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Investigation of Efficient Resource Allocation Schemes for WiMAX Networks

A thesis submitted for the degree of Master of Philosophy

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Abstract

WiMax (Worldwide Interoperability for Microwave Access) is a promising wireless technology with the aim of providing the last mile wireless broadband access designed for both fixed and mobile consumers as an alternative solution to the wired DSL and cable access schemes.

The purpose of this research project is to investigate efficient resource allocation algorithms for WiMax. To achieve this goal, we investigate efficient PHY layer Partial Usage of SubCarriers (PUSC) allocation as well as MAC layer piggyback bandwidth request mechanisms.

At the PHY layer we proposed improvements on the Uplink and Downlink PUSC subcarrier allocation scheme. For the Uplink PUSC we suggested a method by allocating different frequencies to neighbouring cells in combination with the Integer Frequency Reuse (IFR) and Fractional Frequency Reuse (FFR) in order to reduce interferences and collisions. The simulation results exhibit that collision rates can be reduced to zero for both IFR and FFR patterns with the proposed improvement by assuming that perfect power control is used in the system. In addition, there is no collision at cell edges. The results also show that FFR patterns achieve lower inter-cell interference and higher capacities as compared to the IFR patterns. For the Downlink PUSC we introduced an offset scheme with the purpose of increasing the number of users in the system.

At the MAC layer we propose an improvement on the piggyback bandwidth request mechanism by increasing the size of the piggyback bandwidth request in order to reduce the number of bandwidth requests and hence improve the resource utilisation. The simulation results demonstrate that our improved scheme achieves higher throughput, less delay and packet loss rates as compared to the standardised piggyback bandwidth request mechanism.

Acknowledgments

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This thesis is dedicated to my parents whose constant love and support has always been there for me.

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Abbreviations and Acronyms

ADSL	Asymmetric Digital Subscriber Line
ARQ	Automatic Repeat Request
BWA	Broadband wireless access
BE	Best Effort
BER	Bit Error Rate
BS	Base Station
BSSID	Base Station Identification
BWA	Broadband Wireless Access
CBR	Constant Bit Rate
CCI	Co-Channel Interference
CDMA	Code Division Multiple Access
CID	Connection Identification
CM	Cable Modems
CS	Convergence Sublayer
CS SAP	Convergence Sublayer service access point
DSC	Dynamic Service Change
DAMA	Demand Assigned Multiple Access
DL-MAP	Downlink Map
DSA	Dynamic Service Addition
DSL	Digital Subscriber Line
FDD	Frequency Division Duplex
FTP	File Transfer Protocol
FFR	Fractional Frequency Reuse
HT	Header Type
HTTP	Hyper Text Transfer Protocol
IEEE	Institute of Electrical and Electronic Engineers
IFR	Integer Frequency Reuse
IP	Internet Protocol
LOS	Line of Sight
MAC	Medium Access Control
MAC CPS	MAC Common Part Convergence Sublayer

NLOS	Non line of Sight
nrtPS	Non Real-Time Polling Services
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
PDU	Protocol Data Unit
PHY	Physical layer
PHY SAP	PHY Service Access Point
PMP	Point to Multipoint
QoS	Quality of Service
rtPS	Real-Time Polling Services
SAP	Service Access Point
SC	Single Carrier
SFR	Soft Frequency Reuse
SS	Subscriber Station
TC	Transmission Convergence Sublayer
TCP/IP	Transmission Control Protocol/Internet Protocol
TDD	Time Division Duplex
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
VoIP	Voice over Internet Protocol
UGS	Unsolicited Grant Services
UL-MAP	Uplink Map
UMTS	Universal Mobile Technology System
VoIP	Voice over Internet Protocol
WiMax	Worldwide Interoperability of Microwave Access
WLL	Wireless Local Loop

Chapter 1 Introduction

1.1 Problem Definition

The IEEE 802.16 WiMax network has been a promising approach that can utilise wireless communication technologies and provide integrated broadband wireless services upto 50 miles at 150 Mbps. It has the potential to replace the "last mile" of an IP core and is expected to provide the end users with guaranteed QoS support and backhaul services to WiFi.

At the PHY Layer, one of the crucial problems in WiMax is the inter cell interference. Since WiMax technology is based on OFDMA, the total spectrum is divided into subcarriers which are further re-structured in subchannels based on their subcarrier permutation. This leads to a limited amount of spectrum availability. In order to overcome this drawback the subcarriers and subchannels have to be reused in different cells. The increase in spectrum results in Co-Channel Interference (CCI) at the cell edges.

Full Usage of Subcarriers (FUSC) and Partial Usage of Subcarriers (PUSC) technologies are introduced in WiMax to mitigate the inter cell interference problem. As mentioned in [1, 2], the PUSC mechanism offers a better trade-off between higher data rate and more accurate channel tracking than the FUSC scheme, therefore, we investigate PUSC in this thesis. However, the current PUSC defined in the WiMax standard suggests allocating the same frequency to all the neighboring cells, which leads to potential interferences and collisions at cell-edges.

To enable QoS, the IEEE 802.16 WiMax MAC layer specification suggests different types of bandwidth request methods e.g. random access, polling and piggyback bandwidth request mechanisms etc. Among them, the piggyback mechanism enables stations to carry bandwidth requests in normal data packet transmission, which offers potentially higher channel utilisation as compared to other bandwidth request mechanisms. To the best of our knowledge there is limited research work done for analysing and improving it further for WiMax system.

1.2 Aims and Objectives

1.2.1 Aims

WiMax is an emerging technology and has many issues that are yet to be addressed. This thesis aims at the simulation analysis and improvement of the resource allocation schemes for WiMax. This includes improvement at both the PHY and the MAC layer protocols. At the PHY layer we propose an improvement on the PUSC scheme in order to reduce the collisions. At the MAC layer we propose an improvement to the Piggyback bandwidth request mechanism to enhance the resource utilisation.

1.2.2 Objectives

The objectives of this thesis are:

- ✓ To investigate the interference and collision problems in both the uplink and downlink of current WiMax standardised PUSC scheme.

- ✓ To propose an improvement to the Uplink PUSC scheme by allocating different frequencies to the neighbouring cells in combination with Integer Frequency Reuse (IFR) and Fractional Frequency Reuse (FFR) to decrease the interferences and collisions.

- ✓ To propose a new offset scheme in the Downlink PUSC scheme with the aim of increasing the number of users.

- ✓ To investigate the performance of the piggyback bandwidth request defined in the standard.

✓ To propose an improvement to the standardised Piggyback bandwidth request mechanism.

1.3 Structure of Thesis

The thesis is composed of six Chapters. This chapter is the Introduction. The description of the remaining five chapters is as follows:

Chapter 2 describes the overview of the IEEE 802.16 WiMax Technology.

Chapter 3 presents the research work related to the resource allocation schemes for WiMax.

Chapter 4 proposes the improved PUSC for both uplink and downlink in WiMax OFDMA Physical Layer.

Chapter 5 talks about the proposed piggyback algorithm for bandwidth request in WiMax Mac Layer.

Chapter 6 culminates the thesis with conclusions and further recommendations for future research.

1.3 List of Publications

Following are the publications made by the author during the process of completion of this thesis.

1. Usman Ali, Qiang Ni. *Chapter in the Book: Emerging Wireless LANs, Wireless PANs, and Wireless MANs".* Edited by Y. Xiao and Y. Pan, John Wiley & Sons, Inc (2009).

2. Usman Ali, Qiang Ni. ''*A Comprehensive Bandwidth Requesting Method for IEEE 802.16 WiMax networks using Piggyback Requests*.'' Brunel University, RESCON Conference June 2009.

Chapter 2 IEEE 802.16 WiMax Networks

WiMax is designed to support frequency ranges from 2GHz to 11GHz and is an IEEE 802.16 Point-to-Multipoint Broadband wireless access standard. The main goal of WiMax is to provide mobile wireless broadband connectivity but currently WiMax provides portable and fixed nomadic access to broadband.

WiMax base stations have the capability to transmit and receive data up to 30 miles but now-a-days cell based topology is used which has a radius between 3 to 5 miles. For fixed and movable applications WiMax has the ability to transmit 75Mbps per channel.

Figure 1 explains the IEEE 802.16 WiMax standard. It is necessary to understand the reference model before analysing the Physical and MAC layer.

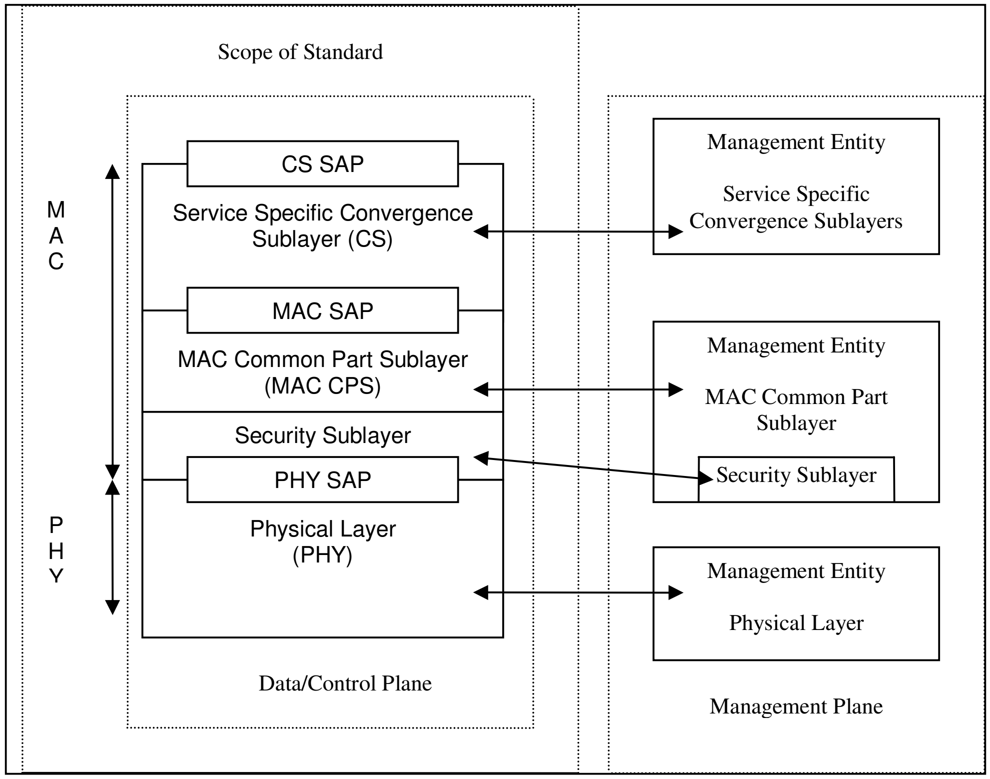

Figure 1: IEEE 802.16 protocol layering, showing SAPs [3]

2.1 Physical Layer

According to the WiMax specification, the function of PHY layer is to perform "*high degree of flexibility in order to allow service providers the ability to optimise system deployments with respect to cell planning, cost, radio capabilities, services and capacity.*" (From [3], Paragraph 8.1.1).

The physical layer of WiMax is based on OFDM technology. The mobile and fixed versions of WiMax have a number of dissimilarities in the implementation of OFDM. The *Fixed WiMax* is based on IEEE 802.16-2004 standard and uses a 256 FFT-based OFDM physical layer whereas *Mobile WiMax* is based on IEEE 802.16e-2005 standard and uses a *scalable OFDMA-based physical layer* [1].

2.1.1 ODFM and OFDMA

Orthogonal Frequency Division Multiplexing (OFDM) is a transmission technique used in wireless systems. In ODFM the total bandwidth is divided into multiple subchannels and is orthogonal to each other. This eliminates the interference between the channels. Each frequency channel can then be modulated with different modulations [4]. Therefore, MAC layer splits up very high data rate into multiple lower data rates matched onto multi parallel subchannels. The frequency bandwidth associated with each of these channels is much smaller as compared to the total bandwidth occupied by a single modulation. The main advantage of the OFDM subchannel is that ODFM has a longer symbol period than single carrier system. Consequently OFDM can deliver better performance in a NLOS metropolitan environment [5, 6].

The OFDM symbols require a cyclic prefix (CP), which must be added at the beginning of each OFDM symbol as shown in Figure 2 [5]. The CP occupies a duration called the guard time (GT denoted as T_G) is a redundancy that must be taken into account while computing data rate. By doing so the CP reduces the system throughput. CP allows the receiver to have much longer delay spread due to multipath and to maintain frequency orthogonality. The length of CP is carefully chosen by adding the CP to an OFDM symbol; the CP then shares the power of the OFDM symbol. If power is degraded too much, the receiver may not be able to receive the desired signal. The ratio of CP time to *"useful time"* T_b is the Guard Interval G i.e. $G=T_G/T_b$. The choice of *G* is made according to the radio channel conditions. A high value of *G* is needed for a bad radio channel and a relatively smaller value of *G* can be used for a good radio channel. This works as a trade off in conjunction with data rate. The WiMax standard indicates for both OFDM and OFDMA PHY layers, once a specific CP duration has been selected by the Base Station (BS) for operation, the value of CP cannot be changed. Any changes in the CP will force all the Mobile Stations (MS) to resynchronize to the BS [6, 1].

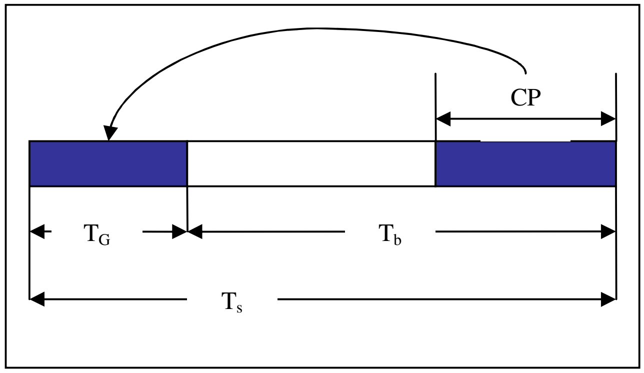

Figure 2: OFDM symbol [1]

The Orthogonal Frequency Division Multiple Access (OFDMA) is a derivative version of OFDM, which provide multiple users to transmit at the same time by using different subchannels. Hence, a user may be assigned more than one subchannels at same time. Also different users can share same subchannel by assigning different time slots. Figure 3 shows an example of subchannelisation of OFDM and OFDMA. The different colours represent different users. High Peak to Average Power Ratio (PAPR) is the main disadvantage of OFDMA. This procedure causes power amplifier to operate in the nonlinear region, which is undesirable.

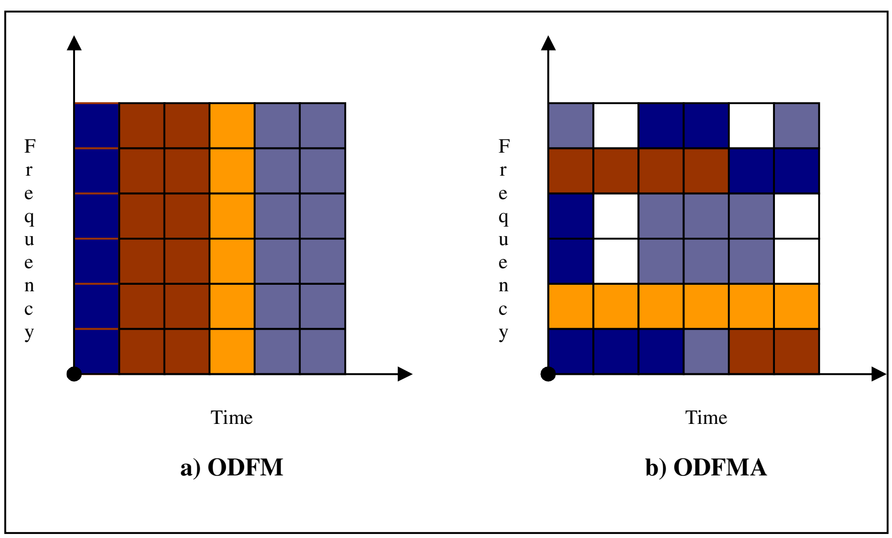

Figure 3: Subchannelisation of (a) OFDM, (b) OFDMA [4]

2.1.2 FUSC and PUSC Resource Allocation

In WiMAX IEEE 802.16e OFDMA systems, Subchannels may be constituted using either contiguous subcarriers or are subcarriers pseudo randomly distributed across the frequency spectrum. Subchannels formed using distributed subcarriers provide more frequency diversity and this method is particularly very useful for mobile applications. WiMAX defines several subchannelisation schemes based on distributed carriers for both the UL and the DL. Two basic modes of distributed subcarrier permutation defined in the standard are:

- ✓ *Full Usage of SubCarriers (FUSC)*
- ✓ *Partial Usage of SubCarriers (PUSC)*

2.1.2.1 Full Usage of SubCarriers (FUSC)

In FUSC, the numbers of pilot and data carriers to be distributed are different from PUSC. The number of guard subcarriers + the DC carrier (in the case of 1024 FFT) is equal to $87 + 86 + 1 = 174$. Therefore, the number of pilot and data carriers to be distributed is equal to $1024 - 174 = 850.$ There are two constant pilot sets and two variable pilot sets depending on the OFDMA symbol parity. Every segment employs both sets of variable or constant pilot sets.

We consider a 1024 - FFT OFDMA symbol for the FUSC mode. This symbol is then divided into 16 subchannels having 48 subcarriers each, thus using all of the $16 \times 48 = 768$ data subcarriers. These data subcarriers are then first divided into groups of contiguous subcarriers.

2.1.2.2 Partial Usage of SubCarriers (PUSC)

The PUSC modes allow the system designer a trade-off between higher data rate and more accurate channel tracking depending on the Doppler spread and coherence bandwidth of the channel. In PUSC, it is also possible to allocate all subsets or only one subset to a given transmitter. By allocating disjoint subsets to neighboring transmitters, it is then possible to separate their signals in the subcarrier space, thus enabling a tighter frequency reuse at the cost of data rate. Such a usage of subcarriers is defined as Segmentation. By using such a scheme, all the sectors in a BS can use the same RF channel, while maintaining their orthogonality amongst subcarriers [6]. Interference averaging is realised by the scheme of distributed subcarrier permutation. In UL process of subcarrier allocation the subcarriers are first assigned as Physical Tiles and then those physical tiles are selected pseudo randomly, according to a predefined permutation base (*UL_PermBase*), in order to constitute a logical subchannel. Thus, in each cell, the constituting subcarriers of each logical subchannel are spread though the whole frequency band [7].

2.1.2.3 Difference between PUSC and FUSC

Partial usage of subcarriers (PUSC) and full usage of subcarriers (FUSC) work very close to each other. The main difference between the two is that there is no cluster or tile partitioning of subcarriers prior to subchannel allocation. Every subchannel subcarrier can be found any where in the bandwidth. DL PUSC works on the same principle as FUSC apart from the fact that all the subcarriers are first divided into six groups. Permutation of subcarriers to generate subchannels is carried out independently inside each group, by breaking up each group from the others logically. There is only one set of common pilot subcarriers in FUSC. In PUSC downlink there is one set of common pilot subcarriers assigned to each group, but in case of PUSC uplink every channel contains its own set of pilot carriers. Therefore, we can conclude that difference between FUSC and PUSC is that FUSC contains only one set of common pilot carriers for each group while in case of PUSC every subchannel includes its own set of pilot carriers [8].

2.2 MAC Layer

The IEEE 802.16 is designed for the point-to-multipoint wireless access applications. It provides very high data rates for both uplink (towards Base Station) and downlink (towards Subscriber Station). Using different bandwidth allocation algorithms can accommodate hundreds of terminals per channel. The services required by SS are different and also include inherited Time division multiplex (TDM) data and voice; Packet sized Voice over IP (VoIP) and Internet Protocol (IP) connectivity. In order to support all these three services the 802.16

MAC must make use of both bursty and continuous traffic [9].

The MAC is a connection-oriented layer. This reduces the protocol complexity but introduces some overhead. . The MAC layer supports both TDD and FDD schemes present in the Physical layer. A MAC frame also permits SSs to allocate uplink and downlink burst profiles dynamically according the link conditions. This mechanism provides an exchange between robustness and capacity in real time systems, hence increasing the capacity two fold in contrast to non-adaptive systems. Figure 4 explains the reference model and the extent of this standard.

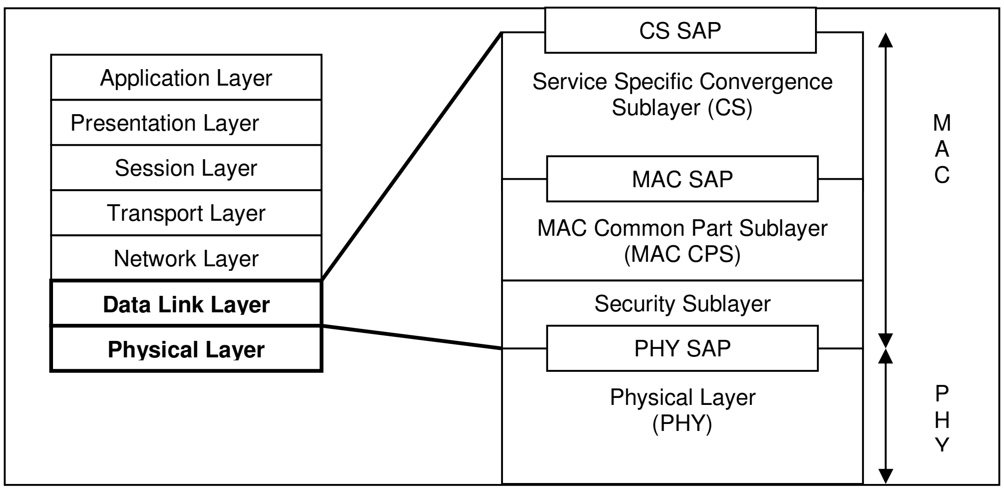

Figure 4: OSI 7 Layer Model and the scope of IEEE 802.16 standard [1]

2.2.1 Bandwidth Request and Grant Mechanism

The BS scheduler decides slot allocation for traffic going to various SSs. It also has to grant slots to various SSs to be able to send the traffic upward. For downlink, the BS has complete knowledge of the traffic such as queue length and packet size to help make the scheduling decision.

For uplink traffic, the SSs need to send the Bandwidth request packets (BWR) to the BS, which then decides how many slots are granted to each SS in subsequent uplink subframes. Although originally the standard allowed BS to allocate the bandwidth per connection - Grant per Connection (GPC) or per station - Grant Per Subscriber Station (GPSS); however, the latest version of the standard recommends only GPSS and leaves the allocation for each connection to the SS scheduler [3].

Basically, there are two types of BWR: Incremental or Aggregate BW Request. There are a number of ways to request bandwidth, such as Unsolicited bandwidth request, Poll-me bit request, Piggybacking BW request, Bandwidth stealing, Codeword over channel quality indicator channel (CQICH), CDMA code-based bandwidth request, Unicast polling, Multicast polling, Broadcast polling and Group polling. The optimal way to request the bandwidth for a given QoS requirement is still an open research topic.

Scheduling is the main component of the MAC layer. It helps assure QoS to various service classes. It works as a distributor to allocate the resources among SSs. The allocated resource can be defined as a number of slots and then these slots are mapped into a number of sub-channels (each sub-channel can be multiple physical sub-carriers), and a time duration (OFDM symbols). In OFDMA, the smallest logical unit for allocation is slot. The definition of slot depends upon the direction of traffic (downlink/uplink) and sub-channelization modes. For example, in partially used sub-channelization (PUSC) mode in downlink, one slot is equal to twenty-four sub-carriers (one sub-channel) for three OFDM symbols duration. In the same mode for uplink, one slot is fourteen sub-carriers (one uplink sub-channel) for two OFDM symbols duration [3].

The mapping process from logical sub-channel to multiple physical sub-carriers is called a permutation. The examples of permutation modes are fully used sub-channelization (FUSC) and adaptive modulation and coding (band-AMC). The term band-AMC distinguishes the permutation from AMC that refers to modulation or coding selection procedure. Basically there are two types of Permutations: distributed and adjacent Permutations. The distributed subcarrier Permutation is suitable for mobile users and adjacent permutation is appropriate for fixed (stationary) users. The scheduler upon logically assigning the resource in terms of number of slots may also consider the physical allocation, e.g., the subcarrier allocations like PUSC and AMC or any other user-defined techniques. In systems with single carrier PHY, the scheduler assigns the entire frequency channel to a SS. Therefore, the main task is to decide how to allocate the number of slots in a frame for each user. In systems with OFDM PHY, the scheduler considers the modulation schemes for various sub-carriers and decides the number of slots allocated. In systems with OFDMA PHY, the scheduler needs to take into consideration the fact that a subset of sub-carriers can be assigned to different users [3].

Consideration should be made for both logical and physical allocation of bandwidth in order to calculate the number of slots and time intervals suitable for each user. For logical allocation, the scheduler should calculate the number of slots based on QoS service classes. For physical allocation, the scheduler needs to select such subchannels and time intervals that are suitable for each user. The goal of logical allocation is to minimise power consumption, to minimise bit error rate, and to maximise the total throughput. There are three distinct scheduling processes: two of them works at BS - one for downlink and the other for uplink, and third one works at SS for uplink purposes. At the BS, packets from the upper layer are put into different queues. This queue is generally referred as per-CID queue and is used to prevent head of the line blocking (HOL). However, by applying an appropriate optimisation technique the number of required queues can be reduced. Then, based on the QoS parameters and some extra information such as the channel state condition, the DL-BS scheduler decides which queue to serve first and how many packets should be transmitted to the SSs. These packets are called Downlink service data units (SDUs).

Since BS controls the access to the medium, the UL-BS scheduler makes the allocation decision based on the bandwidth request from the SSs and the QoS parameters. The third scheduler works at the SS. Once the UL-BS grants the bandwidth for SS, the SS scheduler selects a queue and portion of allocation for use. As the requests are generated per connections, the grants are based on per subscriber and SS is free to choose the appropriate queue to service. The SS scheduler requests a mechanism to allocate the bandwidth in a resourceful way [3].

2.2.2 WiMax QoS Service Classes

IEEE 802.16 classifies five QoS service classes:

1) Unsolicited Grant Scheme (UGS)
2) Extended Real Time Polling Service (ertPS)
3) Real Time Polling Service (rtPS)
4) Non Real Time Polling Service (nrtPS)
5) Best Effort Service (BE).

Each of these has its own QoS parameters such as the way to request bandwidth, minimum throughput requirement, and delay/jitter constraints [1].

1) ***UGS:*** This service class offers a fixed periodic bandwidth allocation. Once the connection is setup, there is no need to send any other requests. This service is intended for constant bit rate (CBR) real-time traffic such as Voice over IP (VoIP). The main QoS parameters are maximum sustained rate (MST), maximum latency, and tolerated jitter (the maximum delay variation) [1].

2) ***ertPS:*** This service is designed to support VoIP with silence suppression. No traffic is sent during silent periods. ertPS service is similar to UGS in that the BS allocates the maximum sustained rate in active mode, but no bandwidth is allocated during the silent period. The BS polls the SS during the silent period to determine the end of silent period. The QoS parameters are the same as those in UGS.

3) ***rtPS:*** This service class is for variable bit rate (VBR) real-time traffic such as MPEG compressed video. Unlike UGS, rtPS bandwidth requirements vary and so the BS needs to regularly poll each SS to determine what allocations need to be made. The QoS parameters are similar to the UGS but minimum reserved traffic rate and maximum sustained traffic rate need to be specified separately. For UGS and ertPS services, these two parameters are the same, if present.

4) ***nrtPS:*** This service class is for non-real-time VBR traffic with no delay guarantee. Only minimum rate is guaranteed. File Transfer Protocol (FTP) traffic is an example of this service class [1].

5) ***BE:*** Most of data traffic falls into this category. This service class guarantees neither delay nor throughput. The bandwidth will be granted to the SS if and only if there is leftover bandwidth from other classes. In practice most implementations allow specifying minimum reserved traffic rate and maximum sustained traffic rate even for this class.

2.2.3 Piggyback Bandwidth Request

Piggyback request is a 16-bit entity, which corresponds to the number of uplink bytes of bandwidth requested for the connection. If the packet interarrival time is shorter than the frame size, all bandwidth requests can be piggybacked on previous packets. In the uplink, SS requests resources by either utilising a stand-alone bandwidth request MAC PDU or by piggybacking the Bandwidth Requests on the standard MAC PDU. In either case the SS employs a grant management subheader. Bandwidth requests in the uplink can either be Incremental requests or Aggregate Requests. When BS receives an incremental bandwidth Request for a SS, it accumulates the amount of bandwidth requested to its current acuity of the bandwidth required. Bandwidth demanded by means of piggybacking mechanism on a MAC PDU will only be an incremental bandwidth [1].

2.3 Summary

This chapter talks about the evolution of IEEE 802.16 WiMax Technology along with the commentary on Physical Layer and MAC layer. The concept of ODFM and OFMDA and two modes of subcarrier allocation namely, Full usage of subcarriers (FUSC) and Partial usage of subcarriers (PUSC) are defined in PHY Layer. The WiMax MAC layers talks about the bandwidth request and grants mechanism and discusses five QoS Service Classes and Piggyback Request. The next chapter remarks on the research work done in WiMax PHY and MAC Layer.

Chapter 3 Literature Review

3.1 Design Factors

To decide which queue to service and how much data to transmit, one can use a very simple scheduling technique such as First in first out (FIFO). This technique is very simple but unfair. A little more complicated scheduling technique is Round robin (RR). This technique provides the fairness among the users but it may not meet the QoS requirements. Also, the definition of fairness becomes questionable if the packet size is variable.

3.1.1 QoS Parameters

The critical factor for the scheduler design is the assurance of QoS requirements for various service classes. The main parameters are the minimum reserved traffic, the maximum allowable delay, and the tolerated jitters. For example, the scheduler may need to reschedule or interleave packets in order to meet the delay and throughput requirements. Earliest deadline first (EDF) is an example of technique used to guarantee the delay requirement. Similarly, Largest weighted delay first (LWDF) has been used to guarantee the minimum throughput.

3.1.2 Throughput Optimisation

In view of the fact that the resources available in wireless networks are restricted, another vital consideration is how to maximise the Total system throughput. The metrics defined here can be the maximum number of supported SSs or whether the link is completely used [3]. One of the best ways to represent a throughput value is by using the Goodput. Goodput is defined as the actual transmitted data and it does not include the overheads and lost packets. The overheads consist of MAC overhead, fragmentation, packing overheads, and burst overhead. Here the question arises how we can optimise the number of bursts per frame and how we can fragment or put a packing on the SDUs into MPDUs.

The bandwidth request is indicated in number of bytes. This does not translate straightforwardly to number of slots since one slot can contain different number of bytes depending upon the modulation technique used. For example, with Quadrature Phase-Shift Keying 1/2 (QPSK1/2), the number of bits per symbol becomes 1. Together with PUSC at 10 MHz system bandwidth and 1024 Fast Fourier transform (FFT) that leads to 6 bytes per slot. If the SS asks only for 7 bytes at a given time, then the BS needs to give 2 slots, which represent 12 bytes. Moreover, the percentage of packet lost is also important. The scheduler needs to use the channel state condition information and the resulting bit error rate in making the resource allocation [15].

3.1.3 Fairness

Aside from assuring the QoS requirements, the leftover resource allocation decision should be made fairly. Since the fairness can be defined as short term or long term (the short-term fairness implies long term fairness but not vice versa), the convergence time to fairness is important.

3.1.4 Energy Consumption and Power Control

The scheduler needs to consider the maximum allowable power. Given the Bit error rate (BER) and Signal to noise ratio (SNR) that the BS can accept for transmitted data; the scheduler can calculate the suitable power to use for each SS depending upon their location. For mobile users, the power is very limited. Therefore, SS scheduler also needs to optimise the transmission power [15].

3.1.5 Implementation Complexity

Since the BS has to handle many simultaneous connections and decisions have to be made within 5 ms WiMax frame duration, the scheduling algorithms have to be simple, fast, and use minimum resources such as memory. The same applies to the scheduler at the SS.

3.1.6 Scalability

The algorithm should efficiently operate as the number of connections increase.

3.2 Scheduling Algorithms

3.2.1 DL-BS Scheduler

The queue length and packet size information are easily available for this scheduler. To guarantee the QoS for SS at UL-BS scheduler, the polling mechanism will be involved. Once the QoS has been assured, the mechanism of how to split the allocated bandwidth among the connections depends on the SS scheduler.

WiMax standard defined three main scheduling techniques Channel-unaware schedulers, Channel-aware schedulers, and Cross-layer schedulers. Basically, the channel-unaware schedulers do not use channel state condition in making the scheduling decision.

Channel-unaware schedulers generally assume error-free channel since it makes it easier to prove assurance of QoS. However, in wireless environment where there is a high variability of radio link such as signal attenuation, fading, interference and noise, the channel-awareness is important. The Cross-layer schedulers use higher-level information in making the scheduling decisions. Ideally, scheduler designers should take into account the channel condition as well as the information passed from the higher level in order to optimally and efficiently make the allocation decision.

3.2.2 Channel-Unaware Schedulers

This type of scheduler makes no use of channel state condition such as the power level and channel error and loss (error-free channel model). These basically assure the QoS requirements among five classes - mainly the delay and throughput constraints. Although, jitter is also one of the QoS parameters, so far none of the published algorithms can guarantee jitter.

3.2.3 Round Robin (RR) Algorithm

Apart from FIFO, round-robin allocation algorithm can be considered the very first simple scheduling algorithm. RR fairly assigns the allocation one by one to all connections. The fairness considerations need to include whether allocation is for a given number of packets or a given number of bytes. With packet-based allocation, stations with larger packets have an unfair advantage [15].

Moreover, RR may be non-work conserving in the sense that the allocation is still made for connections that may have nothing to transmit. Therefore, some modifications need to be made to skip the idle connections and allocate only to active connections. However, now the issues become how to calculate average data rate or minimum reserved traffic at a given time, and how to allow for the possibility that the idle connection later has more traffic than average? Another issue is the duration of fairness? For example, to achieve the same average data rate, the scheduler can allocate 100 bytes every frame for 10 frames or 1000 bytes every 10th frame. Since *RR* cannot assure QoS for different service classes, *RR* with weight, weighted round robin (WRR), has been applied for WiMax scheduling. The weight can be used to adjust for the throughput and delay requirements and can also used for inter-class priority. Basically the weights are defined in terms of queue length and packet delay or the number of slots. The weight is dynamically changed over time. In order to avoid the issue of missed opportunities, variants of RR such as deficit round robin (DRR) or deficit weighted wound robin (DWRR) can also be used for the variable size packets. The main advantage of these variations of RR is their simplicity. The complexity is $O(1)$ compared to $O(log(N))$ and $O(N)$ for other fair queuing algorithms. Here, N is the number of queues.

3.2.4 Priority-Based Algorithm (PR)

In order to guarantee the QoS to different classes of service, the priority-based scheme can be used in WiMax scheduler. For example, the priority order can be: UGS, ErtPS, rtPS, nrtPS, and BE respectively. Or packets with the largest delay can be considered at the highest priority. Queue length can be also used to set priority level, e.g., more bandwidth is allocated to connections with longer queues.

The disadvantage of this scheme is that it may starve some connections of lower priority service class. The throughput can be lower due to increased number of missed deadlines for the lower service classes' traffic. To mitigate this problem, Deficit fair priority queuing (DFPQ) with a counter was introduced to maintain the maximum allowable bandwidth for each service class. The counter decreases according to the size of the packets. The scheduler moves to another class once the counter falls to zero. DFPQ has also been used for inter-class scheduling [3].

3.2.5 Weighted Fair Queuing Algorithm (WFQ)

WFQ is an approximation of General processor sharing (GPS). WFQ does not make the assumption of infinitesimal packet size. Basically, each connection has its own FIFO queue and the weight can be dynamically assigned for each queue. The resources are shared in proportion of the weight. For data packets in wired networks with leaky bucket, an end-to-end delay bound can be provably guaranteed. With the dynamic change of weight, WFQ can be also used to control the guarantee of data rate. The main disadvantage of WFQ is the complexity, which could be $O(N)$.

To keep the delay bound and to achieve worst-case fairness property, a slight modification of the WFQ, Worst-case fair Weighted Fair Queuing *(WF2Q)* was introduced. Similar to *WFQ*, WF^2Q uses a virtual time concept. The virtual finish time is the time GPS would have finished sending the packet. WF^2Q looks for the packet with the smallest virtual finishing time and whose virtual start time has already occurred instead of searching for the smallest virtual finishing time of all packets in the queue. The virtual start time is the time GPS starts to send the packet, which is similar to WRR, in achieving the QoS assurance (throughput, delay, and jitter requirements), procedure to calculate the weight plays the important role. The weight can be based on several parameters. Aside from queue length and packet delay mentioned above, the size of bandwidth request can be used to determine the weight of queue (the larger the size, the more the bandwidth). The ratio of a connection's average data rate to the total average data rate can be used to determine the weight of the connection. The minimum reserved rate can be used as the weight. The pricing can be also used as a weight. Here, the goal is to maximize service provider revenue.

3.2.6 Delay-Based Algorithm

This set of schemes is specifically designed for real-time traffic such as UGS, ertPS and rtPS service classes, for which the delay bound is the primary QoS parameter, and basically the packets with unacceptable delay are discarded. Earliest deadline first (EDF) is the basic algorithm for scheduler to serve the connection based on the deadline. Largest weighted delay first (LWDF) chooses the packet with the largest delay to avoid the missing the deadline.

Delay threshold priority queuing (DTPQ) was proposed for use when both real-time and non real-time traffic are present. A simple solution would be to assign higher priority to real-time traffic but that could harm the non real-time traffic. Therefore, urgency of the real-time traffic is taken into account only when the head-of-line (HOL) packet delay exceeds a given delay threshold. This scheme is based on the trade-off of the packet loss rate performance of rtPS with average data throughput of nrtPS with a fixed data rate. Rather than fixing the delay, the author also introduced an adaptive delay threshold-based priority queuing scheme, which takes both the urgency and channel state condition for real-time users adaptively into consideration.

3.3 Advanced Frequency Reuse

Inter cell interference is one of main issues in WiMax Networks. Advanced frequency reuse is one of the proposed solutions to improve the interference in a multicell WiMax System. The overall aim of reuse partitioning techniques is to have an SINR distribution in the cell that results in a higher spectral efficiency and system capacity. The cell coverage area is separated into zones based on interference conditions. Resources can then be allocated in different ways to the zones in order to improve system capacity. For example, users close to the transmitter are allocated lower power levels than users at the edge that have poor SINR.

In traditional TDMA/FDMA networks, the average reuse factor would generally be around 7. This implies that only a seventh of the available spectrum can be use by each cell. The ideal situation would be to have a reuse factor of 1 where each cell uses the entire spectrum. In OFDMA networks, a reuse factor of one can be used due to the orthogonality of carriers. However, this results in high levels of Co-channel interference (CCI) for users in the edge of the cell. Reuse partitioning can be used to minimise the effects of CCI on edge users.

There are different methods of implementing the reuse partitioning concept such as, Integer Frequency Reuse (IFR), Fractional Frequency Reuse (FFR) and Soft Frequency Reuse (SFR). These methods aim to increase the overall system capacity as well as the signal quality and data throughput for cell edge users.

3.3.1 Integer Frequency Reuse

In integer frequency reuse, all the subcarriers are allocated to a particular cell can also be reused anywhere within a cell and the location of MS is not required at all. However, in the case of reutilisation of those subcarriers within the network the value of reuse factor greater than or equal to one. The Integer frequency reuse is shown in Figure 5(a).

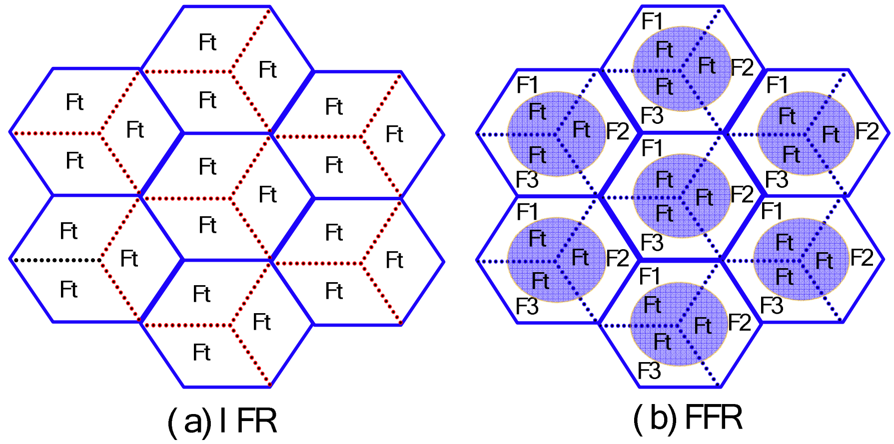

Figure 5: IFR and FFR Cell Configurations [37]

3.3.2 Fractional Frequency Reuse

As shown in Figure 5(b), Fractional frequency reuse is a method that reduces the effects of CCI in cellular networks without using resource allocation coordination between cells. This is achieved by implementing a reuse factor of one in the centre of the cell and a higher reuse factor for the cell edge. FFR was initially proposed in [65] for application to GSM networks. It has since been the focus of attention in research [66, 67] for the standardisation of the 3GPP Long Term Evolution (LTE) Evolved-UTRA air interface. The mitigation of CCI in OFDMA based cellular networks can be achieved using flexible resource reuse schemes based on the FFR concept. The WiMAX Forum suggests the use of FFR in Mobile WiMAX to tackle the cell edge interference problem. The basic principle of FFR is to partition the users in the cell into Cell-centre users (CCU) and Cell-edge users (CEU). The CCU has a reuse factor of 1 while the CEU have a reuse factor of 3. The available spectrum resource is split into subbands (consisting of subchannels), part of which are available for CEU while the other part is only available to CCU. The CCU can still use the subband reserved for the CEU, however, the CEU have priority access to the subband. This implementation results in a reduction of the CCI levels for the CEU.

A key issue in FFR is how to make the decision whether a user is a CEU or a CCU. The decision can be made based on distance or on SINR levels at the user. The SINR method requires measurements by the user equipment to be fed back to the base station. In WiMAX, this information is transmitted on the CQICH feedback channel and is used for purposes such as burst profile scheduling. The WiMAX forum also clarifies that the reuse schemes can be applied dynamically on a frame-by frame basis depending on interference and load.

3.3.3 Soft Frequency Reuse

Soft Frequency Reuse is similar to FFR. The SFR separates the users into cell edge user and cell centre users. The main difference between SFR and FFR is that in SFR the cell/sector has all the available subchannels, which are differentiated for CCU and CEU by different transmit power levels. The division of subchannels is such that CEU have priority to a reserved band, which can still be occupied by CCU if unused. The CCU use a lower transmit power while the edge band uses an amplified transmit power. Such a scheme is shown to reduce the CCI levels as well as improve the cell edge throughput [68]. An adjustable power ratio is used between CEU and CCU users. In high traffic situations on the cell edge, the transmit power can be reduced on the cell centre to improve the CCI at the edge. The ratio of subchannels allocated to the CEU is usually one third of the total subchannels and results in a reuse of 3 for CEU. The subband allocated to the CEU can be alternated in each cell/sector to increase spatial separation of co channel cells. The SFR scheme improves the SINR of a CEU, which results in a higher throughput. Simulation results in [69] show that average cell-edge throughput for an individual can increase by up to 50% when using the SFR method with a non static frequency reuse factor for cell edge users. This increase is at the expense of a slight drop in total cell throughput.

3.4 Modelling Analysis of Bandwidth Request in WiMax

This section is composed of two subsections. The first subsection explains the modelling analysis of bandwidth request without piggyback request and its related work [9, 13, 18]. The second subsection describes the modelling analysis of bandwidth request using piggyback requests [30].

3.4.1 Modelling Analysis of Bandwidth Request without Piggyback

A bandwidth request (BW-REQ) can either be issued as a standalone request or in the form of uplink data packet, which is known as a piggyback request. Two key techniques are suggested by the standard with the aim of determining which SS is allowed to transmit its BW-REQ from multiple candidates. The first method is contention-based random access and the second method is based on contention-free polling. In both of these methods, no explicit acknowledgment (ACK) frame is sent back to specify whether a BW-REQ message is effectively transmitted or distorted.

In [9] the authors have studied and have drawn a comparison based on their performances of random access and polling. They have completed a through investigation on random access and polling mechanisms for both error-free and error-prone channels, and have chosen random packet arrival rates in their system. For this purpose a Bernoulli request arrival process has been given for finite numbers of users. This method does not include the transmission rate of data packets. For modelling purposes polling and random access mechanism round-robin scheduling algorithm has been used. Their study proves that random access method produces better result than polling scheme when the bandwidth request rate is very low. On the other hand the performance level of random access is worse than polling scheme when the channel load is very high.

The performance of random access is studied in [18]. They have calculated the delay in the system by neglecting fixed number of stations and have assumed ideal channel conditions. Markov chain and Binomial distribution has been used for analytical modelling of random access. A solution has been proposed which states that a SS will uniformly choose on of the frame to transmit and one of the slots will uniformly be chosen from the given frame. This scheme has given very accurate mean delay for requested transmissions.

An efficient and comprehensive Bandwidth Request Method for WiMax has been proposed in [13]. This paper is based on Bernoulli request arrival process and ideal channel conditions. The authors have calculated the delay for a requested transmission for constantly varying number of transmissions and for different arrival rates. The Random access system given in this paper shows that all the active stations at the start of each frame use a stochastic process. This process has been modelled with the help of a discrete-time Markov chain. The standard explains that all the SS should be grouped together and random access technique should be used within groups. In the publication they have analysed this situation by increasing the number of groups. They have managed to increase the mean packet arrival rate but since more groups have been introduced the delay has increased.

3.4.2 Modelling Analysis of Piggyback Bandwidth Request

The authors in [30] have assumed in the model that stand-alone bandwidth request message (SREQ) will be transmitted from a tagged SS inside a frame which is totally sovereign of the outcomes generated by the earlier SREQ from that particular SS and from all the other SSs which are in a steady state. As a result, the probability of a SREQ from the tagged SS Colliding with other SSs SREQ will be totally independent from the outcomes of the SS's earlier SREQ transmissions. They have implemented a precise analytical model for the Random Channel Access technique as explained in the IEEE 802.16 WiMax standard. The effects of bandwidth configuration, channel access constraint and piggyback policy on the network performances were investigated. The impact of physical burst profile and non-saturated traffic has also been taken into consideration. The Study showed that the random channel access mechanism is very robust and strong in regards to the number of contending stations.

3.5 Summary

This chapter explains the research work done by different authors in both PHY and MAC layers. Design Issues related to MAC layer like QoS parameters, throughput optimisation, energy consumption and power control mechanisms were discussed in detail. Also a description of different scheduling algorithms like DL-BS scheduler, channel-unaware scheduler and round robin algorithm etc. was provided. A discussion on the most important issue of Interference in PHY Layer was presented by explaining the concept of advance frequency reuse and discussing the three different mechanisms namely: Integer frequency reuse (IFR), Fractional frequency reuse (FFR) and Soft frequency reuse (SFR). Also a modelling analysis was performed on different bandwidth requesting techniques such as random access, polling and piggyback bandwidth request. The next chapter describes the improvements made in uplink and downlink PUSC subcarrier allocation scheme during the course of this research.

Chapter 4 Analysis and Improvement for PUSC Subcarrier Allocation Scheme

4.1 Uplink and Downlink PUSC

4.1.1 Uplink PUSC

Uplink makes use of the Tile structure as the fundamental ingredient to create subchannels/slots. Subchannel is defined as the minimum size of the transmission channel that can be allocated to one user. All the users inside a cell will use the same permutation formula and apply the same *UL_PermBase* in order to construct a logical subchannel and data subchannels. The logical subchannel is used for user allocation and the data subchannel is used to allocate data coming from the MAC layer. The UL-PUSC separates the available subcarriers into tiles as shown in Figure 6. This tile is created over *three* OFDM symbols having *four* subcarriers each. The tile is made up of *four* pilot subcarriers and *eight* data subcarriers. The tiles are then regrouped by means of a pseudo-random scheme and then divided into *six* groups. A sub-channel is then created from these *six* tiles belonging to the same group. There is another form of UL-PUSC, which is known as Optional ULPUSC. This scheme can be used with less number of pilot subcarriers. This procedure increases the number of subcarriers available for data subcarriers and hence resulting in a very high data rate at the expense of channel estimation capabilities. Furthermore, segmentation can also be used in the UL-PUSC scheme to offer a tighter frequency reuse.

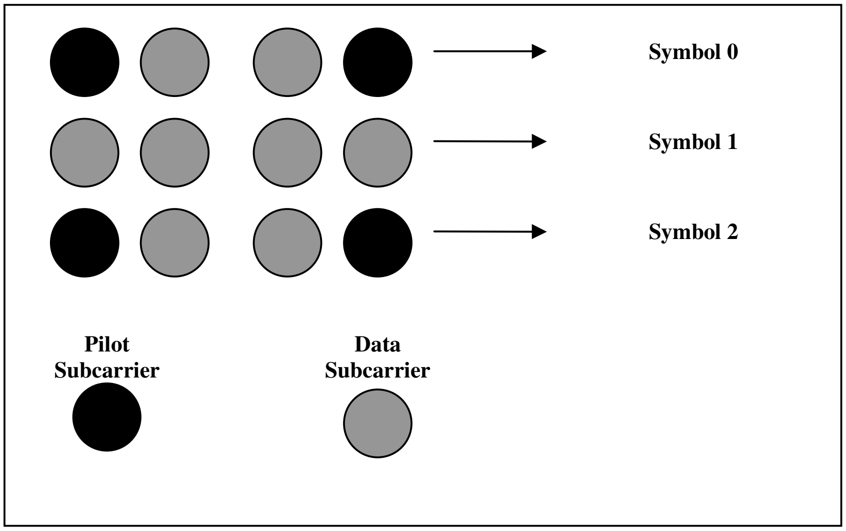

Figure 6: UL-PUSC Tile Structure

4.1.2 Downlink PUSC

The Partial usage of subcarriers (PUSC) scheme is deployed to distribute the frequency band throughout the subcarriers, which are part of the subchannel. This distribution is pseudo random in nature [1, 70]. A randomising equation maps the logical subcarrier numbers to the physical subcarrier numbers using the PUSC scheme.

For downlink PUSC scheme, all the subcarriers except the null subcarriers are first divided into physical clusters. Null subcarriers consist of dc and guard subcarriers. Each of these clusters consists of *fourteen* adjacent subcarriers spread over *two* OFDMA symbols. These physical clusters are then renumbered into logical clusters. The logical clusters are then divided into *six* groups. A permutation formula is applied again to each group that randomises the subcarrier positions and groups are then allocated to subchannels. In PUSC, all or only one subset of *six* groups can be allocated to a given transmitter. By allocating different subsets of the *six* available groups to the neighbouring cells the signals can be separated in the subcarrier space. This enables tighter frequency reuse but at the cost of data rate. This technique is called *segmentation*. E.g. In a cell split into 3 sectors, the BS can use segmentation to allocate two distinct groups out of six to each sector and thus utilizing the same RF frequency in all of them [70]. According to IEEE WiMax standard [1], group 0 is allocated to sector 0, group 2 is allocated to sector 1, and group 4 to is allocated sector 2.

The segmentation scheme permits the BS to use the same RF channel at the same time because it tries to ensure orthogonality amongst subcarriers. Even though segmentation can be used with PUSC but this subcarrier allocation scheme does not require segmentation [70]. The pilot and data subcarrier allocation in each cluster is shown in Figure 7.

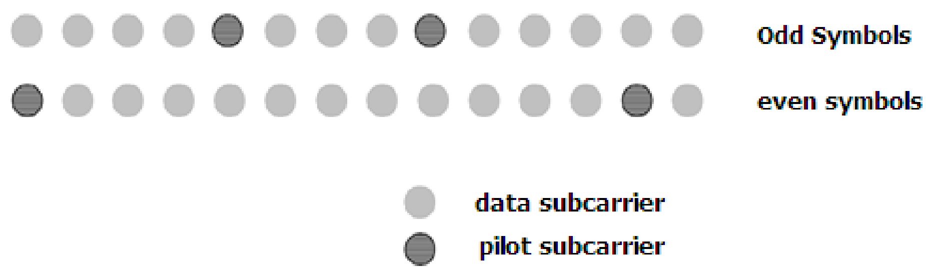

Figure 7: DL-PUSC Cluster Structure [1]

4.1.3 Probability of Collision and Load Factor

Users present within a cell are allocated slots based on their bandwidth requirement. Slots are allocated to every user that joins the cell. The allocations made within a cell are done in a centralised way. Slot allocation ensures that two users would not use the same subcarrier. Therefore, no collision will take place within a cell. However collisions are possible if nearby cells use the same frequency band [1]. The collision count for every user when added to each cell is calculated using MATLAB.

The frame used in Cell 0 is compared with all the other neighbouring cells (Cells 1-6). ***Collision occurs*** if the physical subcarrier-time position under consideration is allocated in any of the cases.. Thus collision count will be incremented by 1. Figure 7 depicts an example of collisions at Cell 0 by neighbouring cells (Cells 1-6).

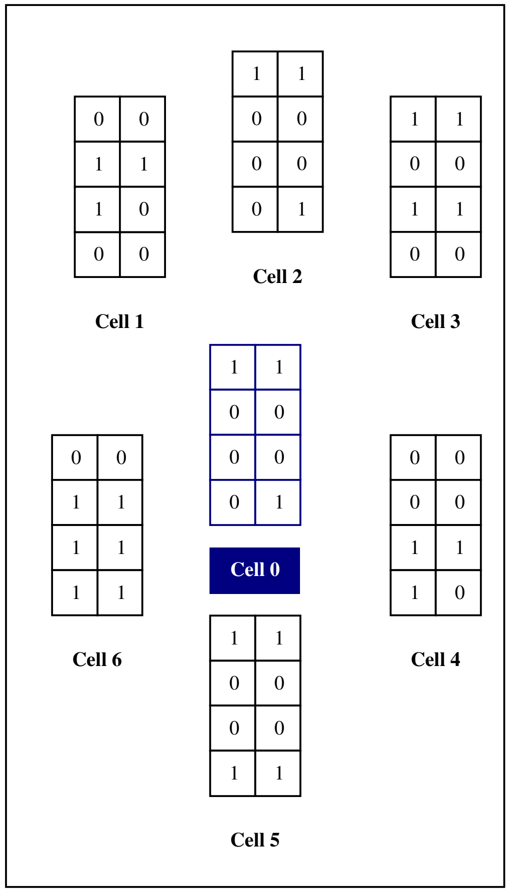

Figure 8: Example for collisions at Cell 0 by neighbouring cells (Cells 1-6)

In Figure 8 we consider collisions for centre cell *0* only. As the users are allocated slots, the initial value of *0* becomes *1* indicating the time/frequency resource position is then allocated. When the cell is completely loaded all the elements in the *840x32* matrix would be *1*. The value *'1'* indicates collisions while *'0'* indicates no collision. Collision count in the above case at cell 0 is 3. **Collision count** is the number of subcarriers within the frame that collides with each other. Using this value we can calculate '**Probability of collision**' as:

$$P_{collisions} = \frac{N_{collided\_subcarriers}}{T_{utilised\_subcarriers}}$$

Equation 1: Probability of Collision

where, $P_{collisions}$ = probability of collision (values between *0* and *1*), $N_{collided\_subcarriers}$ = number of subcarriers that collide, and $T_{utilised\_subcarriers}$ = total subcarriers utilised. E.g. after one user is added to each cell in the 2-tier network for ***N_slots*** =1.

$$P_{collisions} = \frac{10}{1680} = 0.00595$$

Equation 2: Probability of Collision

$N_{collided\_subcarriers}$ is evaluated after conducting the MATLAB simulation. $T_{utilised\_subcarriers}$ has the value of *1680* when the first 2 symbols are used for allocation. Once the slot allocation approaches 3rd and 4th symbols, the value of $T_{utilised\_subcarriers}$ becomes *1680 x 2 = 3360*. For downlink as we consider 32 symbols the maximum value for $T_{utilised\_subcarriers}$ then become *26880*. The number of available subcarriers in a frame is *840* but as we consider more time symbols, $T_{utilised\_subcarriers}$ would be multiple of *840*. For downlink PUSC, $T_{utilised\_subcarriers}$ will be ***multiple of 1680***. '**Load Factor**' can be evaluated as:

$$L_f = \frac{N_{used\_slots}}{T_{slots}}$$

Equation 3: Load Factor

where, L_f = load factor (increases from 0 to 1), N_{used_slots} = number of used slots, and T_{slots} = total number of available slots in the TDD frame. E.g. For Streaming Video, when ***N_slots***=12 and $\boldsymbol{N_{users}}$=11,

N_{used_slots} = 12 x 11 = 132 slots,

$$L_f = \frac{132}{480} = 0.275$$

Equation 4: Load Factor

4.2 Improved Uplink PUSC

The interference problem can be improved by using beam forming antennas and coordinating the transmissions among base stations. In current WiMax systems interference management is usually done by random subcarrier permutation. Therefore, interference may still occur. To avoid interference we propose to allocate different frequencies to the neighbouring cells and assigning different sections within a cell. In section 4.2.1 we analyse the existing uplink PUSC scheme and propose improvements in IFR and FFR.

4.2.1 Analysis of Uplink PUSC

This section explains the Matlab simulation results of the collisions for current PUSC with IFR and FFR with one cell and *seven* cell cellular systems with the assumption that all the subchannels and symbols are fully used in each simulation. The simulations are based on *one slot per-user*, *and two slots* per-user separately. The power control mechanism is not implemented in any simulation. The results show a linearity relation between collisions and the total number of users.

4.2.1.1 One Cell IFR

Under the IFR frequency reuse pattern, the interfering sector to the other sector is distributed throughout the whole cell. If same *UL_PermBase* PUSC permutation is utilised in a cell, the constituting subcarriers of each logical subchannel in every sector remains the same.

a) One Slot per User

The same frequency value is reused *three* times in each cell. The collision happens when more than one user is allocated with the same subcarriers at the same subchannel within a cell. To detect the collisions, compare the three sections' subchannel to each other. The actual comparison was done to evaluate the subcarriers. This scenario is explained in the following Matlab code:

```
collided=0;
for j=1:560;
  for k=1:18;
  % compares section 1 with section 2
cell_collision1(j,:)=ismember(allocated_user1{j}{k},allocated_user2{j}{k});
  % compare section 1 with section 2
cell_collision2(j,:)=ismember(allocated_user1{j}{k},allocated_user3{j}{k});
```

```
  % compares section 2 with section 3
cell_collision3(j,:)=ismember(allocated_user2{j}{k},allocated_user3{j}{k});
  end
 if any(cell_collision1)==1; % counter the collided carriers
   collided1=collided+1;
 end
 if any(cell_collision2)==1;
   collided2=collided1+1;
 end
 if any(cell_collision3)==1;
   collided=collided2+1;
 end
end
```

The above code shows the comparison between three different sections. First we compared *section 1* with *section 2*, then *section 1* with *section 3*, and finally *section 2* with *section 3*. If one collision is detected, the *collided* will increase by *1*. The total collisions are plotted in the figure 9. In this simulation, all sections within a cell are using the same *UL_PermBase*, and each user is consuming one slot only. In order to calculate the collision rate, the total number of available subchannel/slot for IFR is calculated by using equation the following equation:

$$Total\,Number of\ Slots = \frac{Number of\ \text{section}\ per\, cell\ x\ Number of\ subchannel per\ frame x\ Symbol per\ frame}{Symbol per\, subchannel}$$

Equation 5: Total Number of Slots

where, number of sections per cell is *3*, number of subchannel per frame is *35*, Symbol per frame is *48*, and symbols per subchannel is *3*. So the total number of slot is 3 ** 35 * (48/3) = 1680*. The maximum number of user allowed for IFR is *3*(560/1) = 1680*. The computed total number of collided subchannels by the Matlab is *1680*. The collision rate and load factor for one cell IFR can be calculated using the Equation 6 and 7 respectively.

$$Collision\ Rate = \frac{Number\ of\ Collided}{Total\ Number\ of\ slots} = \frac{1680}{1680} = 1$$

Equation 6: Collision rate for one cell

$$Load\ \ factor = \frac{Total\ number\ of\ used\ slots}{Total\ Number\ of\ slots} = \frac{1680}{1680} = 1$$

Equation 7: Load Factor

In the figure 9, the *"*"* represents the number of collided, and the *"o"* represent number of number of allocated user. The graph shows that the collision increase linearly with respect to the number of user allocated. The collision rate = *1*, and the load factor also *1* in this case. The zoom out plot clearly illustrates the collided and allocated number of user from *835* to *845*.

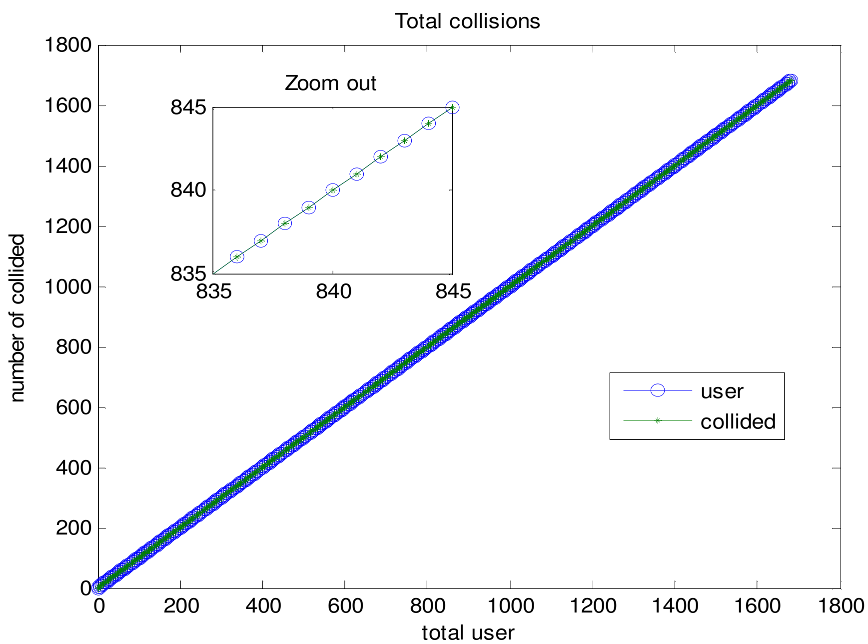

Figure 9: One Cell IFR collision having one slot per user

b) Two Slots per User

Figure 10 shows the simulation results of two slots per user. It is clear from the diagram that the number of user dropped about half of the total number of available slots *(o),* but the number of collided *(*)* remains the same as one slot per user shown in the Figure 9. This is due to the fact that the algorithm counters the collided subchannels, and it does not takes into account how many users are allocated or how many slots per user are required. The zoom out plot demonstrates the collided and allocated number of user from *835* to *845*. Also in this diagram we can see that there is no user found after *840*. The total number of available subchannel is *1680*, and the total number of user has reduced to *3*(560/2) = 840*. The collision rate and the load factor still remains the same at *1*.

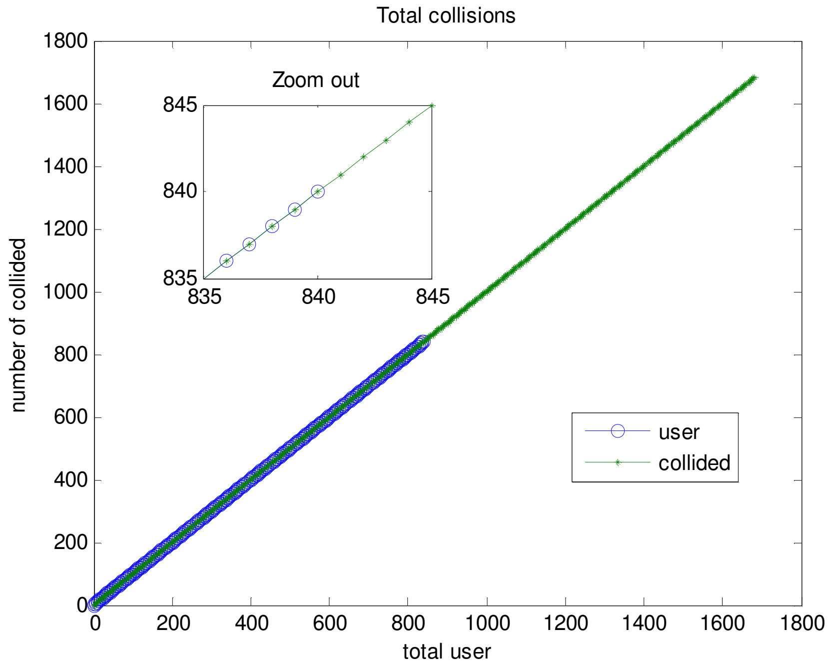

Figure 10: One Cell IFR collision having two slots per user

4.2.1.2 Seven Cells IFR

The collisions with *seven* cells are based on one cell configuration (*7* times of *one* cell). Since we have not introduced any power control in our research, there are no collisions occurring at the cell edges or at the sections boundary present within each cell.

a) One Slot per User

Figure 11 depicts *one* slot per user for *seven* cells IFR. The total number of slots and the number of collided has increased *7 times* and is computed as *11760*. The number of users is *7* 3*(560/1) = 11760.* The ratio of collision rate and load factors is 11760/11760 = 1.

b) Two Slots per User

Figure 12 shows the two slots per user scenario. Total number of user are *7* 3*(560/2) = 5880* and the ratio of collision rate and load factors is calculated as 11760/11760 = 1.

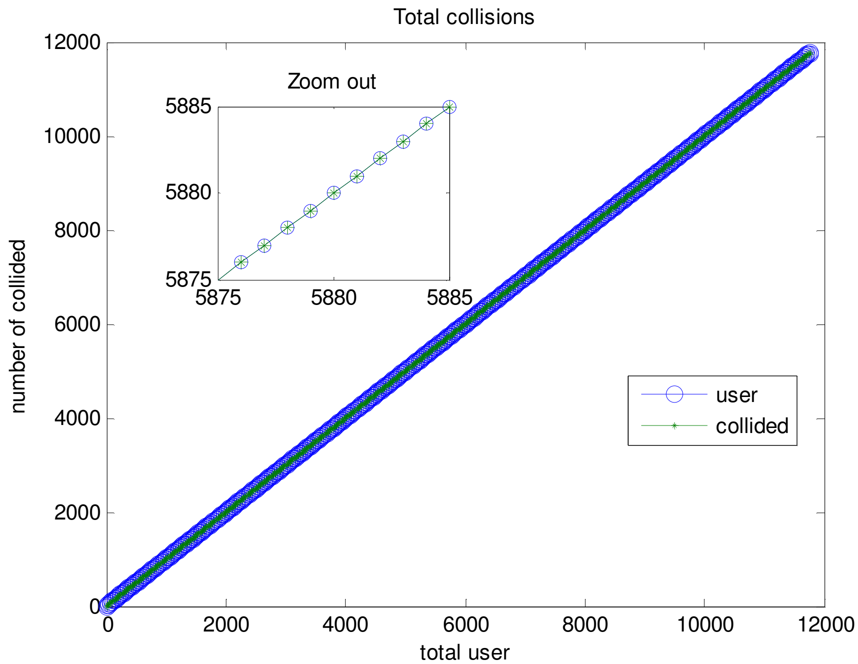

Figure 11: Seven cells IFR collision having one slot per user

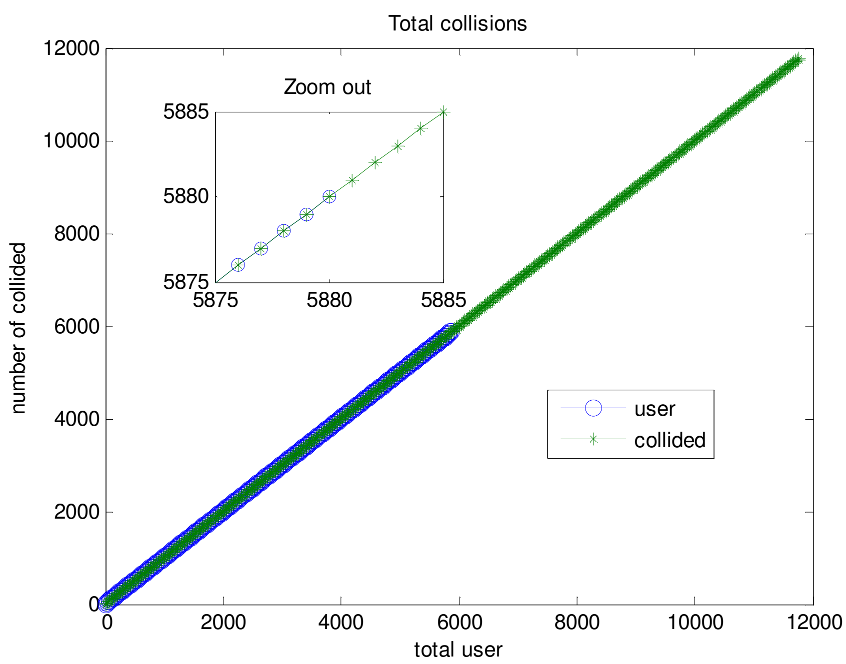

Figure 12: Seven cells IFR collision having two slots per user

4.2.1.3 Seven Cells FFR

As we have seen in the previous sections that the IFR pattern cannot be efficiently utilized, due to the heavy inter cell interference, and the MSs at the cell edge may greatly suffer from degradation in connection quality. The outer cells share the total bandwidth, and split into *3* sections equally. In the FFR pattern, the proposed method implements the inner cell and outer cell collisions separately. The total collided subchannel is the sum of inner cell and outer cell. The total number of available slots and the slot available for outer cell can be calculated with the help of Equation 8 and 9 respectively.

$$Total\ Number\ of\ Slots = \frac{7 cells\ x\ Number\ of\ subchannel\ per\ frame\ x\ Symbol\ per\ frame}{Symbol\ per\ subchannel}$$

Equation 8: Total Number of Slots

$$Outer\ Cell\ Slot = \frac{Number\ of\ subchannel\ per\ frame\ x\ Symbol\ per\ frame}{Symbol\ per\ subchannel}$$

Equation 9: Our Cell Slot

a) One Slot per User

The total number of slot calculated using equation 8 gives *7*3*35*48/3+7*35*48/3 = 15680 number of slots*. The total number of users for one slot per user is equal to *15680/1 = 15680*. The computed total number of collided subchannel is *11760*. The collision rate can be calculated by using the Equation 10 and as all the subchannels are used, we can calculate the load factor using the Equation 11.

$$Collision\ Rate = \frac{Number\ of\ Collided}{Total\ Number\ of\ slots} = \frac{11760}{15680} = 0.75$$

Equation 10: Collision Rate

$$Load\ factor = \frac{Total\ number\ of\ used\ slots}{Total\ Number\ of\ slots} = \frac{15680}{15680} = 1$$

Equation 11: Load Factor

The above scenario clearly explains that collision rate has decreased by 25% to *0.75* as compared to the seven cells IFR where the collision rate was 1 (equation 6). This is due to that fact that outer cells experience no collisions and that total number of users has increased by 25%. The improvement in collision rate is shown in Figure 13, which clearly demonstrates there are no collided subchannels even after the total number of users reaches *11760*.

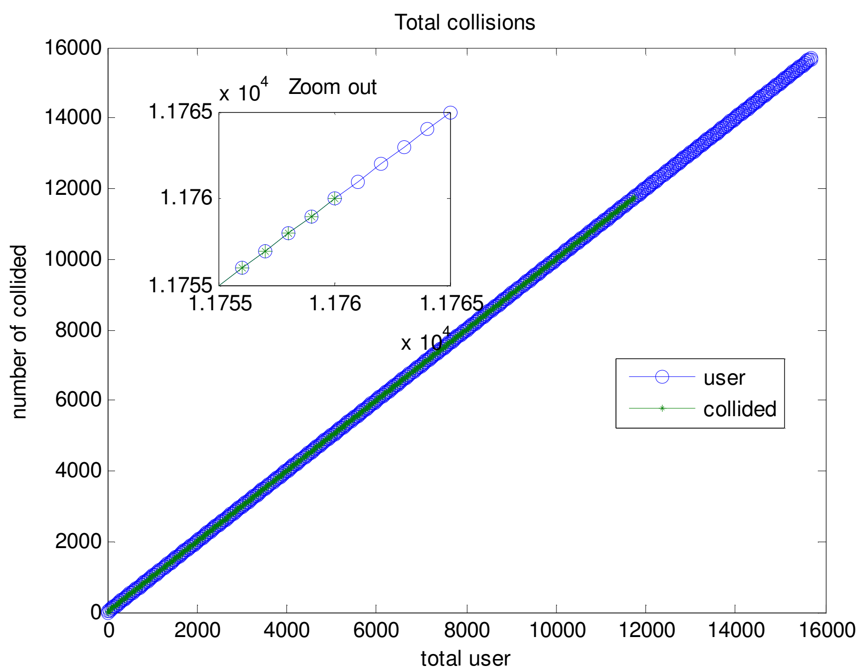

Figure 13: Seven cells FFR collision having one slot per user

b) Two Slots per User

In the two slots per user scenario, the total numbers of available slots are *15680*. The total number of users are reduced to *15680/2 = 7840*. The computed number of collided subchannel remains the same as in the case of one slot per user and is equal to *11760*. Hence we can clearly see that the collision rate and the load factor remains the same for both two slot per user and one slot per user scenario. This behaviour is illustrated in Figure 14.

We can see from Figure 14 that the collided subchannels *(*)* is more than the total number of users *(o)* and the total number of users are reduced by 50% as compared to one slot per user. The zoom out plot clearly explains that the numbers of users cease to increase after *7840*, but the collided number continues to increase.

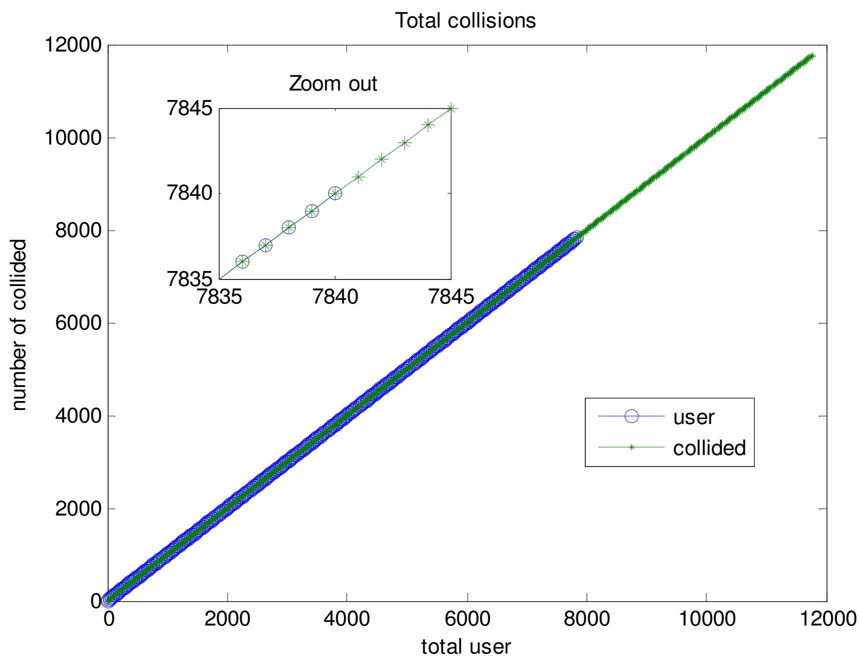

Figure 14: Seven cells FFR collision having two slots per user

4.2.2 Proposed Improvement for Uplink PUSC

In this section we propose improvements for PUSC with IFR and FFR patterns. We have made modifications in *UL_PermBase* within each cell and have used different values for each section. The value of logical tile and the logical subchannel will be different for each section. This result in different physical subcarriers mapping on to the logical tiles, hence the value of subcarriers for each logical subchannel will differ from each other. In IFR cell systems, we choose one section using the default *UL_PermBase* (the unique *UL_PermBase* value assigned by the network), then added a different integer offset to the other two sections. This proposed scheme is explained in the following Matlab code:

```
UL_PermBase=1;% assume is the default value
Tile1=zeros(35,6);Tile2=zeros(35,6);Tile3=zeros(35,6);
for s = 0:N_subchannels-1
```

```
    for n=0:5;
        % Tile1 using the default value
    Tile1(s+1,n+1) = N_subchannels*n+ mod((Pt(mod(s+n,
N_subchannels)+1)+UL_PermBase), N_subchannels)+1;
        % Tile2 add an offset 1 for the UL_PermBase
    Tile2(s+1,n+1) = N_subchannels*n+ mod((Pt(mod(s+n,
N_subchannels)+1)+(UL_PermBase+1)), N_subchannels)+1;
        % Tile2 add an offset 2 for the UL_PermBase
    Tile3(s+1,n+1) = N_subchannels*n+ mod((Pt(mod(s+n,
N_subchannels)+1)+(UL_PermBase+2)), N_subchannels)+1;
    end
end
```

The above Matlab code shows that the *Tile1* is using the default *UL_PermBase*, the *Tile2* is using the default *UL_PermBase +1*, and the *Tile3* is using the default *UL_PermBase+2*. This method can practically be implemented. The BS has to use directional antennas or has to use beam-forming in order to distinguish different sections in a cell for frequency planning. Hence by doing so, the BS informs the MS to add an offset to the *UL_PermBase* corresponding to section allocated. This method may cause problem when the MS needs "hand over".

4.2.2.1 Seven Cells IFR with Proposed Improvements

a) One Slot per User

The simulation result for *seven* cells IFR patterns with one slot per user is shown in Figure 15. The proposed method has shown that the collision rate is down to *zero* as compared to Figure 12 where the collision rate is *1*. The zoom out plot clearly shows that there are no collisions and that the numbers of users are increasing.

b) Two Slots per User

Figure 16 shows IFR patterns for *seven* cells deploying two slots per user. It is clear from the diagram that the proposed scheme has reduced the collision rate to *zero* as compared to figure 12 where the collision rate is *1*. The zoom out plot also proves that there are no collisions and that the number of users is increasing.

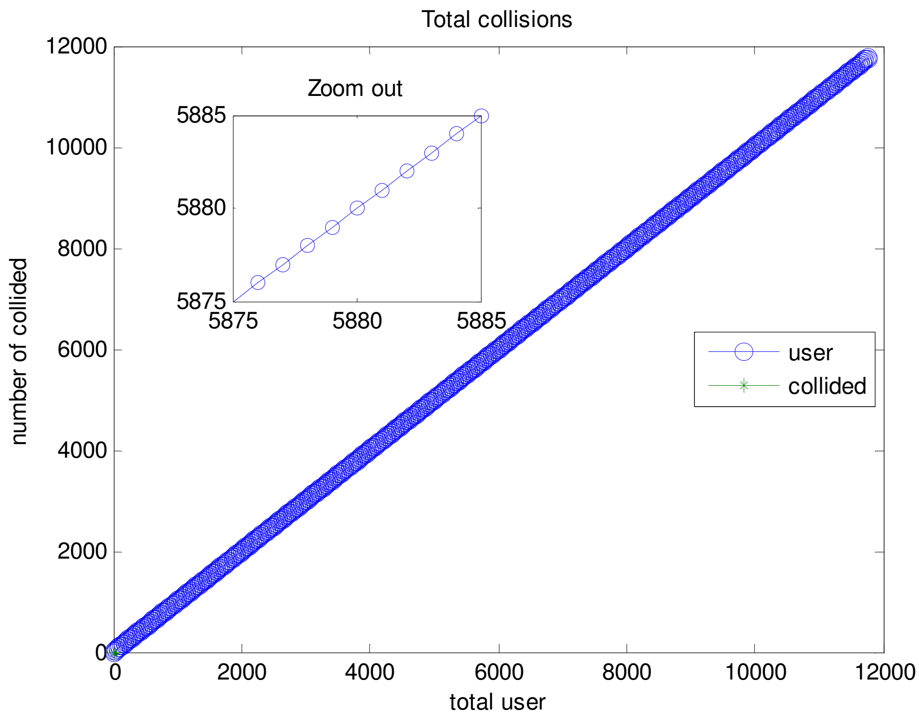

Figure 15: Reduced collision rate for Seven Cells IFR having one slot per user

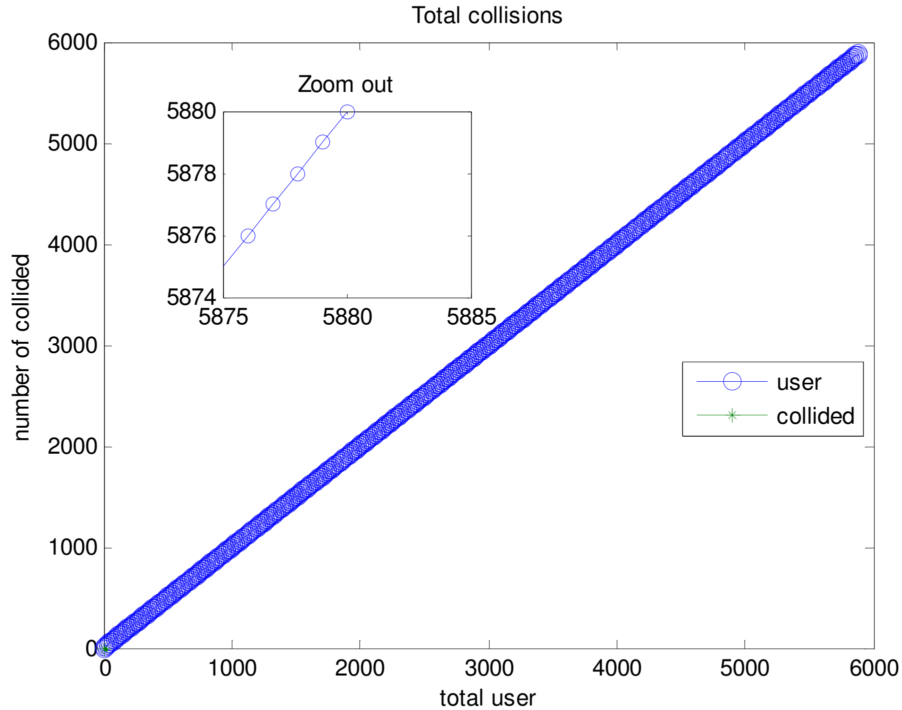

Figure 16: Reduced collision rate for Seven Cells IFR having Two slots per user

4.2.2.2 Proposed Improvement in 7 Cell FFR Patterns

a) One Slot per User

The reduced collision rate for *seven* cells FFR pattern with *one* slot per user is shown in Figure 17. The collision rate for this proposed scheme is reduced to *zero* as compared to the collision rate of 1 in figure. The zoom out illustrates that there are no collisions at cell edges and the number of users is increasing.

b) Two Slots per User

Figure 18 shows the seven cell FFR pattern with two slots per user and the zoom out plots shows that there are no collisions. The number of user is increasing as well. The collision rate of this scenario is calculated as zero. This proves the proposed scheme has reduced the collision from 1 (Figure 14) to zero.

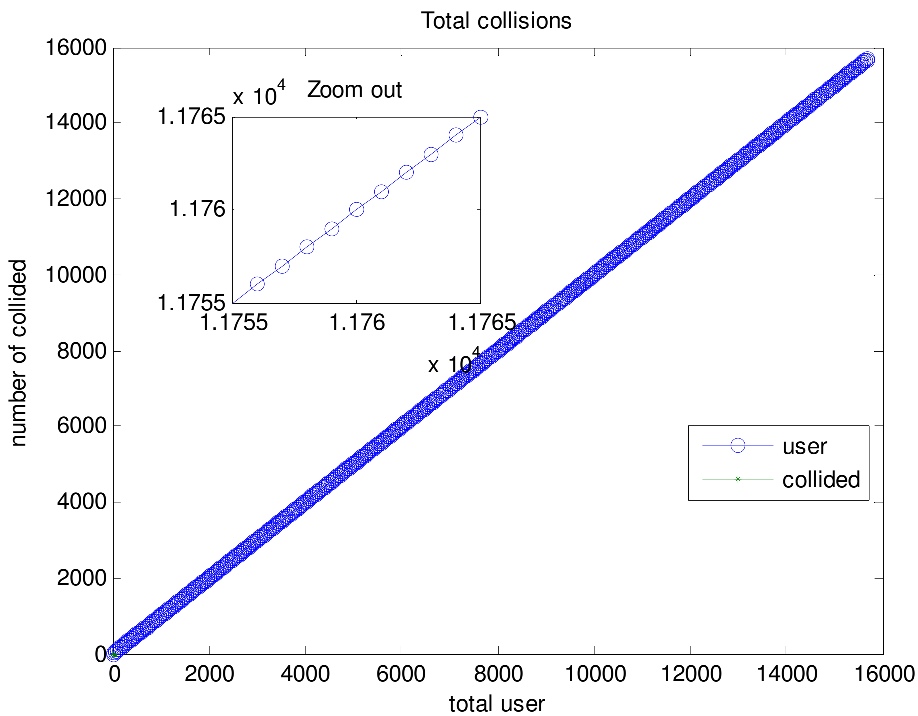

Figure 17: Reduced collision rate for Seven Cells FFR having one slot per user

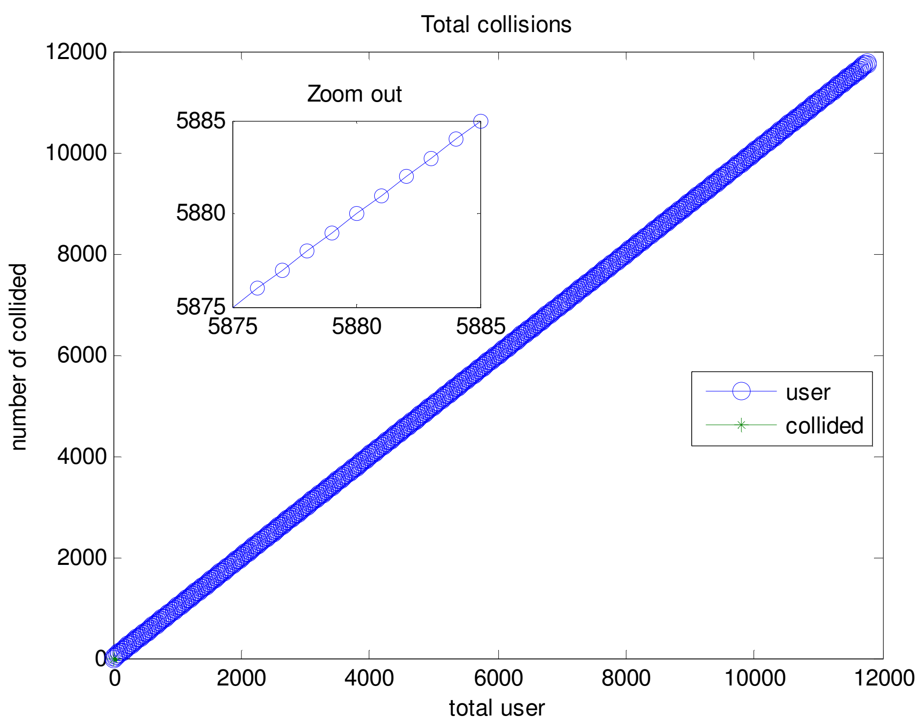

Figure 18: Reduced collision rate for Seven Cells FFR having two slots per user

4.3 Improved Downlink PUSC

4.3.1 Analysis of Downlink PUSC

As stated earlier a TDD frame i.e. an 840 x 32 matrix is considered. Initially this matrix will be assumed to be empty and value 0 will be flooded throughout the frame. Other variables like ***N_slots, users_cell*** etc. are also initialised. Downlink PUSC subcarrier allocation scheme is implemented in order to create a matrix, which contains the randomised subcarrier-time positions. User's data in the form of slots are mapped onto the corresponding physical subcarrier-time positions. Slot size for every user is ***equal*** for the simulation. Thus, for each of the scenarios there would be just one application possible for all users in the 7 cells part of the 2-tier cell network.

Cell loading - Each user gets added (introduced) to all the cells at the same time, i.e. each cell has the same number of users at a particular instant. Maximum users in a cell depend on the slot size. The maximum number of users in a cell for each scenario is evaluated by the formula:

$$U_{\max} = \frac{T_{slots}}{N_{slots/user}}$$

Equation 12: Maximum Number of Users per Cell

Where $U_{\max}$ = maximum users per cell, T_{slots} = number of available slots in a TDD frame, and $N_{slots/user}$ = number of slots assigned for a user (slot size). E.g. for VoIP, when ***N_slots*** = 2, $U_{\max} = \frac{480}{2} = 240$ users. With increase in the value of ***N_slots*** i.e. applications requiring more bandwidth, a reduction in the number of users that can be allocated in the TDD frame is observed.

A 2-tier cellular network with frequency Reuse-1 is assumed. All 7 cells that are part of the 2-tier network are loaded. Collision rate calculations are performed for four different scenarios. In each scenario, the cell will be completely utilised by allocating slots to users till it reaches the maximum possible value of users ($U_{\max}$). As each user is added to each cell the values of the probability of collision and load factor would be calculated by MATLAB.

4.3.1.1 Minimum User Allocation

Minimum user allocation possible in a TDD frame is one slot. When ***N_slot s*** = 1, $U_{\max}$ = 480. Each user is given one slot i.e. one subchannel across two OFDMA time symbols for the downlink.

It is seen from Figure 19 that collision at cell 0 starts as it begins to load and increases till all the slots (30 slots) along the first 2 symbols are utilised. As the subcarriers allocated within both the symbols reaches 1680 probability of collision would increase at a faster rate till it reaches 1. For the first 2 symbols, $N_{collided\_subcarriers}$ increases from 0 to 1680. Thus, $P_{collisions}$ attains maximum value when the first 2 symbols are utilised i.e. when L_f = 0.0625. Users that are allocated slots from the next two symbols (3^{rd} and 4^{th}) will have collisions generated in a similar manner. But $P_{collisions}$ starts from 0.50 as out of the 4 symbols, two have been completely allocated. L_f increases from 0 to 1 as the TDD frame is allocated with users. This results in the zigzag pattern in the plot.

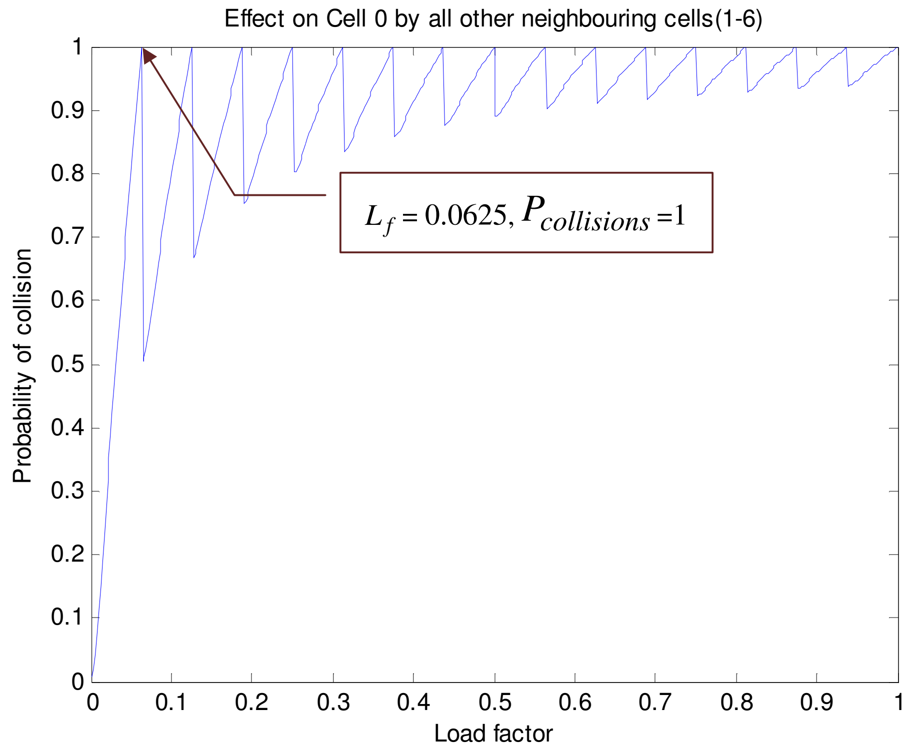

Figure 19: N_slots =1 for increasing load at cell0 by all neighbouring cells.

4.3.1.2 VoIP (Voice Over Internet Protocol)

For VoIP, ***N_slots*** = 2. Thus, $U_{\max}$ = 240. From Figure 20 we can see that collision at the centre cell 0 starts as the users are allocated and increases till all the slots (30 slots) along the first 2 symbols are utilised. In case of VoIP, the number of users that use the 30 slots in the first two symbols is 15 compared to 30 users when ***N_slots*** = 1. For first 2 symbols, $N_{collided\_subcarriers}$ increases from 0 to 1680. Thus, $P_{collisions}$ attains maximum value when the first 2 symbols are utilised i.e. when L_f = 0.0625. The plotted graph is similar to that for ***N_slots*** = 1. L_f increases from 0 to 1 as the TDD frame is allocated with users. As L_f deals with slots and maximum slots over 2 symbols, 30 is a multiple of ***N_slots*** = 2, we get the same zigzagging plot.

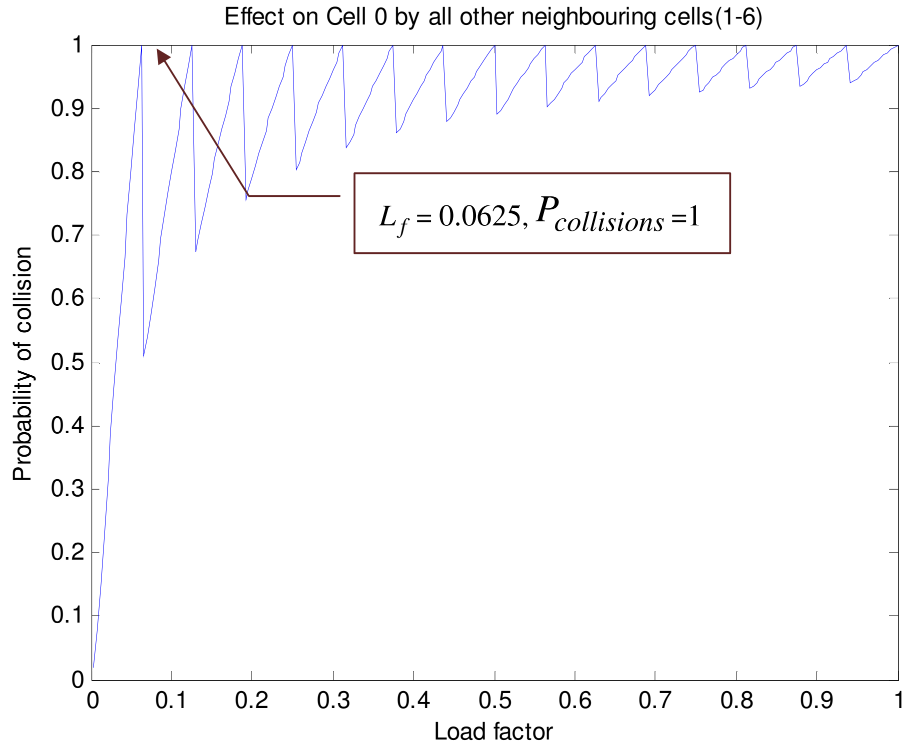

Figure 20: VoIP for increasing load at cell 0 by all neighbouring cells.

4.3.1.3 FTP (File Transfer Protocol)

For FTP, ***N_slots*** = 8. Thus, $U_{\max}$ = 60. From Figure 21 it is seen that the collision at cell 0 starts as the users are allocated and increases as the first 2 symbols are allocated. In case of FTP, users 1-3 use the 30 slots in the first two symbols. Once user 4 is introduced the remaining 6 slots over the 1st and 2nd symbols and 2 slots over the 3rd and 4th symbols are assigned. Thus, $P_{collisions}$ reaches 0.8 after allocation of the first two symbols. We see that $P_{collisions}$ attains the maximum value (= 1) when the first 8 symbols are utilised i.e. when L_f = 0.25. In the case of FTP, maximum slots over 2 symbols, i.e. 30 is not a multiple of ***N_slots*** = 8, the plot follows a zigzag pattern but is different from previous scenarios.

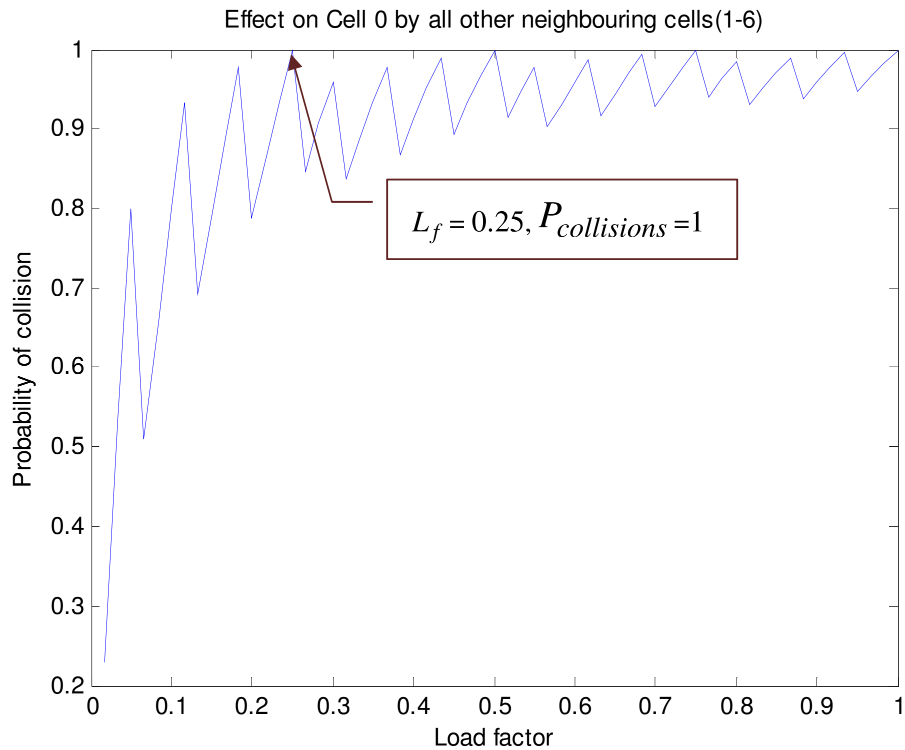

Figure 21: FTP for increasing load at cell 0 by all neighbouring cells

4.3.1.4 Streaming Video

For FTP, ***N_slots*** = 12. Thus, $U_{\max}$ = 40. From Figure 22 it is seen that the collision at cell 0 starts as the users are allocated and increases as the first 2 symbols are allocated. In case of streaming video, the first 2 users that use 24 out of 30 slots over the first two symbols. User 3 uses the remaining 6 slots over the 1st and 2nd symbols and consumes another 6 slots over the 3rd and 4th symbols. Thus, $P_{collisions}$ reaches 0.8 after allocation of the first two symbols. We see that $P_{collisions}$ attains maximum value (= 1) when the first 4 symbols are utilised i.e. when L_f = 0.125. In the case of FTP, maximum slots over 2 symbols, i.e. 30 is not a multiple of ***N_slots*** = 12, the plot follows a zigzag pattern but is different from previous scenarios.

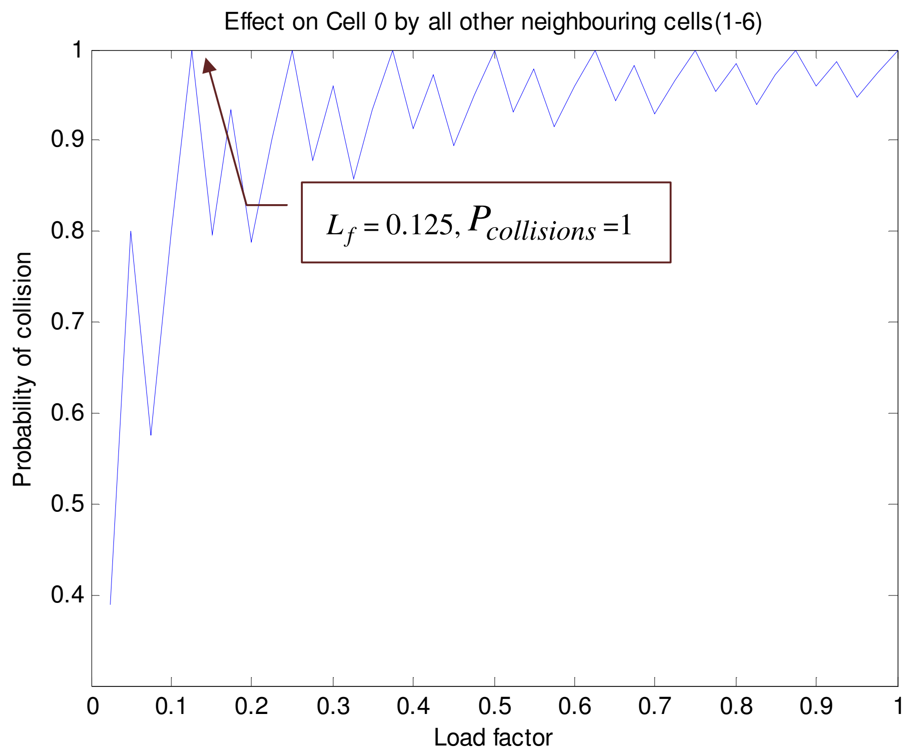

Figure 22: Streaming video for increasing load at cell 0

4.3.2 Proposed Improvement for Downlink PUSC

In this section we propose improvements for downlink PUSC. Different from the standard we introduce an offset scheme in order to increase the number of users in the system. As an example we choose the offset to be 4 symbols. Our offset scheme works as follows:

Cell 0 allocates users from subchannel *0* and from symbol *0.* Cell *1* allocates users from subchannel 0 and symbol 4. We repeat the same procedure for the remaining cells.

4.3.2.1 VoIP with Proposed Offset

Figure 23 shows that collision starts at cell *0* only at a later stage once the *4th* symbol in the frame is allocated. The value of $P_{collisions}$ reached 1 when L_f = 0.1875 which is larger than the value at which the $L_f = 0.0625$ obtained earlier as seen in sub clause 4.2.1.2 (Figure 20). After it reaches the peak value, it follows the same zigzag pattern seen earlier.

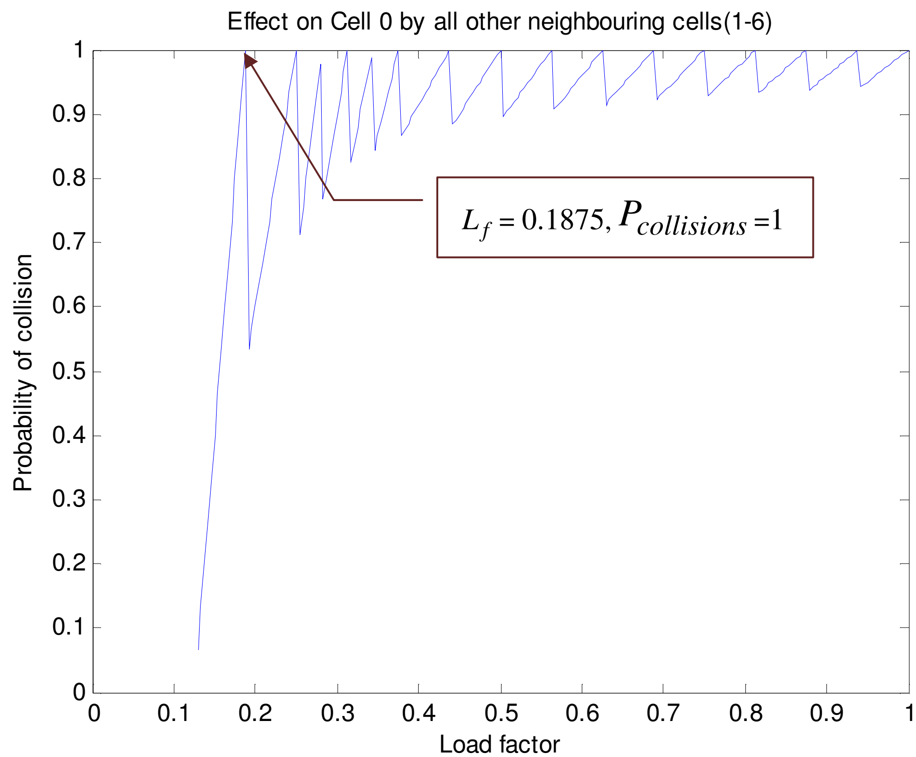

Figure 23: VoIP with Proposed Offset

4.3.2.2 FTP with Proposed Offset

Figure 18 showed that collision started from cell *0* as the users are allocated and started increasing after the allocation of first *2* symbols. In case of our proposed improved scheme the collision started after the allocation of 4^{rth} symbol. This behaviour is shown in figure 24.

4.3.2.3 Streaming Video with Proposed Offset

Our proposed methods clearly shows that the value of Load factor *(L_f)* has increased from *0.125* (figure 22) to *0.25*. Also the collision started when 4rth symbol was introduced in the system. Figure 25 explains this scenario.

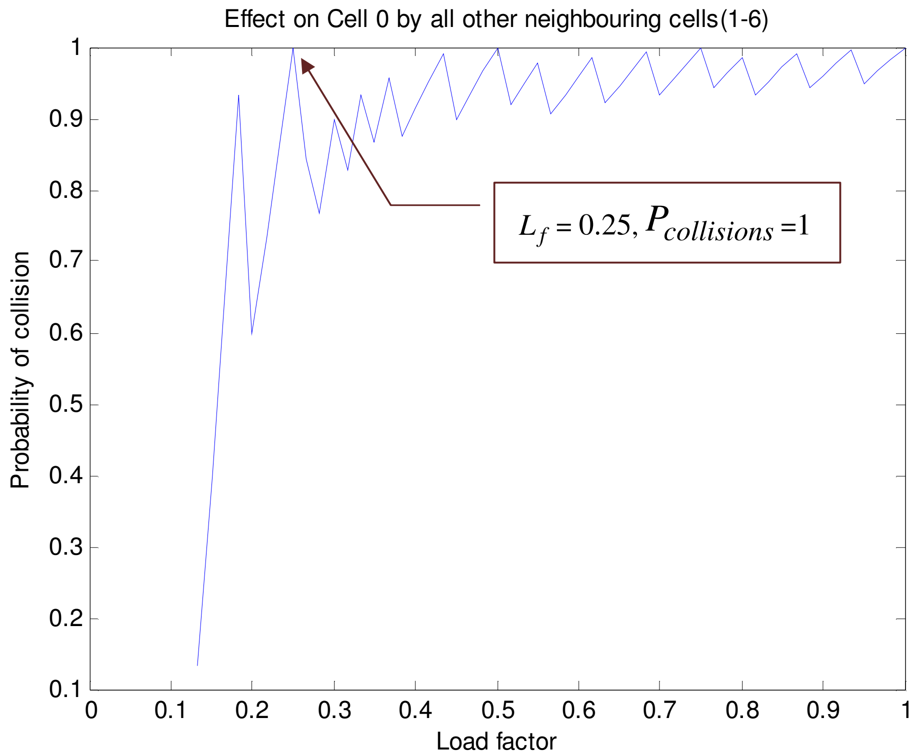

Figure 24: FTP with Proposed Offset

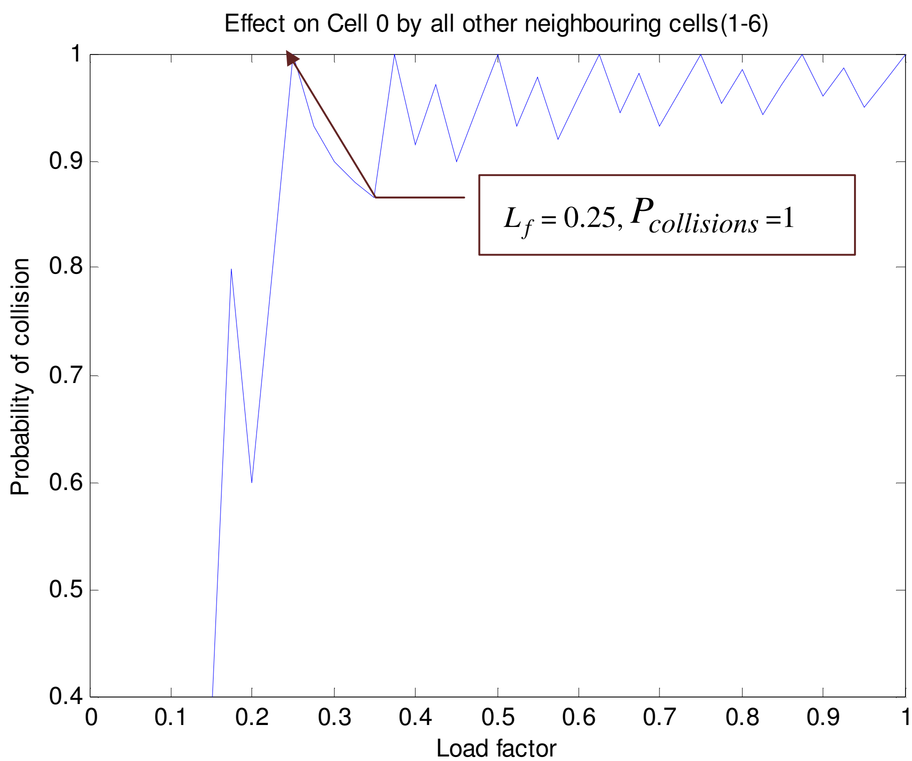

Figure 25: Streaming Video with Proposed Offset

4.4 Summary

This chapter proposed improvements for PUSC subcarrier allocation in both UL and DL. The two major issues i.e. interference and collision rate between cells were analysed and improvements were presented for both cases. For the UL PUSC scheme our proposal is to allocate different frequencies to the neighbouring cells. The simulation results show that collision rates can be reduced to zero for both IFR and FFR patterns with the proposed improvements by assuming that perfect power control is used in the system. In addition, there is no collision at the cell edges. The results also show that FFR patterns achieve lower inter-cell interference and higher capacities as compared to IFR patterns. For DL PUSC we proposed to introduce the offset mechanism. Our results show a significant increase in Load factor and hence more number of users can be accommodated in the system for three cases i.e. VoIP, FTP and Streaming Videos. The next chapter presents the piggyback mechanism explained in the standard and the proposed improvement made in this method.

Chapter 5 Analysis and Improvement for Piggyback Request

5.1 Current Piggyback Mechanism Defined in the Standard

The IEEE 802.16 standard explains a method to ask for bandwidth in which a request is only granted for the amount of desired bandwidth by the HOL–packet which is present in a traffic queue, though, some packets can turn up between the arrival of the first packet thus generating the requesting process and the real time in which this request will be honoured. In order to solve this problem, we have proposed a new aggregate approach for the bandwidth request, in which a piggybacked request is generated previously and then the traffic queue is checked again. It then updates the bandwidth requested to the BS, so that the BS can get a more updated request and like wise a small number of requests will be used for the same quantity of the bandwidth.

Piggyback Request is a 16bit number that represents the number of uplink bytes of bandwidth requested for the connection. If the packet interarrival time is shorter than the frame size, all bandwidth requests can be piggybacked on the previous packets [1].

The piggyback request, shown in Figure 26, is used to clearly designate the total amount of uplink bandwidth required that the SS wants to be granted to itself. A BW request for n packets can be piggybacked on packets n-1, if the packet has arrived between the bandwidth request of packet n-1 and the transmission of packet n-1.

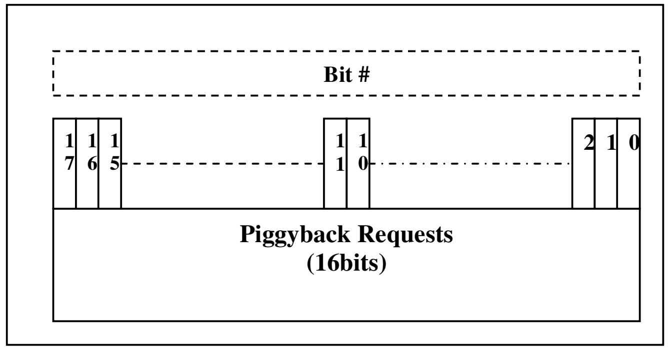

Figure 26: Representation of Piggyback Request in Grant management sub-header [1]

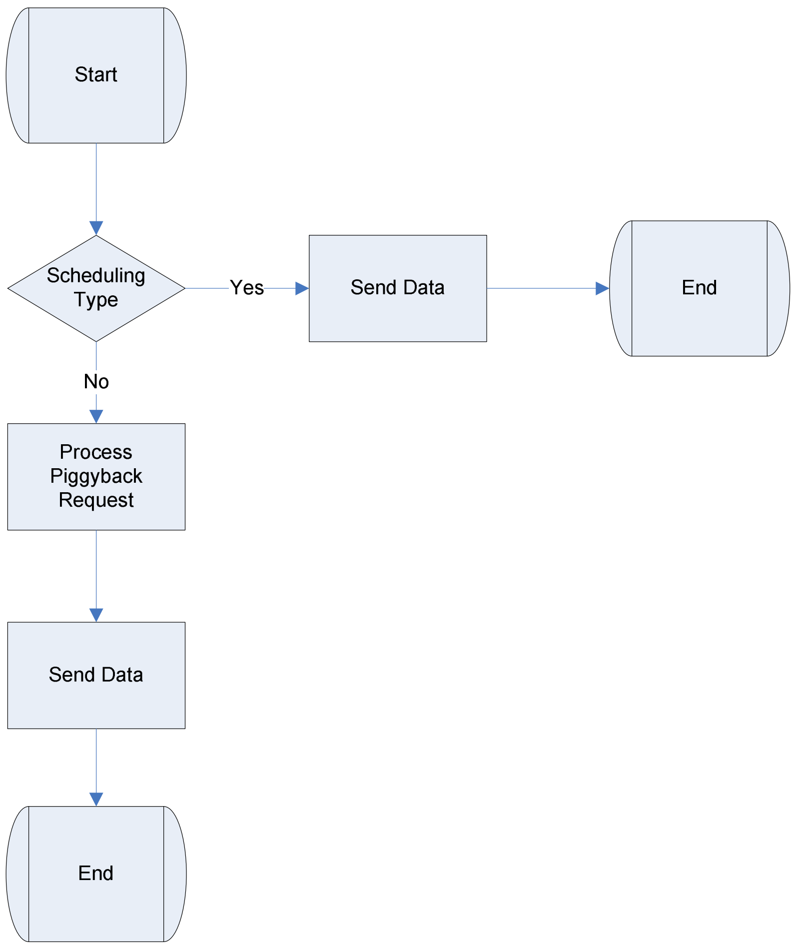

Figure 27: Flow Chart of Piggyback Request

5.2 Implementation Issues

In order to evaluate the performance of piggyback requests, we carried out a comprehensive simulation study using the OPNET Modeller version 14.5 simulation tool. The proposed simulation model works for both MAC and the PHY layer. The WiMax cell was configured with a frame size of 10 ms and utilised TDD having uplink subframe duration of 50 percent of the frame. The total simulation time is set to 1 hour on a computer having Windows XP as an operating system. This computer has a Pentium 4 CPU whose clock speed is 3.06 GHz and has 1 GB of RAM. In this simulation setup, the best effort QoS class with a round robin scheduling technique was used. The Simulation Model and Network layout are shown in Figure 28. The networks consists of one base station, two servers, silver A and silver B, two subscriber stations, A and B and one UGS Subscriber station and one default SS which carries BE traffic.

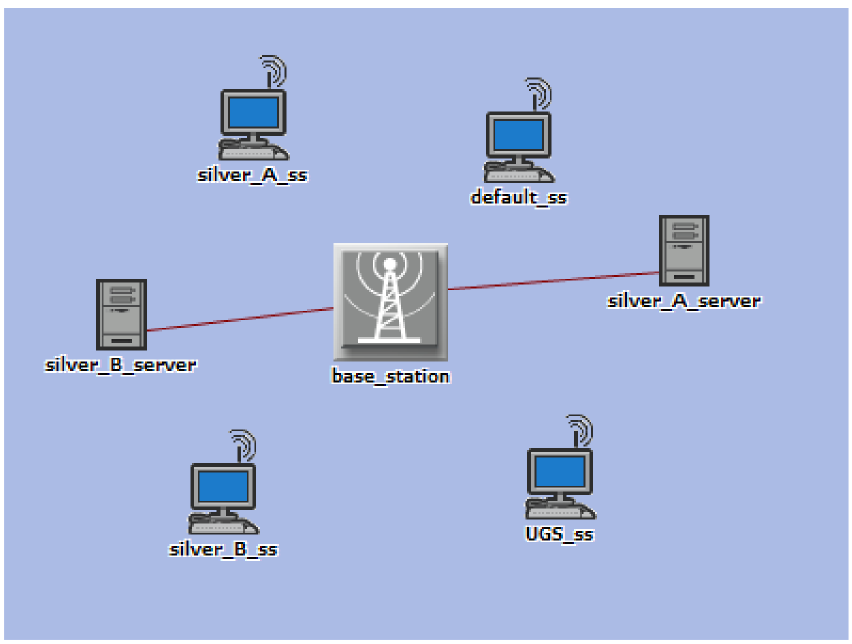

Figure 28: Simulation Model and Network Layout

5.3 Proposed Improvement for Piggyback Scheme

Piggybacked bandwidth request can be employed to successfully increase the bandwidth efficiency. However there is a possibility of increase in channel access delay. The IEEE 802.16 standard introduces a method to request for bandwidth in which a request is only granted for the amount of desired bandwidth by the

HOL–packet which is present in a traffic queue. However, some packets may turn up between the arrival of the first packet thus generating an additional requesting process during which this request will be granted. This will cause channel access delays. In order to solve this problem, we have proposed a new aggregate approach for the bandwidth request, in which a piggybacked request is generated previously and then the traffic queue is checked again. Subsequently it updates the bandwidth requested to the BS, so that the BS can get a more updated request and like wise a small number of requests will be used for the same quantity of bandwidth. The Flow Chart of improved Piggyback Request is given in Figure 29.

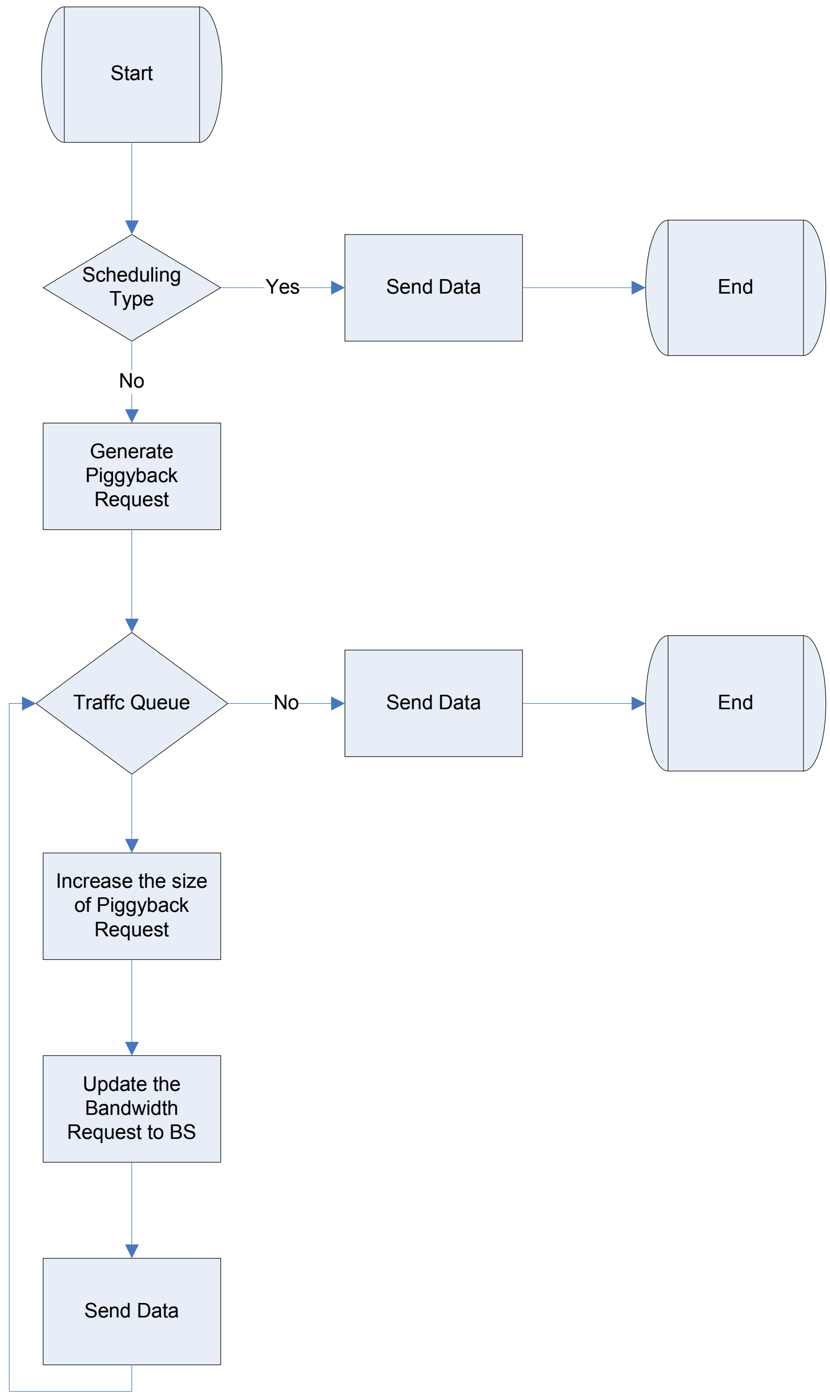

Figure 29: Flow Chart of Improved Piggyback Request

5.4 Simulation Results

5.4.1 Throughput Comparison

Figure 30 shows that Throughput Comparison between Improved Piggyback Request, Standard Piggyback Request and Without Piggyback Request. The X-axis and Y-axis show the Simulation Time (3600 sec) and Throughput (Packets/second).

The Simulation starts from 5 seconds and finished after 1 hour. The Throughput of Improved Piggyback Request has reached 400 packets/second while that of standard and without piggyback is 300 and 100 packets/second respectively. Since at the start of the simulation all stations (with different bandwidth techniques) try to request for bandwidth the throughput of the system increases. The system stabilizes when the BS allocates all of the requested bandwidth.

Our Proposed protocol showed much higher throughput compared to others because we doubled the size of piggyback request. By doing so more bandwidth was allocated to each user, data transmission took less amount of time and wait in the queue reduced as well. Consequently, the proposed Piggyback Method has increased the system’s throughput.

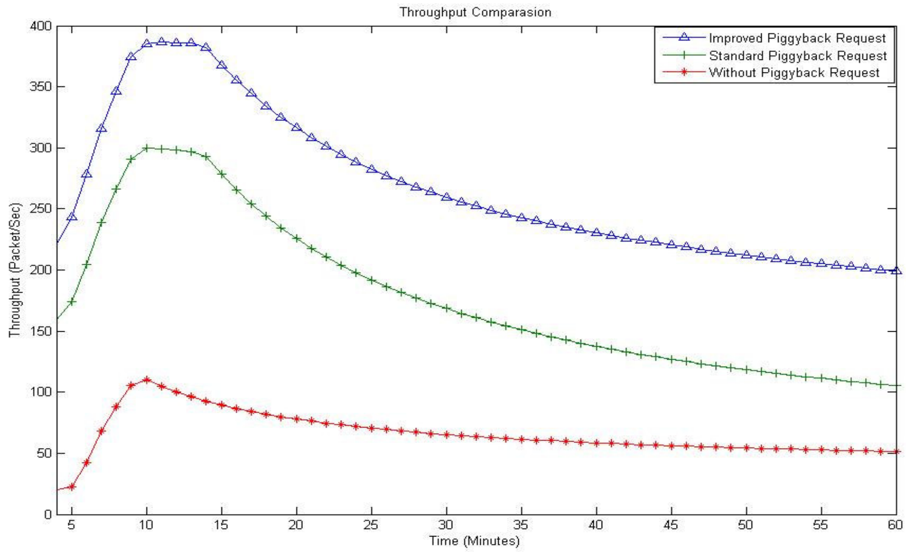

Figure 30: Throughput Comparison

5.4.2 Delay Comparison

Figure 31 shows that Delay Comparison between Improved Piggyback Request, Standard Piggyback Request and Without Piggyback Request. The X-axis and Y-axis show the Simulation Time (3600 sec) and delay (seconds).

Since all the SS have requested for bandwidth at the start of simulation from BS, they have to wait in a queue. This increases the delay when no Piggyback Request Method is applied as shown in Figure 25. When Piggyback is applied the delay reduces.

As the size of Piggyback Request was doubled, the user required less wait time in the queue. In our proposed algorithm it is due the above-explained fact that the delay reduced quite a lot as compared to the standard and with no piggyback request.

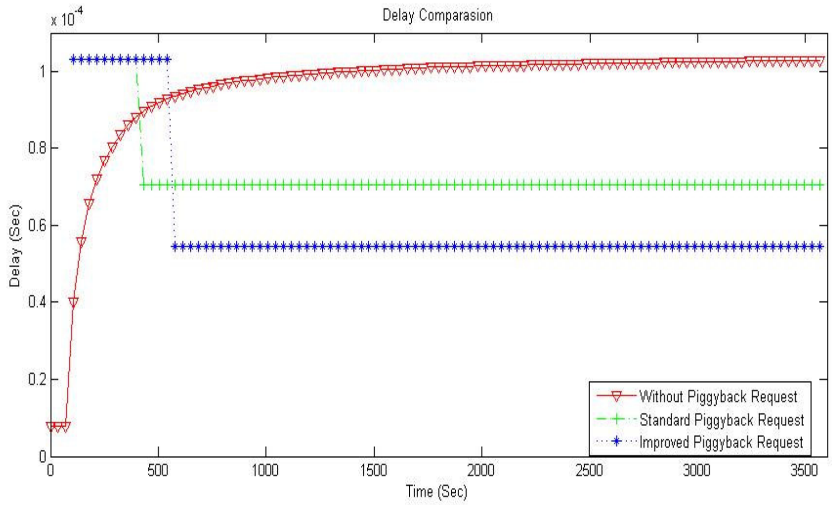

Figure 31: Delay Comparison

5.4.3 Packet Loss Comparison

Figure 32 explains the packet loss scenario. The X-axis and Y-axis show the Simulation Time (3600 sec) and Number of Packets.

The proposed algorithm shows the number of packet loss and compared to standard and with no piggyback scheme has reduced quite significantly.

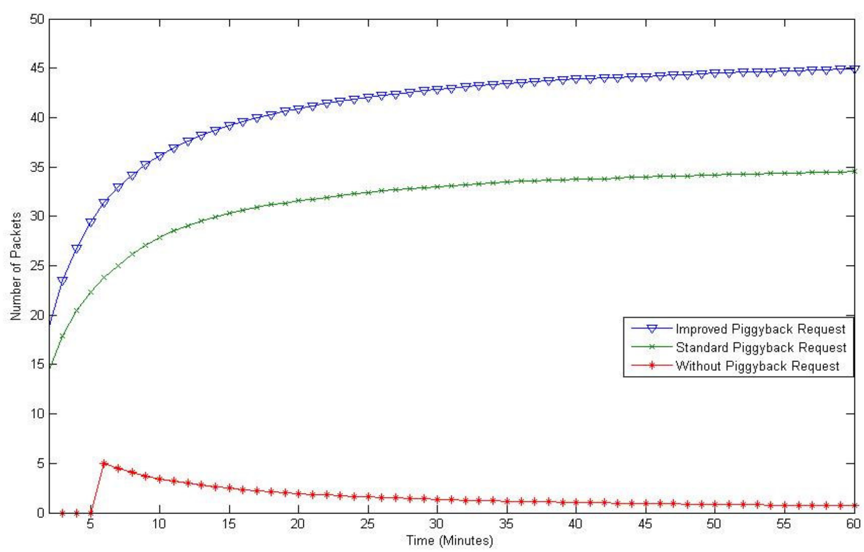

Figure 32: Packet Loss

5.5 Summary

This chapter comments on the Piggyback Bandwidth Request. The functionality and frame structure of Piggyback Method is discussed in detail. In the last section a Comprehensive Bandwidth Request Method using Piggyback Method is discussed and elaborated with the help of figures drawn for Throughput, Delay and Packet Loss. The next chapter concludes the research and presents some recommendations for future research.

Chapter 6 Conclusions and Future work

6.1 Conclusions

WiMax standard is planned to construct a point-to-multipoint broadband network access that is widely obtainable, with no expense and distance restrictions linked with wired solutions. WiMAX is a scheduled protocol where the base stations (BS) hold centralized control for the network. BS also manages and controls the WiMAX network. Subscriber stations (SS) are not allowed to communicate with the network unless and until the base station acknowledges them. The BS then assigns time and frequency to subscriber station so that SS can communicate with BS. It is due to this fact a WiMAX based network would never be overloaded.

A through research was done to understand the concepts behind the PUSC subcarrier allocation scheme for both Uplink and Downlink. Matlab was used for the purpose of simulation and programming. First we initialised the TDD frame for each cell in the 2-tier cellular network for Reuse-1. The uplink and downlink PUSC scheme as per [1, 2] were implemented. After the simulation it was observed that the permutation formulas applied randomised the physical subcarrier positions in each symbol. For each of the seven cells in the 2-tier network as the value of DL_PermBase changed it appeared on the physical subcarrier position in the form of even and odd symbols. The Users were assigned in terms of the number of slots allocated to the logical subchannels. Subsequently the logical to physical mapping was carried out for all the cells. Therefore the user's data was randomised and multiple users were scattered across the frequency spectrum as this is the basic principle of OFDMA.

Also Collisions taking place at cell 0 were calculated for every new user added to every cell of the 2-tier network and were calculated based on the number of collisions. It is therefore concluded that when the load factor L_f increases its vale from 0 to 1, the value of $Pc_{ollisions}$ reaches its maximum value because all the subcarriers stations have used up all the symbols that were allocated to them. When more symbols in the frame become available the value of $P_{collisions}$ reduces but at the same time increases as more slots (users) are assigned.

The PUSC UL subchannelisation scheme is taken into account with the selection of IFR patterns and FFR patterns. They are simulated using different number of slots for each user. The simulation results have shown that the FFR pattern shows lesser interference and gives high capacities as compared to IFR pattern. The collision rate and load factor for each UL cell loading were calculated and it was found that the number of collisions increases with the increase in user. At the end we introduced the use of different UL_PermBase inside a given cell in order to improve the inter-cell interference. Consequently, the Simulation results shoed zero collisions.

6.2 Future Work

For future research power control method can be introduced in both Uplink and Downlink PUSC. Also the same techniques can be used to implement FUSC as this has not been implemented in the standard or proposed so far.

The concept of Soft Frequency Reuse is very much the same as FFR. In the case of the Soft Frequency Reuse users can also be separated into cell edge and cell centre users. The Soft Frequency Reuse has not been implemented so far. So for future work SFR can be applied to both Uplink and Downlink PUSC.

The interference problem can also be improved by making use of the beam forming antennas and synchronising the transmissions amongst different base stations. In WiMAX IEEE 802.16 network standard, interference can be easily avoided by creating different frequency reuse patterns. The Interference averaging can be employed by distributed subcarrier permutation that can further be split up into different multiple operation modes. In Order to avoid this interference problem, the system should try to avoid the same frequencies used by neighbouring cells and also in different sections lying within a cell. This procedure can be performed in two ways i.e. by allocating different frequencies to the neighbouring cells and or by using a special scheduler that can take care of all the collisions. Up to now only the first method is used in the real world. The Second method is very complex and demands a lot of computing overhead.

A comprehensive Bandwidth Request Allocation was introduced using the piggyback requests. The results obtained showed higher throughput and less delay. For Future research the same algorithm can be applied to other QoS classes e.g. Non-Real Time Polling System, Real-Time Polling System, Extended Real-Time Polling System and Best Effort Services. Also this algorithm can be studied by applying different types of traffic e.g. FTP, HTTP and Voice.

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