# Scheduling Alternatives for Mobile WiMAX

# End-to-End Simulations and Analysis

by

**Carlos Valencia, B.Sc.**

A thesis submitted to the Faculty of Graduate Studies and Research

in partial fulfillment of the requirements for the degree of

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Department of System and Computer Engineering,

Carleton University

Ottawa, Canada, K1S 5B6

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The undersigned hereby recommend to

the Faculty of Graduate Studies and Research acceptance of the thesis

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Victor Aitken, Department Chair

Thomas Kunz, Thesis Supervisor

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## Abstract

Fourth Generation wireless technologies depend on the performance of their schedulers to deliver high data throughput and meet quality-of-service commitments. We compare four schedulers for mobile WiMAX using five industry-defined key performance indicators: sector and application throughput, completion time, fairness index and delay. The selected scheduling algorithms are: Proportional Fairness (PF), Modified Largest Weighted Delay First (MLWDF), Highest Urgency First (HUF), and Weighted Fair Queuing (WFQ). Three simulated environments are used: controlled, stationary and mobile. The controlled environment provides insights into the time-related behavior of flows with identical QoS parameters and different RF conditions. Results for the stationary and mobile environments show that algorithms meet QoS requirements within system capacity. Opportunistic algorithms (PF and MLWDF) achieve considerable throughput improvements. MLWDF's throughput results, while better under stationary conditions, fall behind PF in the mobile scenario. No statistically significant differences are observed in the mobile environment for application completion time and fairness.

## Acknowledgements

I greatly acknowledge my thesis supervisor, Professor Thomas Kunz for his competency, motivation, and eagle's eye to help me produce a sound and high quality thesis. Without his tireless reviews of my drafts and continuous feedback this document would not have been possible.

I dedicate this thesis to my beloved family. Thanks to Claudia, my wife, for all her sacrifices and support during these years, and to Arianna, my three year old daughter, for helping me clear my mind with her late night visits when mom was already in bed.

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## List of Acronyms

| | |
|---|---|
| AMC | Adaptive Modulation and Coding |
| ARQ | Automatic Repeat Request |
| BE | Best Effort |
| BER | Bit Error Rate |
| BS | Base Station |
| CBR | Constant Bit Rate |
| CID | Connection Identifier |
| CNS | Carrier to Noise Scheduling |
| DHCP | Dynamic Host Configuration Protocol |
| DRR | Deficit Round Robin |
| DSCP | Differentiated Services Code Point |
| EDF | Earliest Deadline First |
| ertPS | extended real-time Polling Service |
| FEC | Forward Error Correction |
| FIFO | First In First Out |
| GPC | Grant Per Connection |
| GPS | Generalized Processor Sharing |
| GPSS | Grant Per Subscriber Station |
| HOL | Head Of Line |
| HUF | Highest Urgency First |
| IEEE | Institute of Electrical and Electronic Engineers |
| MAC | Medium Access Control |
| MAN | Metropolitan Area Network |
| MCS | Modulation and Coding Scheme |
| MIMO | Multiple Input Multiple Output |
| MLWDF | Modified Largest Weighted Delay First |
| MRTR | Minimum Reserved Traffic Rate |
| MS | Mobile Station |
| MSTR | Maximum Sustained Traffic Rate |
| NCS | Normalized CNR Scheduling |
| nrtPS | non real-time Polling Service |
| OFDM | Orthogonal Frequency Division Multiplexing |
| OFDMa | Orthogonal Frequency Division Multiple access |
| ORR | Opportunistic Round Robin |
| PDU | Protocol Data Unit |
| PF | Proportional Fair |
| PHY | Physical Layer |
| PKM | Public Key Management |
| QAM | Quadrature Amplitude Modulation |
| QoS | Quality of Service |
| QPSK | Quadrature Phase Shift Keying |
| RLC | Radio Link Control |

| | |
|---|---|
| RR | Round Robin |
| RTG | Receive Transmit Transition Gap |
| rtPS | real-time Polling Service |
| SC | Single Carrier |
| SCa | Single Carrier access |
| SDU | Service Data Unit |
| SINR | Signal to Interference Noise Ratio |
| SS | Subscriber Station |
| TDD | Time Division Duplex |
| TGPS | Truncated Generalized Processor Sharing |
| TTG | Transmit Receive Transition Gap |
| UGS | Unsolicited Grant Service |
| VoIP | Voice over Internet Protocol |
| WDRR | Weighted Deficit Round Robin |
| WFQ | Weighted Fair Queuing |
| WF2Q | Worst-case Fair Weighted Fair Queuing |
| WiMAX | Worldwide Interoperability Microwave Access |
| WirelessHUMAN | Wireless High Speed Unlicensed Metro Area Network |
| WirelessMAN | Wireless Metropolitan Area Network |
| WRR | Weighted Round Robin |

# 1. Introduction

Despite delays in certification that pushed the delivery of certified MIMO (Multiple In Multiple Out) products to the end of 2008 [1], and a lot of small to medium size trial deployments yet to materialize into commercial networks, WiMAX (Worldwide Interoperability Microwave Access) is still the most immediate solution to provide a mobile broadband wireless solution worldwide. Its high data rates, quality of service (QoS), mobility, security and scalability features, together with a healthy industry consortium, are strong reasons for considering it a good alternative for wireless voice and data services.

IEEE 802.16 standards for Broadband Wireless Metropolitan Area Networks commercially reflect on two major commercial implementations: Fixed WiMAX, based on 802.16d-2004 [2], used for stationary deployments and Mobile WiMAX, based on 802.16e-2005 [3], with special considerations for mobility including handover procedures, added security and a different PHY layer to support parallel downlink and uplink transmissions. Even though the 802.16e-2005 standard is an amendment to 802.16d-2004, Mobile WiMAX implementations are not backward compatible with Fixed WiMAX, due mostly to considerable PHY layer differences: Based on Orthogonal Frequency Division Mulpiplexing (OFDM) for Fixed WiMAX, and on Orthogonal Frequency Division Multiple Access (OFDMA) based for Mobile WiMAX.

An important component of the WiMAX solution is the scheduler that allocates bandwidth resources to users on every downlink or uplink transmission. Given the diverse factors that govern resource allocation in WiMAX (current modulation rate, QoS parameters, and frame duration) the IEEE committee decided to leave the details of the implementation open. This research work will deal specifically with the issue of efficient scheduling for Mobile WiMAX, based on the OFDMA PHY layer.

This chapter first presents a general view of the WiMAX architecture, highlighting the scope of the WiMAX scheduling problem. Contributions of this research are then explained, followed by a summary of key insights obtained and finally a description of the thesis structure.

## 1.1. WiMAX Architecture

Figure 1.1-1 presents a simplified view of the WiMAX architecture [4] with emphasis on the scheduling function provided at the Base Station (BS) entity. The network is IP-based end-to-end and can be split into three major components: Mobile Stations (MS), also called Subscriber stations (SS) in the Fixed WiMAX specification; Access Service Network (ASN), which provides over-the-air connectivity, backhaul services and WiMAX specific features such as encryption and authentication via the Public Key Management (PKM) module, handover support, radio resource management and Quality of Service (QoS); and the Connectivity Services Network (CSN), which is the point of connectivity to the Internet and corporate networks and provides AAA (Authorization, Authentication and Accounting) services, IP address assignment, QoS configuration and Mobile IP.

WiMAX has very versatile PHY and MAC layers. While the PHY layer has three distinct specifications (SC, OFDM and OFDMA), the MAC layer implements several advanced features such as encryption, security, error correction, link adaptation, power control, automatic retransmission and quality of service.

The focus of this research is on the interface between MS and BS entities, also called the R1 reference point in WiMAX lingo, which is where the downlink and uplink scheduling takes place. When a MS connects to the network, a Policy Function residing on the CSN provides the

ASN all the classification rules to assign MS' specific traffic to different QoS parameters. Based on such classification rules, the ASN gateway will set up service flows (one per classification rule, in each direction) to differentiate the traffic, and can even perform marking of the IP packets using DSCP (Differentiated Services Code Point) to reflect the different expected treatment of the packets over the backhaul. These service flows are reflected at the BS entity as logical connections (called CID, Connection Identifier) to each MS, each one having a specific scheduling service, according to the defined classification rules.

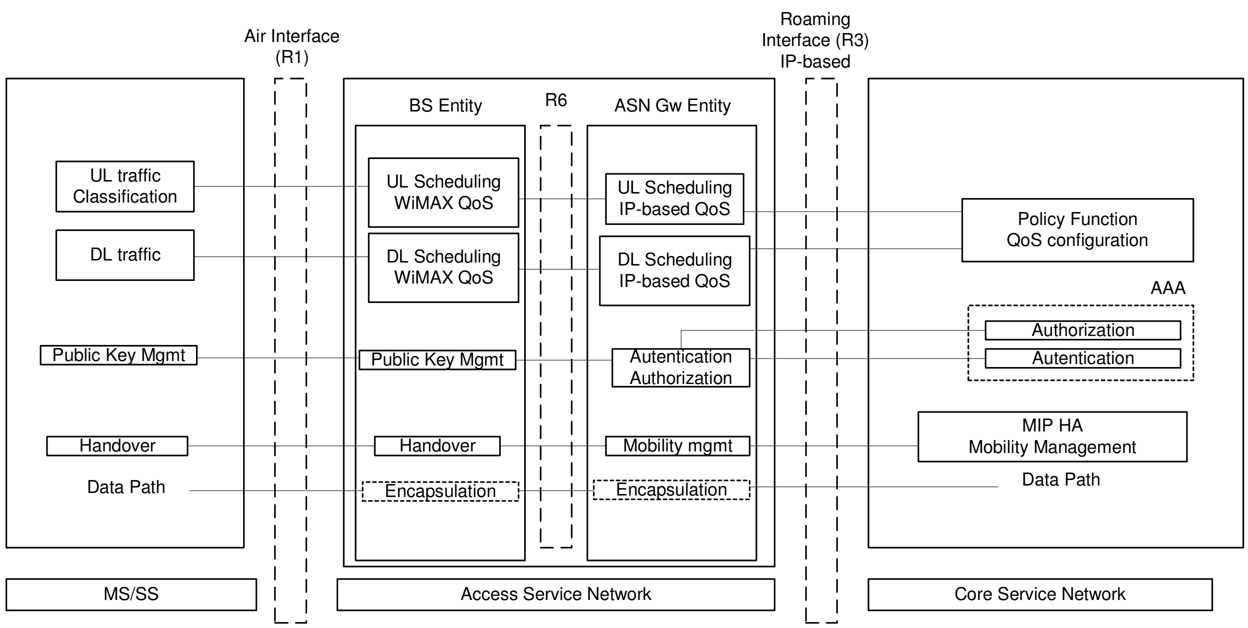



*Figure 1.1-1 WiMAX Architecture*

WiMAX brings about a novel concept to wireless systems: Per-flow quality-of-service. A single subscriber can have different streams of traffic, each one classified and scheduled over the air based on its quality-of-service parameters. Scheduling decisions get particularly complex as additional factors are considered:

- Different supported modulation and coding schemes (MCS) as well as antenna techniques such as MIMO Matrix A/B.
- RF conditions might suddenly change, which will change the MCS and hence the amount of bandwidth that can be allocated on each transmission opportunity.
- Support of error correction methods such as Adaptive Repeat Request (ARQ) and Hybrid ARQ (H-ARQ).
- PHY multiplexing scheme (OFDM vs. OFDMA).

It is important to highlight that for 802.16e (Mobile WiMAX), the WiMAX Forum™ specifies OFDMA as the sole PHY mode to be used [5], and contemplates implementation for all of the MAC features described above. In this context, the MAC scheduling problem for WiMAX OFDMA can be summarized [6] by three fundamental questions:

1. What criteria should be used to decide the next packet to be scheduled?
2. What modulation shall be used for that specific packet?
3. How should the packets be fit on the OFDMA bi-dimensional frame? Or in more technical terms "how to construct the complex OFDMA frame matrix as a collection of rectangles that fit into a single matrix with fixed dimensions?"

In the case of WiMAX OFDM, only questions 1 and 2 require to be answered, while for WiMAX OFDMA, they must all be answered for every single frame, which can be as often as every two milliseconds. It is then crucial for the overall network performance to have a scheduling solution that not only optimizes the costly air link resources but is also efficient and runs within such demanding constrains.

Extensive research on scheduling solutions for other transmission technologies has been conducted in the past. Initial scheduler proposals for WiMAX OFDM are based, at least conceptually, on those solutions; however, the application to WiMAX OFDMA cannot be carried out without additional tweaks and consideration for its more stringent constrains. The chosen scheduling algorithms were found to be the most relevant available in the literature for WiMAX OFDM as well as WiMAX OFDMA, answering the three fundamental questions outlined above as well as presented considerations for supporting multiple QoS scheduling services.

## 1.2. Thesis Contribution

In this thesis, emphasis is given to a comprehensive analysis of four scheduling techniques for downlink traffic in WiMAX. Five industry-defined performance metrics (sector throughput, application throughput, average completion time, fairness index and delay) are used and their applicability to the analysis of scheduling techniques in multiple environments (controlled, stationary and mobility) is explored. Several contributions from this work are presented:

- A review as well as a categorization and analysis of options for WiMAX OFDMA scheduling currently available in the literature.
- Comparison of recent and promising scheduling proposals under similar conditions. Most researchers usually propose advanced implementations that are only tested against a well-known set of scheduling protocols that are not necessarily the most up-to-date options. While this is important to establish a baseline, a good understanding of the newly proposed algorithm's performance compared under similar conditions is preferred.
- Highlight the effects of the characteristics of each environment (controlled, stationary and mobile) on the defined metrics for each scheduling algorithm and identify alternatives for better performance and algorithm improvements.

## 1.3. Thesis Overview

This thesis surveys recent techniques proposed to deal with the question of efficient scheduling of air resources in the WiMAX context, and goes as far as developing the required software to test three of these techniques in the downlink direction, namely Proportional Fairness (PF), Modified Largest Weighted Delay First (MLWDF) and Highest Urgency First (HUF), using Qualnet's WiMAX simulator. The developed algorithms, together with Weighted Fair Queuing (WFQ, the default scheduling algorithm implemented in Qualnet's software) are analyzed using five key performance indicators (KPIs: average sector throughput, application throughput, average completion time and fairness index) defined by the WiMAX Forum, an industry-led consortium promoting the WiMAX ecosystem.

A scheduler with a good average sector throughput should yield equivalent results in terms of application throughput, particularly for the FTP Application, which is the only application simulated in this research that can make use of extra bandwidth if available. Average completion time and fairness index, both based on the performance of the FTP application, are also interrelated. A high fairness index (close to 1) would indicate that resources were shared equally among users with the same bandwidth demands, which would cause, on average, an increase in completion time. Finally, delay results were obtained for delay sensitive applications (CBR and VoIP) and verified to ensure that the schedulers did not violate their QoS commitments.

The response of each scheduling algorithm is analyzed first in a controlled environment with no variation in the radio conditions of each subscriber; second, in a stationary environment by introducing lognormal shadowing; and third, by adding Rayleigh fading to simulate a pedestrian environment in an urban setting.

The decision to run the simulations under three different environments, even though it increased the amount of work involved, proved to be highly beneficial as interesting environment-dependent insights were identified.

For starters, the controlled environment provides an intuitive way to see the behavior of individual flows over time and the effect scheduling decisions have on them. As a matter of fact it helped identify a queue leak causing a high amount of dropped packets after running continuous traffic for a few seconds.

Comparing mobile and stationary environments was equally rewarding. While the stationary environment results favored PF and MLWDF in terms of throughput and completion time, and HUF and WFQ in fairness and delay; under mobile environment, three of the defined KPIs (application throughput, average completion time and fairness index) showed no statistically significant difference among the analyzed schedulers.

In summary, MLWDF was found to be a comprehensive and customizable algorithm that maximized throughput while still being able to maintain its QoS commitments. This is in contrast to PF which, even though it has throughput maximization attributes, does not incorporate mechanisms to guarantee that QoS is being met.

## 1.4. Thesis Structure

The thesis is organized as follows. In Chapter 2, background information about WiMAX and its PHY and MAC layers is presented, with particular emphasis given to the different scheduling services and their quality of service requirements. Chapter 3 presents previous work in the area of scheduling algorithms applicable to WiMAX scheduling and provides a taxonomy to characterize the identified solutions. In Chapter 4, a brief description of Qualnet, the simulation software chosen for the algorithms' implementation, is presented, including its main features as well as known limitations. Additional insights obtained from the literature review are presented in Chapter 5, while Chapter 6 provides a detailed description of the four protocols under analysis. Chapters 7 describes the parameters used for each environment and traffic profiles, and Chapter 8 describes the performance metrics (also called key performance indicators) used to analyze each scheduler. Finally, Chapter 9 summarizes all obtained results and Chapter 10 presents conclusions and recommendations.

## 2. WiMAX Background

WiMAX (Worldwide Interoperability for Microwave Access) is an industry consortium formed to provide a standard solution for broadband wireless access based on the IEEE 802.16 family of protocols. Table 2-1, based on [7], summarizes basis characteristics of the three major standards, two of them (802.16d-2004 and 802.16e-2005) actually implemented by the WiMAX forum by specifying a subset of design choices through what is called a *system profile.*

*Table 2-1 IEEE 802.16 Standards*

| | 802.16 | 802.16d-2004 | 802.16e-2005 |
|---|---|---|---|
| Status | Completed 2001 | Completed 2004 | Completed 2005 |
| Application | Fixed LOS | Fixed NLOS | Fixed and mobile NLOS |
| Transmission scheme | Single carrier only | SC, 256 ODFM, 2048 OFDM | SC, 256 OFDM, SOFDM with 128,512,1024 or 2048 subcarriers |
| Air interface designation | Wireless MAN-SC | Wireless MAN-SCa, Wireless MAN-OFDM, Wireless MAN-OFDMA, Wireless HUMAN | Wireless MAN-SCa, Wireless MAN-OFDM, Wireless MAN-OFDMA, Wireless HUMAN |
| Actual WiMAX implementation by the forum | None | 256-OFDM as Fixed WiMAX | Scalable OFDMA as Mobile WiMAX |

The current research concentrates on scheduling techniques for Mobile WiMAX, which fundamentally complements 802.16-2004 with mobility support as well as OFDMA as the PHY layer air interface. The Mobile System Profile [5] provides the mandatory and optional features that a Mobile WiMAX implementation should support. For the purpose of our research, any simulation tool chosen should adhere to that profile as much as possible. Some of the parameters of the system profile important for this research are depicted on Table 2-2. In the next couple of sections, some of the characteristics of the IEEE 802.16e-2005 PHY and MAC layer are presented.

*Table 2-2 WiMAX Forum Mobile System Profile parameters*

| Parameter | Status | Description |
|---|---|---|
| PHY Mode | Mandatory OFDMA only | OFDMA is the sole PHY mode defined for mobile WiMAX |
| Frame length | Only 5ms is mandatory | Duration of a frame (which corresponds to one downlink and one uplink subframe) in milliseconds. Several other frame durations between 2 and 20 ms are allowed |
| Duplexing mode | Only TDD specified | Time division duplexing. BS and MS will use the same frequency both to transmit and receive. |
| Subcarrier allocation | PUSC, FUSC mandatory for DL. PUSC and band AMC mandatory for UL | Indicates how subchannels (a set of subcarriers, the minimum frequency domain unit allocated to a user) are built. They can be constructed using either a contiguous set of subcarriers (Band AMC) or a set of pseudo-randomly distributed subcarriers (PUSC and FUSC) |
| Modulation | QPSK,16QAM and 64QAM | Combined with the coding scheme, will determine how many bits can be conveyed. 64QAM is optional on uplink |
| Map support | Normal is mandatory while submaps are optional | In order to communicate the allocation of bursts per MS within the frame a map both for DL and UL is used. Those maps are modulated QPSK but the submap feature allows creation of multicast groups that can read submaps at higher modulations |
| Convergence Sublayer (CS) | IPv4 and IPv6 currently mandatory | What kind of packets can be encapsulated directly within the WiMAX MAC. Several other CS like Ethernet, ATM, etc are specified in the standard |
| Fragmentation | Mandatory both for Tx and Rx | Ability to split a SDU to be transmitted over several PDUs. On the Rx side, reassembly should be equally supported. |
| Data delivery services | All optional: UGS, rtVR, nrtVR, BE and ertVR | Connection-oriented services conceived to support a variety of applications. Scheduler must take into account the requirements of each connection and schedule its packets accordingly |

## 2.1. Mobile WiMAX PHY

Several PHY layers have been defined in IEEE 802.16:

- WirelessMAN SC. Single carrier, aimed at frequencies above 11 GHz with LOS requirements for point to point operation.
- WirelessMAN SCa. Single carrier, aimed at frequencies between 2 GHz and 11 GHz for point to multipoint operation.
- WirelessMAN OFDM. The PHY used by Fixed WiMAX, based on 256 FFTs for operation in non-LOS conditions between 2 GHz and 11 GHz.
- WirelessMAN OFDMA. Initially based on 2048 FFTs for operation in non-LOS conditions between 2 GHz and 11 GHz. For Mobile WiMAX, this PHY layer has been extended to support several FFT sizes namely: 128, 512, 1024 and 2048 and it is the sole PHY layer defined by the WiMAX forum in its Mobile System Profile. OFDMA allows multiple subscribers to transmit at the same time during a frame.
- WirelessHUMAN. Similar to the MAN OFDM specification, with the exception that it focuses on unlicensed bands.

Figure 2.1-1 [7] provides an overview of the several functional stages that compose the PHY layer including:

- Forward Error Correction (FEC) including channel encoding, rate matching, interleaving and symbol mapping. Steps to support PHY layer retransmissions (H-ARQ) are also performed at this stage.
- Construction of the OFDM symbol in the frequency domain including space/time coding or MIMO if available, inserting pilot subcarriers for channel estimation purposes and performing subcarrier allocation. The subcarrier allocation process corresponds to the

mapping of subcarriers into subchannels using a subcarrier permutation scheme (PUSC, FUSC, and Band AMC). Those subchannels will later be allocated to specific slots, which is the basic PHY layer allocation unit for a user.

- Conversion of the OFDM symbol from the frequency domain to the time domain through a series of Inverse Fast Fourier Transforms (IFFT) and eventually into the analog domain.

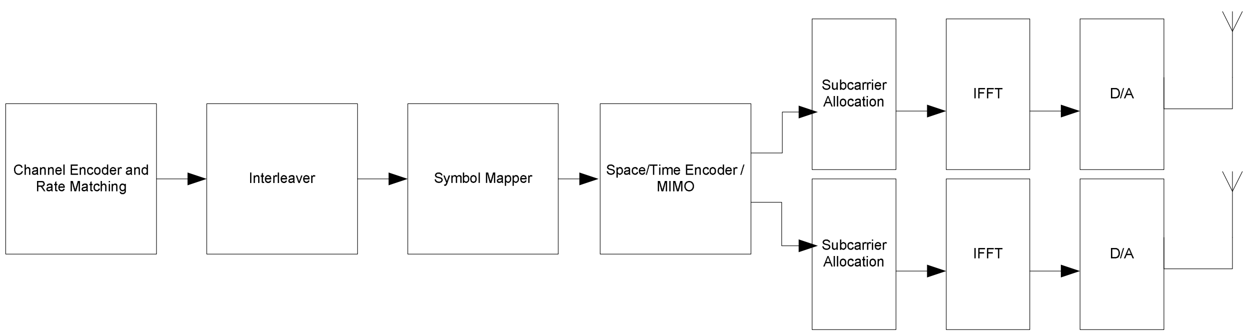



*Figure 2.1-1 Functional Stages of WiMAX PHY*

Figure 2.1-2[7] shows how the subcarrier allocation is performed in the case of the DL PUSC permutation scheme. Other permutation schemes operate in a similar fashion. Fourteen consecutive subcarriers over two symbols are arranged into clusters, which are then renumbered using a pseudorandom scheme and assigned to one of six groups. Two clusters from the same group will then form a subchannel. This subchannel is the frequency domain allocation that will compose a slot. In the case of DL PUSC, a slot is one subchannel (composed of 24 subcarriers) by two OFDM symbols.

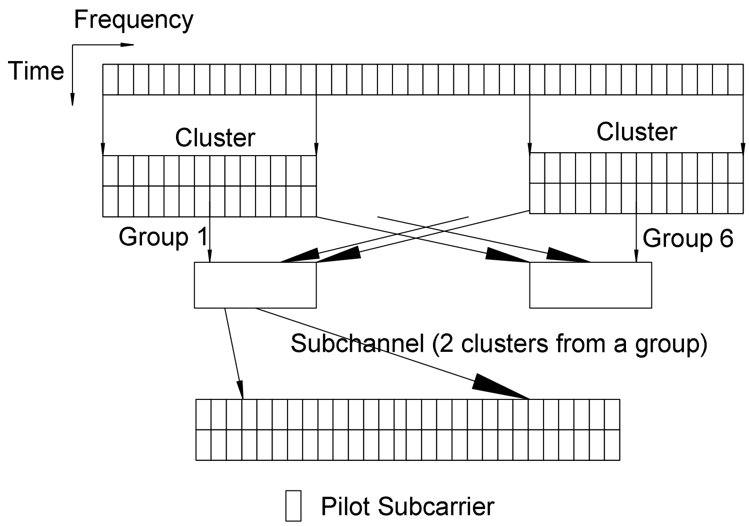



*Figure 2.1-2 DL PUSC Permutation*

## 2.2. Mobile WiMAX MAC

Figure 2.2-1 shows a WiMAX TDD frame structure. Both downlink and uplink subframes are bi-dimensional structures composed of subchannels over a certain number of symbols. Each burst is assigned to a particular user and it is composed of an integer number of slots.

It is up to the MAC layer to allocate these slots to specific subscribers based on their QoS requirements and network conditions. Depending on their throughput requirements and resource availability, a subscriber can be assigned as little as a single slot or as many as all the available slots within the corresponding subframe. Slot allocation information is contained either in the downlink or uplink map depending on the direction of the connection.

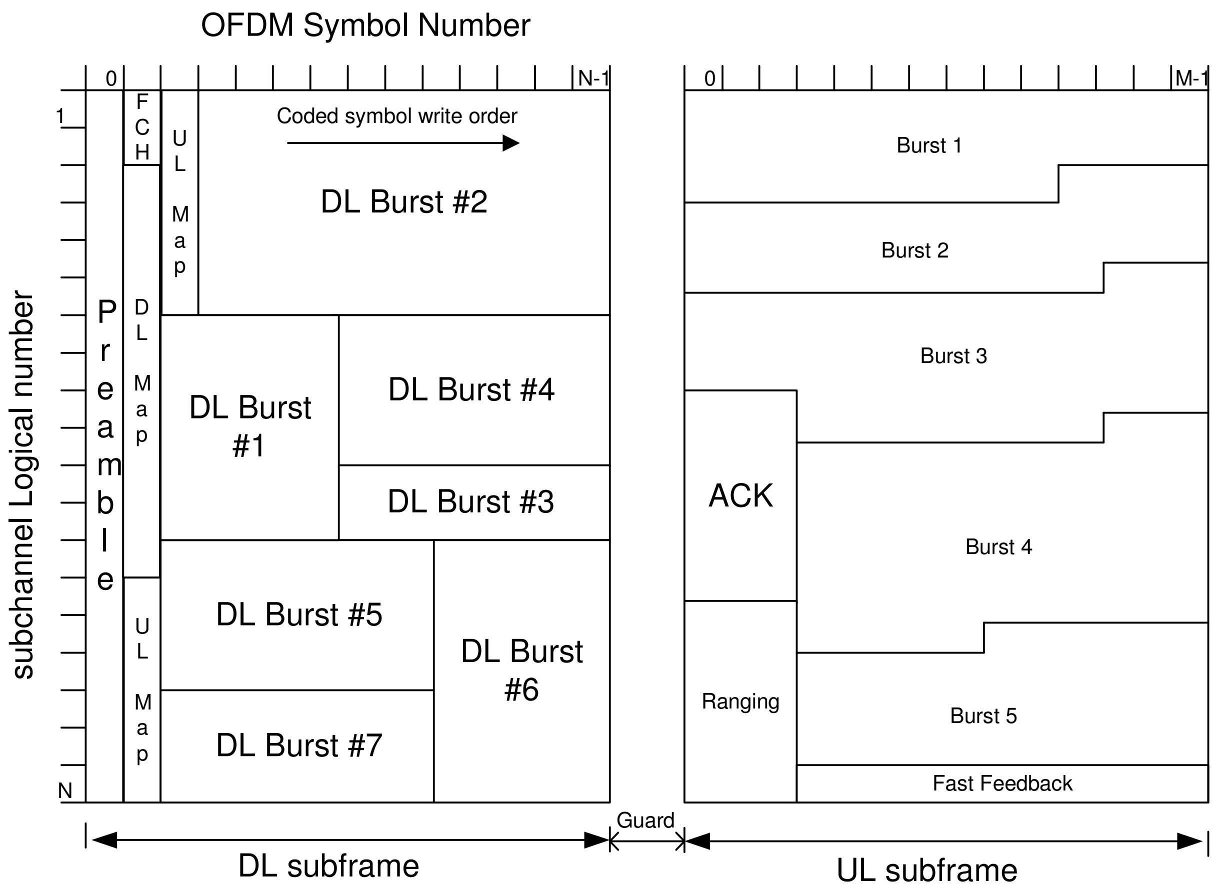



*Figure 2.2-1 WiMAX TDD Frame Structure*

Figure 2.2-2 shows the main components of the WiMAX MAC and how data gets converted from packets all the way to bursts that will be transmitted by the PHY layer on a subframe. Some critical functions of the MAC are:

- Segment or concatenate service data units (SDUs) received from upper layers into MAC protocol data units (PDUs).
- Select the appropriate modulation and coding as well as the power level for the transmission of each burst.
- Retransmission of errored PDUs if ARQ is being used.
- Provide security and key management.

- Provide support to mobility functions.
- Provide QoS control and priority handling of MAC PDUs.
- Schedule MAC PDUs over the PHY resources. In the downlink direction, all scheduling decisions are made at the BS as packets arrive into different scheduling services. In the uplink direction, MS can be granted periodic opportunities to transmit or should send requests for bandwidth, which will be scheduled by the BS entity and indicated to the MS in a subsequent UL map. The following section will explain this process in more detail.

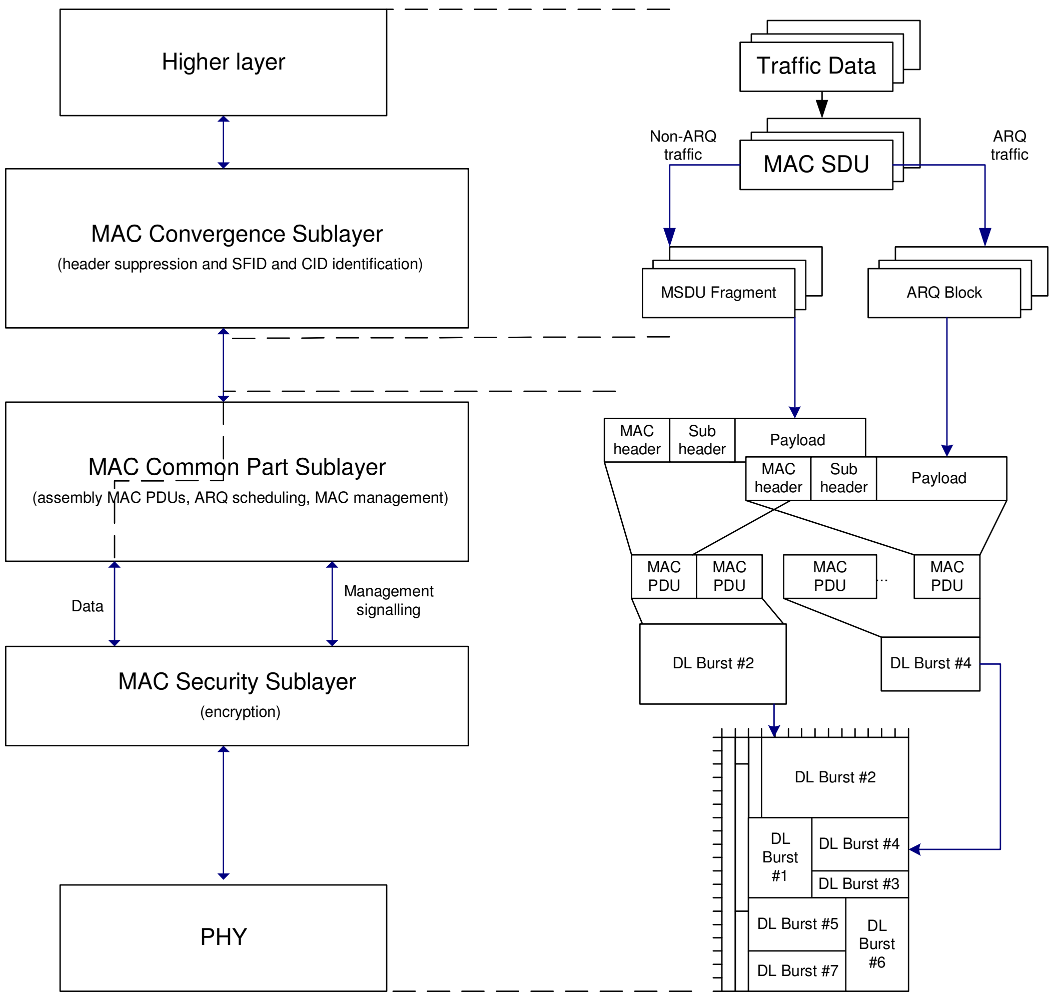



*Figure 2.2-2 WiMAX MAC Layer. Compiled from [7] and [8]*

WiMAX owes its QoS versatility to the different scheduling services supported, which determine how the network will allocate UL and DL transmission opportunities as well as how the MS can request uplink resources. The five scheduling services defined in the standard are shown on Table 2.2-1. A scheduler designed for WiMAX should take into account and accommodate the requirements of each scheduling service.

*Table 2.2-1 WiMAX Scheduling Services*

| **Scheduling Service** | **Application** | **Access to resources** |
|---|---|---|
| Unsolicited Grant Service (UGS) | Real time service flows of constant bit rate and low jitter and delay tolerance such as circuit emulation or VoIP. | Fixed periodic amount of BW is assigned to the connection; MS cannot request additional UGS BW but can request replacement of lost BW via a Slip Indicator (SI). A Poll Me (PM) bit can be used to request a unicast poll for BW needs on non-UGS connections. |
| real time Polling Service (rtPS) | Real time service flows of variable data rate such as streaming video | Periodic request opportunities are assigned, which allow an MS to specify the amount of BW required each time. MS cannot use contention requests opportunities, only the assigned unicast poll. |
| Non-real time Polling Service (nrtPS) | Can be used for TCP-based applications with relaxed delay sensitivity such as FTP. | Similar to rtPS but polling period is longer and contention request opportunities are allowed even though they can be restricted via the transmission/request policy |
| Best Effort (BE) | For services that do not have any QoS requirements, HTTP or e-mail for example | All forms of polling are allowed |
| Extended real time Polling Service (ertPS) | Real time services for which the bit rate varies slightly in time. Implemented having VoIP with silence suppression in mind | MS is allowed to change its BW requirements over time. Periodic grants are assigned like in UGS, those grants can be used to transmit data as well as for requesting additional BW (unlike UGS). |

Some applications such as voice over IP will have very stringent delay and jitter constrains, while consuming little bandwidth; others, such as video streaming, will require much more bandwidth, but are more resilient to longer delays. The quality of service requirements of a certain application, like the maximum tolerated latency and jitter and the minimum throughput required to operate properly are mapped into QoS parameters and depending on these parameters, mapped to a scheduling service that supports them. Table 2.2-2 shows the scheduling services and QoS parameters supported by each one. Applications should be mapped to a scheduling service that supports the QoS parameters that they require to operate properly. Voice over IP for example, which requires a consistent delay and jitter should be mapped to UGS or ertPS (ertPS having the advantage that bandwidth requirements can change over time, so during silence periods the bandwidth requirement can be set to zero), while an e-mail application, which does not have an specific bandwidth or delay requirement can be sent over a BE scheduling service.

*Table 2.2-2 Scheduling Services and their supported QoS Parameters*

| **QoS parameter** | **UGS** | **rtPS** | **nrtPS** | **BE** | **ertPS** |
|---|---|---|---|---|---|
| Maximum Sustained Traffic Rate (MSTR). Defines the peak information rate (bits per second) of the service. Used for policing and traffic shaping of the flow | Y | Y | Y | Y | Y |
| Minimum reserved traffic rate (MRTR). Specifies the minimum rate (bits per second) reserved for the flow calculated excluding MAC overhead | N | Y | Y | N | Y |
| Maximum latency. Specifies the maximum interval between the reception of the packet at the transmit end and the arrival of the packet at the receive end | Y | Y | N | N | Y |
| Tolerated jitter. Specifies the maximum delay variation for the connection. | Y | N | N | N | Y |
| Traffic priority. Specifies the priority of the associated service flow. It is used to prioritize one flow over the other | N | Y | Y | Y | Y |

When a WiMAX subscriber ranges into the network, two bi-directional MAC layer connection identifiers (CID) are set up for management traffic between the subscriber and the BS entity: A primary CID, which is used for delay-sensitive management messages such as ranging or bandwidth allocation; and a basic CID, used for less sensitive MAC messages such as IP address request. Additionally, unidirectional data CIDs will be set up to identify specific traffic flows between the subscriber and the BS. It is these data CIDs that could map into different scheduling services depending on classification rules defined for the user.

For the downlink, it is up to the BS entity to decide which packets to schedule next as queues for different scheduling services start to fill up. It will then communicate the scheduling decision in the DL map, together with the corresponding burst within the same frame.

In the uplink direction the process is a little more complex. Depending on the scheduling service, connections can either have periodic transmission grants (UGS, ertPS), periodic opportunities to request BW (ertPS, rtPS, nrtPS), or contention opportunities to request BW (ertPS,nrtPS, BE). These grants can then be allocated based on two modes:

- GPSS: Grant per subscriber station. BS grants bandwidth based on the aggregate of requests. Grant is communicated to the SS (Subscriber Station) via its primary CID (Connection Identifier). It is then up to the subscriber to decide how to distribute the BW, and the SS itself has to apply a certain level of scheduling logic to decide what connection to allocate the grant to.
- GPC: Grant per connection. The BS Entity decides the specific connection to grant the bandwidth to. As this mode is more controlled and saves scheduling decisions at the subscriber, it introduces additional overhead as now the UL map should have grant information for each connection.

GPSS will be most likely the mode of choice as it allows for higher scalability since it saves a considerable amount of space on the UL map.

# 3. WiMAX Scheduling Techniques

Queuing theory as well as scheduling techniques are widely researched topics in telecommunications and computing. It is reasonable then that initial scheduler solutions for WiMAX were adaptations of current scheduling techniques already proven for other technologies. Additionally, over the last few years there has been a good amount of research on complementary techniques to take into account the variability of the wireless channel through opportunistic algorithms, channel awareness and cross-layer designs.

While some similarities to the wired world can be drawn, there are certain characteristics of the wireless environment that make scheduling particularly challenging. Five major issues in wireless scheduling are identified in [9] :

- Wireless link variability: Due to characteristics of the channel as well as location of the mobile subscribers.
- Fairness: Refers to optimizing the channel capacity by giving preference to spectrally efficient modulations while still allowing transmissions with more robust modulations (and hence, consuming a major amount of spectrum) to get their traffic through.
- QoS: Particularly for WiMAX, QoS support should be built into the scheduling algorithm to guarantee that QoS commitments are meet under normal conditions as well as under network degradation scenarios.
- Data throughput and channel utilization: Refers to optimizing the channel utilization while at the same time avoiding waste of bandwidth by transmitting over high loss links.

- Power constrain and simplicity: Be considerate of the terminals' battery capacity as well as computational limitations both at the BS and MS.

Figure 3-1 presents a taxonomy of scheduling algorithms found in the literature. Even though there is no clean cut between each branch, it helps to visualize some of the techniques used and to explain the basic concepts behind them.

Early algorithms have characteristics that clearly differentiate them and hence are easily classified; [7] and [10], for example, define algorithms in terms of what gets optimized: maximum overall capacity, fairness in terms of allocating resources equally to all the users, or fairness proportional to bandwidth requirements or link condition. More recent algorithms are much harder to categorize as they usually combine several techniques targeting specific requirements of each scheduling service in order to meet QoS requirements, while implementing some sort of fairness to avoid starvation of BE and nrtPS connections and even incorporate admission control.

While we adopt part of the taxonomy proposed by [11], algorithms are matched to their respective families based on similarities in their formulation as well as the parameters used to make the scheduling decision:

- Balance fairness and throughput. Algorithms that pursue a middle ground between sector throughput and allocating a fair amount of resources to subscribers in the sector share the basic formulation presented in [12]. Proportional Fairness is a representative example of this category.
- Based on weight/deficit calculations. This category includes algorithms implementing calculations assigning weights, deficit, or delay counters to each connection that later will

be used to perform scheduling decisions. Solutions inspired by general processor sharing algorithms like TGPS, WRR and DRR are representative examples of this category.

- Opportunistic and cross-layer algorithms. Opportunistic algorithms look at exploiting the variability of the wireless channel condition by giving preference of transmission to subscribers with good channel quality [13]. The term "cross-layer algorithm" is used extensively and requires extra care; [14] presents a taxonomy identifying six different kinds of cross-layer designs. In the context of this research, cross-layer refers to algorithms that integrate both the scheduling of packets to meet QoS commitments and the scheduling of radio link resources (slots, subchannels) to optimize them. MLWDF, for example, factors in a QoS-based priority and a delay counter, as well as channel capacity information in its scheduling decision.
- Hierarchical and hybrid algorithms are algorithms that combine several scheduling techniques, in order to meet the particular needs of each scheduling class. Usually these algorithms distribute the available resources among the different scheduling services, as the first layer of the hierarchy, and then independent scheduling techniques are applied to decide the next packet to be scheduled for each scheduling service. Some solutions also incorporate a certain level of admission control to avoid starvation of lower priority scheduling services.

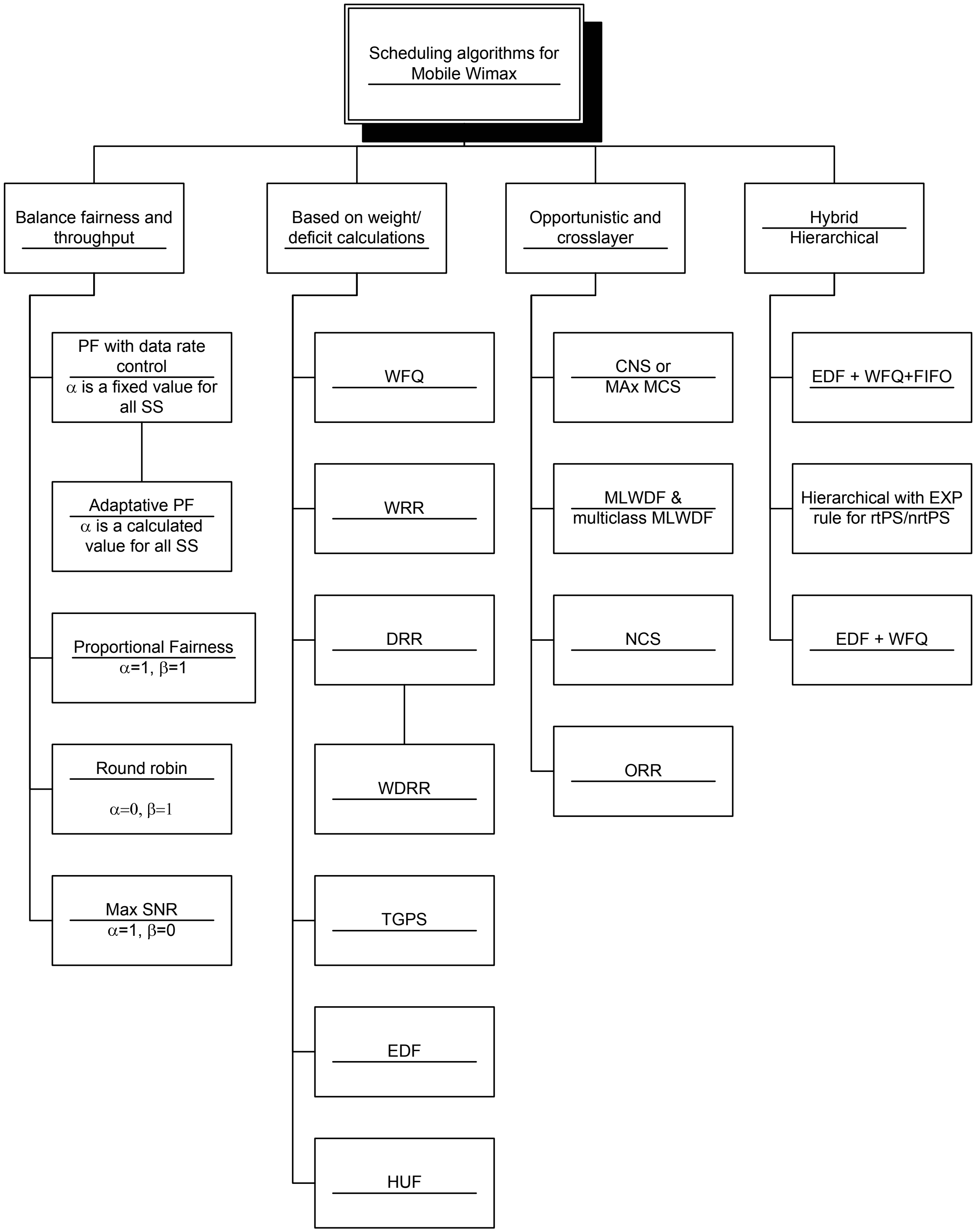



*Figure 3-1 Taxonomy of Scheduling Algorithms for Mobile WiMAX*

A classification of recent scheduling proposals for WiMAX is also presented in [15], where scheduling techniques are classified in two main categories: channel-unaware and channel aware depending on whether or not RF channel information is used for scheduling decision. Channel-aware algorithms are further categorized based on the objective of their formulation: fairness, QoS guarantee, system throughput maximization and power optimization.

While this classification is interesting, we believe a taxonomy based on formulation and method of operation helps identify better commonalities among schedulers. For example, according to the channel-unaware vs. channel-aware classification, WFQ would be a channel-unaware algorithm, but that same algorithm could be adapted to make it channel-aware by incorporating dynamic channel conditions into the calculation of a connection's weight.

## 3.1. Algorithms that balance Fairness and Throughput

The fundamental premise of algorithms that balance fairness and throughput is to achieve a good overall throughput while avoiding starvation of the subscribers that are not using spectrally efficient modulations [16]. Algorithms on this category share the form [12]:

$$j = \arg\max_{1 \le i \le N} \frac{D_i(t)^{\alpha}}{R_i(t-1)^{\beta}}$$

Here $j$ is the user that is next to be scheduled, $i$ is one of the $N$ users that have packets to be scheduled. $D_i(t)^{\alpha}$ represents the data rate currently supported by user $i$ based on its channel conditions, and $R_i(t-1)^{\beta}$ corresponds to the average data rate for user $i$. The observation window, used to calculate the average data rate, is a parameter specified in the definition of $R_i$ [12]. As the function looks to maximize the data rate to average data rate ratio, fairness is implicit: users will be scheduled if they can support a good data rate $D_i(t)^\alpha$ , but users that start to average a low data rate will eventually get scheduled.

The parameters α and β are tuning parameters. α can be used as a method to limit the data rate, and hence incorporate traffic shaping into the algorithm. β can be factored in to control the way the data rate averaging is performed. Table 3.1-1 shows different combinations of α and β found in the literature.

Even though these algorithms perform reasonably well at balancing throughput vs. fairness over the air link, one can conclude by looking at the formulation that prioritization is not embedded in the algorithm itself. Additional steps need to be taken to incorporate prioritization among scheduling services. In [17] for example, a simple method is used to deal with this situation: the minimum number of slots to meet QoS requirements are pre-allocated in order: UGS first, rtPS second and only then unused slots are allocated to other scheduling services in order : nrtPS and BE; ertPS is not considered here.

*Table 3.1-1 Algorithms that balance Fairness and Throughput*

| A | B | Algorithm |
|---|---|---|
| 1 | 1 | PF algorithm used in CDMA EVDO 1x [16]. It is the prime example of this category as it uses the feedback on the currently used MCS, combined with the average data rate used by each subscriber to determine which packet gets access to the resources. |
| 1 | 0 | Max SNR [10] algorithm, which always serves the terminal with best RF conditions. Although it optimizes overall throughput, it doesn’t have any fairness considerations. |
| 0 | 1 | Round robin [11] scheduling with time slots assigned according to the average data rate of each subscriber |
| *n* | 1 | PF with data rate control [12]. *n* is a predetermined value that will control the data rate allocated to subscribers. The value of n is the same for all subscribers and hence different data rate limits cannot be allocated |
| $C_i$ | 1 | Adaptive PF [12] . It complements the previous algorithm by introducing $C_i$, a dynamic data rate control value for user *i* |

## 3.2. Algorithms based on Weight/Deficit Calculations

Interesting complements to the PF-based algorithms are the ones based on Generalized Processor Sharing (GPS). While the PF-based algorithms use the bandwidth requirements and the MS' current bandwidth capacity as the inputs to their scheduling decision, these algorithms base their decision on weights, delay or deficit measurements that are allocated dynamically considering different factors. Factors that determine the weight can be service priorities, fairness considerations, bandwidth or delay requirements; giving these algorithms some more flexibility. QoS prioritization, for example, could be built into the scheduler by incorporating them into the calculation of the weights.

A classical example of this kind of algorithms is TGPS (Truncated Generalized Processor Sharing) proposed for OFDM by [18]:

$$M_i^k = \left\lfloor \frac{\phi_i}{\sum_{j \in B} \phi_j} M_{eff}^k \right\rfloor$$

$M_i^k$ corresponds to the allocation of resources for user *i* at time *k*, while $M_{eff}^k$ is the number of available subcarriers available at time *k*. $\phi_i$ is the weight (not specified in the initial formulation of the algorithm) assigned to user *i*, which is weighted against all active users (set B), represented by $\sum_{j \in B} \phi_j$ , so the service ratio for user *i* is determined in proportion to its weight and the aggregate weight of other active transmissions.

WRR (Weighted Round Robin) [11], while similar in formulation to TGPS, does not allocate subcarriers but a weight to each subscriber with packets to transmit. The weight is calculated based on the subscriber's minimum reserved rate (MRR) using the following formula:

$W_i = \frac{MRR_i}{\sum_{j \in n} MRR_j}$, $W_i$ is the weight assigned to user *i*, and *n* is the number of subscribers

The subscriber with the highest weight is then next in line to obtain bandwidth. While the formulation is pretty simple, there are no considerations for a BE scheduling service, which does not have specific MRR values.

Weighted Fair Queuing [19] (WFQ) assigns a weight to each subscriber the same way as WRR, but the argument used to make a scheduling decision is the *finish number*, an estimation of the time at which each individual packet will finish service. The packet with the lowest finish time will be scheduled next. The finish number is calculated based on the subscriber's weight, the finish number of the previous packet scheduled on that connection and the length of the packet. This algorithm was proposed for WiMAX OFDM in [11], at which point its complexity was deemed high. In an OFDMA system, several connections can be served at once during a single frame, which would require multiple rounds of the algorithm and hence higher complexity.

DRR (Deficit Round Robin) accounts for connections not scheduled, increasing a deficit counter for each connection by a certain quantum unit. The deficit counter will be used in subsequent scheduling rounds to compare to the size of the head-of-the-line (HOL) packet on each active connection. If the connection's deficit counter is larger than the HOL packet, it will be scheduled, otherwise it will remain in the queue and the deficit counter will be increased by the quantum while other connections are being served. DRR operates with packet sizes and relies on knowledge of the head of line packet per connection, which is not known from the BS perspective on the uplink. The algorithm in [20] presents a modified DRR algorithm for WiMAX in which the quantum size is in units of slots, the queue sizes are converted from bytes to slots based on the subscriber's MCS and queue size is represented by virtual UL queues created based on the UL bandwidth requests. The algorithm runs in several rounds until all possible slots in the frame are allocated.

A variant of DRR is WDRR (Weighted DRR) also presented in [20], where preference is given to connections with higher MCS by multiplying the quantum size (in slots) by bytes/slot supported by the connection's MCS and then dividing by six (which is the bytes per slot for the most robust MSC: QPSK-1/2). This way connections with a higher MCS will have a bigger quantum than connections with lower MCS and hence a higher probability of being scheduled first.

A classical algorithm to deal with stringent delay requirements is Earliest Deadline First (EDF), which assigns deadlines to packets on each connection and allocates bandwidth to the subscribers based on such deadlines. It is then only applicable to UGS or rtPS scheduling services that have specific delay requirements, but is a good candidate to be part of hybrid algorithms that combine several scheduling solutions [21].

Highest Urgency First (HUF), presented in [22], is a modulation, latency and priority-aware algorithm that builds on the fact that latency-dependent flows not necessarily have to be served first as long as they are scheduled within their delay tolerance window. A deadline indicator, calculated when packets arrive at physical queues on the downlink or virtual queues on the uplink, is used for such purpose.

## 3.3. Opportunistic and Cross-Layer Algorithms

While the algorithms mentioned in the previous sections indirectly account for signal quality by looking at the modulation supported by the subscriber (which at the end of the day is a function

of signal quality), the opportunistic algorithms in this section actually use the signal quality reading (CNR, CINR, e-CINR, etc) as the argument used to make a scheduling decision.
Four well-known opportunistic algorithms that use signal quality as their basic input are presented in [13]. They all are functions of signal quality, sharing the general form:

$$i^*(t_k) = \arg\max_{1 \le i \le N} X_i(t_k),$$

$X_i(t_k)$ is the metric function, calculated at the beginning of time slot $t_k$ and $i^*(t_k)$ corresponds to the index of the user picked to be scheduled. Table 3.3-1 presents the 4 algorithms and the metric used by each one.
In this category, cross-layer algorithms that incorporate both QoS-awareness and opportunistic behavior are also considered. [13] further classifies these algorithms as non-queue aware, which do not factor the influence of queue behavior on delay and hence on QoS, and queue aware, which consider the effect of queue-related conditions in the behavior of the scheduler.
An algorithm that accounts for queuing delay, channel conditions and QoS prioritization (hence making it a queue-aware cross-layer opportunistic algorithm) is Modified Largest Weighted Delay First (MLWDF) [23], initially designed for CDMA systems, which has the following formulation:

$$i^*(t_k) = \arg\max_{1 \le i \le N} \gamma_i W_i(t_k) r_i(t_k),$$

Where $\gamma_i$ corresponds to a priority factor, $W_i(t_k)$ is the HOL packet delay (or queue length on implementations that consider non-delay sensitive BE traffic [24] ) and $r_i(t_k)$ is the channel capacity with respect to flow *i*. By keeping an eye on queue states, as well as channel conditions, the algorithm optimizes the throughput delivered to certain connections, while still keeping queues from getting into a full congestion state. In fact, the authors claim that its behavior is throughput optimal, maintaining all feasible traffic while still keeping all queues stable.

A WiMAX OFDMA version of MLWDF is presented in [24], extending the algorithm to relax the priority constrains when delay sensitive traffic is far from approaching its deadline, effectively giving some transmission opportunities to scheduling services that would usually have to wait for the delay sensitive traffic to be scheduled first.

*Table 3.3-1 Opportunistic Algorithms*

| Metric | Algorithm |
|---|---|
| $\gamma_i(t_k)$ | CNS (Carrier to Noise Scheduling). Metric corresponds to CNR reading for user *i* on time $t_k$. |
| $\frac{\gamma_i(t_k)}{\overline{\gamma_i}}$ | NCS (normalized CNR Scheduling). $\overline{\gamma_i}$ corresponds to the average CNR for user *i.* As CNS is too aggressive, scheduling always the highest CNR reading, NCS introduces some fairness by scheduling the highest normalized CNR on each time slot. |
| $\frac{r_i(t_k)}{T_i(t_k)}$ | Proportional Fair Scheduling. This is the same algorithm described in Section 3.1. |
| Max CNR in each round | Opportunistic Round Robin (ORR). Users are scheduled in rounds of N competitions. For the first time-slot in a round, the user with the highest CNR is chosen. This user is then taken out of the remaining competitions of the round, and for the next time-slot the user with the highest CNR of the remaining users is scheduled. A normalized version (N-ORR) that considers the normalized CNR as opposed to pure CNR also exists. |

## 3.4. Hierarchical / Hybrid Algorithms

Hierarchical/hybrid algorithms build on the fact that scheduling services have different and sometimes conflicting requirements. UGS services must always have their delay and bandwidth commitment met, so simply reserving enough bandwidth for those services and controlling for oversubscription would be enough; rtPS or ertPS services have little tolerance for delay and jitter, so an algorithm guaranteeing delay commitments would be more suitable; and finally, BE and nrtPS will always be hungry for bandwidth with no considerations for delay, so a throughput maximizing algorithm might be preferred.

While hierarchical refers to two or more levels of decisions to determine what packets to be scheduled, hybrid refers to the combination of several scheduling techniques (EDF for delay sensitive scheduling services such as rtPS, ertPS and UGS, and WRR for nrtPS and BE for example). There could be hierarchical solutions that are not necessarily hybrid, but hybrid algorithms usually distribute the resources among different service classes, and then different scheduling techniques are used to schedule packets within each scheduling service, making them hierarchical in nature. In [25], the authors use a first level of strict priority to allocate bandwidth to UGS, ertPS, rtPS, nrtPS and BE services in that order; and then on a second level in the hierarchy, different scheduling techniques are used depending on the scheduling service: UGS, as the highest priority, has pre-allocated bandwidth, EDF is used for rtPS, WFQ for nrtPS, and FIFO for BE. Similarly, [11] explains an algorithm that uses EDF for ertPS and rtPS classes, and WFQ for nrtPS and BE classes.

In [26], the authors implement a two-level hierarchical scheme for the downlink in which an ARA (aggregate resource allocation) component first estimates the amount of bandwidth required per scheduler class (rtPS, nrtPS, BE and UGS) and distributes it accordingly. An extended exponential rule algorithm is then proposed for rtPS and nrtPS, leaving scheduling of BE and UGS as future research.

Even though admission control techniques are independent from the scheduling task, and could be incorporated into any of the scheduling techniques presented so far, they are particularly important for algorithms in this category. As certain scheduling services have higher priority than others, starvation control has to be considered. Admission control, together with traffic policing, is proposed in [25] and [26] implements an admission control module interacting with the resource allocation module to dynamically decide if new connections are allowed.

# 4. Current Options for Mobile WiMAX Simulations

When one follows the evolution of scheduling solutions proposed, two parallel patterns starts to emerge: One favoring simplicity and speed and the other one in favor of more elaborate alternatives, with higher execution time and complexity. Simulations should help compare schedulers that are simple in design and consider a few factors to more elaborate techniques that consider a higher number of variables but have a higher complexity.

Several options to perform mobile WiMAX simulation are currently available. Initially, most researchers used MATLAB to simulate portions of the WiMAX implementation, and later had to write their own MAC/PHY implementation for end-to-end simulation tools like NS-2, Opnet and Qualnet. Such implementations were not usually made publicly available, leaving no chance for other researchers to replicate similar conditions for fair and unbiased comparisons of results. Only until a couple of years ago commercial and open source solutions started to appear:

- Opnet released its WiMAX module in February 2006 and it has continuously improved it since then. The latest release supports major features of the IEEE 802.16e PHY/MAC, including all the scheduling services, radio link control, ARQ, MAC messaging, mobility and OFDMA path loss model.
- Qualnet’s WiMAX module was introduced October 2006. Its latest release implements all the WiMAX features mentioned for Opnet above, missing a security implementation (PKM) and soft handoff.
- An ns-2 based WiMAX module is publicly available from the National Institute of Standards and Technology (NIST) [27]. While the module is fairly well documented, implements QoS, different scheduling services and mobility, it lacks OFDMA support, making it usable for Fixed WiMAX simulation only.

- The Network and Distributed Systems Laboratory (NDSL) in Taiwan released an ns-2 based module in August 2006 [8]. The module had several releases adding QoS parameters and OFDMA PHY scheduling services, but it does not implement mobility, lacks documentation (as a matter of fact, their authors did not reply to any of the attempts to contact them via e-mail) and a major issue has been identified by [28], causing the scheduler not to account properly for the number of slots already allocated and hence distribute an unlimited amount of resources.
- An ns-2 based WiMAX module is being developed for the WiMAX forum by several universities including the Network and Distributed Systems Laboratory (NDSL), Washington University in St. Louis (WUSTL), Rensselaer Polytechnic Institute (RPI) and the Wireless Internet and Networks Laboratory (WiNE). This module would have been ideal for the current research, but unfortunately it is not yet completed and the forum will initially make it available to WiMAX forum members only.

## 4.1. Mobile WiMAX Simulation in Qualnet

Given the lack of availability of a reliable open source tool for mobile WiMAX scheduling simulations, only commercial alternatives can be considered at this time. Qualnet's Advanced Wireless Model [29] was chosen for this research due to the flexibility of their research license (Opnet only allowed their software to be installed on-campus while Qualnet offered an option to run a license server on-campus and a Qualnet client off-campus) and the features currently implemented:

- OFDMA PHY. Very important for realistic simulation of mobile WiMAX, which requires multiple access both on downlink and uplink.

- MAC messaging: ranging, bandwidth request/allocation, handover, sleep mode, paging, power control.
- Adaptive modulation and coding (AMC) to allow BS and subscribers to change their modulation according to radio link conditions.
- Mobility support. Will allow scenarios under mobility conditions. A great advantage over the ns-2 based module available from NDSL which allowed testing under stationary conditions only.
- Support for all five service classes (UGS, ertPS, rtPS, nrtPS, BE) specified in the standard.
- Basic admission control via a token bucket mechanism. Important as some of the proposed algorithms operate in conjunction with admission control.

The current scheduling algorithm implemented in Qualnet's simulation software is a hierarchical algorithm (hierarchical, but yet not hybrid and a single algorithm is used) using strict priority combined with a basic WFQ scheme.

Strict priority initially classifies the connections according to their scheduling service and serves them in order: UGS, ertPS, rtPS, nrtPS and BE. There is then no consideration for delay requirements as even connections that have packets reaching their delay deadline in ertPS or rtPS queues will not be served until the UGS queue is empty. Moreover, packets in nrtPS or BE queues could potentially starve if admission control were not implemented.

Within each scheduling service, WFQ chooses the next packet to be scheduled using a basic formulation:

$$Si = \left\lfloor \frac{S * w_i}{\sum_{j \in N} w_j} \right\rfloor,$$

Here $w_i$ is the weight of each connection, calculated based on its bandwidth requirements. S and $S_i$ are the total number of slots to be distributed and the number of slots assigned to connection i respectively. N is the set of all connections with packets waiting to be scheduled.

## 4.2. Limitations of Qualnet Simulator

There are still some limitations to Qualnet's simulation software in regards to certain WiMAX features not yet implemented, or partially implemented, which should be considered in the context of this research:

**1.** There is no authentication or traffic encryption. While not having authentication will only imply not having MAC authentication messages during network entry or handoff, there is a direct impact on the throughput obtained as additional overhead is introduced when encryption over the air is enabled. All throughput numbers produced in this research will not consider encryption a part of the equation.

**2.** Packet header compression is not implemented. Although it should not directly impact the behavior of a certain scheduler vs. another one, it is a consideration when reading throughput numbers.

**3.** The currently implemented WFQ scheduler does not consider priorities among connections within the same scheduling service.

**4.** Uplink bandwidth scheduler is not implemented as an API. While the downlink scheduler uses a well-defined API to perform scheduling tasks such as adding packets to queues, setting and retrieving current priorities of the queues and adding changes to modify the behavior of the scheduler, the uplink direction is implemented over several files and hundreds of lines of code with no documentation. Writing schedulers for both uplink and downlink direction would then imply working on not three but six schedulers, which is not achievable within the time planned for this research.

5. Applications' QoS parameters are not configurable. QoS parameters are actually determined based on the configured application. In the current release, only CBR and VBR applications map properly to their corresponding QoS parameters. As an example, a CBR application configured to send 128 bytes packets every second would map to the following QoS parameters:

   maxSustainedRate = 1024 bps (128 bytes/second * 8 bits/byte)
   minReservedRate = 1024 bps
   maxLatency = 1000000000 (1000 ms)
   toleratedJitter = 0 (0 ms)

   This seems pretty convenient as service flow parameters are automatically configured, but limits the number of applications that can be properly simulated. Voice over IP for example, is mapped only partially. A voice over IP application, using a G.711 codec which requires at least 64 kbps before overhead is mapped to the following QoS parameters:

   maxSustainedRate = 800 bps
   minReservedRate = 800 bps
   maxLatency = 100000000 (100 ms)
   toleratedJitter = 100000 (0.1 ms)

   Such a flow is not enough to carry the voice over IP traffic, as it results in a considerable uplink delay and packet drops when ertPS or UGS service flows that rely on pre-allocated bandwidth to deliver their data are used. Not using UGS or ertPS for voice traffic, however, would eventually have a negative impact as latency could not be guaranteed and the traffic would be competing with throughput-intensive applications. This is another reason for limiting the scope of the simulations to downlink only as the configured QoS parameters could not be used for uplink VoIP traffic without some rework to either map the service flow properly or implement a way to configure the QoS parameter independently from the application.

Other important applications such as FTP and HTTP suffer the same limitation. FTP and HTTP applications for example do not map to any QoS parameters and there is no way to manually configure them, so it is not possible in the current implementation to configure HTTP in a service class different from BE.

## 4.3. Qualnet's WiMAX Scheduler

A UML diagram of the current WiMAX Scheduler implementation for WFQ can be seen in Appendix A. All schedulers, including the ones that will be implemented as part of this research, derive from the root Scheduler class, which defines the basic member functions that all scheduler must implement: scheduler initialization, add and remove queues, and insert/dequeue packets from to/from a specific queue. Depending on the implementation, additional data structures and variables to keep track of counters, weights, ratios and flags will be required.

For a WiMAX downlink scheduler, the MacDot16Bs structure contains a pointer to a structure of Scheduler type which is initialized as part of the instantiation of the WiMAX MAC, and all the required member functions to create/delete queues and insert/retrieve packets to/from the queues are accessed from there. A scheduler has a number of queues, each one corresponding to a WiMAX CID. Each queue then has a dynamic array which stores the packets that need to be scheduled.

Every time a new downlink WiMAX connection is established, a temporary queue is created to store packets sent to that connection while a new queue is added to the scheduler. Once the queue has been setup, packets from the temporary queue are then moved over and any subsequent packets arriving for that connection will be enqueued using the insert member function. It is then up to the scheduler to decide what queues to serve on each scheduling cycle and call the retrieve function to do so.

Qualnet implements the WFQ algorithm in the WfqScheduler class, derived from the FQScheduler class. The FQScheduler class exists to provide some common functionalities to other weight-based schedulers, so only the specifics of the insert and retrieve member functions (which are particular to WFQ) need to be implemented.

The process of scheduling a downlink subframe is shown in Figure 4.3-1. Every 5ms (the configured frame duration) a new MAC frame has to be built, so a function is called to reset all the previous downlink and uplink allocations. Uplink allocation happens first, in order to determine the size of the uplink map, and the number of slots that will be left to build the downlink map and for data allocations. When the ScheduleDlSubframe function is called, the data schedulers (one for each scheduling service) will be checked in order to determine if there are any queues requiring service. Only when all the queues in a higher priority scheduling service are empty, the next priority scheduler will be served. The process will continue until no more slots are available or until all queues have been served.

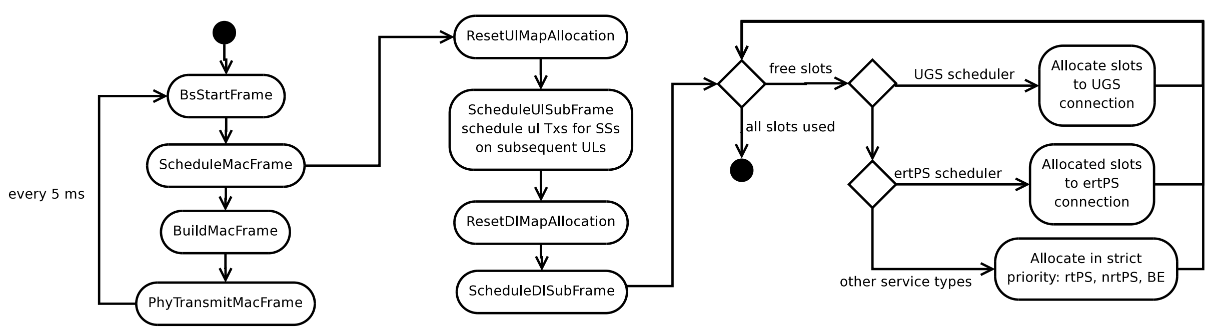



*Figure 4.3-1 Scheduling a Downlink Subframe*

The process of building the DL subframe is not linear, every time slots are allocated a check has to be made to ensure that the capacity of the sub frame will not be exceeded when mapping overhead is added. If that check fails, the frame is considered full and the last packet that was supposed to be added to the subframe is left on the scheduler.  Once the contents of the DL subframe have been defined, the MAC frame including UL and DL maps as well as downlink data is built and passed to the PHY layer for transmission. The process will start over in the subsequent scheduling cycle.

# 5. Scheduling Design Dimensions

We have summarized scheduling solutions for mobile WiMAX and have produced a taxonomy that classifies the protocols in four categories, according to their underlying formulation: Balance fairness and throughput, weight/deficit based, opportunistic/cross-layer, and hybrid/hierarchical. While such a classification is not perfect, it contrasts with [11], which categorizes solutions into homogenous (protocols based on legacy techniques adapted to WiMAX), hybrid (a combination of homogenous protocols) and opportunistic (algorithms exploiting channel conditions although some homogenous techniques already do that), and with [12], which follows the evolution of different scheduling protocols over time.

Several interesting conclusions can be drawn from reviewing the literature:

1. The scheduler problem can be seen as the combination of three interdependent problems: choosing which connection to serve next, choosing the right modulation for the data and fitting corresponding bursts on the frame. The current research will focus mostly on the first issue, comparing four promising scheduling techniques found in the literature: WFQ, PF, MLWDF and HUF.
2. A complete end-to-end scheduling solution should account for admission control and traffic shaping.
3. Scheduling in WiMAX OFDMA can be summarized as meeting QoS commitments while trying to maximize sector throughput. The scheduling algorithms chosen for implementation do precisely that one way or the other.
4. Scrutinizing current scheduling alternatives under the same conditions is ideal to have a more realistic comparison of the performance of each algorithm.

## 5.1. Scheduling Subproblems

Figure 5.1-1 presents a high level view of the scheduling process in WiMAX, depicting the three decisions that need to take place. Physical queues are maintained for the downlink direction for each scheduling service, while virtual queues are maintained in the uplink direction based on bandwidth requests coming from the mobiles or the configured sustained traffic rate for UGS and ertPS. It is up to the scheduler in each direction to sort through those queues and pick a subset of PDUs to be scheduled. Uplink packets update the virtual queues and uplink modulation and a feedback loop exists between the subscriber and the BS in order to identify the modulation to be used in the DL direction.

In addition to having to take care of building the DL/UL maps, the 2D mapper entity has to accommodate the PDUs within bursts per subscriber that will later constitute the downlink subframe. During the 2D mapping process, some portions of a PDU might not fit entirely so they will have to be sent back to the scheduler to be processed during the next round.

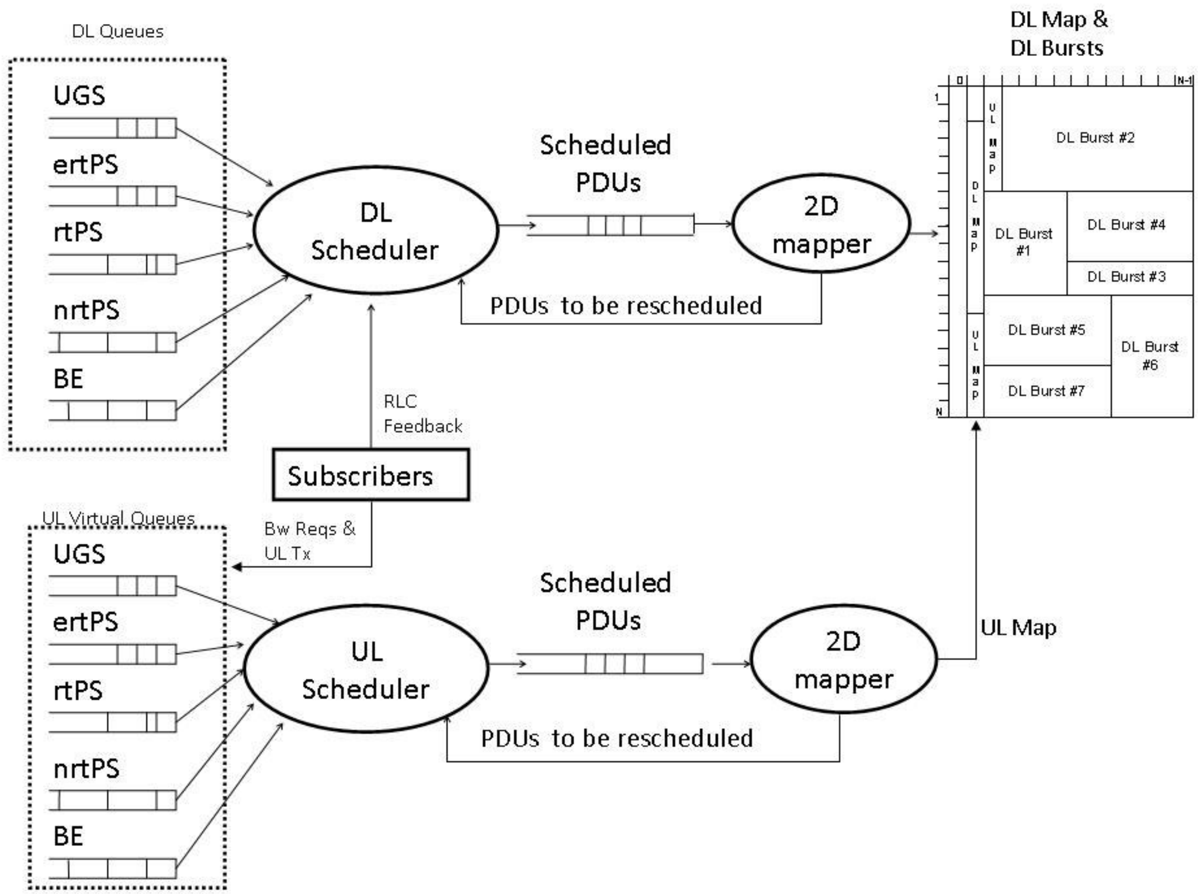



*Figure 5.1-1 High Level View of Scheduler*

According to [6] and [30], there is a circular dependency between those processes that should be broken somewhere. While [30] proposes to first choose the next connection to be scheduled, then the modulation, and finally the frame fitting process, [6] prefers the approach of treating the modulation as an exogenous process and then breaking down the scheduling problem into two sub-problems:

a. Macro scheduling. Assume that a certain profit for transmitting a frame as well as the modulation to be used has been previously assigned to each connection. The authors formulate this problem as a multiple choice knapsack [31] with $s_1 \ldots s_m$ PDUs, a capacity *C* (number of slots on a frame) and each PDU having a well-known modulation and coding rate (the weight $w(s_i)$) and a profit ($p(s_i)$) and propose an approximation algorithm that runs in polynomial time.

b. Micro scheduling. A decision as to how to build the frame is made based on a greedy algorithm that locally minimizes the wasted space.

For the simulations in this research, the approach proposed by [6] of assuming the modulation as an attribute of the connection checked at scheduling time will be adopted. It is also important to highlight that while the process of 2D mapping is required for any implementation of an OFDMA scheduler, most papers do not elaborate on how their algorithm is to build the DL/UL subframes and how to deal with unused slots and bumped PDUs due to frame fitting. Given such limitations, the current research will focus on the problem of choosing the PDUs to be scheduled over the air, conserving the frame fitting technique already implemented in the Qualnet simulation software.

## 5.2. Admission Control and Traffic Shaping

Admission control and traffic shaping should also be contemplated as part of the end-to-end scheduling solution that requires enforcement of a maximum sustained traffic rate. Even a well-engineered network can suddenly start running out of sector capacity if RF conditions change. In such situations, a well-defined algorithm that decides which connections should stay up and which ones to drop or lower their bandwidth is important.

In [32], the authors propose a hierarchical algorithm for admission control that first assigns thresholds to each scheduling service and then decreases a capacity counter per scheduling service every time a new connection is accepted. Even though a scheduling service can exceed its threshold, its priority to access the capacity will decrease and eventually could get some of its connections dumped if a need arises. There is also a provision for traffic policing using a token bucket mechanism. There is no reason why such an approach could not be combined with any of the scheduling algorithms to provide a complete solution to the scheduling problem.

## 5.3. Meeting QoS while Maximizing Throughput

Scheduling in WiMAX OFDMA can be summarized as meeting QoS commitments while still maximize sector throughput. Chosen alternatives use different approaches to achieve that double goal.

Fairness is an important factor as sector capacity cannot be maximized to a point where connections that have poor conditions starve and do not have any service, but at the same time subscribers with poor conditions should not be allowed to dramatically decrease the sector capacity. Figure 5.3-1, inspired by [17], illustrates the issue of poor vs. good conditions. It can be seen, for example, that in order to reach a sector throughput around 4,9Mbps using QPSK ½ modulation would require over 500 slots, while when using an average modulation like 16QAM ½ about 250 slots are required. This would then increase the sector capacity as the remaining slots can be used for other subscribers, or to supplement the current transmission with additional bandwidth. A more efficient modulation like 64QAM ½ would use only a little over 100 slots, versus more than 500 slots using QPSK ½.

On the other hand, some of the algorithms found in the literature, while interesting, do not have any consideration for meeting QoS requirements, which make them impractical for a real WiMAX implementation and are considered incomplete for the purpose of this research.

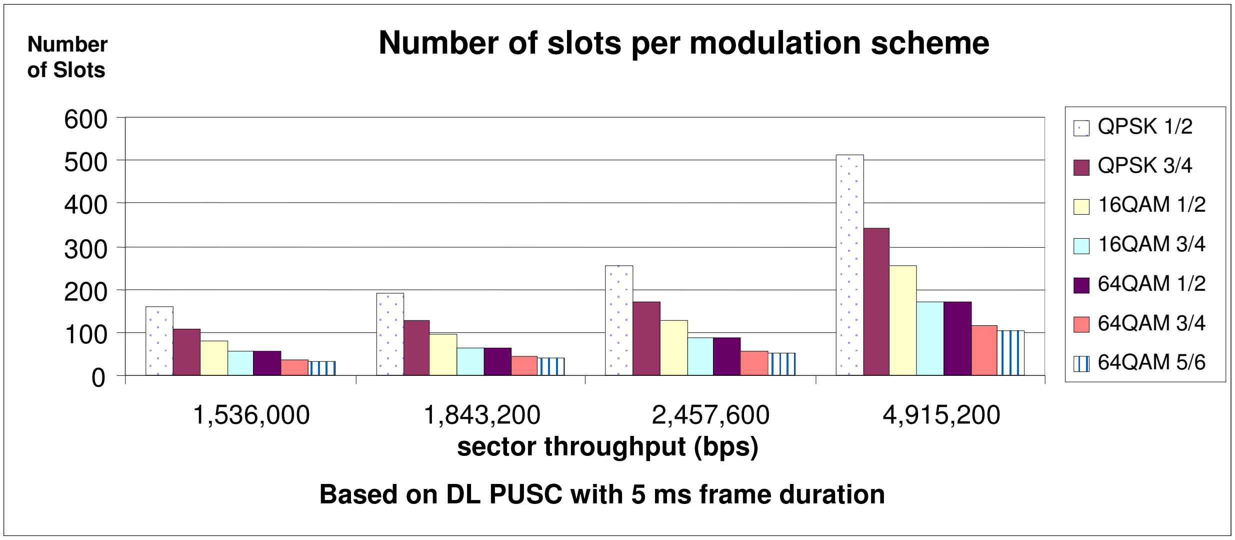



*Figure 5.3-1 Spectral Efficiency of Different Modulations*

## 5.4. The Need for Realistic Scenarios

Most papers that proposed new algorithms only compare themselves to the two extremes of the spectrum: max Carrier to Interference (C/I) ratio (allocating resources to the subscriber with the best RF conditions at a given time) and FQ (allocating resources equally no matter the modulation being used). While this is important from a baseline perspective, those algorithms do not satisfy QoS requirements, so they could not be possibly implemented in real life. Furthermore, they represent the maximum and minimum bound of performance and one would expect that any new scheduling solution would be somewhere in between these two extremes. The value of this research is in (1) testing several recent OFDMA WiMAX scheduling proposals under the same conditions, so more realistic conclusions can be drawn and (2) going through the implementation of the actual pseudo-code proposed, highlighting assumptions that would not hold ground in an actual implementation. A similar objective is pursued in [33], where a comparison of three allocation schemes was performed using the same simulation tool but once again several reasons make the algorithms in that paper not feasible for real deployment :

- Max Waiting Time: The connection with the largest waiting time for the HOL packet is selected. It is basically an EDF implementation, but all connections are treated the same as there are no considerations for different QoS parameters.
- Round Robin: A connection is selected in classical Round Robin manner. Once again QoS parameters are not considered and there is no balance between fairness and throughput.
- Max SINR Gain: Unlike the other two schemes, this strategy finds the optimum resource-connection pair. Each resource is assigned to the connection with the highest SINR gain compared to the mean SINR. Such an algorithm, if implemented as-is, would simply starve connections with poor RF conditions.

# 6. Detailed Description of Selected Scheduling Algorithms

In addition to WFQ, the scheduling algorithm already implemented in Qualnet which will be used for initial simulations, three algorithms have been chosen for implementation in the Qualnet simulation software: Proportional Fairness (PF), a well-known algorithm that balances fairness and throughput adapted to Mobile WiMAX by [17] ; multiclass MLWDF [24], a hierarchical, cross-layer, queue-aware opportunistic algorithm with two implementations: one using strict priority among the scheduling services, and another one relaxing the priority leaving some BE and nrtPS traffic to go through first when UGS and rtPS traffic is far from reaching its delay expiration; and Highest Urgency First (HUF) a weight-based, hierarchical, modulation, latency and priority-aware algorithm that reserves bandwidth for the more urgent requests and allocates the rest according to additional criteria.

The algorithms were chosen for multiple reasons. For starters, only a few of the algorithms surveyed are suitable for implementation as most do not meet the requirements of Mobile WiMAX. Second, several basic algorithms like WRR, RR and FQ [11][12][13] and some legacy algorithms like DRR, WDRR [20] and MLWDF [24] have already been tested in the context of Mobile WiMAX in previous research, so not many additional insights are expected from implementing them. Third, two of the chosen algorithms, namely Multiclass MLWDF and HUF, incorporate a novel concept not seen in other papers: they contemplate deferring the transmission of delay sensitive traffic until their delay commitment is close to expiration, hence favoring throughput-optimizing scheduling services. Analyzing the throughput improvement of such an approach while comparing its accuracy in meeting delay commitments is an interesting deliverable of the current research.

For a full scheduling implementation, a hybrid approach could be more convenient given the different requirement of each WiMAX scheduling class. We however decided in favor of testing each scheduler performance individually, in order to identify the strengths and weaknesses of each implementation.

## 6.1. Weighted Fair Queuing

Qualnet's scheduler implementation for WiMAX is based on the Weighted Fair Queueing (WFQ) algorithm, widely implemented over WAN links thanks to Cisco, which uses it as the default queuing mode on most T1/E1 serial interfaces [34].

WFQ is an algorithm based on weight calculations, derived from the General Processor Sharing (GPS) algorithm. As mentioned in Chapter 3.2, WFQ uses a metric called *finish number*, which is an estimation of when the HOL packet for a certain queue will finish its transmission and is defined for the $k_{th}$ packet in the $i_{th}$ queue as :

F(k,i) = S(k,i) + L(k,i)/W(i),

Being F(0,i)=0;
S(k,i) = max [F(k-1,i) , RoundNumber], called the *start number* ;
L(k,i) the length of packet *k* in queue *i*;
and W(i) the weight of queue *i*.

RoundNumber represents the progression of virtual time, increased in each scheduling cycle, and is defined as:

RoundNumber(t)=RoundNumber(t-1)+RoundRate(t);
RoundRate(t)=1 / (Sum of active queues' weights at time t)

A queue is defined as active if it is not empty and its weight for the WiMAX implementation is the normalized minimum reserved traffic rate (MRTR) expressed as:

W(i)=MRTR(i)/(Sum of MRTR for all queues)

Finally, the WFQ scheduler will serve the queue whose HOL packet has the smallest finish number.

Assuming a fixed packet size for all connections, queues will be served at about a rate equal to W(i), their normalized MRTR. This behavior can be observed with a synthetic example, presented in Table 6.1-1, where queue 1 has a weight that is half the weight of queue 2, and in each cycle there is a new packet of size 1 in each queue .

*Table 6.1-1 WFQ Behavior*

| RoundRate-> | 1 | | | | 2 | | | | 3 | | | | 4 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Queue 1 L(k,1)=1, W(1)=1/3, L(k,1)/W(1)=3 | **Pkt#** | **1** | **2** | **3** | **Pkt#** | **1** | **2** | **3** | **Pkt#** | **2** | **3** | | **Pkt#** | **2** | **3** | **4** |
| | **S(k,1)** | 1 | | | **S(k,1)** | 1 | 4 | | **S(k,1)** | 4 | 7 | | **S(k,1)** | 4 | 7 | 10 |
| | **F(k,1)** | 4 | | | **F(k,1)** | 4 | 7 | | **F(k,1)** | 7 | 10 | | **F(k,1)** | 7 | 10 | 13 |
| Queue 2 L(k,2)=1, W(2)=2/3, L(k,2)/W(2)=1.5 | **Pkt#** | **1** | **2** | **3** | **Pkt#** | **2** | **3** | | **Pkt#** | **2** | **3** | | **Pkt#** | **3** | **4** | **5** |
| | **S(k,1)** | 1 | | | **S(k,1)** | 2.5 | | | **S(k,1)** | 2.5 | 4 | | **S(k,1)** | 4 | 5.5 | |
| | **F(k,1)** | 2.5 | | | **F(k,1)** | 4 | | | **F(k,1)** | 4 | 5.5 | | **F(k,1)** | 5.5 | 7 | |
| **Served queue** | **Queue 2** | | | | **Queue 1** | | | | **Queue 2** | | | | **Queue 2** | | | |

WFQ's behavior is ideal in a wired scenario: It will fairly distribute the available bandwidth to all the active flows, by giving each flow the proper priority as indicated by its weight. On the other hand, flows that try to exceed their traffic rate will suffer the consequences as they will be limited by their defined weight.  Finally, low volume traffic streams will benefit as they will be able to quickly complete their transaction without much impact on high volume applications. It will be demonstrated later that these benefits come at a disadvantage in the wireless environment, as connections that exhibit poor RF conditions will be treated the same as connections that do not, effectively lowering their efficiency.

## 6.2. Proportional Fairness

Proportional Fairness (PF) [20] is the most representative example of algorithms that balance throughput and fairness. PF is used in CDMA networks and several current implementations of Fixed and Mobile WiMAX, so it serves as a good, realistic baseline to compare other algorithms.

PF assigns slots to connections with the best ratio of achievable rate per slot, $D_i(t)$, over the previously achieved rate, $R_i(t)$, according to the following formulation:

$$j = \arg\max_{1 \le i \le N} \frac{D_i(t)}{R_i(t)},$$

$D_i(t)$ is the number of bytes supported by the current modulation of connection *i* and $R_i(t)$ is the averaged rate, in bytes per slot, given to connection *i* using the following formulation:

$$R_i(t) = (1 - \frac{1}{t_c}) * R_i(t-1) + \frac{1}{t_c} * D_i(t)$$ , if the connection was just served,

$$R_i(t) = (1 - \frac{1}{t_c}) * R_i(t-1)$$ , Otherwise.

Connections with good $D_i(t)$ will get preference, but as connections with a bad $D_i(t)$ start to be underserved, the $R_i(t)$ factor will start to gain weight and influence the value of the ratio. $R_i(t)$ is an exponential moving average [35], with a smoothing factor $\alpha=1/t_c$. Parameter $t_c$, called the observation window, is a unit-less time constant that helps tune the tradeoff between throughput and fairness. The effect of $t_c$ on the PF ratio can be seen using a synthetic example assigning only one slot to either a 64QAM or a QPSK connection during each scheduling cycle as shown in Figure 6.2-1 to Figure 6.2-4. Assuming RF conditions remain the same, leaving $D_i(t)$ unchanged, a smaller $t_c$ value will make the $R_i(t)$ factor decrease faster (Figure 6.2-1) and the PF ratio will increase (Figure 6.2-2), making connections with bad RF conditions more likely to be served. Bigger $t_c$ values will do the opposite: $R_i(t)$ (Figure 6.2-3) will decrease and the PF factor (Figure 6.2-4) will increase slower, delaying the scheduling cycle at which the connection with worse RF conditions is served.

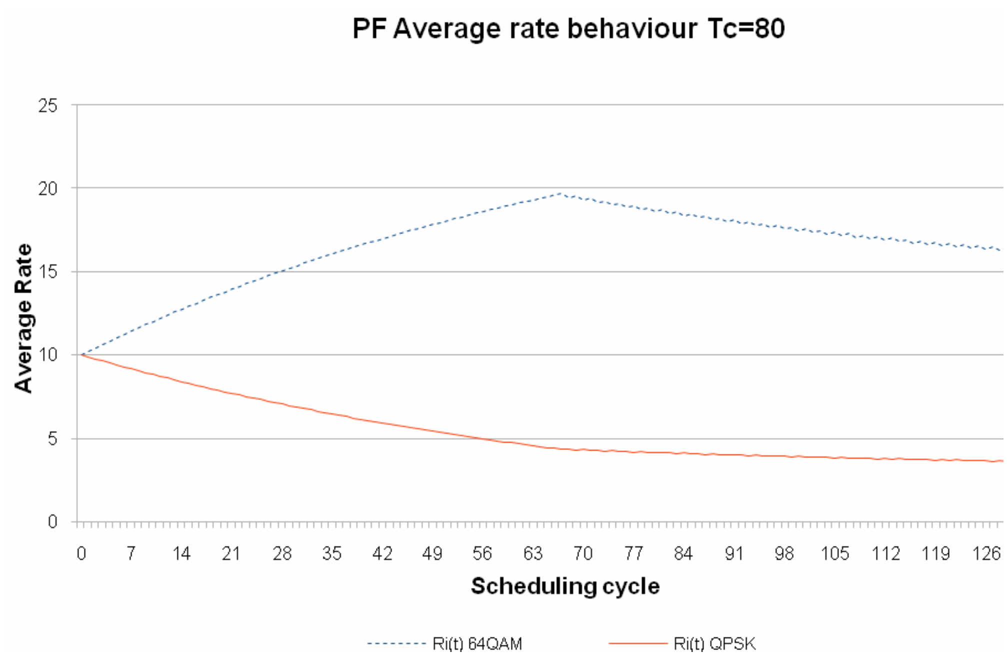



*Figure 6.2-1. Behavior of Ri(t) with $t_c$=80*

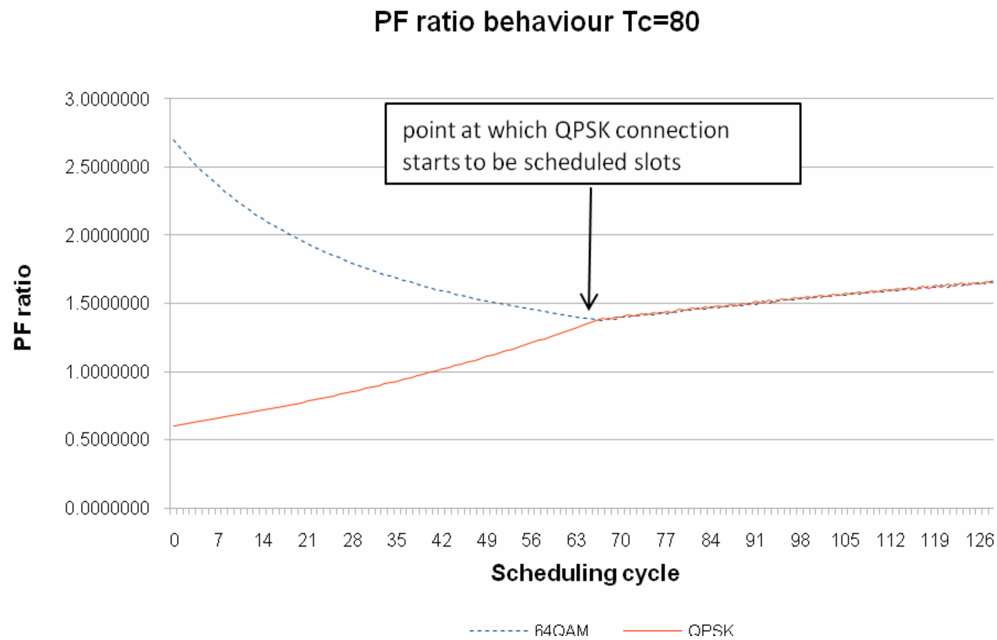



*Figure 6.2-2 Behavior of PF Ratio for $t_c$=80*

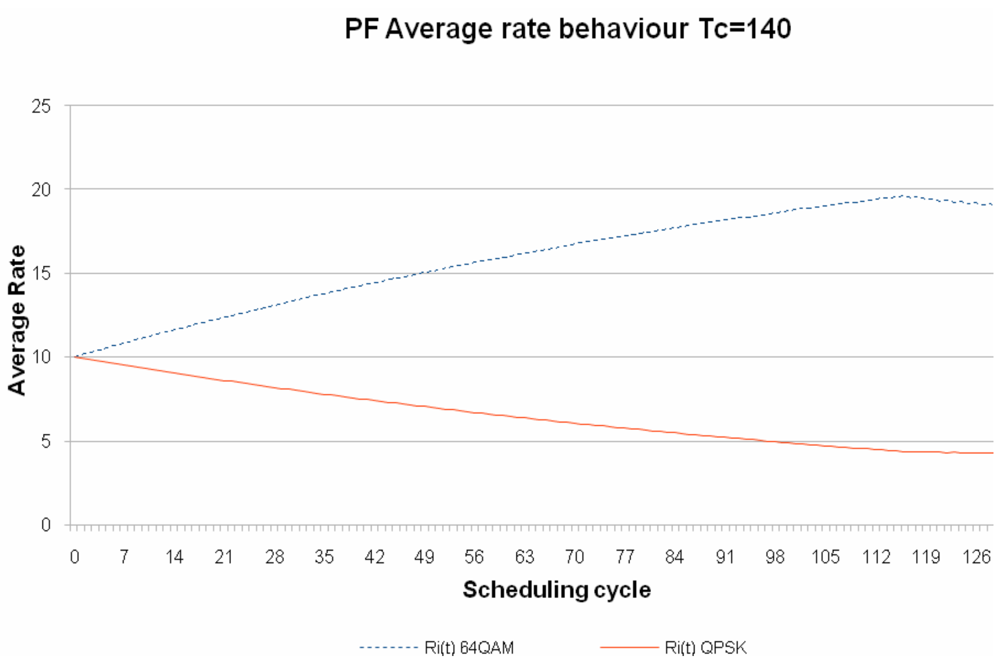



*Figure 6.2-3 Behavior of Ri(t) for $t_c$=140*

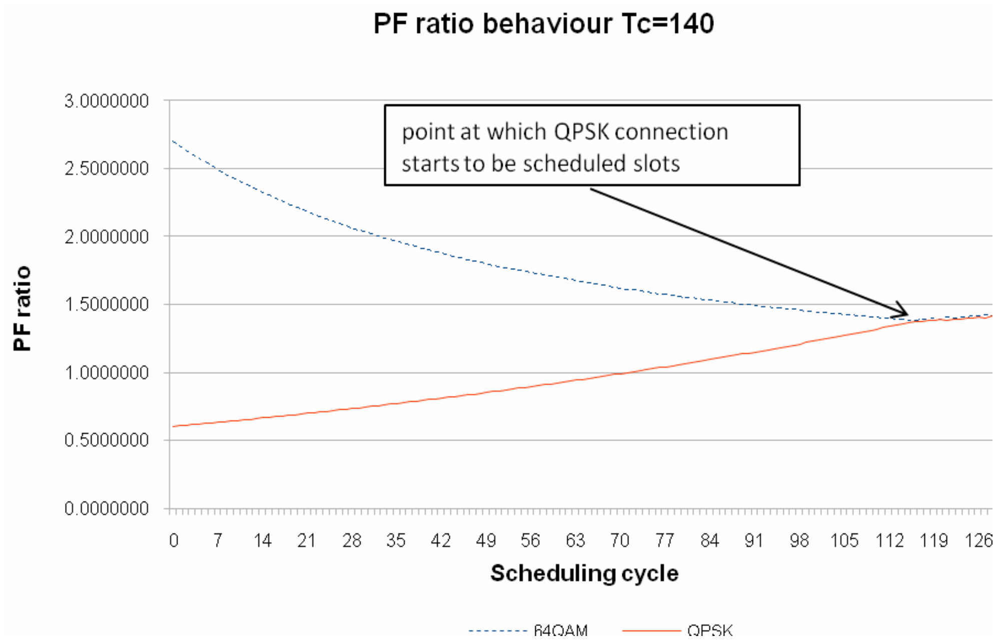



*Figure 6.2-4 Behavior of PF Ratio for $t_c$=140*

The authors in [20] make several assumptions to accommodate the protocol to the particulars of WiMAX:

- The initial averaged rate $R_i(0)$ is obtained based on the sector average rate divided by the expected number of connections.
- Consider $t_c$ values between 100 and 100000 slots, which for an average number of slots of 500 per DL or UL subframe and a 5ms subframe would correspond to values between 100*(5ms/500 slots)=1 ms and 100000*(5ms/500 slots)=1 second.
- As prioritization is not contemplated in this algorithm, a hierarchical approach is used: management data and UGS are always served first, and then on strict priority ertPS, rtPS, nrtPS and BE respectively. The PF scheduler is applied to the four later scheduling services.

The premise of PF is simple, yet elegant: Give preference to the flow with best channel conditions in order to maximize the use of the spectrum and have that flow finish first, but at the same time conserve fairness by keeping track of how long flows with poor channel conditions have been without service and allowing to fine-tune the behavior by modifying the value of the unit-less parameter $t_c$. This can be seen in operation in Figure 6.2-5 with an extreme example using the PF scheduler implemented as part of this thesis: Two subscribers (SSs) running each an FTP transfer start at the same time, one of the subscribers has perfect channel conditions and a modulation of 64QAM 3/4, while the other is in conditions that yield QPSK 1/2 modulation only. It can be observed how the scheduler gives preference to the flow with higher slot efficiency, allowing it to complete its data transfer quite rapidly, while the flow with lower slot efficiency goes without service.

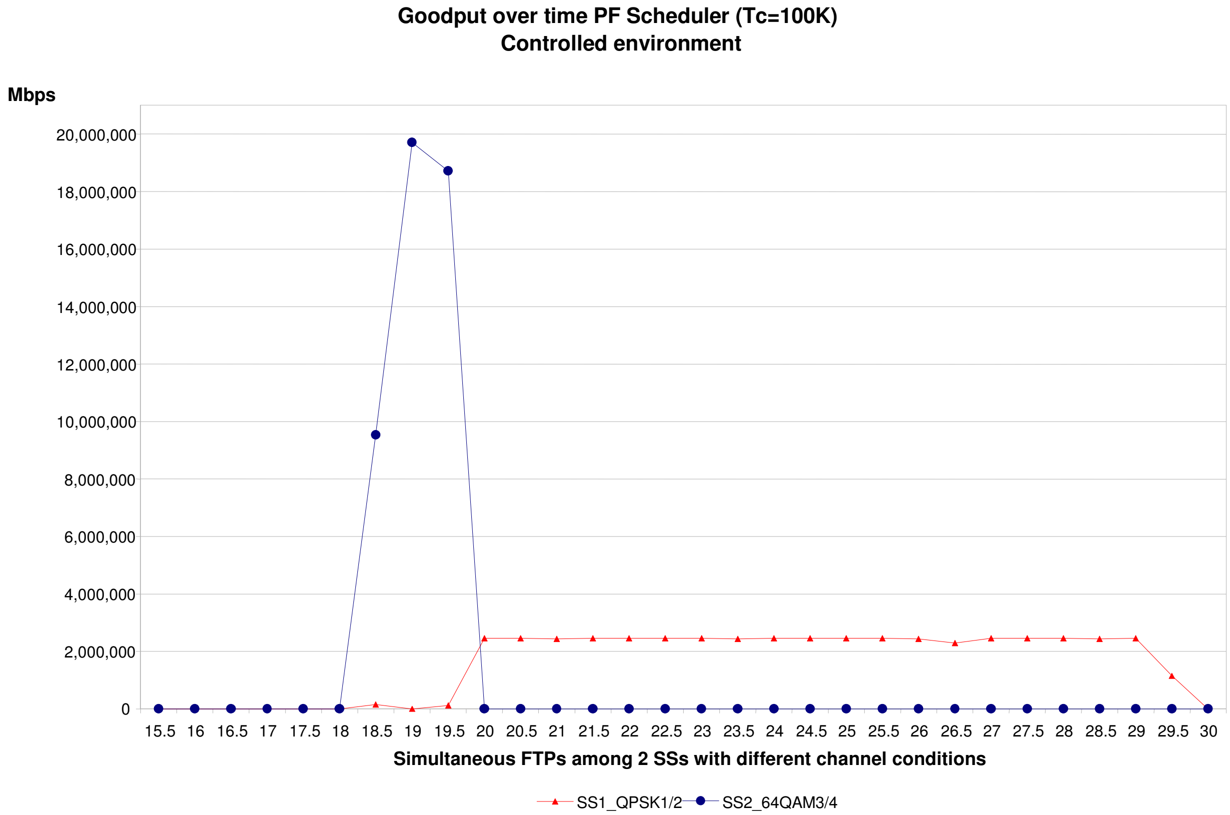



*Figure 6.2-5 Goodput for Subscribers Under Different Channel Conditions PF $t_c$=100K*

The amount of time a service will go without service can be tuned by setting $t_c$, the observation window parameter. Figure 6.2-6 shows the same run, this time with a $t_c$ value that is half of the value configured for the previous figure. It can be seen how at about half of the transmission time of the flow with better modulation, slots start to be assigned to the subscriber with worse modulation, and the available resources start to be shared among the two flows.

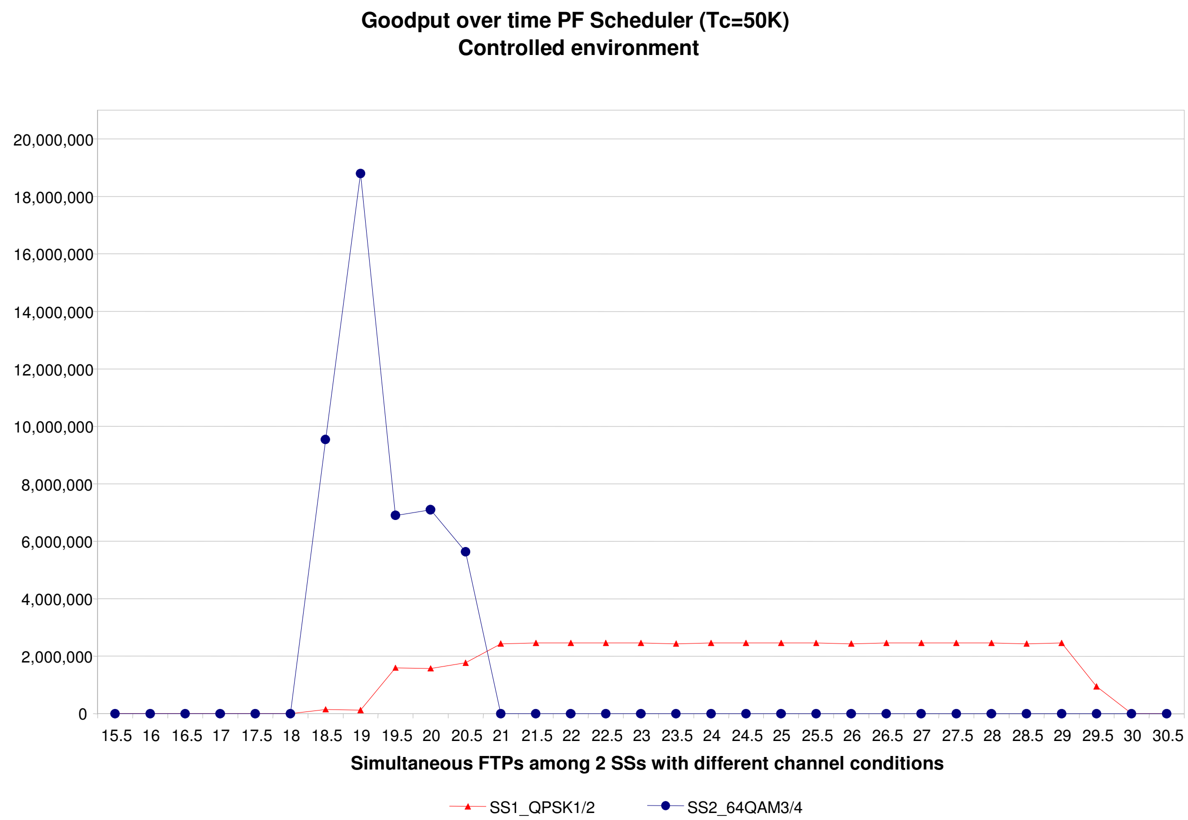



*Figure 6.2-6 Goodput for Subscribers Under Different Channel Conditions PF* $t_c$*=50K*

One can see the dramatic contrast of the scheduling decision when running the same FTP test using the Weighted Fair Queue (WFQ) implemented in Qualnet (Figure 6.2-7). It can be seen how the flow for SS number 2 gets constrained by the slots being assigned to SS number 1, effectively lowering its achievable throughput and causing TCP to slow down and having both flows terminate at about the same time. While the improvement in sector throughput using the PF scheduler is considerable, in real life flows are usually limited in how much throughput they can achieve by their Maximum Sustained Traffic Rate (MSTR) parameter. The impact of this constrain will be explored further in the simulation results section.

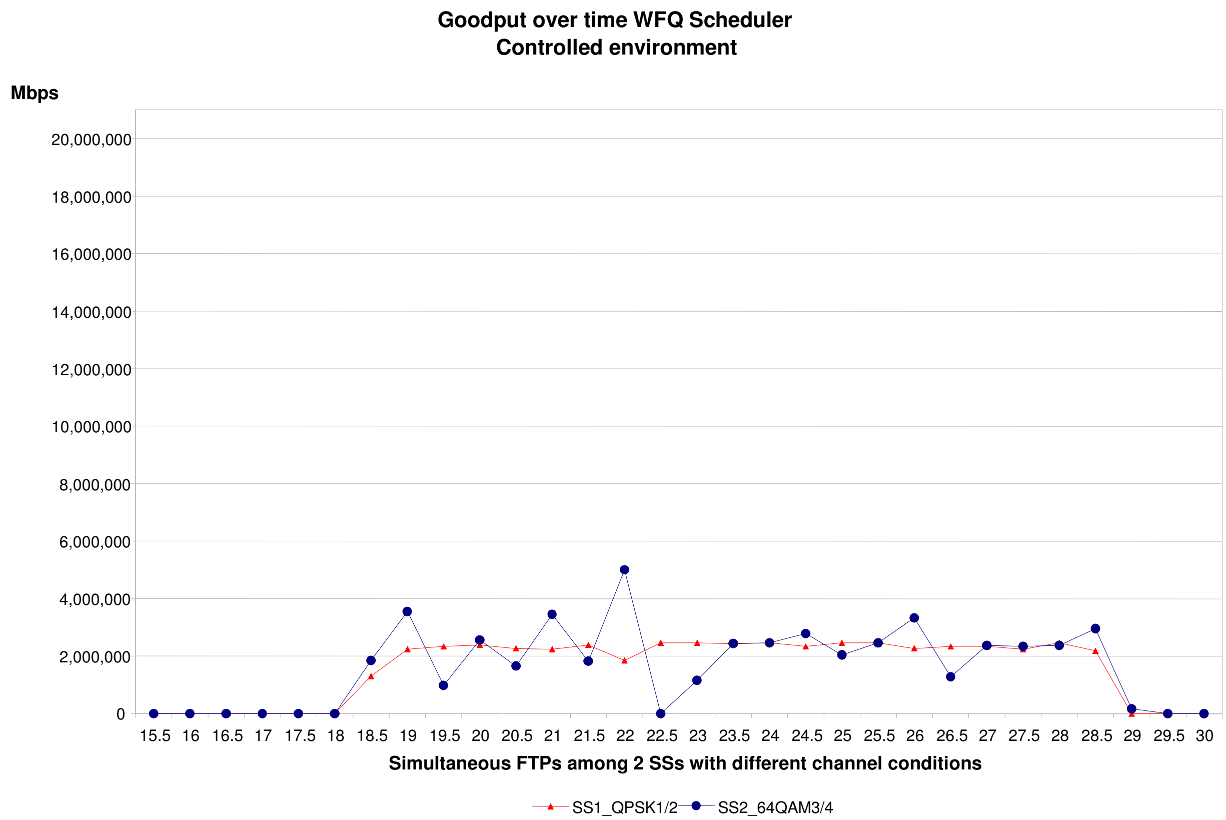



*Figure 6.2-7 Goodput for Subscribers WFQ Scheduler*

## 6.3. Multiclass MLWDF

Multiclass MLWDF [24] is a cross-layer, queue aware opportunistic algorithm with several improvements over the original MLWDF algorithm proposed in [23]: Multiple traffic classes as well as multi-channel connections are considered. The main improvement, which makes it an interesting candidate for implementation, is relaxing the strict priority constrain imposed by having packets with QoS requirements always scheduled over packets without any QoS requirements. That is, if QoS packets still have a long time-to-live, such packets can be delayed a little and in the meantime BE packets are scheduled instead of having to wait in favor of the delay-sensitive traffic.

The authors propose a scheduler based on the HOL delay for QoS based scheduling services and queue length for BE and nrtPS traffic. The QoS scheduler has priority over BE, an enhanced implementation called Joint Scheduler (JS) is proposed to relax this rule and schedule BE traffic together with QoS traffic when the QoS packets are far from their delay expiration. They use a 50% heuristic (if delay is less than 50% of the deadline, BE packets will be scheduled over QoS packets) to perform such decision. The pseudo code of the proposed implementation is shown below.

```
At each scheduling instance {
for j=1 to N { update CR(j), QLB(j), QLQ(j) and WT(j)
        AR(j) = w*AR(j) + (1-w)*CR(j) }
QoS_schedule = 0
for j=1 to N {
        if (WT(j) > x*MD(j)) { QoS_schedule = 1 }
}

if (QoS_schedule > 0){SM= arg max j ( CR(j)/AR(j)*WT(j)/MD(j) )
        else { SM = arg max j ( CR(j)/AAR(j)*(QLQ(j) + QLB(j))) }

for j=1 to N {
         if (SM==j) { AAR(j) = w*AAR(j) + (1-w)*CR(j) }
        else {AAR(j) = w*AAR (j) } }
}
```

**< Variables>**
***AAR(j)*** **: Moving average of MS *j*'s allocated channel rate (bits)**
***AR(j)*** **: Moving average of MS *j*'s CR(j) (bits)**
***CR(j)*** **: MS *j*'s current channel rate (bits)**
***MD(j)*** **: Maximum allowed delay of MS *j*'s QoS class connection (ms)**
***N*** **: Number of active queues**
***QLB(j)*** **: MS *j*'s BE class queue length (bits)**
***SM*** **: Index of the selected MS**
***w*** **: Weighting factor, used value is 0.99**
***WT(j)*** **: Waiting time of Head-of-line packet in the MS *j*'s QoS class queue**
***QLQ(j)*** **: MS *j*'s QoS class queue length (bits)**
***x*** **: threshold parameter, used value is 0.5**

A couple of parallels can be drawn between MLWDF and PF. For starters, they both consider the connection's modulation efficiency as part of their scheduling decision; secondly, they both use an exponential moving average to keep track of the progression of achieved rate. However, MLWDF's ratio is different for QoS-aware connections (UGS, ertPS, rtPS), and it also uses additional metrics for its calculation. A closer look at the algorithm above reveals that there are actually two ratios, one to be used for QoS-aware connection:

$$SM = \arg\max_{1 \le j \le N} \frac{CR(j)}{AR(j)} * \frac{WT(j)}{MD(j)},$$

where the HOL Packet's Waiting Time to maximum delay ration is considered; and another one for non-QoS connections:

$$SM = \arg\max_{1 \le j \le N} \frac{CR(t)}{AAR(j)} * QLQ(j) + QLB(j),$$

where the number of enqueued bytes both for QoS-aware and non-QoS-aware connections for that subscriber are considered.

In summary, Multiclass MLWDF behaves similarly to PF, giving preference to connections with good RF conditions first. In addition, QoS-aware connections are delayed in favor of non-QoS-aware ones when they are far from violating their delay commitments. It will be seen in the results section that this actually improves throughput performance, with the effect of adding extra delay on QoS-aware connections.

In the real world, major adjustments would be required to come up with a full implementation of this scheduler: The scheduler only contemplates the downlink direction, for which HOL delay and queue length can be easily calculated. In the uplink direction, virtual queues represent the load of a specific connection and the HOL delay is calculated from the moment a bandwidth request is observed for that connection, so maintaining the accuracy of the information is not trivial and would represent a considerable challenge for connections with stringent delay requirements.

## 6.4. Highest Urgency First

HUF [22] is a hierarchical algorithm in the sense that there is a first level that schedules all connections according to their deadline (in order to guarantee QoS commitments) and allocates the remaining bandwidth to the HOL packet on the queue with the highest *AverageUFactor*.

The algorithm is also weight-based in the sense that it relies on an urgency indicator to make scheduling decisions. The urgency indicator (called UFactor) considers latency requirements, priority and modulation of packets in a connection and is formulated as follows:

$$\text{Ufactor}_{i,j} = \frac{N_i * (P_j + 1)}{D_i}, \text{ where}$$

$$N_i = \# of\_slots\_required = \left\lfloor \frac{SizeofPacket_i}{bytes\_per\_coding\_rate} \right\rfloor, \text{ and}$$

$$D_i = \begin{cases} \left\lfloor \frac{MaxLatency}{FrameDuration} \right\rfloor, for\ real\ time\ applications \\ -1, otherwise \end{cases}$$

Parameter i corresponds to the packet index, j is the queue or connection, and $P_j$ is the priority of each connection, a configurable parameter from 1 to 7. HUF was the only algorithm found in the literature that explicitly contemplates the connection's priority as part of its scheduling decision. Having the UFactor for each packet, the *AverageUFactor* is calculated for each queue, and the queue with the highest *AverageUFactor* will be served.

The AverageUFactor for queue *j* is calculated as follows:

$$\text{AverageU-factor}_j = \frac{\sum_{i=1}^{n} U - factor_{i,j}}{n},$$

Where *n* is the number of requests (i.e. active packets on the queue ready to be served) on the queue and $UFactor_{i,j}$ corresponds to the *i*th request on queue j. Head-of-the-line requests for each queue are then dispatched in decreasing order of *AverageUFactor*. Only the HOL request of each connection is served each time, so if there are any slots left after all the queues have been dispatched, the *AverageUFactor* will be recalculated for all queues and the remaining bandwidth will be allocated accordingly. The algorithm can be summarized as follows:

```
At each scheduling cycle {
for j=1 to N {
        for each packet i on queue j {
           deadline(i,j)=deadline(i,j)-1
          if (deadline(i,j)==1 and slots_available>=slots_required(i,j)) {
           dispatchPacket(i,j)
          slots_available=slots_available - served_slots(j)
         }
      }
}
while (slots_available>0)
{
        for j=1 to N {
           AverageUFactor(j)=0
           for each packet i on queue j {
                  update_U_factor(i,j);
                  AverageUFactor(j)= AverageUFactor(j)+UFactor(i,j)
          }
        AverageUFactor(j)= AverageUFactor(j) /NumPackets(j)
      }
SM=argmax j (AverageUFactor(j))
Serve_slots(SM)
slots_available= slots_available-served- served_slots(SM)
}
```

**<Variables>**
*deadline(i,j)* **: Deadline of packet i on queue j**
*slots_available* **: Number of slots left on current scheduling cycle**
*slots_required(i,j)* **: Slots required to transmit packet i on queue j**

***served_slots(j)* : Number of slots served to queue j**
***AverageUFactor(j)* : Average U Factor of queue j**
***NumPackets(j)* : Number of packet on queue j**
***UFactor(i,j)* : U Factor of packet i on queue j**
***N* : Number of active queues**
***SM* : Index of the selected MS**

# 7. Simulation Parameters

Several efforts have been made to follow standard guidelines to make results as comparable as possible: First, system parameters in Section 7.1 reflect the default values specified by the WiMAX Forum; second, based on the defined system parameters, theoretical maximum throughput numbers have been calculated in Section 7.2 in order to have a proper baseline for further evaluations; third, in Section 7.3 two scenarios are proposed: one simulating a closed-loop environment under which signal levels and modulation schemes are kept constant, and another scenario in which a Rayleigh fading model is introduced to simulate an urban pedestrian environment, creating variability on reception levels and modulation schemes used by the subscribers.

## 7.1. WiMAX-specific System Parameters

In order to have a scenario as realistic as possible to what initial WiMAX deployments will be using, the WiMAX system parameters were chosen according to the recommended default values from the WiMAX Forum Mobile System Profile [5] which lists all the WiMAX system parameters, their status (mandatory, potential mandatory or optional), and their supported value and valid combinations with other parameters. Table 7.1-1 lists relevant parameters as well as the chosen value for the Qualnet simulation.

While most of the parameters align with what is specified in the Mobile System Profile, H-ARQ, authentication and encryption, are not supported by the Qualnet simulation software.

Fragmentation was initially enabled, but had to be disabled as a bug was found causing queue leaks when fragmentation was taking place. Also, in order to be able to properly characterize the behavior of the different schedulers, ARQ was disabled so retransmissions do not occur when packets are discarded.

*Table 7.1-1 WiMAX Simulation Parameters*

| System Parameter | Value |
|---|---|
| PHY Mode | OFDMA |
| Band Class frequency range | 2.3 – 2.5 GHz |
| Channel Bandwidth | 10 Mhz |
| FFT size | 1024 |
| Duplexing mode | TDD |
| Sampling Factor | 28/25 |
| Cyclic Prefix | 1/8 |
| Frame length | 5 ms |
| TTG | 10 µs |
| RTG | 10 µs |
| SSTG | 4 µs |
| Number of symbols per frame | 47 |
| DL / UL symbol ratio | 32/15 |
| Number of subchannels on downlink direction | 30 |
| Number of subchannels on uplink direction | 35 |
| DL subcarrier allocation scheme | PUSC |
| UL subcarrier allocation scheme | PUSC |
| Initial ranging in PUSC zone with 2 symbols | YES |
| Periodic ranging in PUSC zone with 1 symbol | YES |
| BW request in PUSC zone with 1 symbol | YES |
| ARQ and H-ARQ | Disabled |
| Authentication | Disabled |
| Encryption | Disabled |
| Fragmentation | Disabled |

## 7.2. Maximum Throughput Calculations

As mentioned in Section 2.1, a slot is constituted of a number of subcarriers over several symbols. In the case of DL PUSC, a slot is composed of 24 data subcarriers over two symbols, so a total of 48 data subcarriers per slot can be modulated in order to transmit a stream of bits. As shown in Table 7.2-1, knowing how many bits can be transmitted for each modulation, one can obtain the number of bits that can be carried in a slot depending on the modulation and coding scheme.

*Table 7.2-1 Bits per Slot for each Modulation and Coding Scheme*

| Modulation | Bits/symbol | Coding | Bits/slot |
|---|---|---|---|
| QPSK | 2 | 1/2 | 2x1/2x48=48 |
| | | 3/4 | 2x3/4x48=72 |
| 16QAM | 4 | 1/2 | 4x1/2x48=96 |
| | | 3/4 | 4x3/4x48=144 |
| 64QAM | 6 | 1/2 | 6x1/2x48=144 |
| | | 2/3 | 6x2/3x48=192 |
| | | 3/4 | 6x3/4x48=216 |

It is then easy to estimate the maximum throughput per modulation and coding scheme based on the number of slots available for the downlink and uplink direction. Based on the numbers in Table 7.1-1, one can perform the following calculation to obtain the number of slots for each direction:

NumSlots=NumSubChannels * NumSymbols * [1/2 for DL | 1/3 for UL]

The 1/2 and 1/3 factors correspond to the number of symbols that compose a slot for downlink and uplink PUSC respectively.

This calculation yields 480 downlink slots per frame and 175 uplink slots per frame. As there will be 200 frames per second, given a 5ms frame duration, the number of slots per second for the downlink will be 96,000 and 35,000 for the uplink. The throughput expressed in bits per second according to each modulation scheme is shown in Table 7.2-2 .

The numbers below are the highest achievable throughput calculated based on the maximum number of slots available. In each frame there will be overhead due to IP layer, MAC PDU, and PHY layer encapsulation.

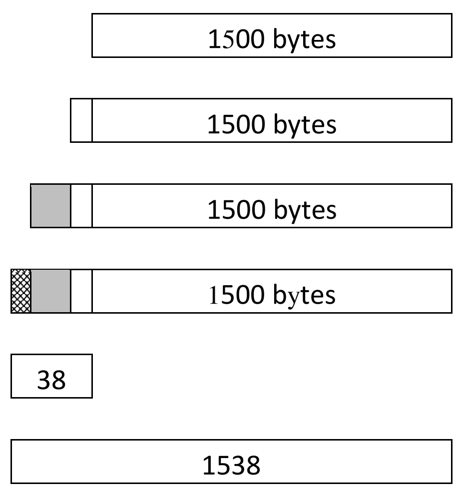
Table 7.2-3 shows some IP and MAC layer encapsulation overhead calculations for the case of a UDP encapsulated CBR stream of 1500 bytes packets. For situations where the packet arrival rate is lower than the frame duration, several IP packets for the same subscriber may be packed together into a single MAC PDU, saving some overhead, so these calculations assume the worst case scenario of one MAC header for every single IP packet.

*Table 7.2-2 Calculated Downlink and Uplink Throughput*

| Modulation | Coding | Downlink throughput bps | Uplink throughput bps |
|---|---|---|---|
| QPSK | 1/2 | 4’608,000 | 1’680,000 |
| | 3/4 | 6’912,000 | 2’520,000 |
| 16QAM | 1/2 | 9’216,000 | 3’360,000 |
| | 3/4 | 13’824,000 | 5’040,000 |
| 64QAM | 1/2 | 13’824,000 | - |
| | 2/3 | 18’432,000 | - |
| | 3/4 | 20’736,000 | - |

*Table 7.2-3 Overhead Calculations IP and MAC Layers*

| Layer | Size (bytes) |
|---|---|
| Application layer (CBR Traffic over UDP) | 1500 |
| UDP header | 8 |
| IPv4 Header | 20 |
| WiMAX MAC (MAC PDU Overhead) | 10 |
| Overhead bytes up to MAC layer | |
| Total PDU Size (bytes) | |




Overhead percentage at MAC layer (rounded up) = 3%

At the PHY layer, one has to consider the downlink and uplink direction independently when performing overhead calculations:

- Downlink direction. The most important overhead components are the downlink and uplink maps, which carry information in regards to the structure of the frame and slot allocations. Not as periodic are the Downlink Channel Descriptor (DCD) and Uplink Channel Descriptor (UCD) PDUs, that carry information required by the subscribers to perform network entry. DL and UL maps account for 10 slots of fixed overhead in every frame (every 5 ms given the frame length chosen for our simulation) plus a variable overhead of 2 slots for each active connection (i.e. connections that are being served on the current frame and have an allocation in the DL or UL Map). DCD and UCD account for 40 extra slots of overhead every 5 seconds in the case of Qualnet's simulation software. It is important to highlight that subscribers will not be able to perform network entry and start sending traffic until they have read at least one UCD or DCD, so during simulations traffic should not start before the DCD / UCD interval in order to avoid loss of traffic. Even though the number of slots required for DCD and UCD in a single frame is high, the overall impact in the number slots per frame is low: Forty slots every 5 seconds would theoretically yield 8 slots/second or 0.04 slots for every frame.
- Uplink direction. Some of the slots in the uplink direction are reserved for initial and periodic ranging (30 slots), and bandwidth request (6) purposes for a total of 36 slots per uplink subframe of overhead.

Table 7.2-4 summarizes the throughput calculations after MAC and PHY overhead has been considered, assuming only one active user and CBR traffic being sent in such a way that all slots are consumed on each frame. A total of 466 downlink slots per frame and 139 uplink slots per frame are considered, and a conservative 3% for MAC overhead is discounted. These numbers will be used as the upper theoretical limit to compare against actual tests.

*Table 7.2-4 Calculated Downlink and Uplink Throughput after Overhead*

| Modulation | Coding | Downlink throughput bps | Uplink throughput bps |
|---|---|---|---|
| QPSK | 1/2 | 4’339,392 | 1’249,368 |
| | 3/4 | 6’509,088 | 1’941,552 |
| 16QAM | 1/2 | 8’678,784 | 2’588,736 |
| | 3/4 | 13’018,176 | 3’883,104 |
| 64QAM | 1/2 | 13’018,176 | - |
| | 2/3 | 17’357,568 | - |
| | 3/4 | 19’527,264 | - |

A simple test was then conducted to validate the calculations performed in Table 7.2-4 and have an idea of the performance that should be expected during simulation scenarios.

The actual simulation numbers obtained for a single subscriber using CBR traffic with packets at a fixed size of 1500 bytes are shown in Table 7.2-5.The inter packet delay and amount of packets sent were adjusted in order to always run for 10 seconds. All measurements were performed at 0% packet error rate (PER) and on the uplink direction UGS service type was used in order to avoid the extra overhead incurred due to the bandwidth request process. It can be seen how the simulated numbers closely match the calculated numbers.

*Table 7.2-5 Measured Single User Downlink and Uplink Throughput*

| Modulation | Coding | Downlink throughput bps | Uplink throughput bps |
|---|---|---|---|
| QPSK | 1/2 | 4’317,022 | 1’213,828 |
| | 3/4 | 6’040,665 | 1’829,004 |
| 16QAM | 1/2 | 7’580,443 | 2’451,468 |
| | 3/4 | 12’726,546 | 3’679,690 |
| 64QAM | 1/2 | 12’726,546 | - |
| | 2/3 | 17’081,205 | - |
| | 3/4 | 19’503,087 | - |

## 7.3. Simulation Scenario

Given the objective of the thesis of comparing four scheduling techniques, using the same scenario of a single cell with surrounding subscribers, shown in Figure 7.3-1, all performance metrics proposed in Chapter 8 will be run through two different test environments: A stationary environment introducing a lognormal shadowing model to simulate conditions of users working on a laptop or desktop without mobility; and another one introducing a Rayleigh fading model in order to simulate mobility in an urban environment.

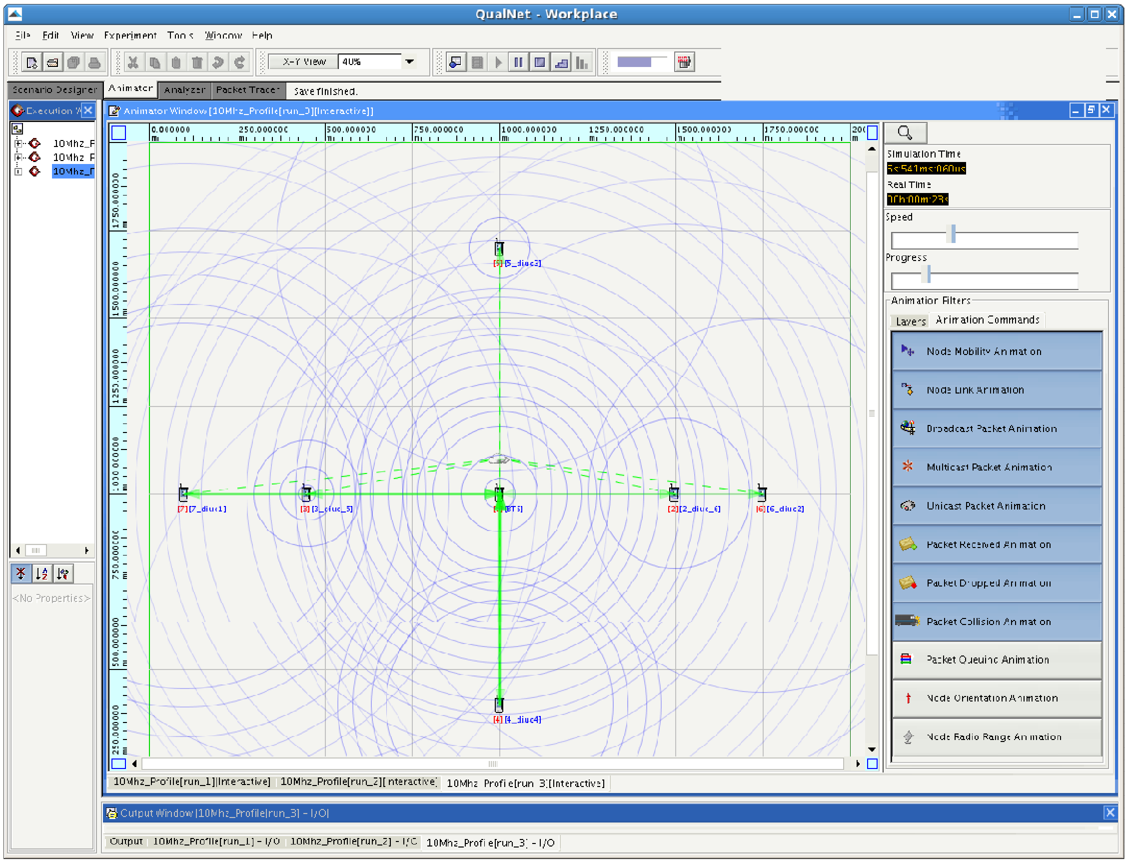


*Figure 7.3-1 Qualnet Simulation Screenshot*

Additionally, a controlled environment mimicking a closed-loop lab setup in which systems are initially validated, isolated from the inherently stochastic wireless channel, will be used. This environment will allow checking the limits of the scheduler while controlling the modulation and coding scheme assigned to each subscriber and hence will provide insights in regards to maximum system capacity. The average sector throughput performance metric for the case of six mobiles will be analyzed using this environment.

The stationary and mobility environments will provide more realistic settings where subscribers will be subject to changes in their radio conditions and hence their modulation and coding schemes, introducing additional work for the schedulers being evaluated.

All simulations are repeated 10 times in order to obtain 95% confidence intervals.

The number of users in the cell is six, fifteen, twenty-five and thirty-five or until signs of scheduler outage are observed. The initial distribution of modulation and coding schemes across the sector, shown in Table 7.3-1, has been defined based on numbers from a real deployment. While such a distribution will vary depending on a number of factors such as user mobility, time of day and operator preferences among others, it is preferred to the alternative of randomly dropping subscribers into the sector [36].

*Table 7.3-1 Modulation and Coding Distribution Across Sector*

| Modulation | Coding | Distribution |
|---|---|---|
| QPSK | 1/2 | 15% |
| | 3/4 | 25% |
| 16 QAM | 1/2 | 20% |
| | 3/4 | 5% |
| 64 QAM | 1/2 | 15% |
| | 2/3 | 15% |
| | 3/4 | 5% |

WiMAX built-in QoS and high bandwidth allows a good variety of applications to be run. The decision of what kind of services to provide will depend more in the market needs. While for a developed market, WiMAX players have signaled the intention of providing a full-fledged quadruple play (voice, video and broadband Internet with wireless services provisions) deployment with on-the-move high quality video, voice and broadband Internet services [37], developing markets are looking at addressing the need of broadband Internet and voice for rural areas [38]. Either way, it is safe to assume that most deployments will consider at least broadband Internet services and voice as part of their offering, so simulations will include a voice + data pair in each subscriber.

Twenty percent (all numbers will be rounded to the lower integer) of the subscribers in each simulation will also have variable bit rate (VBR) sessions simulating streaming video traffic and, in order to assess the behavior of UGS, ten percent of the subscribers will have CBR traffic running. This traffic mix will be applied differently depending on the simulation environment: For the closed-loop environment, a full-buffer model [39] sends data continuously for the duration of the simulation time in order to obtain aggregate throughput and delay numbers; whereas for the stationary and mobility environments, traffic will be sent at more realistic intervals, specified in Table 7.3-2 below.

All the applications are actual simulation implementations provides by Qualnet, with the exception of video streaming, which is put together using a VBR application and numbers from the WiMAX System Evaluation Methodology [36] published by the WiMAX Forum.

*Table 7.3-2 Application Parameters for Stationary and Mobility Environment Simulations*

| **Application** | **Service class** | **Parameters** |
|---|---|---|
| CBR | UGS | 256 kbps flow with 512 bytes packet size and 16 ms inter packet delay |
| VoIP | ertPS | Average call duration: 120 seconds<br>Average talk time: 80 seconds<br>Codec: G.711<br>Packetization interval : 20 ms |
| VBR | rtPS | To simulate a 60 seconds 176x144 resolution video clip = 2.725 Kbytes * 25 frames/second * 60 sec = 4,125,000 bytes file.<br>Packet size: 1460 bytes<br>Inter packet delay: Exponential with 20 ms mean<br>Duration: 60 seconds |
| FTP/GENERIC | BE | 3400 packets x 1460 bytes = 4.96 Mbps file |

The only service class not included as part of the simulations is nrtPS. The reason for this decision is twofold: first, from a downlink perspective, a nrtPS flow behaves identically to a BE service flow, only varying in priority between one and the other if implemented at the scheduler; second, as explained in Section 4.2, only the four applications mentioned in Table 7.3-2 can be mapped to QoS parameters, so one of them would have to be reused. VBR would be the best candidate to do so, but in that case the comparison would be the same as the one that can be made between rtPS and BE.

The application and service classes put to the test contrast with the approach used by the original designers of the scheduling solutions under analysis, which chose only a small subset of tests to be run over two scheduling classes. The designers of the HUF protocol in [22] compared nrtPS and BE using video and FTP traffic, so the implementation is not being evaluated against the more stringent delay requirements of ertPS and UGS. A similar method was used to evaluate PF in [20], with video streaming, FTP, HTTP and VoIP traffic simulated over BE and rtPS service classes only. Finally, MLWDF was evaluated generating small amounts of video traffic to subscribers with a rtPS service class, and some UDP traffic to a BE connection.

# 8. Performance Metrics

This section describes the performance metrics (also called KPIs, Key Performance Indicators) selected to evaluate the data generated with the traffic mix described on the previous chapter. All metrics will be collected for mobile and stationary scenarios. Additionally, the controlled environment will be used to analyze the behavior of the scheduler solutions for the case of six MS.

Once again, in an effort to provide results that could easily be analyzed by the research community, most of the chosen metrics have been collected from the forum's WiMAX System Evaluation Methodology [36]:

1. Average sector throughput [kbps/sector]. Measured as:

$$R = \frac{b}{T},$$

   Where b is the total of correctly received bits by all subscribers, and T is the simulated time. A high number would indicate better overall sector throughput. This metric is proposed to obtain an estimate of the upper throughput limit one could expect for the given scenario and it is also very useful to demonstrate the behavior of each scheduler. The KPI will be run under a controlled as well as the mobile and stationary environments in order to contrast what one would normally see in the lab with what could potentially be seen in a real deployment. As this performance metric requires a constant data rate during the simulation time, the traffic will be CBR with a packet size of 512 bytes and an inter packet delay configured in such a way that each flow always has packets to send. In order to be able to post process instant throughput information, each simulation will run for 10 seconds. It is also important to highlight that this metric is reported at the MAC layer, factoring 28 bytes of IP plus UDP overhead for each packet.

2. Aggregate throughput per application. Also called goodput, it is measured as:

$$AggTput_{App-j} = \sum_{i} Tput_i ,$$

with $j$ being one of the three selected applications: CBR, mapped to UGS; VBR mapped to rtPS and FTP, mapped to BE; and $i$ one of the active connections during the simulation. A high number would indicate better throughput results for the application being measured.

3. Average transaction completion time:

$$AvgEndTime = \frac{\sum_{i}^{N} EndTime_i}{N},$$

with $N$ being the total of active connections during the simulation. This metric will be calculated for FTP traffic only and it will be measured as the time between the start of the FTP connection and the end of the file transfer.

4. Fairness among similar users. Measures the variation of throughput among users with similar demands and is calculated for FTP traffic only. This metric will be the base to analyze the behavior of each scheduler when subscribers have the same throughput requirements but different radio conditions.

$$FairnessIndex = \frac{\left[\sum_{i}^{n} C_i\right]^2}{n\sum_{i}^{n} C_i^2},$$

Here *n* is the number of active users, and Ci the completion time for the ith user. This index will be 1 if all n users get equal service and k/n if only k of the n active subscribers are given service during a simulation run.

5. Delay. This metric is inspired by the throughput outage defined by the forum, but rather focusing on the average delay served to VoIP and CBR applications. Delay outage for a connection is declared if the average end-to-end delay exceeds its delay requirements.

# 9. Simulation Results

In this chapter, results for the proposed scenarios are presented and studied based on the metrics defined in Chapter 8. Results for the controlled environment are shown first in order to exhibit the fundamental behavior of each scheduler for subscribers under different RF conditions. Section 9.2 presents relevant results for the stationary and mobile scenarios. With the exception of the controlled environment, in all experiments 95% confidence level are determined based on 10 independent runs.

## 9.1. Controlled Environment

In the controlled environment, the 6 MS Average Sector Throughput KPI, together with instant throughput graphs, were obtained. This was accomplished by post processing Qualnet's XML-based trace files using a script in order show instant throughput graphs. This allowed to demonstrate each scheduler's response over time to flows under different modulation and coding schemes. This data was captured for every scheduler only with 6 MS for two fundamental reasons: First, as the trace files dump every single packet generated during the simulation, post processing time and memory consumption start to become an issue with more than 10 flows sending data. Second, with a high number of mobiles, identifying each subscriber individually becomes virtually impossible, thus defying the purpose of the graph.

WFQ assigns a fraction of the slots to each flow based on its weight. Since the weight of each flow is based on its MRTR (Minimum reserved traffic rate), which is configured differently for each modulation, flows with higher modulation (and hence higher configured weight) will have their packets scheduled at a higher rate than packets for flows with lower modulations. However, as the packets are scheduled proportionally based on each flow's weight, a flow with high modulation (which could potentially achieve a much higher throughput if all available slots were allocated to it) has to share the available slots with flows that have lower spectral efficiency.

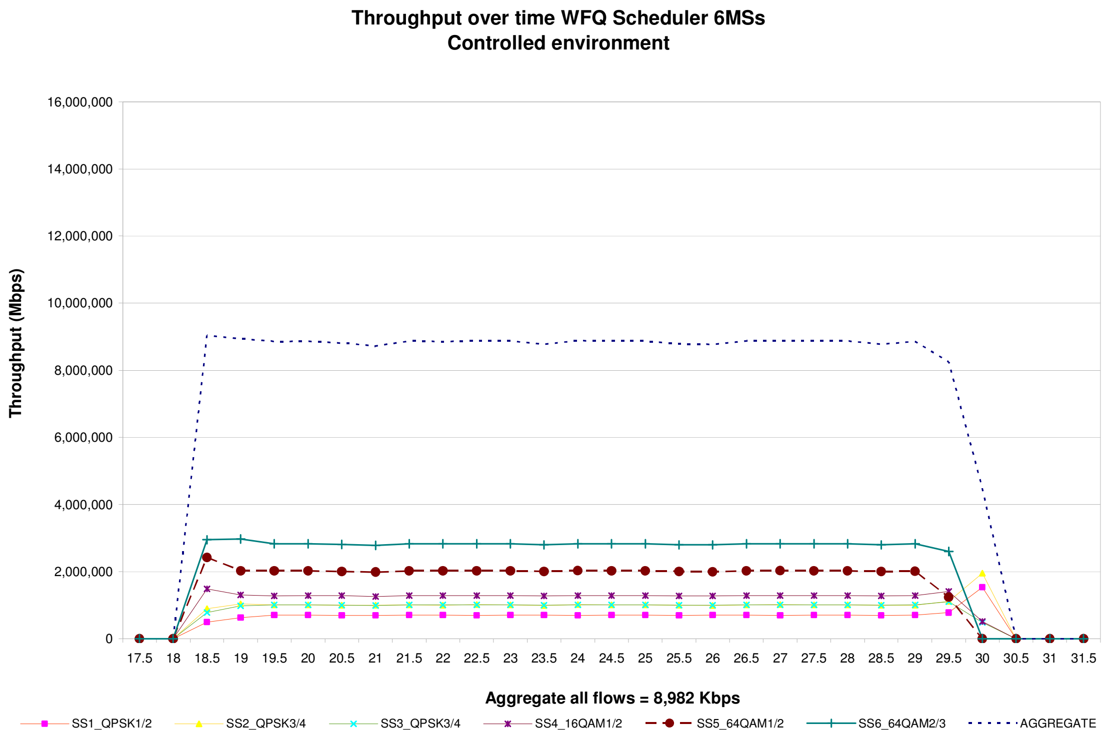



*Figure 9.1-1 WFQ Instant Throughput*

PF, on the other hand, gives preference to flows with higher spectral efficiency, serving packets from those connections first. The parameter $t_c$ helps control for how long flows with poor spectral efficiency will be left without service. *Figure 9.1-2 to Figure 9.1-4* exemplify the behavior when modulation of each flow is kept constant and the slot capacity is exceeded, as packets on each flow are being sent at the achievable rate according to their modulation. In *Figure 9.1-2* it can be seen how the three flows with higher modulation, SSs 4 to 6, are allocated all of the slots, leaving SSs 1 to 3 without any service. In reality, SS 6 gets allocated *all* the slots until the PF ratio of the SS with next best modulation (SS5) catches up and starts getting served; subsequent flows will start to get served in the same manner.

Assuming modulation levels and traffic rates persist, once the PF ratio of the flows with lower modulation catches up with the PF ratio of flows with higher modulation, the behavior of PF is practically the same as WFQ. However, the initial preference given to flows with better modulation is enough to boost the instant throughput readings and cause the final average sector readings to be better. It is also important to point out that $t_c$'s effect is not linear, being the smoothing factor of an exponential moving average.

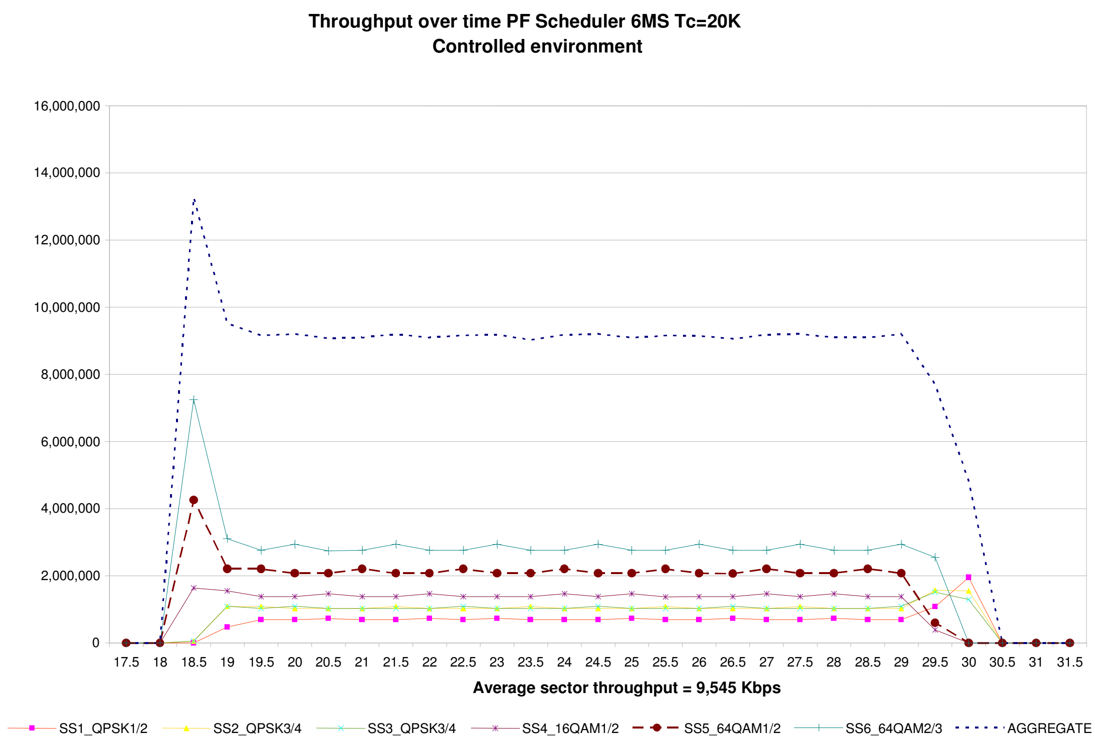



*Figure 9.1-2 PF Instant Throughput for $t_c$=20000*

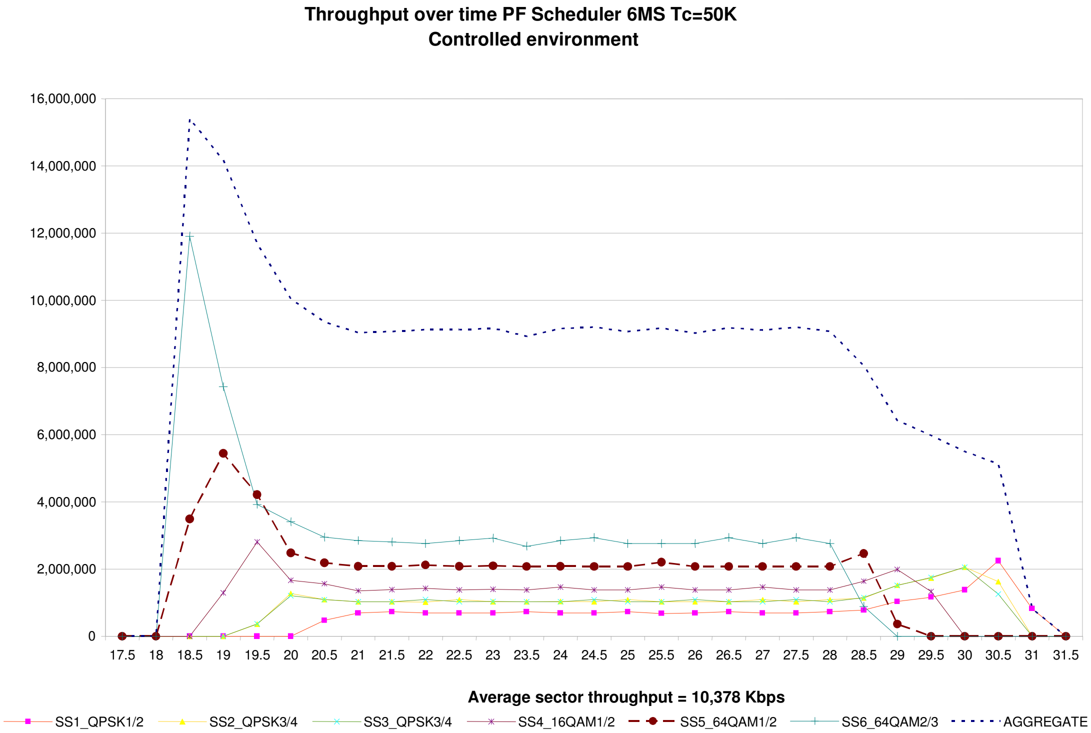



*Figure 9.1-3 PF Instant Throughput for $t_c$=50000*

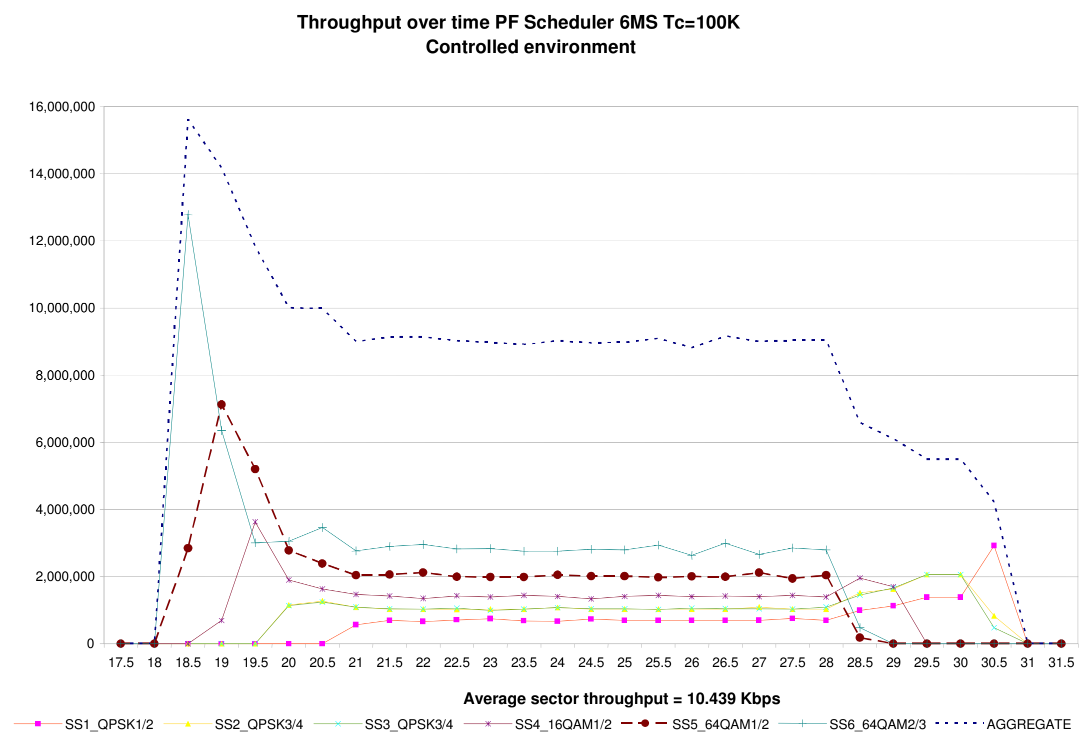



*Figure 9.1-4 PF Instant Throughput for $t_c$=100000*

An interesting contrast to PF is the result obtained with Multiclass MLWDF, shown in *Figure 9.1-5*. The simulation was run using BE flows only, so the metric used for the scheduling decision was always:

$SM = \arg\max_{1 \le j \le N} \frac{CR(t)}{AAR(j)} * QLB(j)$, as described in Section 6.3.

It can be observed how initially MLWDF follows the same pattern as PF, giving preference first to the flow with highest modulation, but as other connections start to get underserved and their respective queues to fill up, preference is then given to those connections, one at a time in order to allow the connection to lower its queue length. A flow with lower modulation that has been waiting for a considerable period of time, at a certain point is scheduled most of its enqueued packets, leaving others with no service for a few scheduling cycles. Eventually, once all queues have reached stability, the PF-like behavior reestablishes and continues until the end of the simulation.

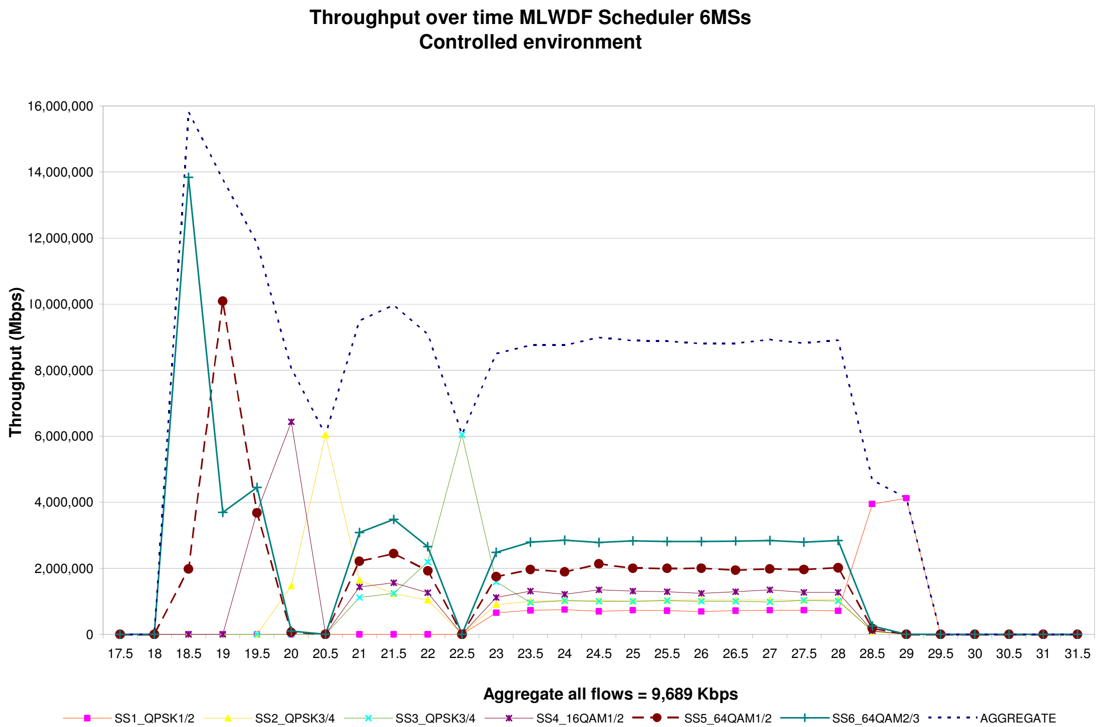



*Figure 9.1-5 MLWDF Instant Throughput*

HUF's behavior differs quite dramatically from the other analyzed schedulers. Contrary to PF and MLWDF, which initially give preference to the subscriber under the best RF conditions, the UFactor used by HUF gives preference (at least initially) to subscribers that have lower modulation efficiency. This can easily be seen in *Figure 9.1-6*, where the first flow to start sending data is the SS1, with QPSK 1/2 modulation, while subscribers with better modulation like SS5 (64QAM 1/2) and SS6 (64QAM 3/4) only get to transmit until about half a second later. This can be explained by looking at the conditions of the test as well as the ratio used to calculate the UFactor. For starters, apart from the bytes_per_coding_rate, the two other variables used to calculate the UFactor (deadline and priority) are the same for all subscribers. Second, the UFactor will be driven by the $N_i$ ratio, which increases with lower bytes_per_coding _rate.

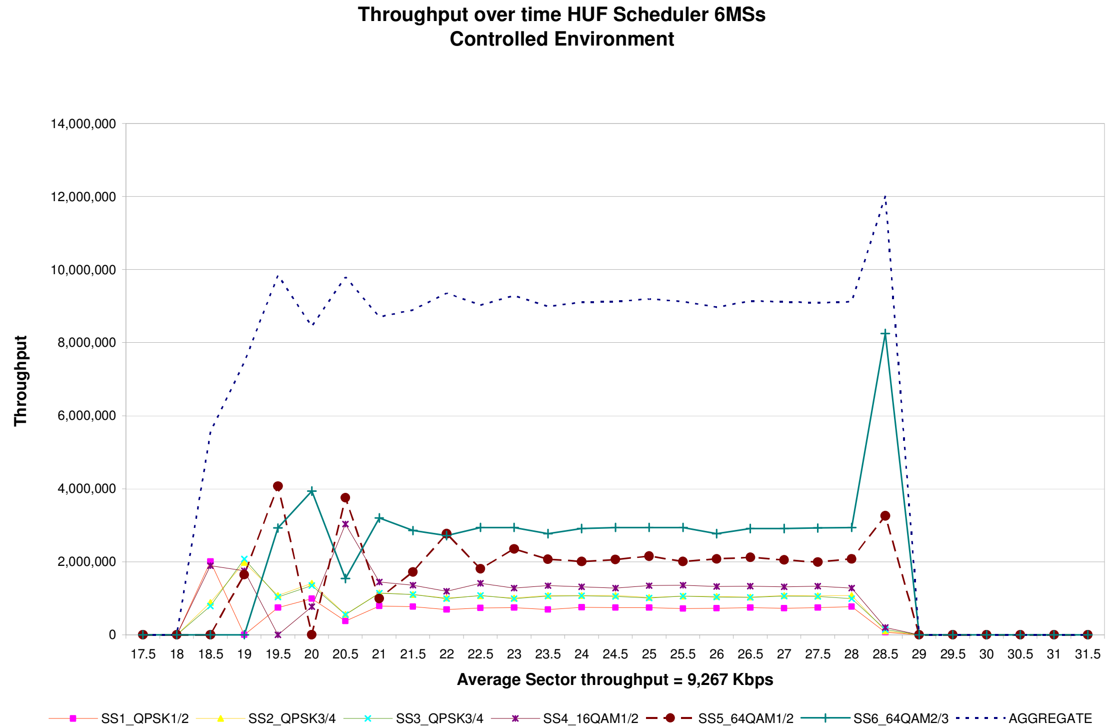



*Figure 9.1-6 HUF Instant Throughput*

## 9.2. Stationary and Mobile Environment Results

In this section, results for each KPI under stationary and mobile environments are presented. For the stationary case, shadowing conditions are added in order to emulate an environment where there is only minor variation in RF conditions during each run. These conditions will resemble a deployment where home routers are used to connect to the WiMAX network.

For the mobile simulations, a Rayleigh propagation model is introduced in order to emulate a mobile environment with users and objects moving around. A maximum velocity of 3 km/hr was configured, simulating a deployment with pedestrian mobility at the street level.

### 9.2.1. KPI1: Average Sector Throughput

The results with respect to KPI1 (Average Sector Throughput) are shown in Figure 9.2.1-1 and Figure 9.2.1-2. In both environments, it can be seen how Proportional Fairness effectiveness depends on two variables: the setting of the observation window and the number of MS involved in the test. As demonstrated by observing PF's performance with a $t_c$=20,000 (PF 20K) in comparison with WFQ, a small observation window would cause PF to start behaving like WFQ a few seconds after the flows have been competing for bandwidth, causing the throughput numbers to be pretty similar.

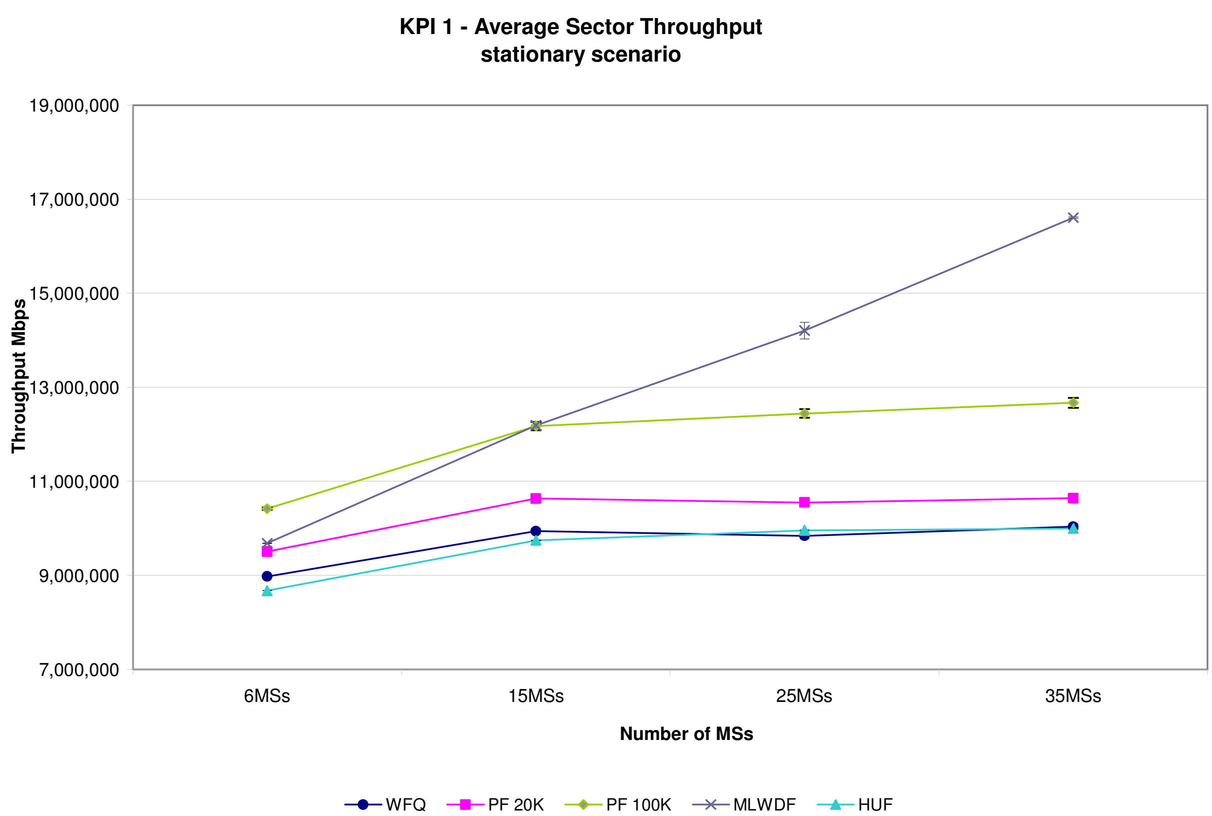



*Figure 9.2.1-1 Stationary Average Sector Throughput*

Observations are in line with the results of [20], indicating that as the number of connections increase, so do the chances of PF scheduling a connection with a good modulation, having a positive effect on sector throughput.

An interesting finding was the considerable difference in performance for MLWDF and HUF depending on the environment. While under stationary conditions the algorithm outperforms all other schedulers, it does not do the same in the mobility scenario, actually falling behind PF's performance.

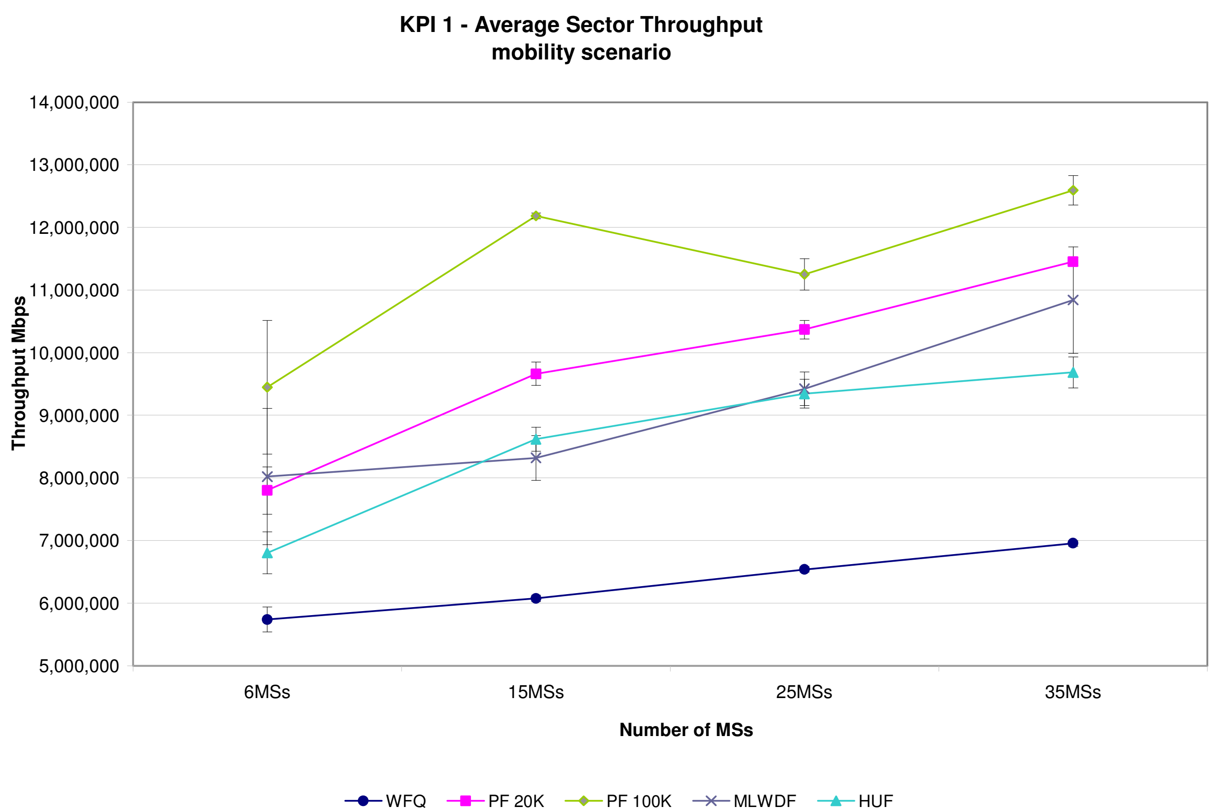



*Figure 9.2.1-2 Mobile Average Sector Throughput*

MLWDF's behavior under mobile conditions can be explained by going back to its formulation and the metric used to perform scheduling decisions: MLWDF considers not only RF conditions but also queue states. In the stationary environment, RF conditions remain practically the same, and as more traffic is being send to queues with better conditions a positive effect is created, biasing the algorithm even more in favor of flows with good conditions. Once the mobility factor is introduced, the opposite occurs: flows that have lots of packets in their queues but are no longer under good RF conditions still have a high chance to be served, hence lowering the final average sector throughput. On the other hand, as PF regards RF conditions as the main factor to make scheduling decisions, the probability of serving a queue that has better RF conditions increases and hence the better KPI reading.

### 9.2.2. KPI2: Application Throughput

KPI2, Application Throughput, was calculated first with nothing but FTP traffic running over BE service flows; and later with three simultaneous applications running: FTP, VBR and CBR, according to the parameters defined in Section 7.3. The purpose of running several applications simultaneously is twofold: first, to verify that QoS requirements were being met by all scheduling algorithms; and second, to determine the effect of QoS-aware (VBR and CBR) traffic on the behavior of BE (FTP) traffic .

As shown in Appendix B, all algorithms met QoS requirements, although using different techniques: strict prioritization in the case of WFQ and PF; and, in the case of MLWDF and HUF, keeping track of waiting time and deadline for QoS-aware queues in order to schedule packets accordingly.

FTP throughput results are plotted in *Figure 9.2.2-1*and *Figure 9.2.2-2* for stationary and mobile environments respectively. It can be seen how in both cases MLWDF outperforms other schedulers as the number of mobiles increase, with a higher probability of subscribers with better spectral efficiency being selected. Also in both environments, it is important to highlight how

WFQ delivers considerably lower application throughput (three to four Mbps depending on the number of subscribers) due to the fact that it does not consider spectral efficiency in its scheduling decisions.

For the stationary scenario, either with only FTP traffic running (*Figure 9.2.2-1*), or with FTP running together with VBR and CBR traffic (Figure *9.2.2-3*), a considerable improvement for FTP throughput can be observed for the PF and MLWDF schedulers.

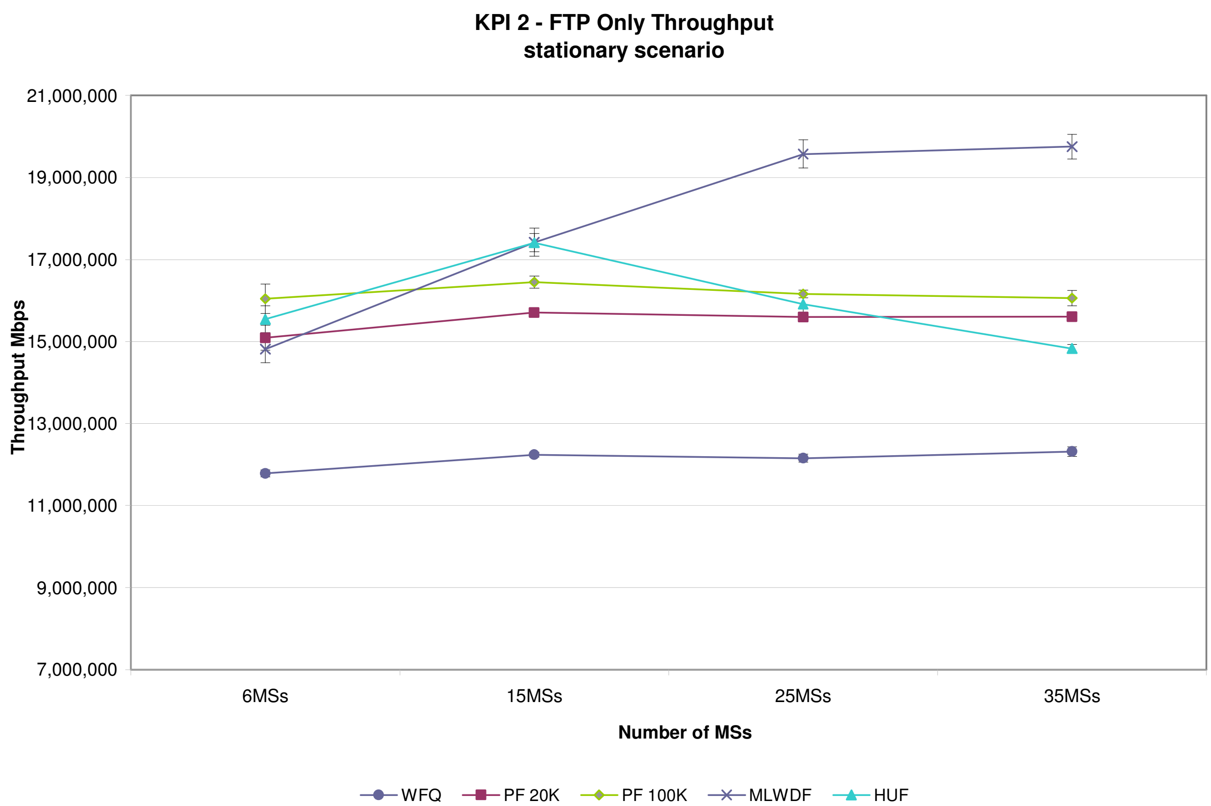



*Figure 9.2.2-1 Stationary Application Throughput (FTP only)*

It is also important to highlight the effect of number of subscribers on the performance of the HUF scheduler (*Figure 9.2.2-1* and *Figure 9.2.2-3*), which for 6 and 15 subscribers behaves pretty well but then falls behind PF's performance for 25 and 35 subscribers. As HUF uses a deadline mechanism that is applied to all flows in order to avoid starvation, as more connections are added, queues reach their deadline faster, and have to be served no matter their spectral efficiency, decreasing the overall aggregated throughput.

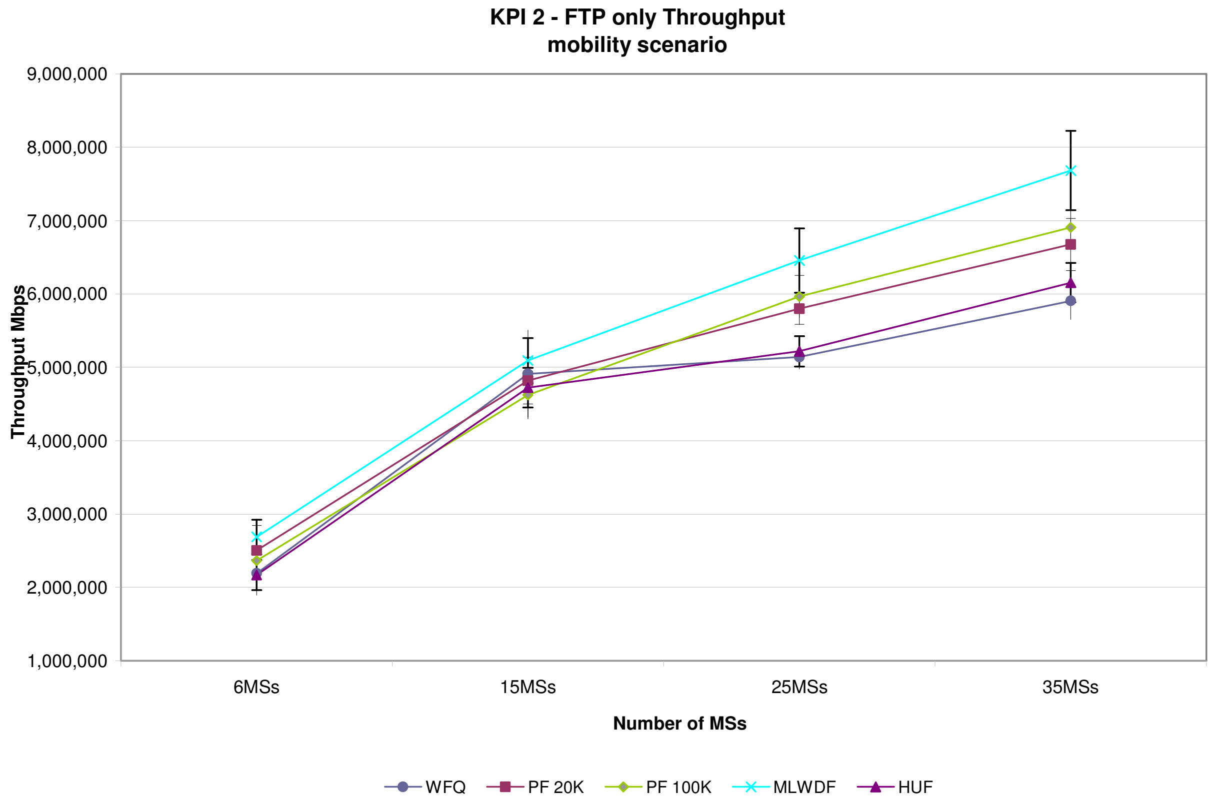



*Figure 9.2.2-2 Mobile Application Throughput (FTP Only)*

The effects of the variability introduced by the mobility environment are also observed (Figure 9.2.2-2 and Figure 9.2.2-4). In the case of FTP combined with VBR and CBR (Figure 9.2.2-4), two factors contribute to the poor throughput numbers. First, as RF variations introduce changes in modulation and packet loss, TCP naturally reacts by throttling down its data rate. Second, the scheduler must still serve VBR and CBR traffic over BE even under these conditions, affecting the FTP's application throughput even more. The effects of stopping VBR and CBR traffic are shown in Figure 9.2.2-2, where statistically significant throughput improvements of MLWDF over PF, and PF over WFQ are observed for 25 and 35 MS runs.

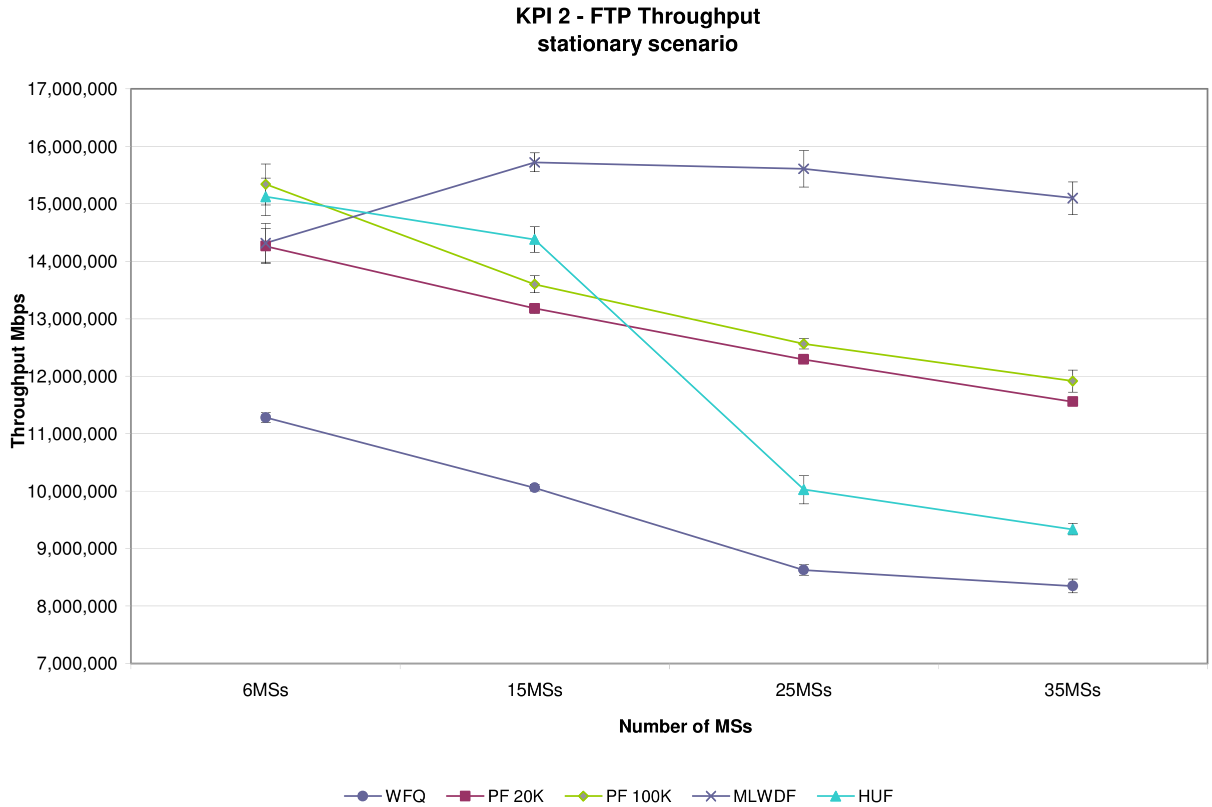



*Figure 9.2.2-3 Stationary Application Throughput (FTP)*

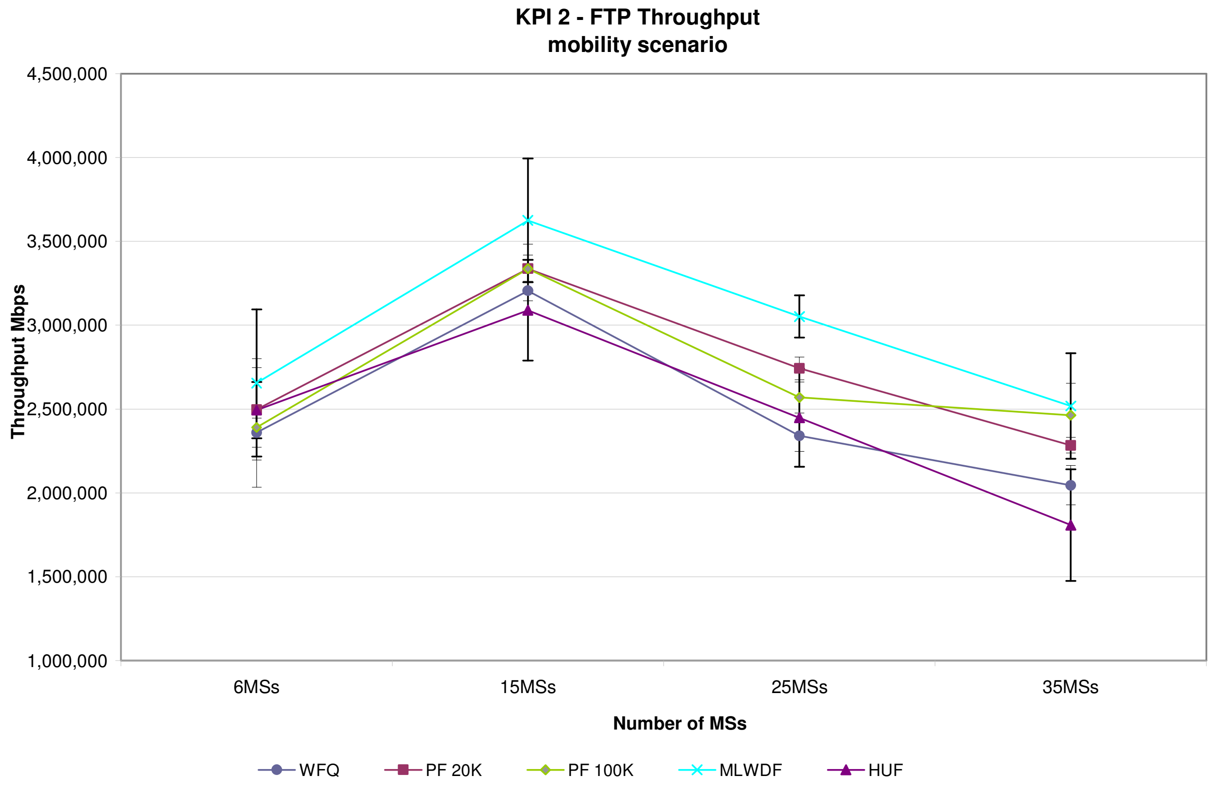



*Figure 9.2.2-4 Mobile Application Throughput (FTP)*

### 9.2.3. KPI3: Average Completion Time

KPI3, Average Completion Time, was obtained for the FTP application, which is the only application with a variable termination time. This KPI shows the lowest variance among the KPIs for the stationary scenario. This is due to granularity of the KPI, as the reported unit is seconds.

Presented in Figure 9.2.3-1, the termination times for WFQ and HUF as compared to PF and MLWDF indicate a clear advantage to PF's and MLWDF's approach of giving preference to flows with better conditions, allowing them to finish first and quickly free up bandwidth for other flows.

Mirroring the behavior observed in Section 9.2.2, HUF behaves close to PF's performance for a small number of subscribers but once they are increased to twenty five and thirty five, HUF's performance starts to decrease.

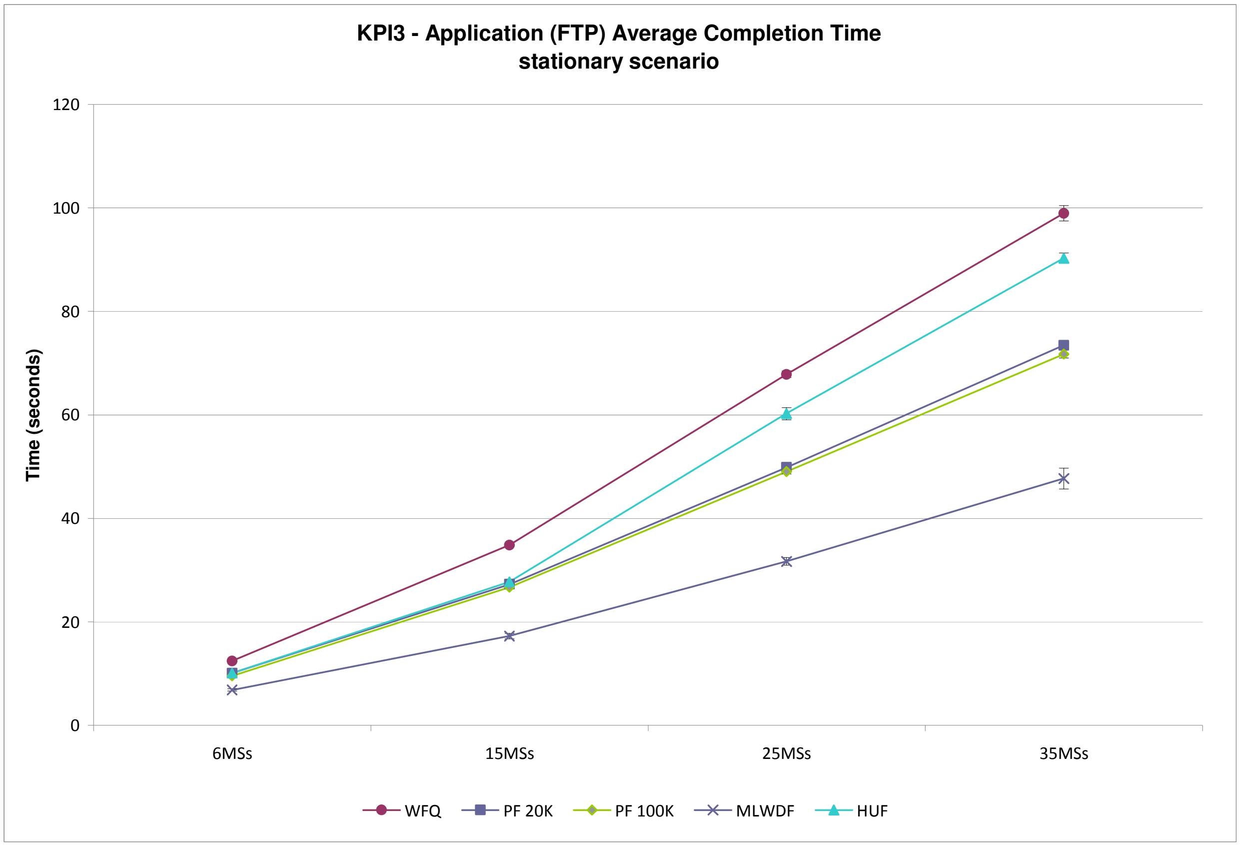



*Figure 9.2.3-1 Stationary Average Completion time for FTP*

For the mobile environment, shown in *Figure 9.2.3-2*, no statistically significant difference is detected among the analyzed schedulers in terms of completion time. However, it is important to read this result together with the numbers obtained for FTP application throughput in *Figure 9.2.2-4*, for which MLWDF and PF perform statistically better for the 25 and 35 MS Results.

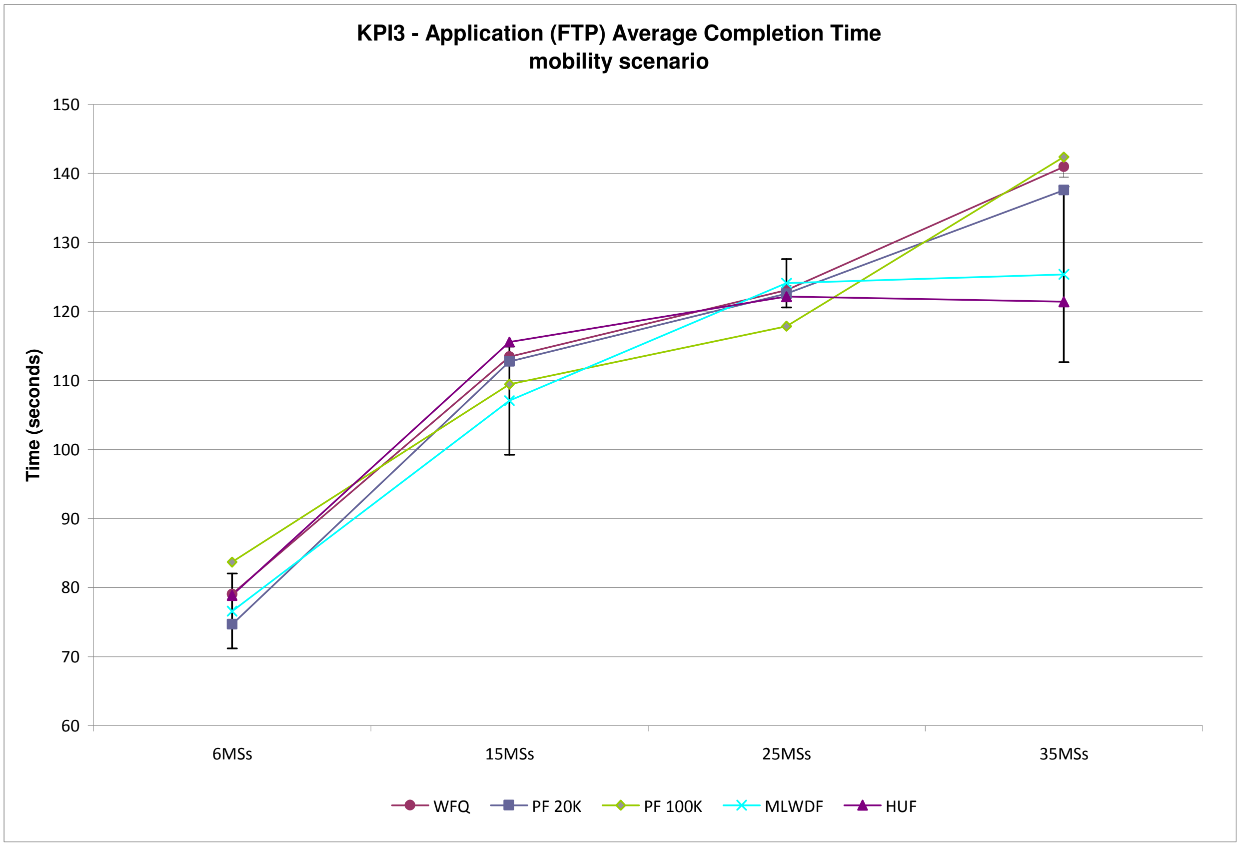



*Figure 9.2.3-2 Mobile Average Completion Time*

### 9.2.4. KPI4: Fairness Index

The Fairness Index (KPI4) is measured based on completion time of FTP sessions as explained in Chapter 8. In the context of the KPI's definition, a "fair" scheduler assigns equal resources to users with similar demands. A perfectly fair scheduler would have an index of 1, while less than perfectly fair schedulers would have a lower value.

WFQ is the fairest scheduler as it virtually assigns the same amount of bandwidth to each FTP connection, even though the number of slots required to serve the bandwidth required for a connection under poor RF conditions will be much higher. PF and HUF rank below WFQ, while MLWDF is by far the most unfair of the schedulers under analysis with a fairness index around 0.7.

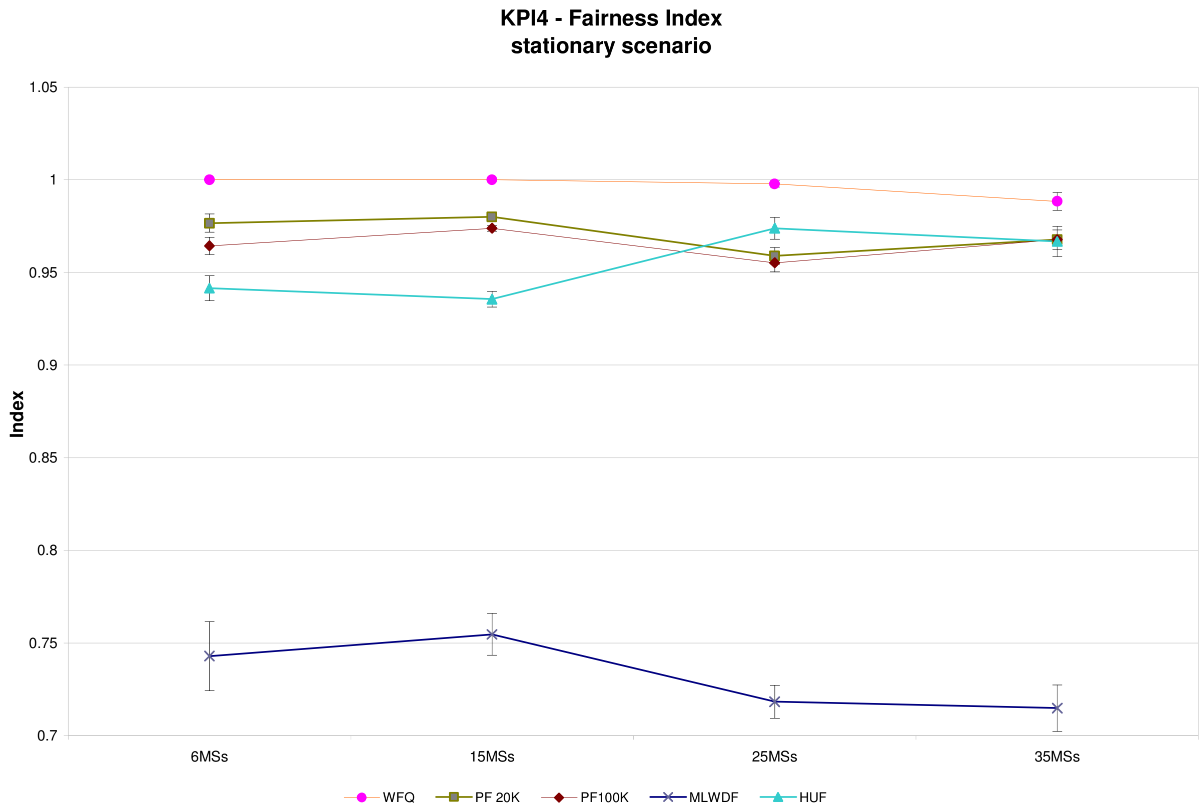



*Figure 9.2.4-1 Stationary Fairness Index*

Following the same behavior observed for the completion time KPI, the Fairness Index for the mobile environment, presented in Appendix C, shows no statistically significant difference among the schedulers under test.

### 9.2.5. KPI5: Delay

KPI5, Delay, validates that QoS-aware flows are served properly in order to satisfy their delay requirements. This metric was obtained for both CBR and VoIP traffic.

In the case of CBR traffic, packets arrive at the UGS queues with a constant inter-packet delay of 16 ms. For VoIP, using ertPS queues, the arrival rate might vary but the application calls for a transit delay not exceeding 100 ms.

Results for the stationary environment are shown below. Mobile environment results, similar to the stationary case, are shown in Appendix D.

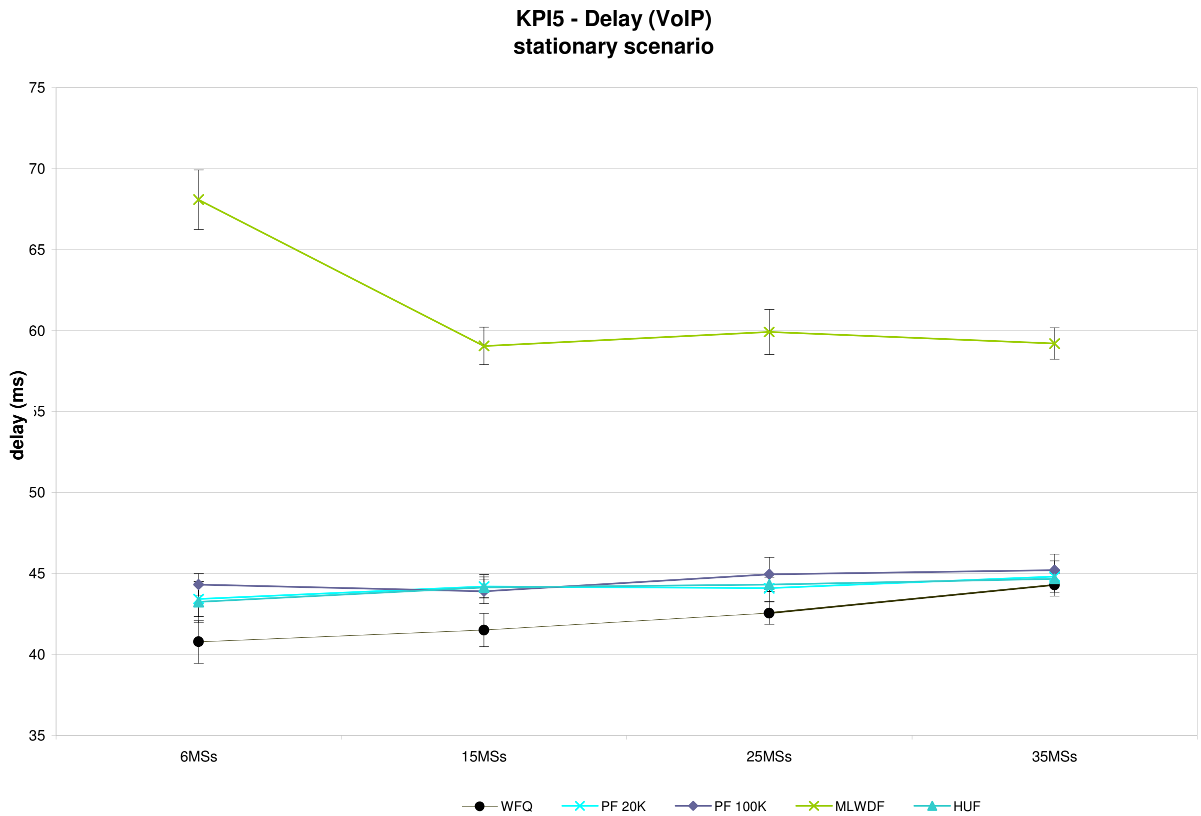



*Figure 9.2.5-1 Stationary Application delay (VoIP)*

None of the analyzed scheduling algorithms reached delay outage, defined as the violation of the delay requirements of the scheduling class, mostly due to the nature of the traffic. This is, in all simulations there were enough slots available to accommodate all of the delay-sensitive traffic in a single frame if required. In other words, there was no over-subscription of resources for QoS-aware services.

In the case of HUF, WFQ and PF, which use strict priority to schedule QoS-aware traffic over any other kind of traffic, delay sensitive traffic is scheduled almost right away. This is easily verified by looking at Figure Figure 9.2.5-2, where the average delay for CBR traffic is very close to 5ms, the frame duration. A similar situation occurs for the VoIP delay, shown in Figure Figure 9.2.5-1, which indicates a delay between 40 and 45 ms, given that the average packet interval is 40 ms.

As expected, MLWDF was the only protocol with the capacity to impact the delay, but still its performance was within the limits of the tolerated delay for each application.

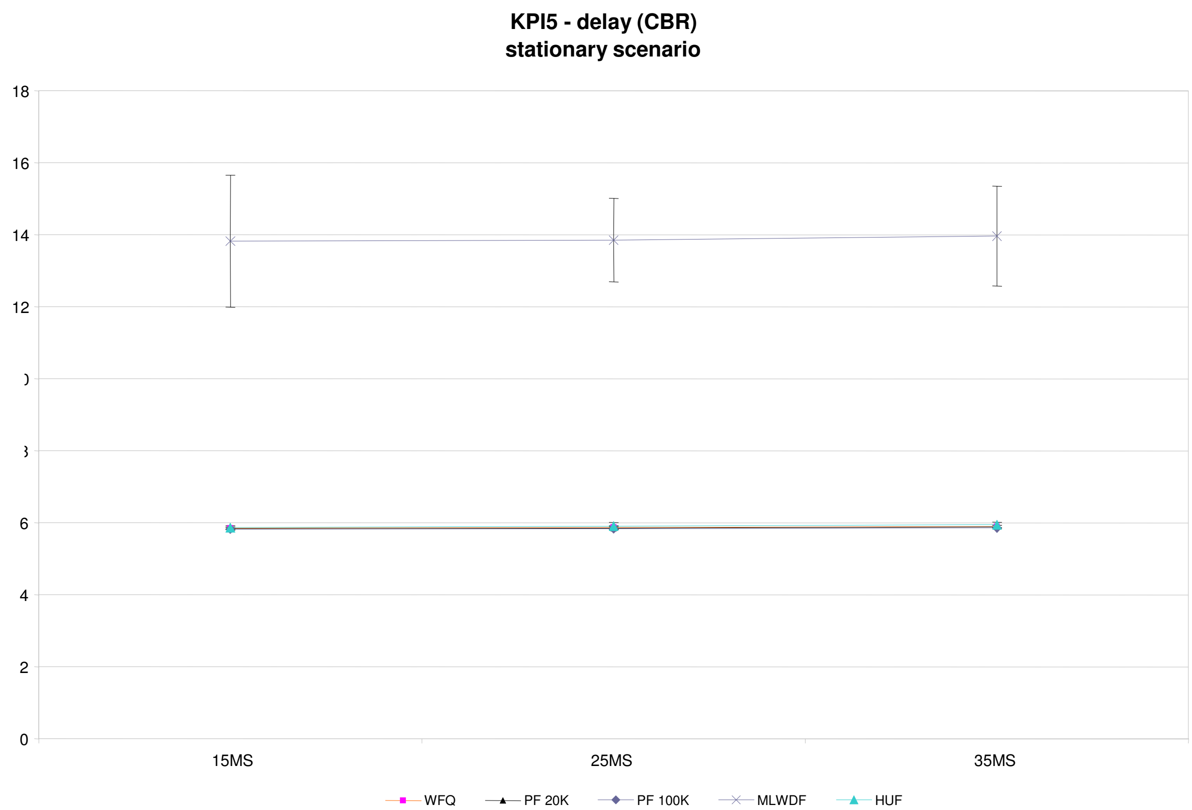



*Figure 9.2.5-2 Stationary Application Delay (CBR)*

# 10. Conclusions

In this research, four scheduler alternatives for Mobile WiMAX were compared using detailed analysis under a controlled environment as well as in stationary and mobile environments using a number of metrics recommended by the WiMAX Forum. This chapter presents a discussion of the results, some notes on the usability of Qualnet's simulation software and considerations for aggregate throughput engineering. We conclude with research limitations and future work.

## 10.1. Discussion of the Results

The impact of different environments is demonstrated with this research. Some of the KPIs, namely application throughput, average completion time and fairness index indicate no statistically significant difference between the analyzed schedulers under mobile conditions. However, schedulers show significant differences in performance under stationary conditions. The Average Sector Throughput and Application Throughput metrics provide the greatest observable difference or both stationary and mobile environments. It was found that FTP throughput highly benefits by the PF and MLWDF approach when compared to WFQ and HUF. This can be explained by looking at the behavior shown under a controlled environment, in which flows with good RF conditions practically get a head start of about half a second (depending on the configuration of the observation window) over flows with lower modulations. As initially all resources are allocated to subscribers with good RF conditions, their transport layer will benefit from having access to all the available bandwidth, using it to finish their transmission quite rapidly. Additionally, the delay metrics for VoIP and CBR traffic allowed to validate that schedulers did not reach outage scenarios, and to identify the impact of delaying QoS-aware traffic as proposed by MLWDF.

It is important to highlight that the average completion time and fairness index KPIs should be analyzed together with the application throughput KPI, as looking at them independently would not provide the whole picture about the behavior of certain applications: While these KPIs under the mobile environment indicated no significant difference among the schedulers, the FTP throughput KPI indicated significant differences in favor of MLWDF and PF for 25 and 35 subscribers. Table 10.1-1 summarizes results obtained for each KPI under stationary and mobile scenarios.

*Table 10.1-1 KPI Results for Stationary and Mobile Scenarios*

| KPI | Results Stationary | Results Mobility |
|---|---|---|
| Avg. Sector Throughput | MLWDF shows considerable improvements for 25 and 35 MS, followed by PF | In contrast, PF provides better results for all number of subscribers |
| Application Throughput (FTP only) | In line with previous KPI, MLWDF shows considerable improvements over other schedulers for 25 and 35 MS. HUF behaves well for 6 and 15 MS but rapidly falls behind PF's performance for more subscribers | MLWDF and PF show statistically significant throughput improvements at 25 and 35 subscribers. |
| Application Throughput (FTP/VBR/CBR) | Same as above | Some significance in favor of MLWDF and PF, particularly for 25 and 25 subscribers |
| Average completion time | MLWDF and PF are clearly advantageous. For 35 MS, MLWDF's average completion time is about half the one of WFQ. | No statistically significant difference among different schedulers |
| Fairness Index | WFQ is the fairest scheduler, while MLWDF is the most unfair. | No statistically significant difference among different schedulers |
| CBR/VoIP delay | While all other scheduler's delay number are quite consistent, MLWDF introduces a considerable delay, but still within the delay requirements of each application | |

By looking at the different metrics, it can be seen how each scheduler has its unique characteristics: HUF focuses on meeting delay commitments, WFQ is the fairest of all analyzed schedulers and PF aims at maximizing short-term throughput. MLWDF's approach of postponing delay-sensitive traffic until a certain threshold in favor of throughput maximization is quite effective, and yet allows fine-tuning by configuring the threshold to a different value.

Even with its poor throughput results, there is something to say in favor of WFQ: It implicitly allows meeting the minimum rate of certain flows by simply setting its weight to the desired value. This is quite important as the Minimum Reserved Traffic Rate parameter for rtPS, nrtPS and ertPS flow can be mapped directly to the flow's weight without any extra steps. In a similar way, HUF does the same with the flow priority, which is implicitly specified as part of the metric to make scheduling decisions.

PF demonstrates the advantage in throughput improvements that can be obtained from giving preference to flows under good RF conditions. Meeting QoS requirements is done via strict priority, whereby QoS-aware flows are always served before any other flows.

MLWDF introduces the relaxation of the strict priority rule, and allows BE flows to exploit the short-term availability of bandwidth. WFQ does very well at maintaining the fairness of the connections, which could be of great use in situations of congestion. Finally, HUF incorporates priorities, which would need to be implemented by other schedulers in some other manner.

In summary, a complete alternative could be a hybrid algorithm that incorporates MLWDF's idea of delaying QoS-aware traffic, but then uses a conservative and highly fair algorithm such as WFQ to schedule traffic for UGS, rtPS, nrtPS and ertPS scheduling classes in order to avoid starvation of flows for subscribers in less than ideal conditions.

## 10.2. Usability of Simulation Software

In total, twenty four submissions were made to Qualnet's support forum as part of this research. While some were general questions on configuration procedures, four of the contributions were actual problems that had to be corrected in order to obtain proper results.

A considerable limitation in the WiMAX implementation stems from the way flows are being configured. WiMAX parameters for certain flows are configured based on the parameters configured for the application that is supposed to run over that flow. For example, FTP and HTTP traffic automatically gets configured with no minimum reserved traffic rate, so there is no way to guarantee a minimum level of bandwidth for that kind of services. Similarly, in order to configure certain flows to support a minimum reserved traffic rate of 512 Kbps, a specific application has to be configured to send that specific amount of traffic, thus limiting the kind of traffic one can generate.

Another limitation particularly impacting for this research is the lack of statistics for scheduler analysis. Most of the data presented on this thesis had to be extracted manually via scripts or debug statements introduced into the code, as they are not currently implemented in Qualnet's statistics framework.

An advantage of Qualnet is its object-oriented approach for scheduler design. This certainly allowed reuse of good portions of code, and provided the framework from which all the schedulers were written. A similar approach should be used for the uplink scheduler, which is currently not implemented as an object.

In summary, despite some limitations in features and a few bugs, once the way the code was organized was figured out; adding new schedulers was a relatively fast. Tools to analyze the respective schedulers, however, had to be written completely from scratch.

## 10.3. Considerations for Throughput Engineering

None of the papers reviewed for this research consider something that is common practice in WiMAX deployments: The use of the Maximum Sustained Traffic Rate (MSTR) to control the maximum amount of traffic a user is allowed. WiMAX operators use this parameter for two reasons: first, they want to provide different levels of service (and obviously charge differently) by allowing different levels of maximum rate to users according to their contract; and second, they want to control improper use of air link resources, which could eventually happen in a free-for-all environment.

Figure 10.3-1 to Figure 10.3-4 illustrate the difference using WFQ and PF schedulers as a reference. The simulations in this case have been configured in such a way that oversubscription has occurred and some packets will have to be discarded. Instant throughput graphs are shown for two cases: One, the link rate instance, on which the only constrains each flow has are its modulation and the number of slots that get assigned to it by the scheduler; and another one, the equal share instance, on which an additional constrain of 1Mbps MSTR has been configured for each flow.

In the case of WFQ for example, the behavior is quite different: While for the link rate instance flows are allocated roughly the same amount of slots, resulting in different throughput levels depending on the modulation of each subscriber; for the equal share instance all flows, no matter their modulation, are capped at 1 Mbps, leaving some extra slots available to be shared among the remaining users. The result is an instant throughput graph that looks totally different, even if the scheduler is the same.

A similar situation occurs in the case of the PF scheduler, shown for $t_c$=100K in Figure 10.3-3 Figure 10.3-4. In this case the difference is more dramatic as PF maximized the number of slots allocated to subscribers with better conditions, but that is limited as the flow has a MSTR that is lower than its achievable bandwidth. It can also be observed how towards the end of the simulation, flows under better conditions finish their transmission and free up some slots, allowing flows that had been starving to clear their queues, hence increasing their instant throughput.

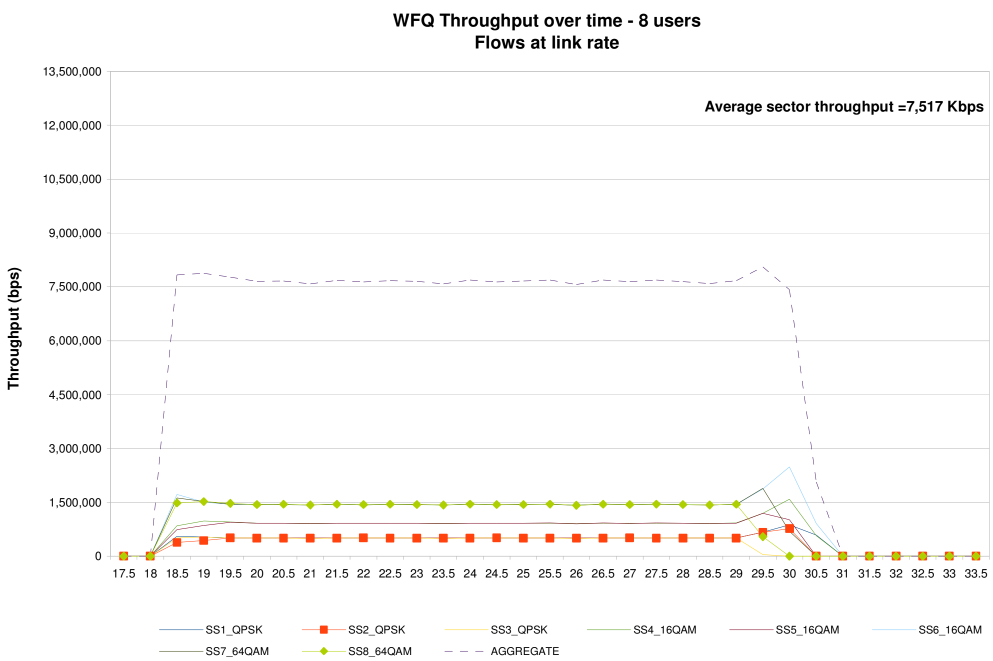



*Figure 10.3-1 WFQ Throughput Over Time with Flows running at Link Rate*

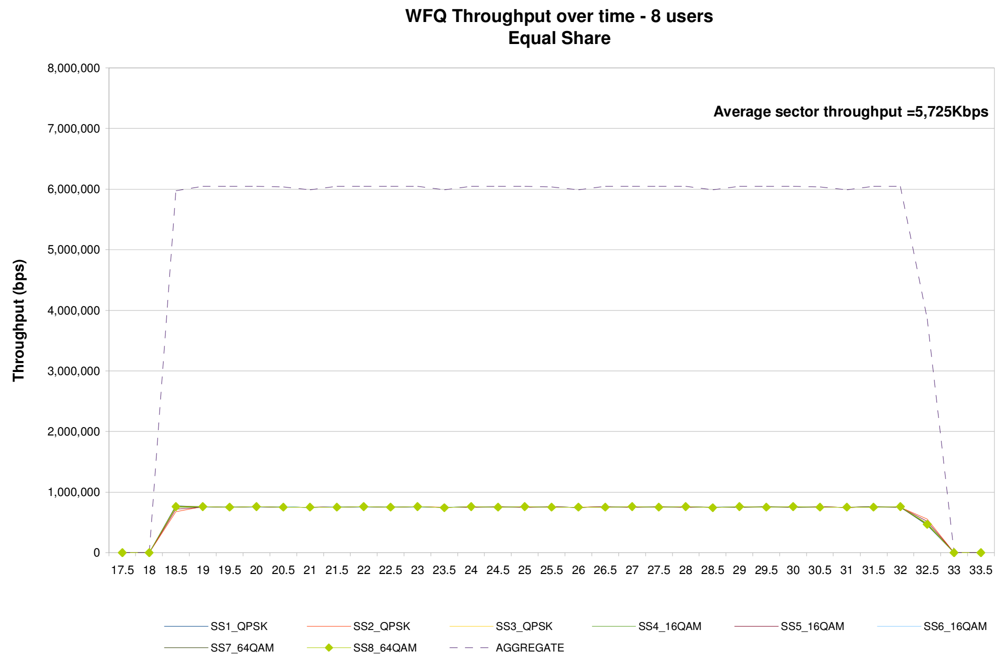



*Figure 10.3-2 WFQ Throughput Over Time with Flows Running at MSTR = 1 Mbps*

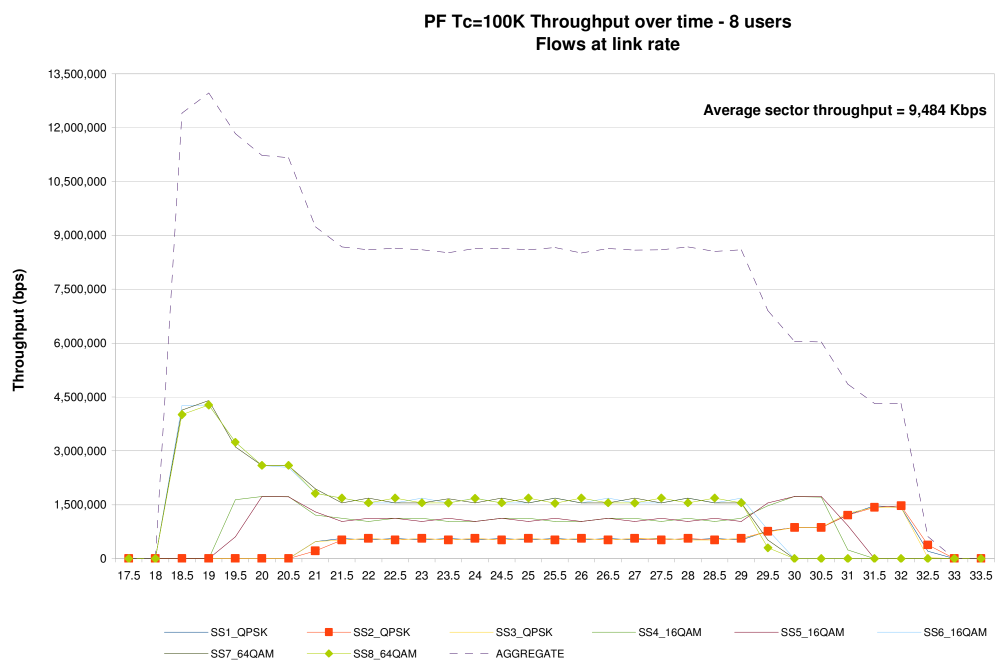



*Figure 10.3-3 PF $t_c$=100K Throughput Over Time with Flows Running at Link Rate*

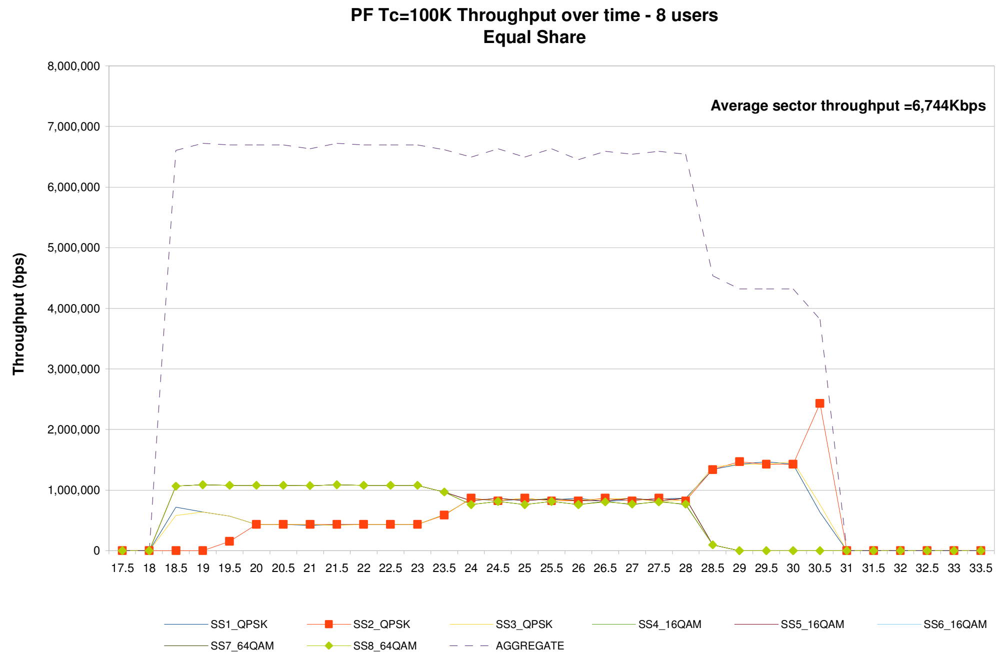



*Figure 10.3-4 PF $t_c$ =100K Throughput Over Time with Flows Running at MSTR = 1 Mbps*

## 10.4. Research Limitations and Future Work

Several limitations are worth mentioning as part of this research. First, given the extent of the KPIs and the number of schedulers under analysis, only the downlink direction was considered. The simulation software currently allows only a few applications (CBR and VBR) to properly map their QoS parameters to those of the different WiMAX scheduling classes. While this is manageable in the downlink direction, in the uplink direction it would cause incorrect configuration of QoS parameters that could not be resolved without modifications to the convergence sublayer.

Second, application throughput numbers are based solely on a TCP-based application: FTP. As a matter of fact, two of the KPIs: Average completion time, fairness index are based only on FTP. Ideally, additional applications such as HTTP would provide a more realistic scenario regarding user experience. More recent applications like Internet gaming and peer-to-peer, which would be perfect candidates for BE traffic, could also provide means to further test schedulers' performance.

The analysis of the HTTP protocol performance is particularly interesting as it is in reality a set of multiple TCP sessions working together to load a certain page. From the user perspective, only once the page is completely displayed can the session been considered as completed. From that point of view modifications to metrics such as completion time and fairness index should be introduced to reflect that expectation of the protocol.

Third, while in our simulation scenarios all the traffic was cautiously estimated, in real life scheduler designers must not assume that the network will be carefully engineered or that oversubscription of QoS-aware traffic will not occur. For the latter, even in a carefully engineered network, failure scenarios may occur causing a sector that was running with certain traffic ratio of BE to QoS-aware to go into situations of oversubscription for its QoS-aware traffic. Under these situations, schedulers like PF and WFQ, which do not explicitly keep an eye on meeting QoS requirements, will eventually start to violate their QoS commitment. In contrast, HUF and MLWDF incorporate explicit checks to ensure that delay commitments are being met at all times. MLWDF particularly proved to be an effective alternative to maximize sector throughput while still being able to guarantee a minimum level of service for QoS-aware traffic. In summary, our research lacks metrics and scenarios to check for graceful degradation of service under congestion situations.

Fourth, results indicate that for the mobile environment, average sector throughput using UDP traffic is considerably higher than the application throughput numbers. Furthermore, the difference among schedulers is much more significant with the average sector throughput KPI vs. the FTP Application throughput KPI, indicating that the TCP response to the wireless conditions could be better. Finding ways to lower that gap between the performance observed with UDP traffic vs. the numbers obtained for TCP-based applications would certainly be a good topic for future research.

Another interesting topic left for future work is the scheduler response in the presence of retransmission schemes such as ARQ or H-ARQ, especially in faded channel that will cause a nontrivial amount of retransmissions over the air. Under those situations, bursts that were not acknowledged should be retransmitted right away, and as some of the schedulers are sensible to waiting time, they would probably change in terms of their performance under those conditions. Similar, but much more challenging in scope, is the topic of scheduler performance under high speed mobility scenarios involving multiple handovers. Questions that will most likely be developed in future research work will include: should the subscriber scheduler context (waiting time or current averaged rate for example) be transferred to the target BS during a handover event? Or will the results obtained for the mobile environment hold for higher speeds?

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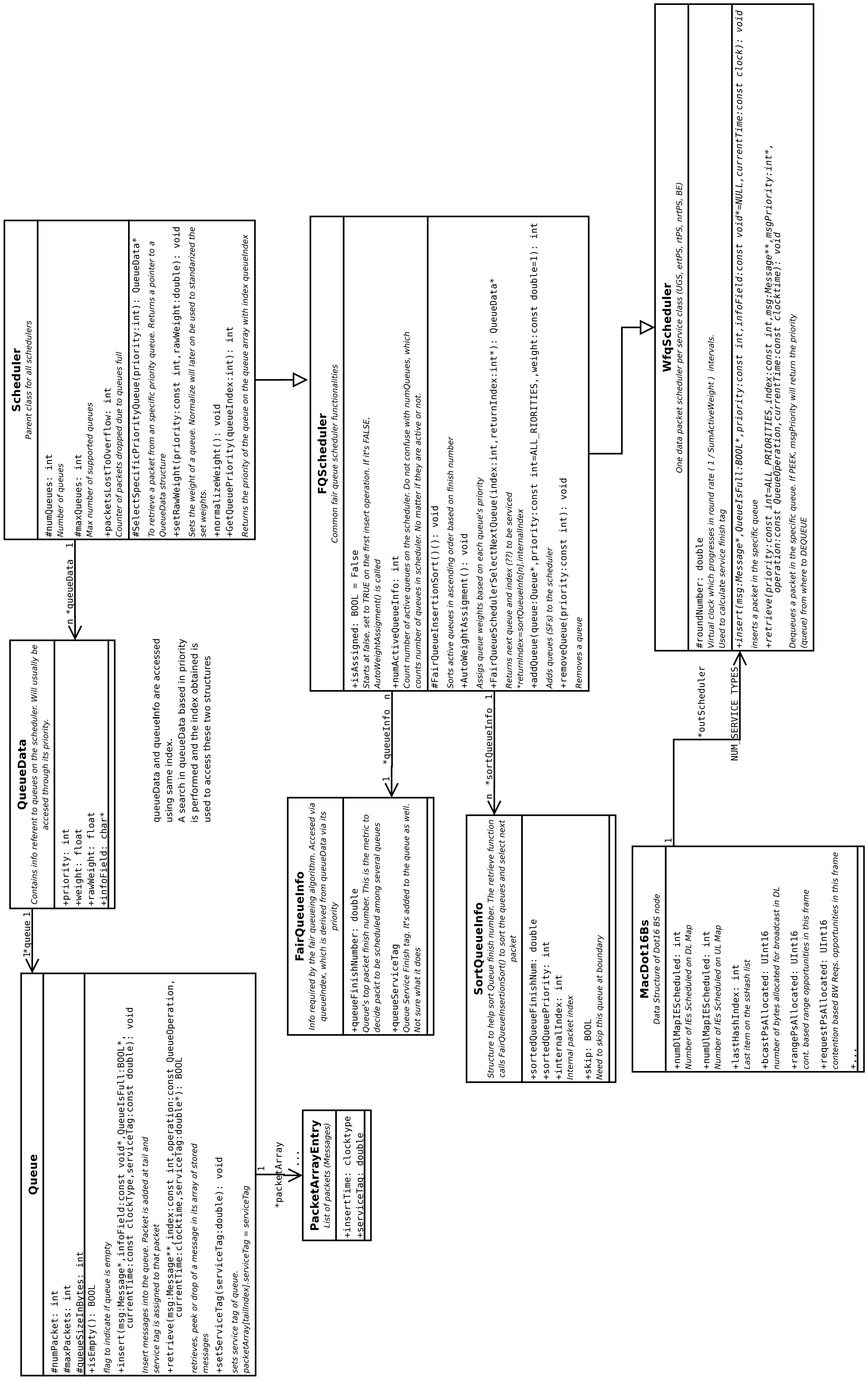
# Appendix A: WFQ Scheduler Class Diagram



## Appendix B: CBR and VBR Throughput for Stationary and Mobile Scenarios

With the exception of the controlled environment, simulations include simultaneous UGS (CBR), ertPS (VoIP), rtPS (VBR) and BE (FTP) traffic. This was done with the intention of verifying that QoS-aware traffic (CBR, VoIP and VBR) was given the proper treatment in order to satisfy its data rates.

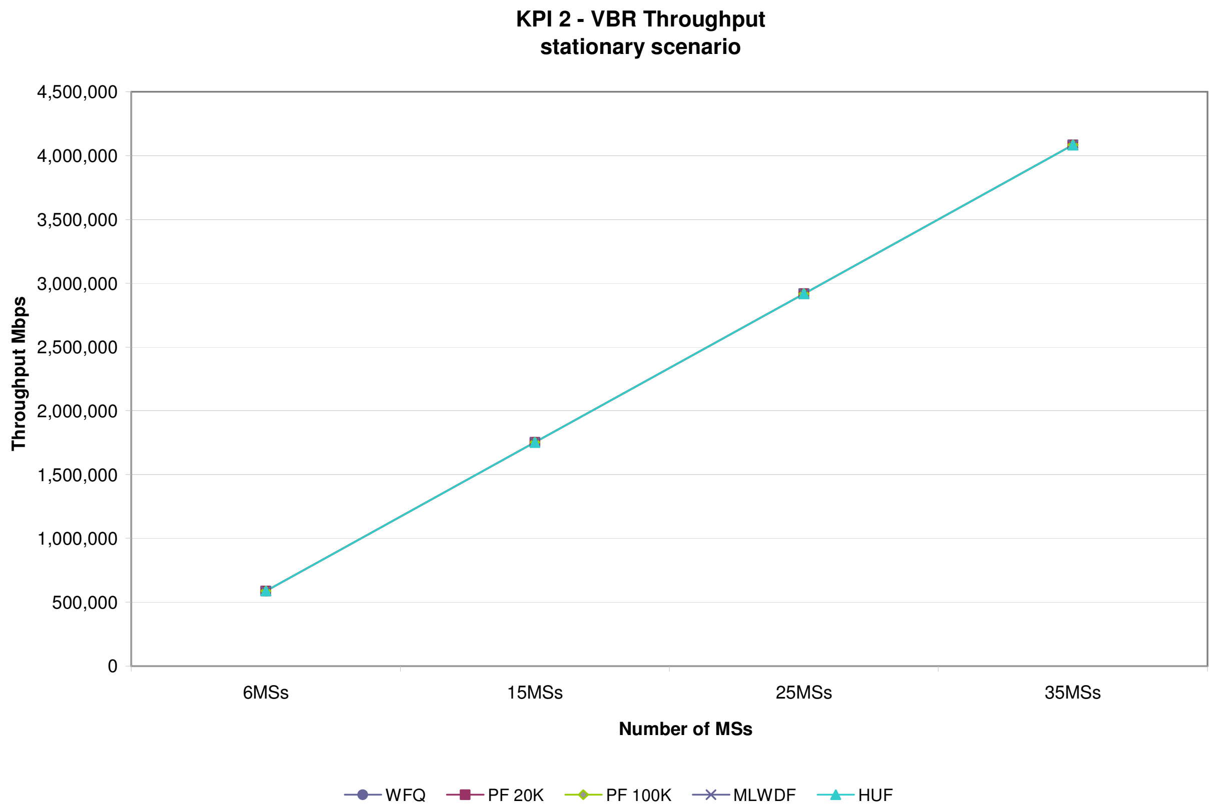
Throughput graphs are presented below for stationary and mobile scenarios. For CBR and VBR, a percentage of subscribers (twenty and ten respectively) were running that kind of traffic. The table below summarizes the number of subscribers with VBR and CBR traffic, as well as the expected throughput in each case.

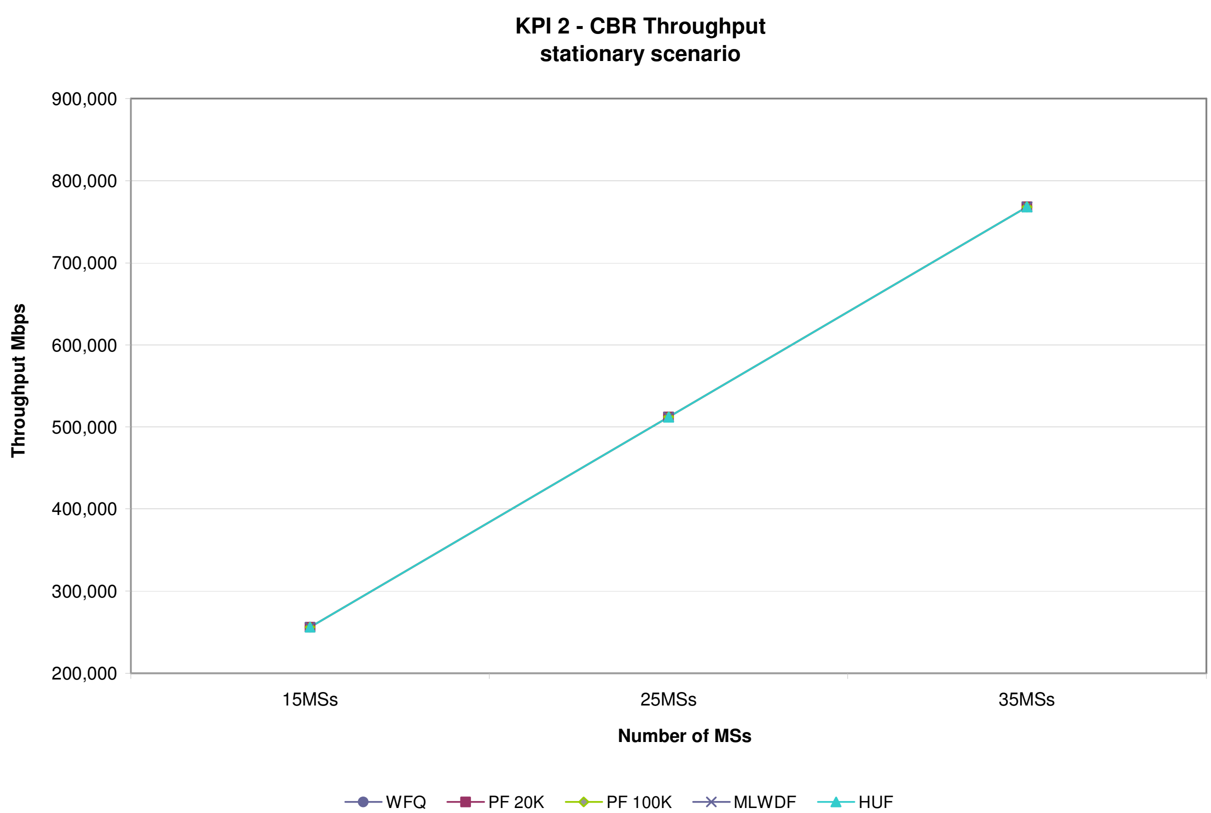
| Users/Simulation | Users running VBR | VBR Throughput | Users running CBR | CBR Throughput |
|---|---|---|---|---|
| 6 | 1 | ~584 Kbps | 0 | 0 |
| 15 | 3 | ~1752 Kbps | 1 | 256 Kbps |
| 25 | 5 | ~2920 Kbps | 2 | 512 Kbps |
| 35 | 7 | ~4088 Kbps | 3 | 768 Kbps |

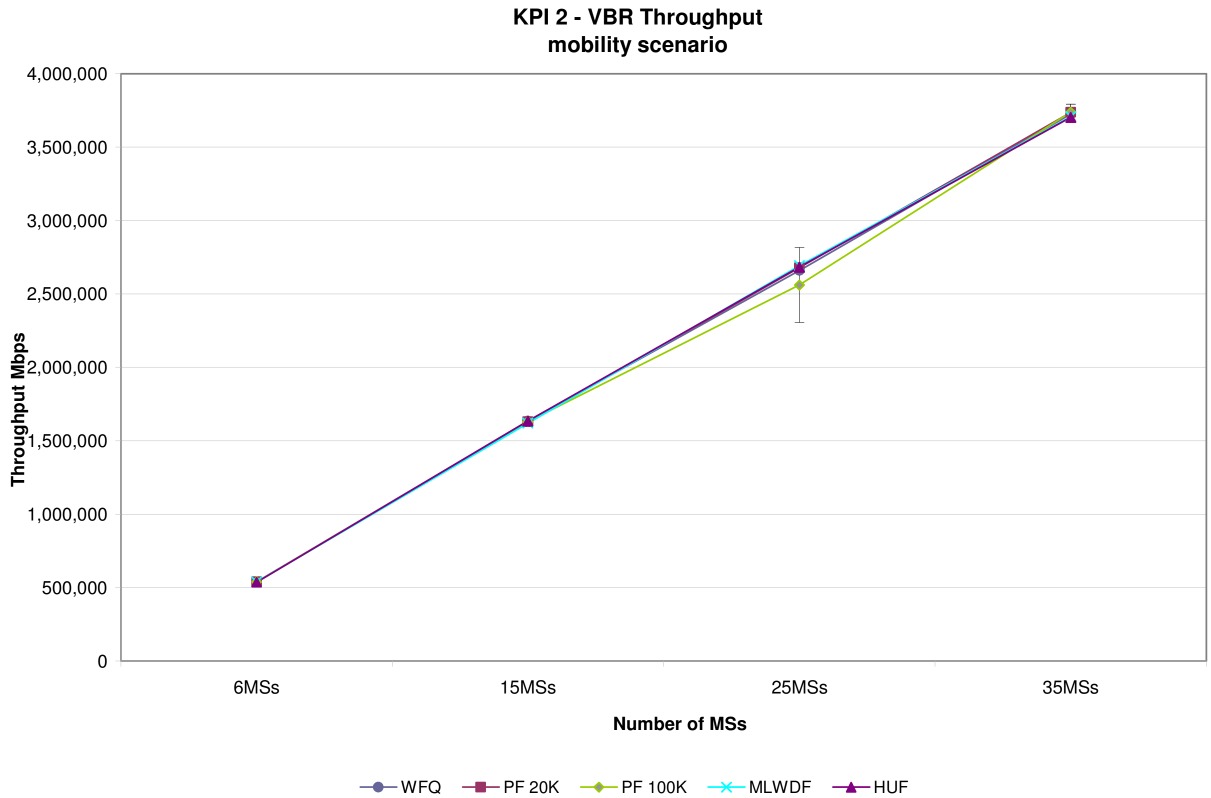
Each scheduler accomplishes prioritization in a different manner. In the case of WFQ and PF, a strict priority scheme giving service to QoS-aware queues first is applied. As all queues from UGS, ertPS and rtPS service classes are dispatched first, their bandwidth requirement is always satisfied.

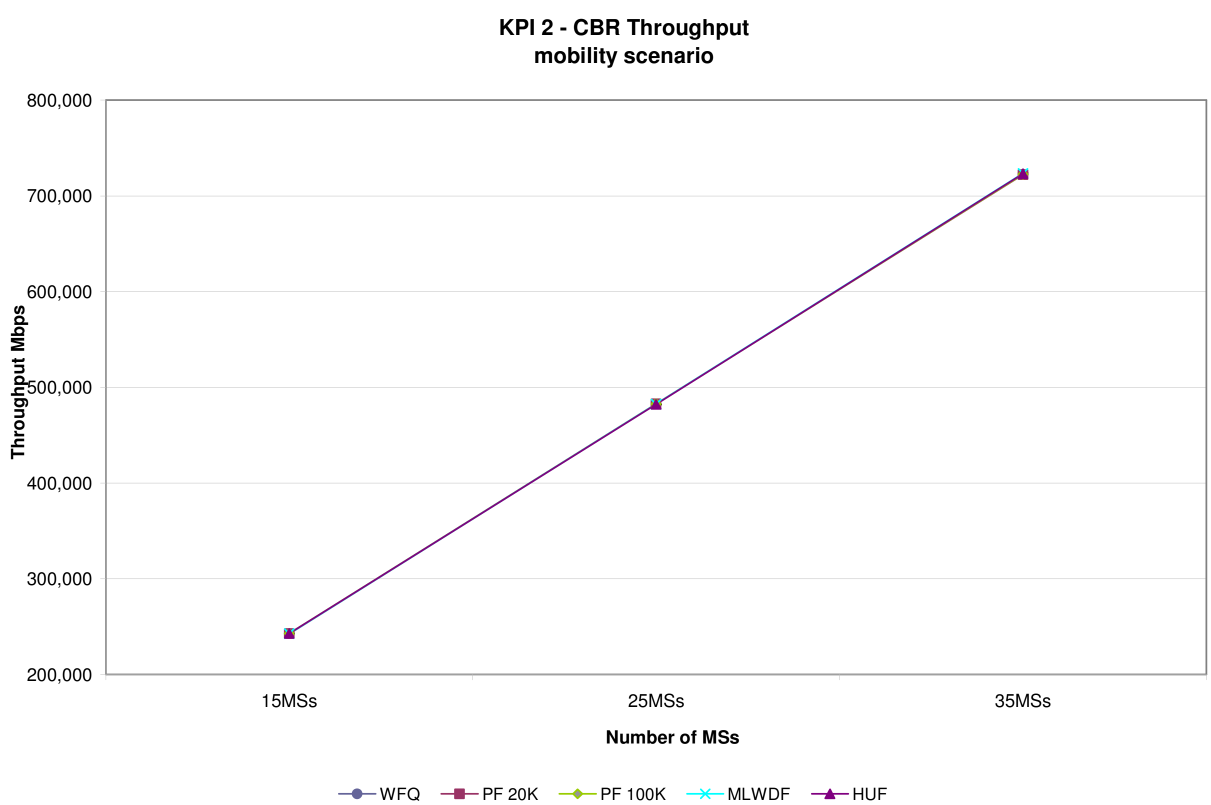
For MLWDF on the other hand, each delay-sensitive packet is tagged with a waiting time which is checked at each scheduling cycle. If the waiting time of the HOL packet of a certain queue has exceeded a certain threshold (hard-coded at 50%), that queue is served entirely.

HUF uses a similar criteria, assigning a deadline to each packet based on its delay requirements to each packet upon arrival and decreasing it in each scheduling cycle. Once the packet has reached a deadline of one, it is immediately scheduled.

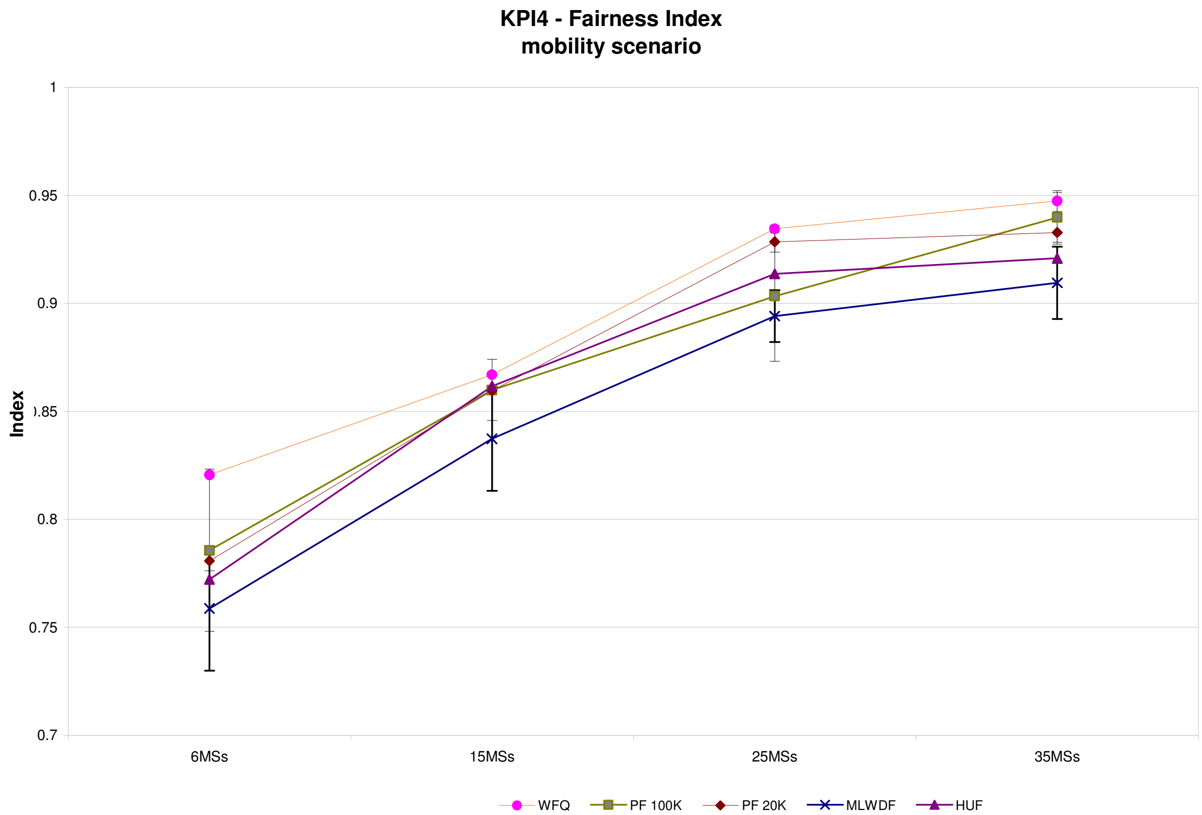

KPI 2 - VBR Throughput
stationary scenario
Throughput Mbps
4,500,000
4,000,000
3,500,000
3,000,000
2,500,000
2,000,000
1,500,000
1,000,000
500,000
0
6MSs
15MSs
25MSs
35MSs
Number of MSs
WFQ
PF 20K
PF 100K
MLWDF
HUF


KPI 2 - CBR Throughput
stationary scenario
Throughput Mbps
900,000
800,000
700,000
600,000
500,000
400,000
300,000
200,000
15MSs
25MSs
35MSs
Number of MSs
WFQ
PF 20K
PF 100K
MLWDF
HUF

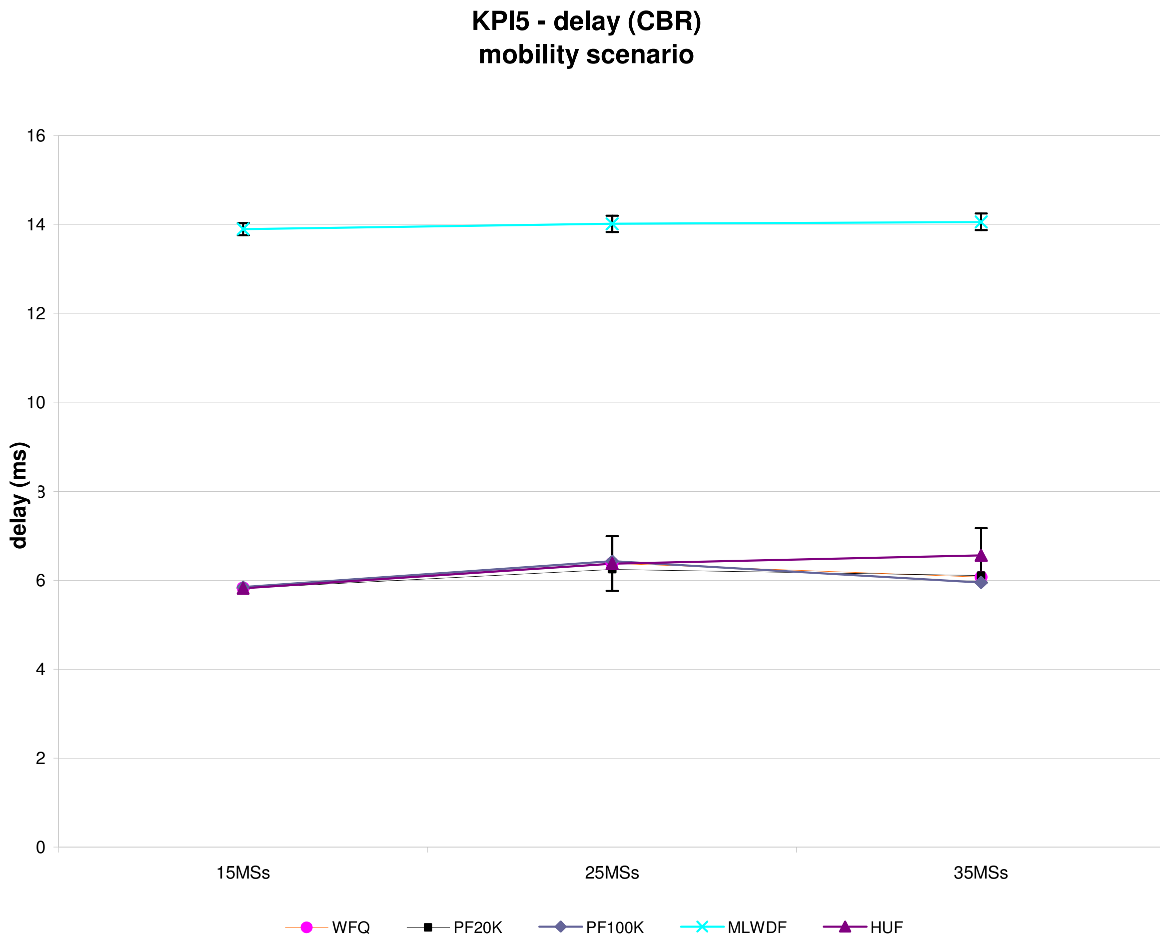

KPI 2 - VBR Throughput
mobility scenario
4,000,000
3,500,000
3,000,000
2,500,000
2,000,000
1,500,000
1,000,000
500,000
0
Throughput Mbps
6MSs
15MSs
25MSs
35MSs
Number of MSs
WFQ
PF 20K
PF 100K
MLWDF
HUF

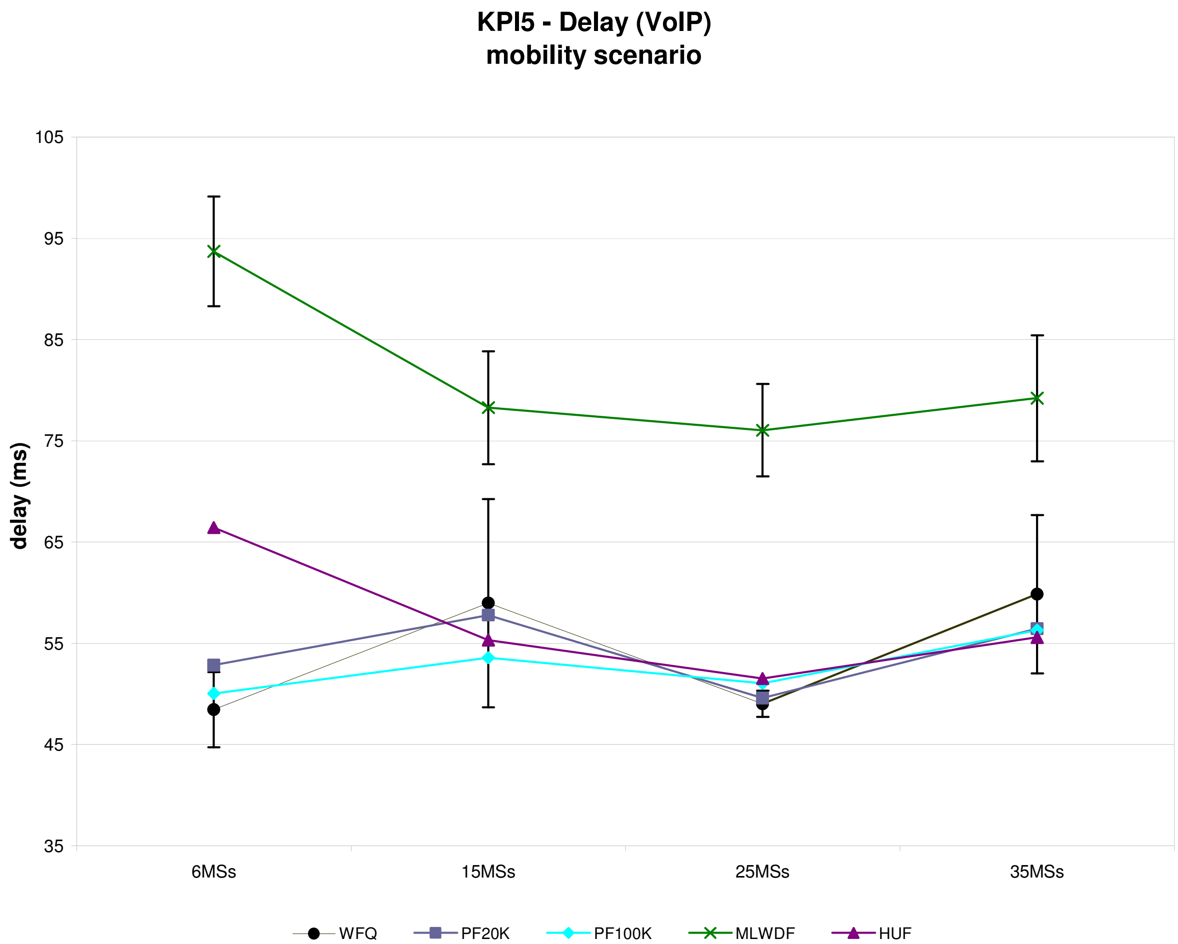

KPI 2 - CBR Throughput
mobility scenario
800,000
700,000
600,000
500,000
400,000
300,000
200,000
Throughput Mbps
15MSs
25MSs
35MSs
Number of MSs
WFQ
PF 20K
PF 100K
MLWDF
HUF

# Appendix C: Fairness Index Results for Mobile Environment



## Appendix D: Delay Results for Mobile Environment




KPI5 - Delay (VoIP)
mobility scenario
delay (ms)
105
95
85
75
65
55
45
35
6MSs
15MSs
25MSs
35MSs
WFQ
PF20K
PF100K
MLWDF
HUF