately 2048kbps, flow 1, which is the medium priority flow, has an increased average

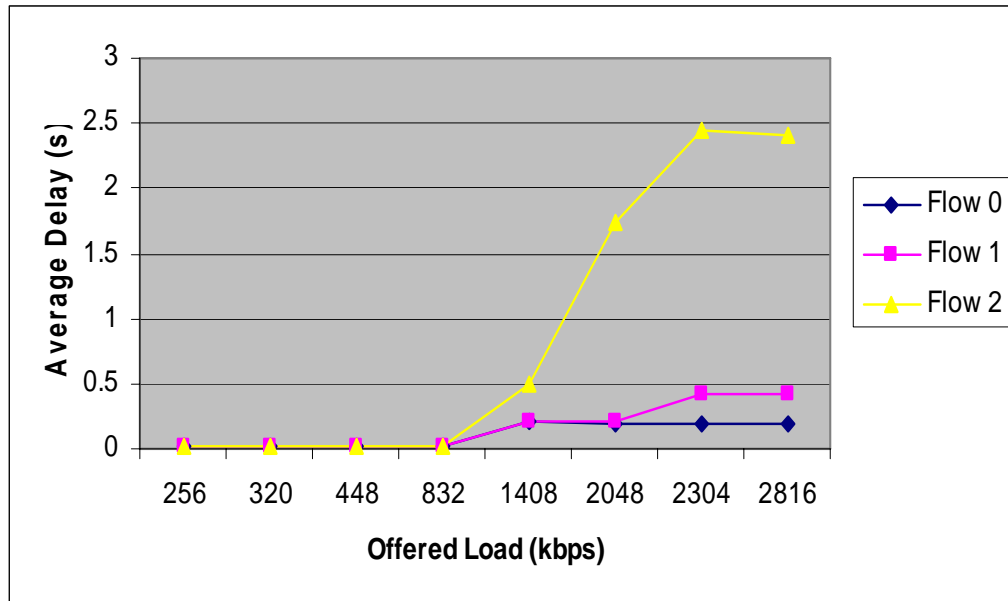
delay due to the new effect of the 2Mbps bottleneck link.

The throughput and average delay obtained after setting the wired bottleneck link to 1 Mbps is illustrated by the graphs in Figure 5.3 and 5.4.



**Figure 5.3: Throughput after Setting Wired Bottleneck Link to 1Mbps**

From Figure 5.3, it can be seen that beyond an offered load of 832kbps, flow 0 is the most affected of all the flows in terms of throughput. Beyond 832kbps, flow 0 has a throughput of 100kbps which is less than its offered load. Beyond an offered load of 1408kbps, both flow 1 and 2 suffer from decreased throughput when compared to their offered load. The throughput performance of all three flows can be attributed to the effect of the 1Mbps bottleneck link.



**Figure 5.4: Average Delay after Setting Wired Bottleneck Link to 1Mbps**

From Figure 5.4, it can be seen that up to an offered load of 832kbps all flows have a very low average delay (the experimental data indicates a value in the region of 10ms). Beyond an offered load of 832kbps, flow 0 and 1 have a delay of 200ms because of the combined effect of the WLAN saturation mode of operation and the 1Mbps wired bottleneck link. This is in contrast to the results of Figure 5.2 where the effect of 2Mbps wired bottleneck link is only felt at an offered load of 2048kbps. Flow 2, has a greatly increased delay after an average load of 832kbps, because it has the lowest priority in the WLAN EDCA QoS scheme.

From the results above it can be seen that with the wired bottleneck link set to 2MB, flows 1 and 2 peak at higher throughputs than when the wired bottleneck link is set to 1MB. The average delay performance of flow 0 and 1 is better when the wired bottleneck link is set to 2MB, than when it is set to 1MB.

From the results presented above, it can be seen that setting the wired bottleneck link to 1MB results in an effective wired-link bottleneck.

## 5.2 Comparing WRR and WRR with Alternate Priority Mode

In this part of the experiment, the aim is to compare the performance of the baseline network, which does not include the proposed scheme, with a network that implements the proposed scheme. The aim is to show that with the introduction of the proposed design for mapping QoS traffic classes across a WLAN-wired network, there will be an improvement in the service differentiation capabilities of the network.

All the experiments for the QoS enabled wired network are conducted using the same general parameters used for the bottleneck link experiment. The bottleneck link is set to 1Mbps.

WRR queue scheduling is compared with a combined WRR and alternate priority queue scheduling mechanism, which shall be known as AP/WRR. The priority queue is queue 0, which contains packets from the highest priority flow 0. The purpose of using AP/WRR is because a specified premium service traffic class, such as VoIP which is delay sensitive, has been designated.

Different weight combinations for WRR and AP/WRR will be investigated, and the best WRR or AP/WRR weight combination will be selected. Four different weight combinations will be investigated and they are listed in Table 5.2.

**Table 5.2: WRR Weight Combinations**

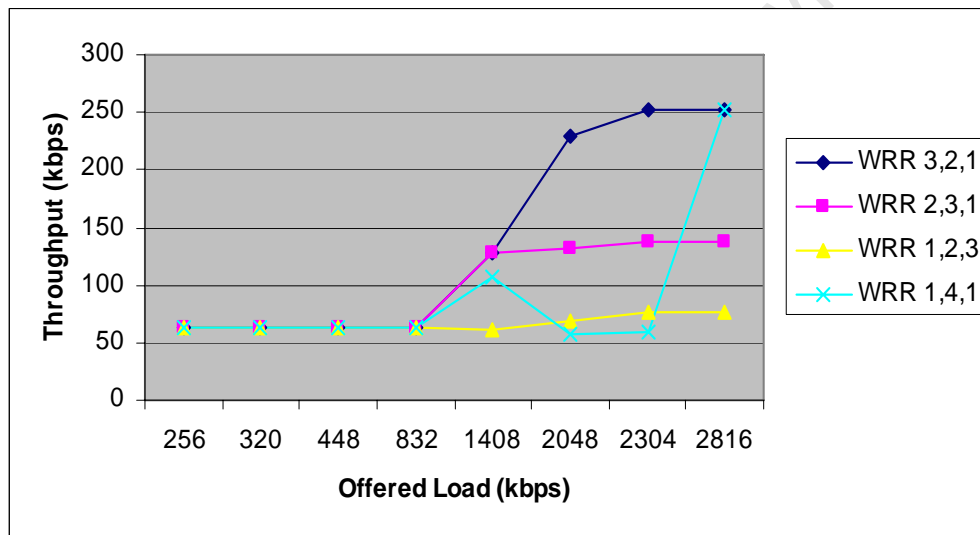
<b>WRR Weights</b>	<b>Flow 0/ Priority 0</b>	<b>Flow 1/ Priority 1</b>	<b>Flow 2/ Priority 2</b>
3, 2, 1	3	2	1
2, 3, 1	2	3	1
1, 2, 3	1	2	3
1, 4, 1	1	4	1

The reason for investigating different weight combinations is to ensure the highest priority traffic is getting very good service, and to see if the starvation of lower priority traffic can be minimized. It should be borne in mind that WRR has more of an impact on the delay experienced by the packets as opposed to the bandwidth distribution among the different queues.

## 5.2.1 Results from Experiment

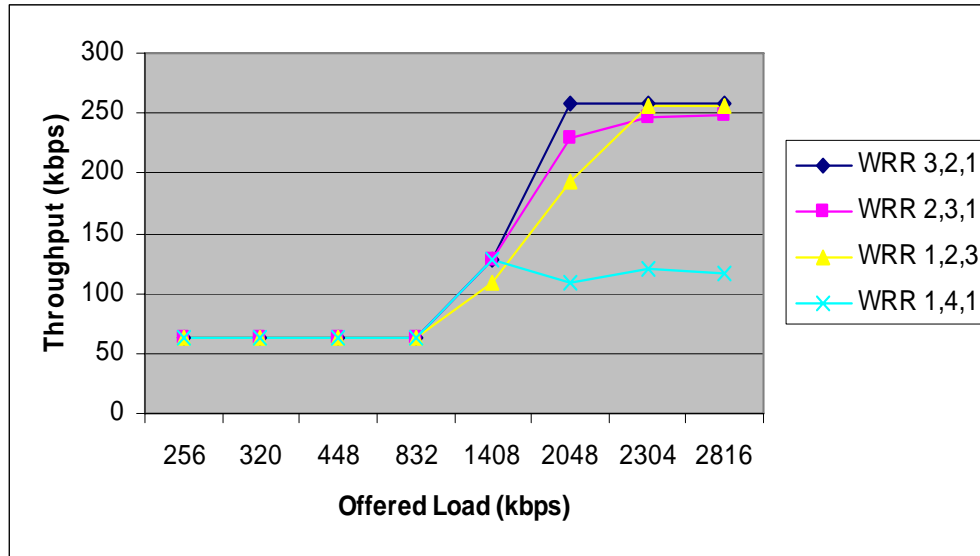
Experiments with WRR and AP/WRR enabled on the bottleneck link are carried out using the WRR values shown in Table 5.2. The performance of flow 0 will be used as the criteria for performance improvement of the WRR and AP/WRR system. This is because flow 0 is premium service VoIP traffic and it is critical that it receives premium service QoS. The other two traffic classes are not considered to have QoS needs that are as crucial as those of flow 0.

The following graphs show the results obtained for the throughput and average delay of flow 0.



**Figure 5.5: Throughput of WRR Flow 0 with Different WRR Settings**

From the graph shown in Figure 5.5, it can be seen that up to an offered load of 832kbps, the throughput of all the high priority flows, which are flow 0, are the same as the offered load. Beyond an offered load of 832kbps, flow 0 of the network with WRR settings of 3, 2, 1 has the best throughput performance. This is because WRR assigns half the total of the queue servicing weight to flow 0, as opposed to the other flows. As expected the network with WRR settings 2, 3, 1 has the next best throughput performance due to its flow 0 obtaining one third of the total queue servicing weight. The networks with WRR weights 1, 2, 3 and 1, 4, 1, have the worst throughput performance.

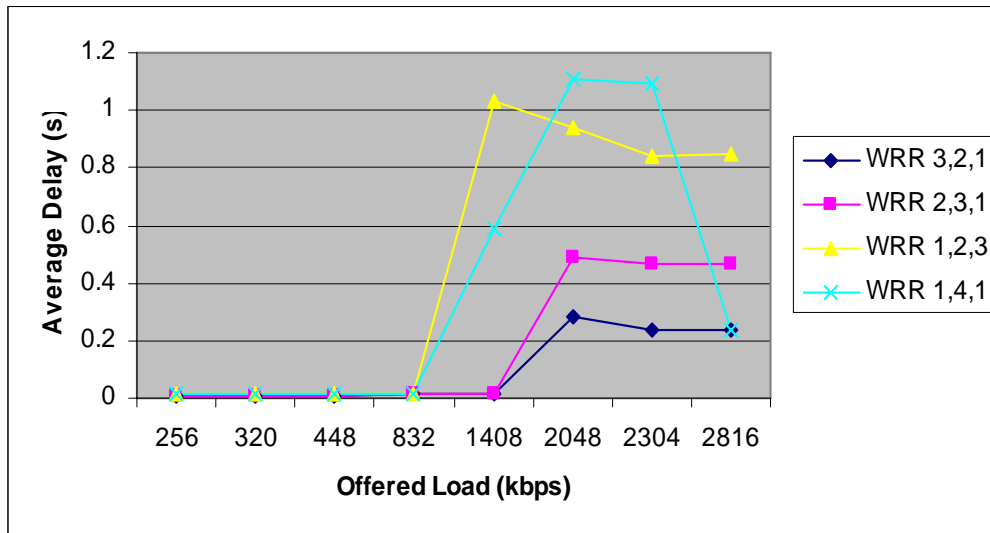


**Figure 5.6: Throughput of AP/WRR Flow 0 with Different WRR Settings**

From Figure 5.6 above, it can be seen that up to an offered load of 832kbps, the throughput of all the high priority flows, which are flow 0, are the same as the offered load. Beyond an offered load of 832kbps the networks with WRR weights 3, 2, 1, weights 2, 3, 1, and weights 1, 2, 3 have the best throughput performance, because of the effect of the alternate priority queuing. However flow 0 in the network with WRR weights 1, 4, 1, does not have a very high throughput performance due to the fact that WRR allocate two thirds of the queue service weight to the medium priority flow 1, which competes more efficiently (than flow 2) for scheduling resources with flow 0.

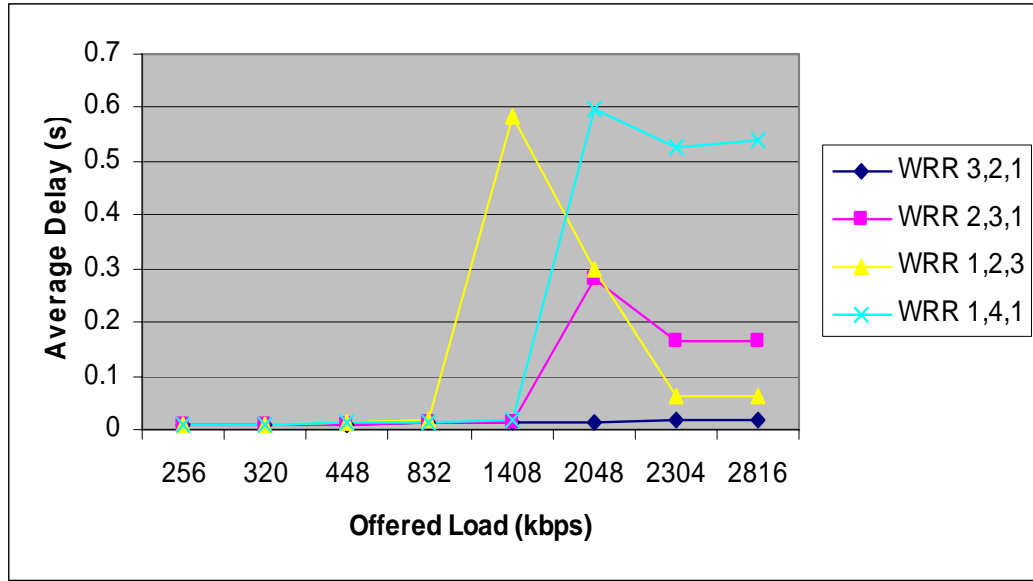
From the results above, it can be seen that WRR and AP/WRR give an improved throughput performance for the high priority flow 0 when compared to the baseline network. However, AP/WRR gives a better throughput performance for flow 0 for a variety of WRR weights. All the improvements in throughput performance are observed after the WLAN starts operating in its saturation region.

The average delay performance results for flow 0 with WRR and AP/WRR enabled on the bottleneck link are presented below.



**Figure 5.7: Average Delay of WRR Flow 0 with Different WRR Settings**

From Figure 5.7 above, the average delay of all the high priority flows, which are flow 0, is almost 0 seconds (the experimental data indicates a value in the region of 10ms) up to an offered load of 832kbps. Beyond an offered load of 832kbps, flows 0 for networks with WRR weights 1, 2, 3 and weights 1, 4, 1 have an increased delay, with both flows having a delay in the order of 1s for an offered load of 1408kbps. Flows 0 for networks with WRR weights 1, 2, 3 and weights 1, 4, 1 experience an increased delay beyond an offered load of 832kbps because flows 0 are allocated the least proportion of the total servicing weight when compared to other flows. Flows 0 for networks with WRR weights 3, 2, 1 and 2, 3, 1 have a constant low delay (the experimental data indicates a value in the region of 10ms) until an offered load of 1408kbps where the average delay increases to a value above 200ms. The increase in the average delay of flows 0 for networks with WRR weights 3, 2, 1 and 2, 3, 1 is due to the WLAN operating in saturation mode and the 1Mbps bottleneck link.



**Figure 5.8: Average Delay of AP/WRR Flow 0 with Different WRR Settings**

From Figure 5.8 above, it can be seen that up to an offered load of 832kbps flows 0 of all the networks have a low average delay (the experimental data indicates a value in the region of 10ms). This is because the WLAN is not operating in its saturation region yet, and the offered load is not equal to the bandwidth of the 1Mbps bottleneck link. Beyond an offered load of 832kbps the average delay of flow 0 of the network with WRR weight 1, 2, 3 increases to a maximum of approximately 600ms, because of receiving the lowest proportion of the WRR servicing weights, and it then falls to a delay of 60ms at an offered load of 2304kbps and beyond. Flows 0 of the networks with WRR weights 2, 3, 1 and weights 1, 4, 1 have an increased delay beyond an offered load of 1408kbps due to the WLAN operating in the region of saturation and the effect of the 1Mbps wired link. The average delay of flow 0 of the network with WRR weights 3, 2, 1 does not change for all the offered loads due to the fact that flow 0 is the priority queue and it receives half of the WRR servicing weights.

From the average delay results obtained above it can be seen that up to an offered load of 1408 kbps, WRR performs better than the baseline system for flow 0. For loads higher than 1408 kbps, flow 0 in the WRR enabled system performs worse than the baseline system. AP/WRR with weights 3, 2, 1, gives the best average delay performance for flow 0 with an average delay of less than 20 ms.

All the improvements in performance are visible when the offered load is approximately 1Mbps. Since the effective WLAN bandwidth is approximately 1Mbps, when the offered load exceeds 1Mbps it is expected that the WLAN will begin operating in the saturation region. This implies that up to 1Mbps there is no congestion in the network and there will be no noticeable difference in performance for the baseline, WRR, and AP/WRR systems. An improvement in performance beyond the 1Mbps point for the WRR and AP/WRR systems is noticed due to the implemented QoS from the proposed scheme.

Based on the results obtained for throughput and average delay performance, AP/WRR weights 3, 2, 1 will be used to validate the proposed design, mainly because it gives the best average delay performance for flow 0. The focus on the performance of flow 0 as the criteria for performance improvement is because flow 0 is VoIP traffic, which is premium service traffic. VOIP traffic is delay sensitive and its average delay performance is important in the evaluation.

In the following sub-section the performance of the baseline system will be compared with that of the AP/WRR enabled system with weight parameters of 3, 2, 1.

### **5.3 Comparison of Baseline System with Proposed Scheme**

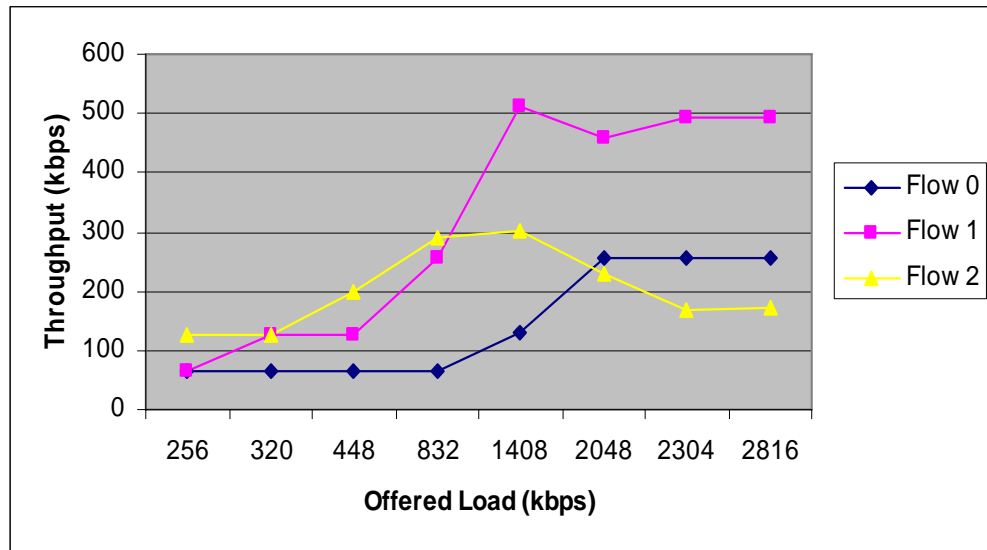
The experiments conducted so far have consisted of:

- determining a suitable bottleneck link bandwidth
- and determining a suitable WRR queue scheduling mechanism that will provide a limited implementation of a differentiated services QoS scheme on the wired network. It was observed that the use of AP/WRR with weight parameters of 3, 2, 1 provides a good QoS scheme that ensures premium service to the highest priority traffic, which is delay sensitive VOIP traffic.

A sufficient QoS mechanism for the wired network has been identified and it enables the comparison of a baseline system, which does not implement QoS on the wired network, with the proposed mapping scheme. The results of the experiments are presented in the following sub-section.

### 5.3.1 Results from Experiment

The results obtained for the throughput performance for a system with AP/WRR with weight parameters of 3, 2, 1, are shown in Figure 5.9.

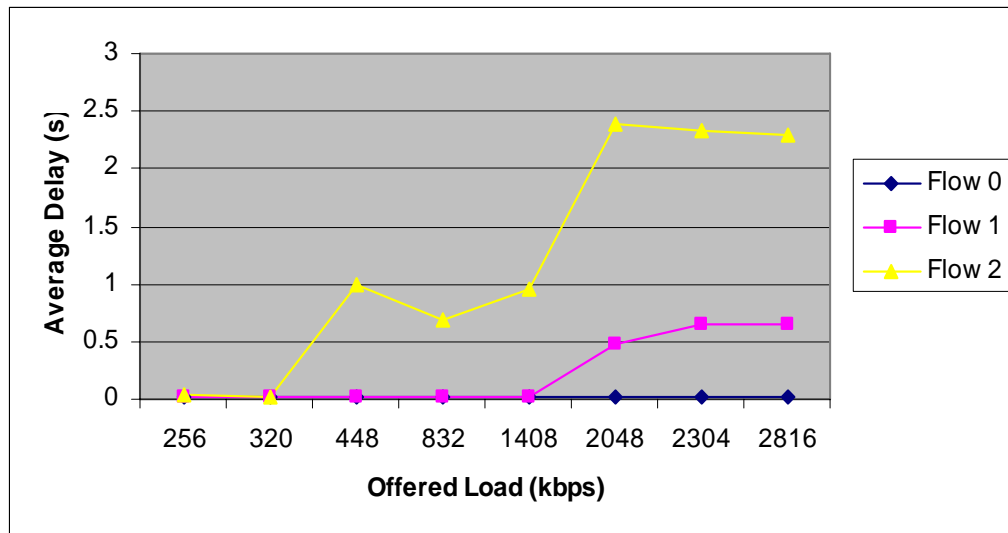


**Figure 5.9: Throughput Performance of AP/WRR (3, 2, 1) for all Flows**

From the throughput graph for all flows in the AP/WRR system, it can be seen that the throughput of the highest priority traffic does not lose any packets, due to flow 0 receiving half of the WRR servicing weight. The medium priority traffic does not lose any packets for an offered load below 1408kbps. Beyond an offered load of 1408kbps, the medium priority traffic loses packets because it receives a smaller proportion of servicing weights, when compared to the highest priority traffic. The lowest priority flow starts losing packets at an offered load of 320kbps and beyond.

The lowest priority flow is not completely starved of service even when the WLAN is operating in the saturation region, which begins beyond the point where the offered load is 1Mbps.

The average delay performance for a system with AP/WRR with weight parameters of 3, 2, 1, are shown in Figure 5.10.



**Figure 5.10: Average Delay Performance of AP/WRR (3, 2, 1) for all Flows**

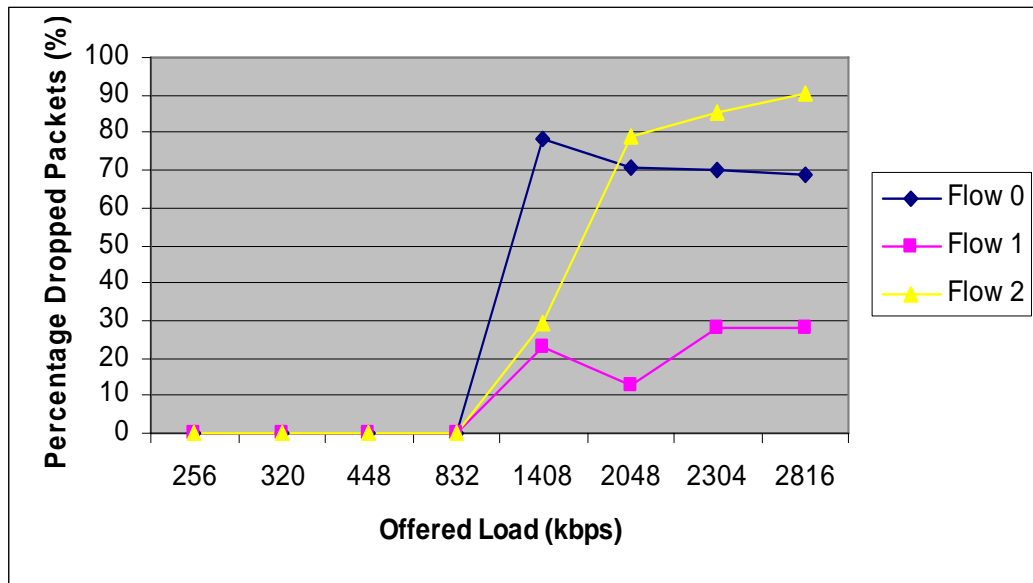
Flow 0 and 1 of the AP/WRR network with weights 3, 2, 1 has an average delay of almost 0 seconds (the experimental data indicates a value in the region of 10ms) for an offered load of up to 1408kbps. Beyond an offered load of 1408kbps, the average delay of flow 1 increases to above 500ms at an offered load of 2048kbps and beyond. This is because flow 1 receives the second highest proportion of the servicing weights. The delay of flow 0 does not change because it is the priority queue and it receives the highest proportion of the servicing weights. The average delay of flow 2 of the network with weights 3, 2, 1 increases at an offered load of 320kbps and beyond, because it receives the lowest proportion of the servicing weights.

Considering the average delay graph, AP/WRR performs better than the baseline system up to an offered load of 1408 kbps. Beyond an offered load of 1408 kbps, the AP/WRR system's flow 0 performs better than the baseline's flow 0.

Conversely, beyond an offered load of 1408 kbps AP/WRR flow 1 performs worse than the baseline system flow 1. This is because the AP/WRR mechanism allocates more resources to the higher priority flow 0 in the outgoing interface queues of the router, which reduces the resources available to other lower priority flows.

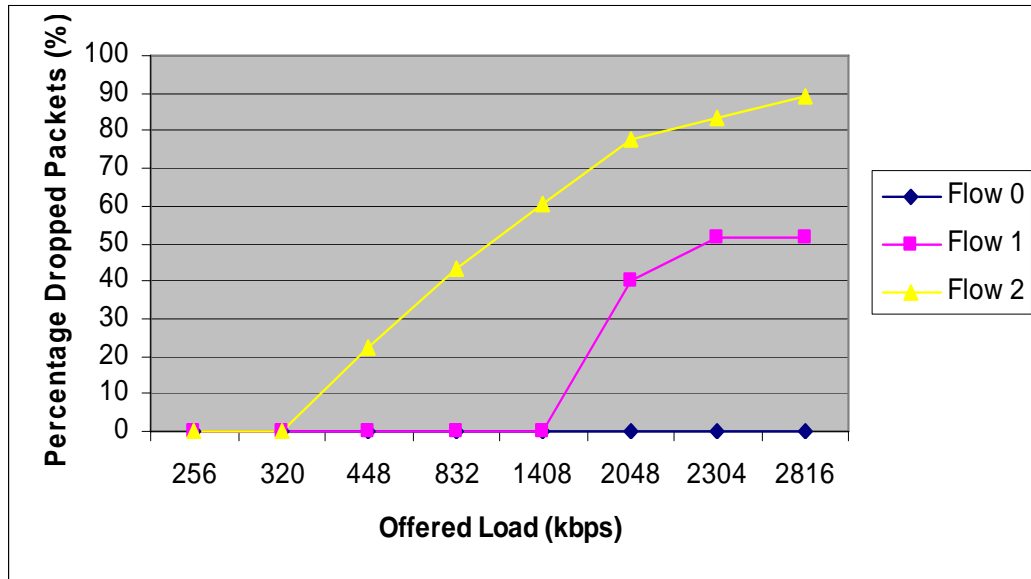
The percentage of dropped packets experimental results for the baseline system and the

AP/WRR system with weight parameters given by 3, 2, 1, are presented in the following graphs.



**Figure 5.11: Packet Loss Performance for all Flows for the Baseline System**

Considering the dropped packets graph for the baseline system, all flows start dropping packets after an offered load of 832 kbps. This is due to the WLAN operating in the saturation region and the effect of the 1Mbps bottleneck link.



**Figure 5.12: Packet Loss Performance for all Flows for the AP/WRR System**

Considering the dropped packets graph for the AP/WRR system, flow 0 does not drop any packets for all offered load values, because it is the priority queue and it receives half of the queue servicing weights. The AP/WRR system's flow 2 starts dropping packets at a load of 320 kbps and drops up to 60% of its packets for an offered load of 1408 kbps. This is due to the previously mentioned reason of the AP/WRR mechanism scheduling more resources to the higher priority flow 0 in the outgoing interface queues of the router, hence reducing the resources available to other lower priority flows. This means that although the lowest priority traffic is not completely starved, it suffers the most from reduced access to the network service.

## 5.4 Performance of the Proposed Scheme

The performance evaluation results from an experiment that compares the proposed QAP-located mapping module scheme with a baseline network that does not implement the mapping module scheme were presented.

The mapping module scheme maps IEEE 802.11-2007 MAC layer QoS classes to IP layer QoS classes at the WLAN-wired interface in a QAP at the boundary of the WLAN-wired network.

The experimental results show that the proposed scheme achieves uniform and consistent end-to-end QoS in the heterogeneous WLAN-wired network. The mapping scheme performs better than a normal WLAN-wired network which does not implement the mapping scheme.

Although the proposed scheme dropped many packets for flows other than the premium service flow, this is a consequence of a congested link and QoS prioritization. The solution to this issue would be to implement admission control and proper network dimensioning, which are outside the scope of this research.

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## Chapter 6 Conclusions

The main objective of this research was to design a scheme that enables the implementation of end-to-end QoS in a heterogeneous WLAN-wired network. The research has focused on the lower layer implementation of end-to-end QoS on a WLAN-wired network using prioritized QoS. Based on the research conducted, the following conclusions were drawn.

The need to ensure a seamless QoS scheme from WLAN to wired networks was identified. The scheme is required to support multimedia services in WLAN-wired networks.

End-to-end QoS in a WLAN-wired network involves the implementation of QoS at different layers of the OSI stack in WLAN and wired networks. The IEEE 802.11-2007 EDCA scheme is the widely accepted industry standard for implementing prioritized QoS in WLAN. The IETF specified Diffserv scheme is widely implemented in wired IP networks for the provision of prioritized QoS.

Various schemes have been proposed to address end-to-end QoS in WLAN-wired networks on the higher and lower layers of the OSI stack. However, the proposed schemes have a number of shortcomings, which include:

- their complexity of implementation because the end stations are required to implement Diffserv
- and the validation of these proposed schemes, which have been mostly conducted in a WLAN only environment, instead of a WLAN-wired environment.

This research proposed the introduction of a mapping module in the QAP at the boundary of the WLAN-wired network. The mapping module is able to map layer 2 EDCA AC traffic classes to layer 3 DSCP or flow label identifiers (IDs). The mapped traffic classes allow the traffic to be manipulated by their respective QoS schemes. The proposed mapping scheme is simple to implement since it is located in the QAP and designed to work with any available differentiated services QoS scheme in a wired IP network.

The performance objectives of the proposed scheme were to provide differentiated service to different traffic classes, ensure higher priority traffic receives better treatment than lower priority traffic and to ensure lower priority traffic is not starved of service.

The simulations conducted in NS2 network simulator show that the proposed scheme provides differentiated QoS to different traffic classes. The scheme also ensures uniform and consistent service differentiation in terms of prioritization of traffic classes across the WLAN and wired networks.

The proposed scheme provides very good QoS to the highest priority service when compared to the lower priority services. The proposed scheme also ensures the non-starvation of the lower priority traffic classes, although it does not adequately cater for their network resource needs. This is explainable by the fact that the limited network resources are allocated more to the highest priority traffic class using a combined WRR and alternate priority mode scheduling mechanism. Another reason for the inadequate servicing of lower priority traffic classes was the lack of admission control mechanisms in the experimental network.

Because the module has a very simple function in that it reads traffic class values in one network and uses a table to lookup the corresponding value in the other network, the mapping will always result in a correct mapping as a packet moves from one network to another. Erroneous mapping would arise if the wrong priorities were to be assigned to any of the QoS classes in either the WLAN or wired network. Hence if a high priority traffic class were to be defined as low priority or vice versa there would be a lack of end-to-end QoS. Erroneous mapping would be caused by human error in the definition of wrong QoS class priorities in the WLAN or wired network and not by the module implementation or design.

## **6.1 Recommendations**

Based on the conclusions presented in the previous sub-section the following recommendations are made.

The proposed mapping scheme should be implemented in WLAN-wired networks that are required to support multimedia services. This is because it has been proved to provide

premium service to the highest priority traffic class. The highest priority traffic class is usually VoIP traffic. An NGN WLAN access network would use the proposed mapping module in its QAP to realize a PEP that is able to inter-operate with the NGN policy-based QoS management scheme.

The presented mapping scheme is a very useful contribution to the inter-working of WLAN-wired networks and boosts the case for the deployment of WLAN as a telecom-grade access network. If WLANs can provide the same level of service guarantees as copper lines in the local loop, they could be used to easily deploy telecommunication networks in new unserved markets. WLAN could prove useful in providing a low cost last-mile solution in low income areas such as rural areas.

## **6.2 Future Work**

This research focused on presenting a proposed mapping module in a QAP WLAN-wired interface. The mapping module was and evaluated in comparison to a WLAN-wired network with no QoS in the wired part of the IP network. The experiments in this research were conducted with uplink traffic only due to software limitations. Further work has to done to evaluate the performance of the proposed scheme, using downlink traffic from the wired network to the WLAN.

Future work could examine the performance of a WLAN-wired network that implements the proposed mapping module and admission control.

Further research could also include the evaluation of a WLAN-wired network that implements the full version of the Diffserv scheme in the wired IP network. The full version of the Diffserv scheme would include rate limiting, traffic policing, and standard PHB service differentiation.

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## Appendix A: NS2 Experimental Setup

The experiments conducted in this research are carried out in the NS2 network simulator environment. NS2 is written in the C++ programming language and uses the Tcl script language to run the simulation experiments.

Appendix A describes and presents the Tcl scripts used to carry out the experiments in this research.

### A.1 NS2 Software Setup

NS2 version 2.28 is used in this experiment. The NS2 software is patched by the CMU\_WLAN\_patch available from [75]. The NS2 TKN EDCA software module available from [75] is then installed. The NS2 No Ad-Hoc Routing Agent (NOAH) routing protocol software module, available from [78], is also installed.

To implement the WRR and AP/WRR functionality in NS2, the ns2rr-0.0.3.tar.gz, software module available from [77], is installed. The NS2 software is then fully ready to be used to conduct the experiments in this research.

### A.2 NS2 WLAN Setup

This section presents the WLAN nodes setup in the Tcl scripts. The parameters to be set are the data rate, packet size, physical and data link layer characteristics, and the WLAN bandwidth. The section of the Tcl script that sets the aforementioned parameters is given below.

```
#number of nodes
set num_appls 16
set num_wired_nodes 5
set num_mobile_nodes 4
set num_bs_nodes 1 ;# number of base stations
set num_nodes [expr $num_wired_nodes + $num_mobile_nodes + $num_bs_nodes]
set bs_id $num_wired_nodes
set packetSize0 160
set packetSize1 500
set rate0 64k
```

```
set rate1 256k
set rate2 384k
```

```
# Parameter for wireless nodes
```

```
set opt(chan)      Channel/WirelessChannel  ;# channel type
set opt(prop)      Propagation/TwoRayGround ;# radio-propagation model
set opt(netif)     Phy/WirelessPhy        ;# network interface type
set opt(mac)       Mac/802_11e           ;# MAC type
set opt(ifq)       Queue/DTail/PriQ       ;# interface queue type
set opt(ifqlen)    50                     ;# interface queue length
set opt(ll)        LL                     ;# link layer type
set opt(ant)       Antenna/OmniAntenna    ;# antenna model
set opt(ifqlen)    50                     ;# max packet in ifq
set opt(adhocRouting) NOAH                ;# routing protocol
set opt(x)         670 ;# X dimension of the topography
set opt(y)         670 ;# Y dimension of the topography
```

```
#setting WLAN bandwidth
```

```
Mac/802_11e set dataRate_ 2Mb
Mac/802_11e set basicRate_ 2Mb
Mac/802_11e set backoff_mode_ 1
```

The following part of the Tcl script describes the setup of the base station. The base station is used to interface and route packets between the WLAN and the wired network.

```
# creating base station
```

```
$ns node-config -adhocRouting $opt(adhocRouting) \
  -llType $opt(ll) \
  -macType $opt(mac) \
  -ifqType $opt(ifq) \
  -ifqLen $opt(ifqlen) \
  -antType $opt(ant) \
  -propType $opt(prop) \
  -phyType $opt(netif) \
  -channel $chan \
  -topoInstance $topo \
  -wiredRouting ON \
  -agentTrace ON \
  -routerTrace OFF \
  -macTrace OFF \
  -movementTrace OFF
```

## A.3 Topology Setup

The topology setup of the experiment is described in the Tcl script code below.

```
set chan [new $opt(chan)]
set topo [new Topography]
$topo load_flatgrid $opt(x) $opt(y)

# Create God
create-god [expr $num_mobile_nodes + $num_bs_nodes]

# creating wired nodes
for {set i 0} {$i < $num_wired_nodes} {incr i} {
    set W($i) [$ns node 0.0.$i]
    puts "wired node $i created"
}

set BS(0) [$ns node 1.0.0]
$BS(0) random-motion 0
puts "Base-Station node $bs_id created"

#provide some co-ord (fixed) to base station node
$BS(0) set X_ 1.0
$BS(0) set Y_ 2.0
$BS(0) set Z_ 0.0

# linking of root to base-station node
#$ns duplex-link $W(0) $BS(0) 2Mb 2ms DropTail
#$ns duplex-link $W(1) $W(0) 2Mb 2ms DropTail

$ns duplex-link $BS(0) $W(0) 2Mb 0ms DropTail
$ns duplex-link $W(1) $W(0) 1Mb 10ms DropTail
#$ns simplex-link $W(0) $W(1) 1Mb 10ms CBWRR
#$ns simplex-link $W(1) $W(0) 1Mb 10ms DropTail

#$ns duplex-link $W($i) $W(0) 2Mb 5ms DropTail

# linking of wired nodes to root node
for {set i 2} {$i < $num_wired_nodes} {incr i} {
    $ns duplex-link $W(1) $W($i) 2Mb 2ms DropTail
}
```

## A.4 Routing Between WLAN and Wired Network

The routing between the WLAN and wired network was accomplished by the NOAH routing protocol, through the base station node. The WLAN and wired networks were placed in two different routing domains and hierarchical routing was used to route packets between the two domains. The Tcl script that accomplished this is shown below.

```
#set up for hierarchical routing
#(needed for routing over a basestation)
$ns node-config -addressType hierarchical
AddrParams set domain_num_ 2      ;# domain number
lappend cluster_num 1 1          ;# cluster number for each domain
AddrParams set cluster_num_ $cluster_num
lappend eilastlevel $num_wired_nodes [expr $num_mobile_nodes + $num_bs_nodes] ;# number
of nodes for each cluster
AddrParams set nodes_num_ $eilastlevel
# creating mobile nodes
$ns node-config -wiredRouting OFF
for {set i 0} {$i < $num_mobile_nodes} {incr i} {
    set wl_node_($i) [$ns node 1.0.[expr $i + 1]]
    $wl_node_($i) random-motion 0      ;# disable random motion
    puts "wireless node $i created ..."
    $wl_node_($i) base-station [AddrParams addr2id [$BS(0) node-addr]]
    $wl_node_($i) set X_ [expr $i * 10]
    $wl_node_($i) set Y_ [expr $i * 10]
    $wl_node_($i) set Z_ 0.0
}
```

## A.5 Application Traffic Setup

The application traffic setup is described in the following section of the Tcl script. The code describes the assignment of the AC priority to the application traffic.

```
set src_udp($i) [new Agent/UDP]
$src_udp($i) set class_ $k
# highest priority
$src_udp($i) set prio_ $k
set dst_udp($i) [new Agent/Null]
$ns attach-agent $wl_node_($j) $src_udp($i)
$ns attach-agent $W(2) $dst_udp($i)
set app($i) [new Application/Traffic/Exponential]
```

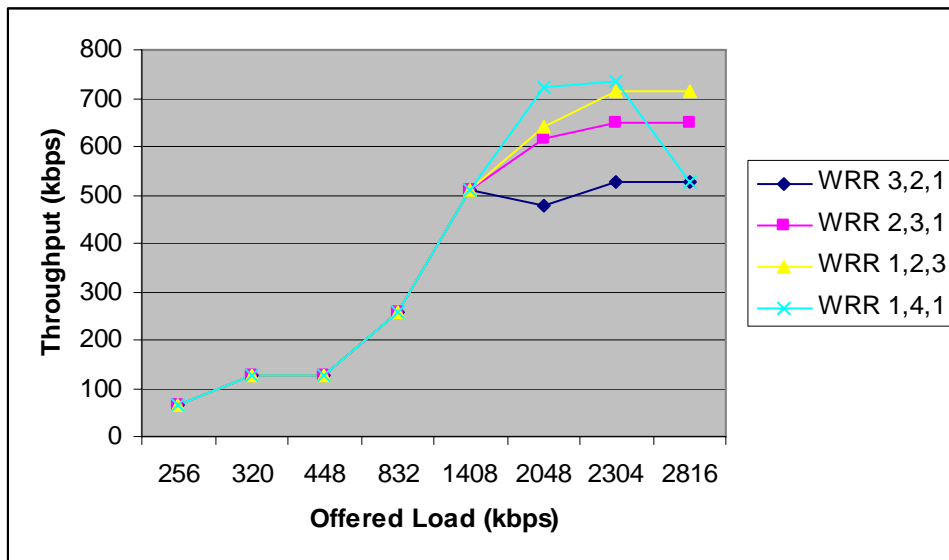
```
$app($i) attach-agent $src_udp($i)
$app($i) set burst_time_ .5
$app($i) set idle_time_ .5
$app($i) set packetSize_ $packetSize0
$app($i) set rate_ $rate0
$app($i) set fid_ $k
$ns connect $src_udp($i) $dst_udp($i)
$ns at 1.0 "$app($i) start"
```

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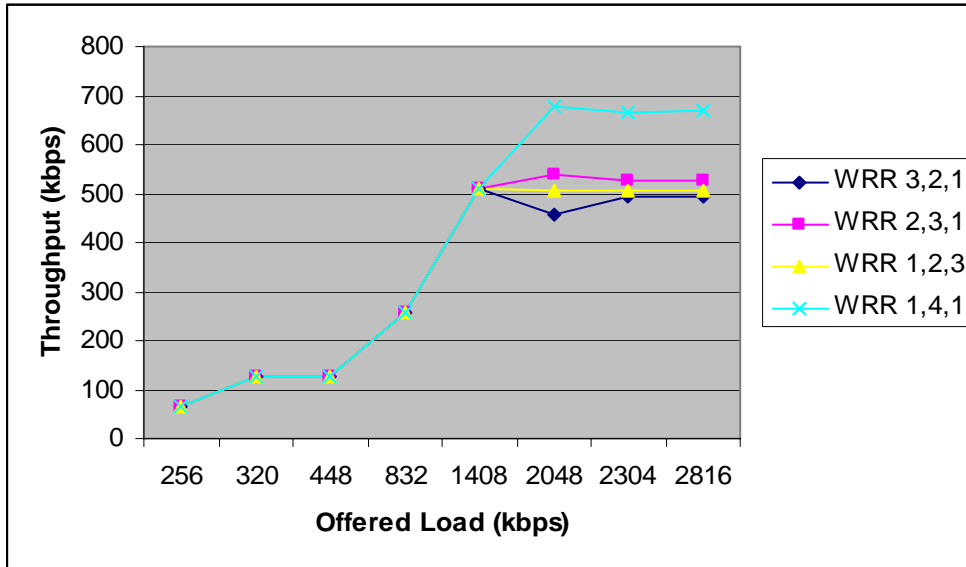
## Appendix B: Other Experimental Results

Some of the experimental results that were not presented in the main thesis report are shown in the following sub-sections.

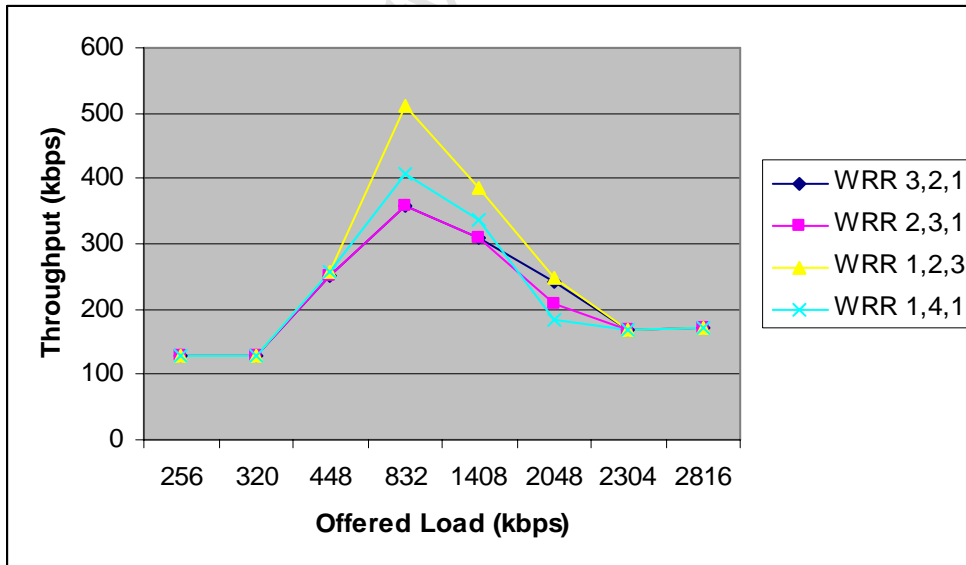
### B.1 Throughput of WRR Flow 1 with Different WRR Settings



## B.2 Throughput of AP/WRR Flow 1 with Different WRR Settings



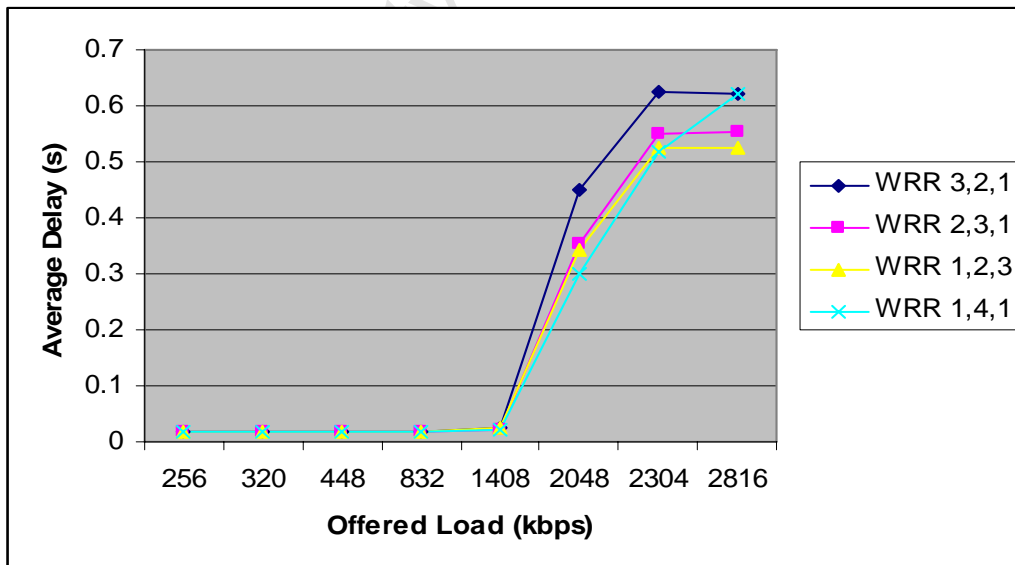
## B.3 Throughput of WRR Flow 2 with Different WRR Settings



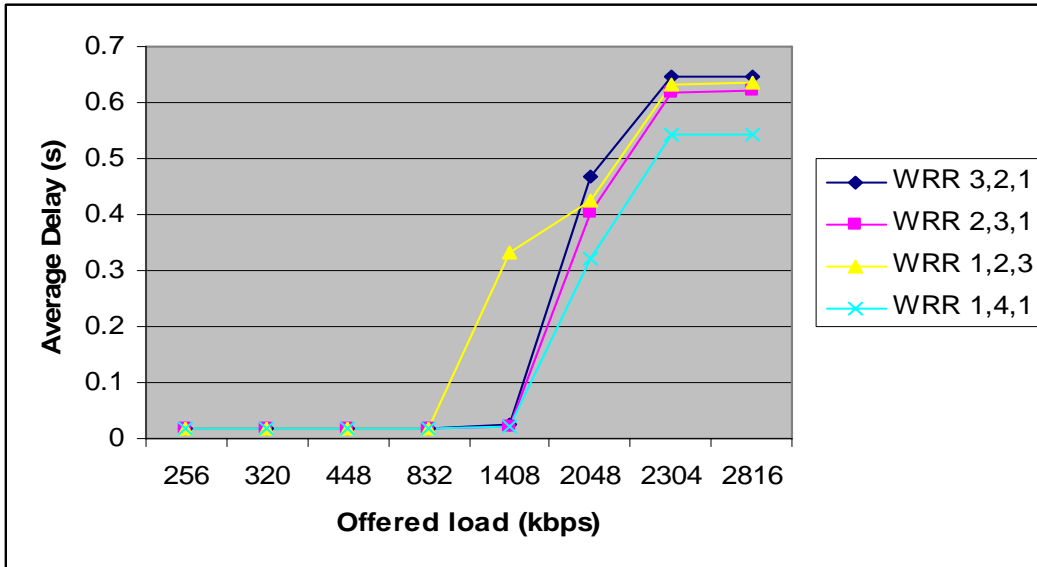
## B.4 Throughput of AP/WRR Flow 2 with Different WRR Settings



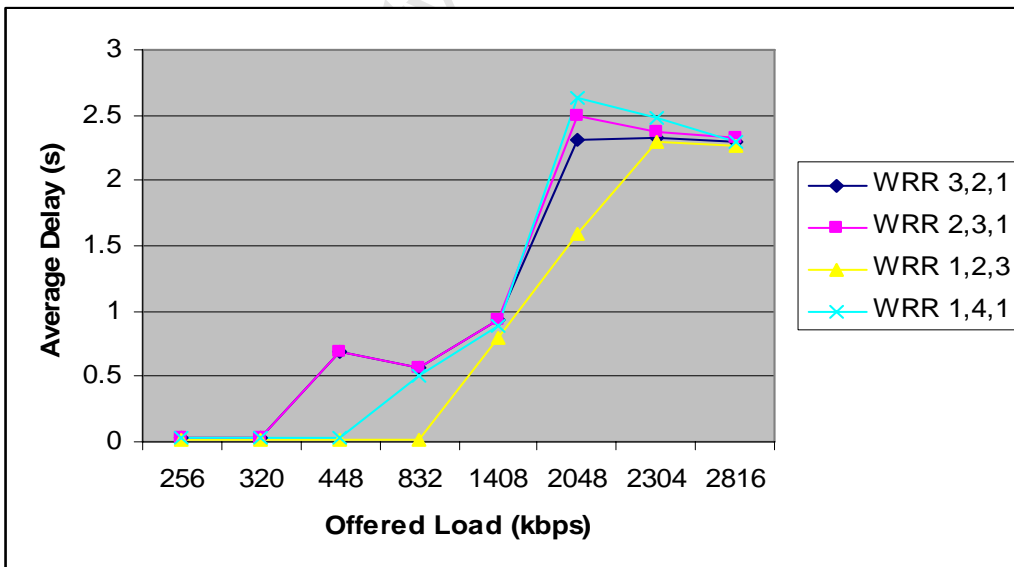
## B.5 Average Delay of WRR Flow 1 with Different WRR Settings



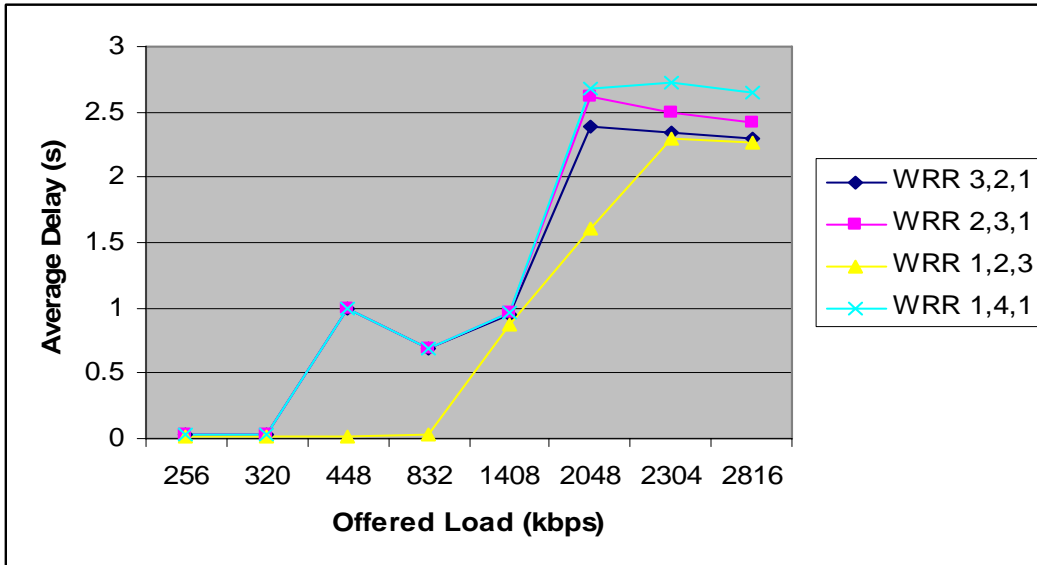
## B.6 Average Delay of AP/WRR Flow 1 with Different WRR Settings



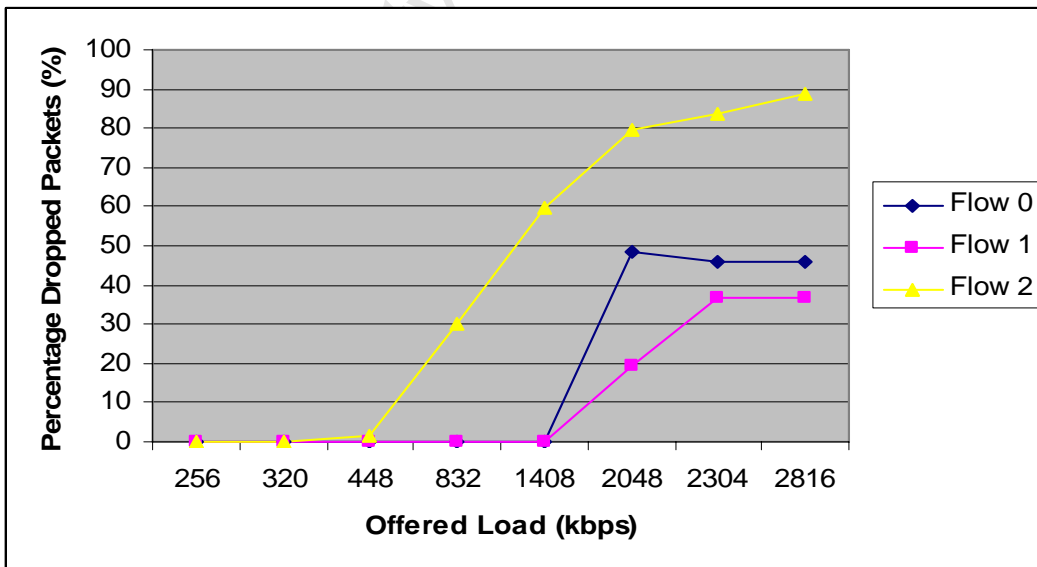
## B.7 Average Delay of WRR Flow 2 with Different WRR Settings



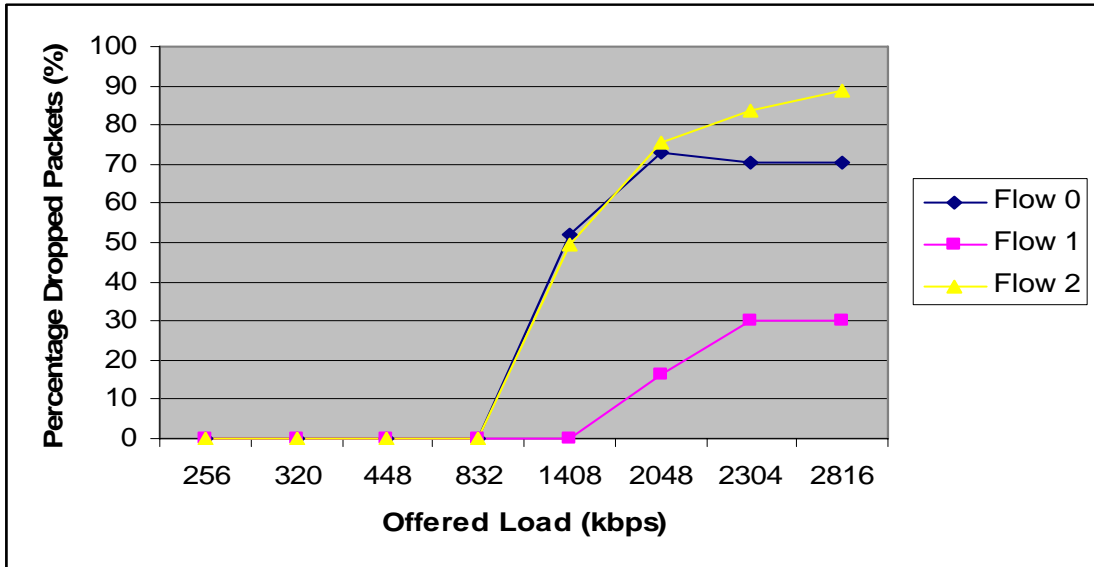
## B.8 Average Delay of AP/WRR Flow 2 with Different WRR Settings



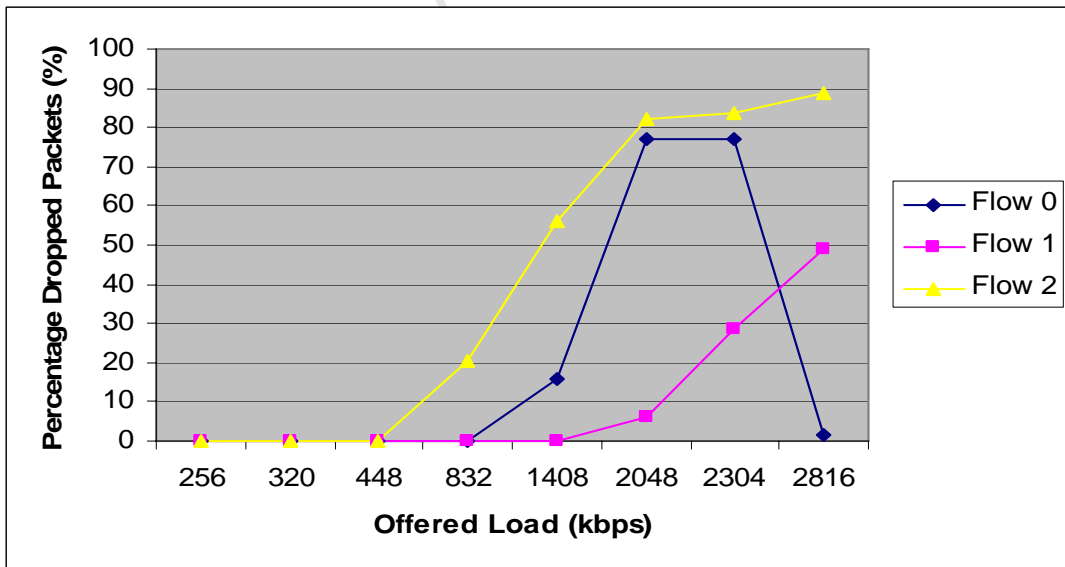
## B.9 Percentage Dropped Packets of WRR with Settings 2,3,1



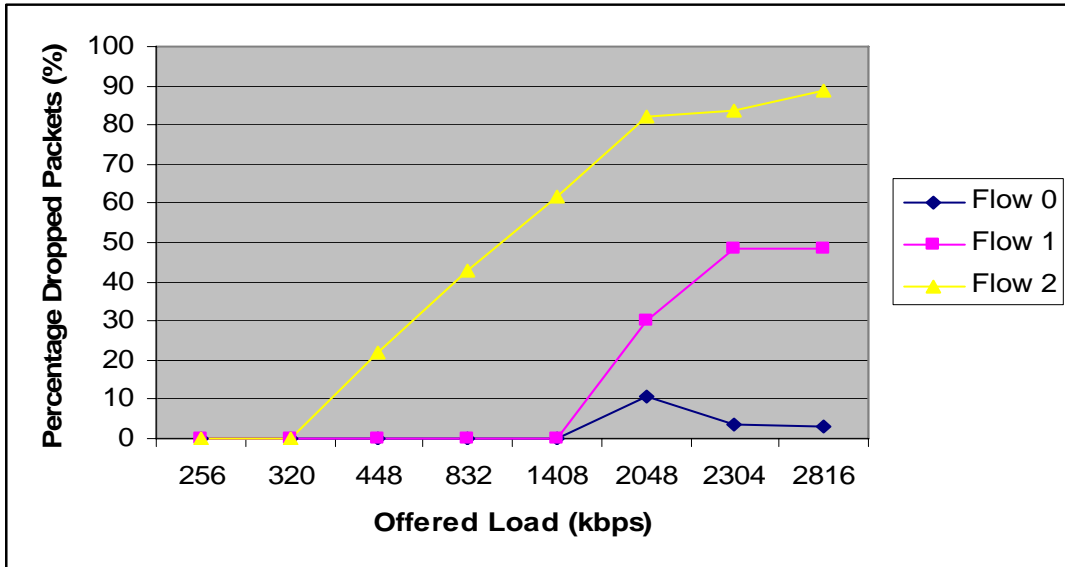
### B.10 Percentage Dropped Packets of WRR with Settings 1,2,3



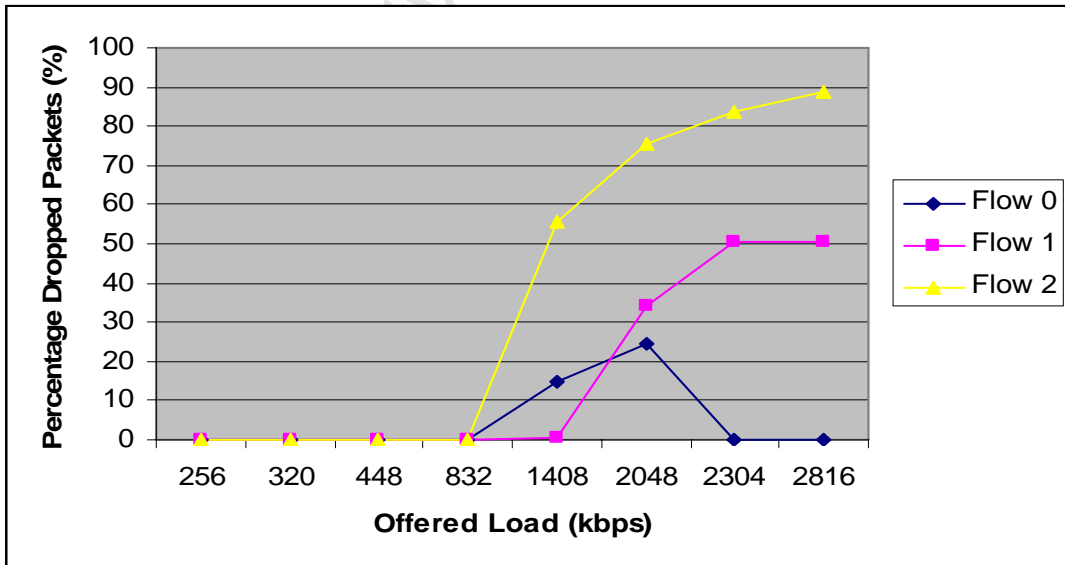
### B.11 Percentage Dropped Packets of WRR with Settings 1,4,1



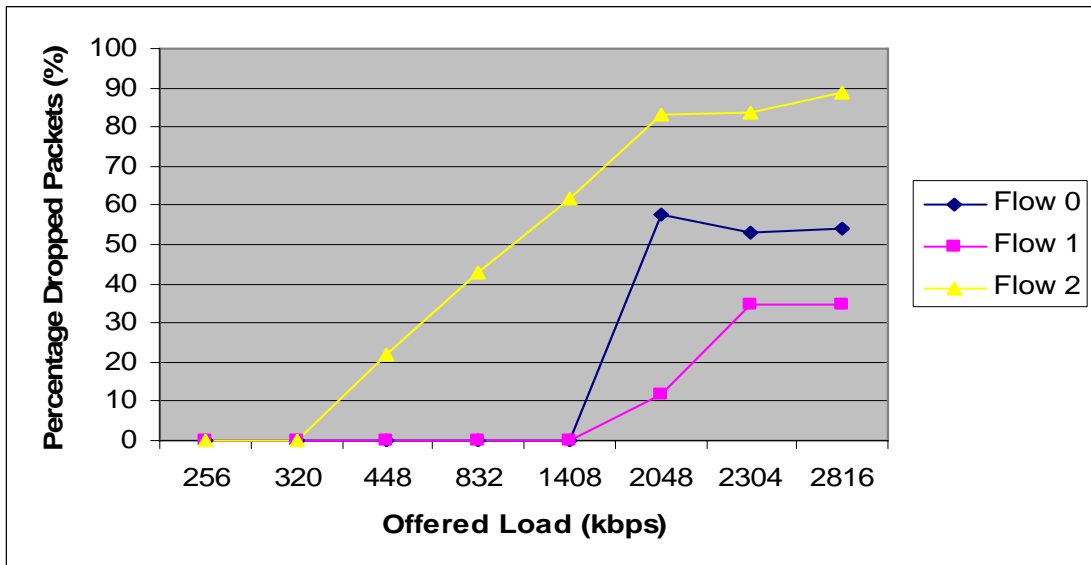
### B.12 Percentage Dropped Packets of AP/WRR with Settings 2,3,1



### B.13 Percentage Dropped Packets of AP/WRR with Settings 1,2,3



## B.14 Percentage Dropped Packets of AP/WRR with Settings 1,4,1



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## **Appendix C: Research Publications**

This research work has produced a peer reviewed conference paper in an international conference. The publication was:

- Samuel Senkindu and H. Anthony Chan, "Design of a QoS Enabled WLAN in an IP Multimedia Subsystem Network," Information Society Technologies in Africa (IST-Africa), Maputo, Mozambique, 9-11 May 2007, ISBN: 1-905824-04-1.

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## **Appendix D: Accompanying CD-ROM**

The CD-ROM included in this thesis report contains:

- The thesis report in Adobe Acrobat format.
- The NS2 version 2.28 simulation software. This includes the software modules and patches described in appendix A.1.

The research papers and publications used as references in this research work.

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