

## SCHEDULING IN WiMAX BASED WIRELESS NETWORKS

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SCHEDULING IN WiMAX BASED WIRELESS NETWORKS

Srivathsan Soundararajan

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## VITA

Srivathsan Soundararajan, son of Soundararajan and Geetha Rajan, was born on July 29, 1985 in Chennai, India. He completed his Bachelor of Engineering at SSN College of Engineering, Anna University, in Chennai, India. He entered the Electrical Engineering graduate program at Auburn University in August of 2006.

THESIS ABSTRACT

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This thesis describes two transmission scheduling algorithms and a hybrid ARQ transmission handling algorithm designed for WiMAX based wireless networks. WiMAX networks are based on Orthogonal Frequency Division Multiple Access (OFDMA) technique. In OFDMA based wireless networks, the bandwidth is divided into narrow sub-divisions, each of which is called a sub-carrier. Sets of these sub-carriers are allocated to users. The first algorithm is based on graph theoretic techniques and is employed to schedule user transmissions by assigning selective OFDMA subcarriers. This algorithm allocates resources based on the instantaneous channel properties like signal to interference and noise ratios experienced by users.

The second scheduling algorithm deals with transmission scheduling in WiMAX based hybrid wireless networks. An important application of WiMAX technology is to serve as backbone to connect to the internet for 802.11 networks. The proposed scheduler aims at minimizing the delay experienced by 802.16 users due to increase in the number of 802.16 users. The design and implementation of these algorithms is discussed and the results are summarized in the subsequent chapters.

Hybrid Automatic Repeat Request (HARQ) is a technology used to enhance the correctness in wireless transmissions. HARQ efficiently uses both forward error correction and error detection techniques in order to provide better throughput performance in poor signal quality conditions. The effectiveness of this technology in Orthogonal Frequency Division Multiple Access (OFDMA) based wireless networks is studied. The proposed HARQ algorithm assigns sub-carriers for retransmissions and schedules them in time. The algorithm is tested for certain applications such as video, VoIP that pose stringent limits on delay and jitter. These applications have critical delay requirements especially on retransmitted packets, as delayed out-of-sequence packets are generally ignored. In the proposed algorithm, a timestamp is attached to the retransmission request and its value is determined based on delay requirements. The OFDMA scheduler allocates sub-carriers and time offsets to these packets based on channel properties and the timestamp value. In the case when the timestamp value is less than the estimated propagation time, the retransmission is aborted. Therefore, the traffic load introduced by unnecessary retransmissions is reduced and the throughput performance of the system can be improved.

This thesis report explains the importance of effective transmission scheduling in WiMAX networks with the help of these three cases.

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## CHAPTER 1

### INTRODUCTION

WiMAX, officially termed as IEEE 802.16 standard is the state of the art technology developed for wireless metropolitan area networks (WMANs). While the 802.11 standard was designed for local area wireless networks, the 802.16 standard was designed to address wireless metropolitan area networks. This technology offers several advantages such as longer range of up to 30 miles and high data rates up to 70Mbps [1]. Salient features of IEEE 802.16 include adaptive modulation scheme from 64-QAM to QPSK, OFDM technology, directional antennas and transmit and receive diversity. Some of the major MAC layer improvements incorporated in this technology are connection oriented protocol, QoS based packet scheduling and differentiated services based on traffic requirements [2]. The primary function of WiMAX is to offer last-mile wireless broadband services. But, the 802.16 network can also be designed to efficiently serve as a backbone for 802.11 access points (AP) for connecting to the Internet. The advantages of WiMAX over other popular technologies such as WiFi are explained in [3].

There are two types of deployment of WiMAX networks - point to multipoint and mesh network topology as shown in Figure 1.1. The most common type is point-to-multipoint (PMP) where every communication has to be routed through the base station. In such networks, transmission scheduling is easier. The mesh and PMP topologies are compared in [4]. The remainder of this report is based on WiMAX networks working in PMP topology.

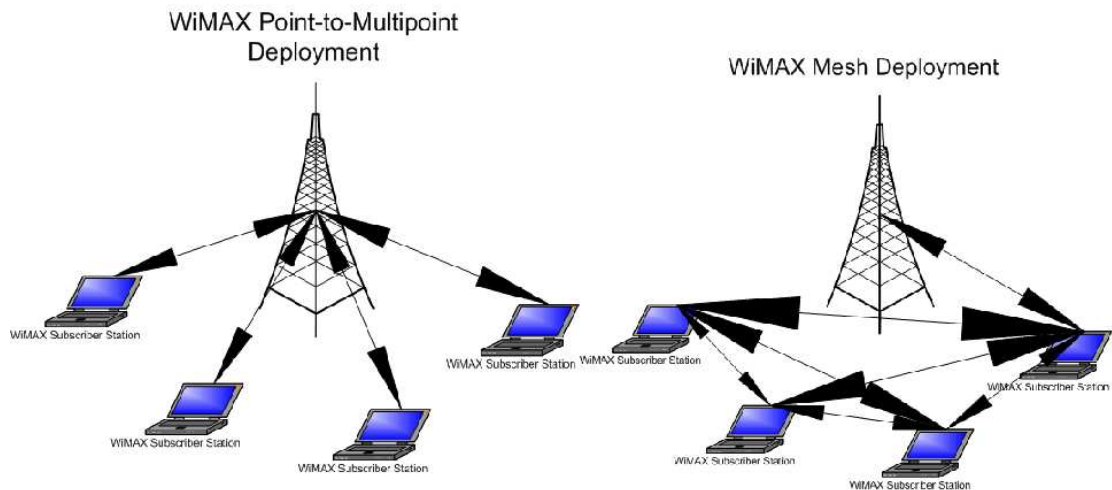


Figure 1.1: WiMAX network deployment options

The flavors of this standard are described as follows:

1. 802.16a - This amendment specifies non-line-of-sight extensions in the 2-11 GHz spectrum and supports data rates up to 70 Mbps and range up to 20 miles.
2. 802.16d - This amendment was developed to address backhaul applications. The standard focusses on the 11 to 66 GHz unlicensed spectrum.
3. 802.16e - The 802.16e amendment enables support for combined fixed and mobile operation for licensed and license-exempt frequencies below 11 GHz. It is expected to support mobility in the order of 70 - 80 mi/hr.

### 1.1 WiMAX basic operation

The basic operation of WiMAX is explained as follows. The MAC layer is divided into three sub-parts convergence sub-layer (CS), Common Part sub-layer (CPS) and security sub-layer. Service specific convergence sub-layer classifies service data units (SDUs) to the

proper MAC connection. It provides a mapping between the service flow ID and the connection ID. This mapping depends on the type of services. The convergence sub-layer is also responsible for payload header suppression and reconstruction to enhance airlink efficiency. MAC protocol data unit (PDU) consists of a fixed length MAC header (generic or bandwidth request), a variable length payload and a cyclic redundancy check (CRC). Bandwidth request messages do not contain any payload. WiMAX MAC employs fragmentation that divides the SDU into smaller chunks called fragments and packing that combines multiple SDUs into a single PDU. In order to eliminate interference at an 802.16 base station (BS) due to multiple packet arrivals, the subscribers are required to synchronize with the BS before establishing communication links. Such synchronization requires round trip delay that depends on the distance between 802.16 subscriber and BS. These delay measurements are done using a ranging method. The BS estimates the timing offset and operational power level for each subscriber and broadcasts a ranging code. A detailed analysis over the initial ranging process is described in [5]. The MAC layer at the BS defines a set of subcarriers as a ranging channel. The 802.16 subscribers are allowed to contend in the ranging channel for the initial ranging process and only those successful subscribers can establish communication with the BS [5].

In 802.16 networks, the uplink channel (from Subscriber Station (SS) to BS) employs TDMA (Time Division Multiple Access) and the downlink channel employs TDM (Time Division Multiplexing). The BS dynamically determines the timeslots at which each SS can transmit on the uplink channel. The BS broadcasts the data packets on the downlink channel and an SS accepts only the packets destined to it. A detailed analysis over the 802.16 MAC is provided in [6]. The number of time slots assigned to an SS and the channel access grants provided by the BS depends upon the number of other 802.16 users and their service requests.



The entire data transmission is divided into frames and subframes. The DL sub-frame is made up of a preamble, Frame Control Header (FCH), and a number of data bursts. The FCH specifies the burst profile and the length of one or more DL bursts that immediately follow the FCH. The DL-MAP, UL-MAP, DL Channel Descriptor (DCD), Channel Descriptor (UCD), and other broadcast messages that describe the content of the frame are sent at the beginning of these first bursts. The remainder of the DL sub-frame is made up of data bursts to individual SSs. Each data burst consists of an integer number of OFDM symbols and is assigned a burst profile that specifies the code algorithm, code rate, and modulation level that are used for those data transmitted within the burst. The UL sub-frame contains a contention interval for initial ranging and bandwidth allocation purposes and UL PHY PDUs from different SSs. The DL-MAP and UL-MAP completely describe the contents of the DL and UL sub-frames. They specify the SSs that are receiving and/or transmitting in each burst, the sub-channels on which each SS is transmitting (in the UL), and the coding and modulation used in each burst and in each sub-channel. The SS listens to the downlink channel for the entire downlink sub frame duration to check if there is a packet intended for it. Downlink data packets intended for it are sent to higher layers. SS determines its uplink transmission time and duration of transmission by decoding uplink control message. SS also generates bandwidth requests to be sent to BS. SS then schedules uplink data packets and request packets in the allocated slots and transmits them accordingly.

At the BS, the incoming packets classified into one of the four-service classes are shaped and placed in one of the downlink traffic queues. BS also receives uplink data and request packets sent on uplink channel by various SSs. Data packets are handed over to higher layer while request packets are given to uplink grant classifier. The BS examines the downlink and uplink traffic queues and divides the total bandwidth between downlink and uplink

sub frames. BS then schedules the downlink data into the downlink sub frame and creates downlink control messages. BS also encodes the information about the bandwidth allocated to each SS in uplink control message. At the start of the frame, BS transmits downlink and uplink control message on downlink channel followed by downlink data for various SSs. The design of a WiMAX based last mile network solution is provided in [7]. The differences between the 802.16 and 802.11 standards are listed in table .

Table 1.1: Differences between 802.16 and 802.11 standards

Parameters	IEEE 802.16	IEEE 802.11
Standards	802.16a in April 2003, 802.16d in 2004, 802.16e in 2005	802.11b in Oct 1999, 802.11a in Oct 1999, 802.11g in June 2003
Frequency of Operation	NLOS - below 11 GHz (primarily 5 - 6 GHz), LOS - 11 - 66 GHz	802.11b/g - 2.4 to 2.6 GHz, 802.11a - 5.15 - 5.25/ 5.25 - 5.35/ 5.725 - 5.875 GHz
Data rate	802.16d - 75 Mbps, 802.16a/e - 30 Mbps	54 Mbps
Range	Optimized for 7 - 10 km, theoretically up to 50 km	up to 110 m
Medium access method	QoS based re- quest/grant	CSMA/CA
Spectral Efficiency	3.8 bps/Hz	2.7 bps/Hz
Security	128 bit 3-DES and 1024 bit RSA	WEP, WPA and WPA2

### 1.1.1 Quality of Service in WiMAX

The most important application of IEEE 802.16d standard is to provide backhaul services for 802.11 hotspots. The main advantage of this technology is its long transmission range that can blanket a large number of 802.11 hotspots. Transmit diversity and Multi-Input Multi-output (MIMO) antennas, space time coding and other physical advantages make WiMAX a popular solution for backhaul services. The 802.16e standard that deals with mobility in WiMAX networks aim at providing last mile services to end users. It supports mobility up to 70 miles per hour and data rates up to 40 Mbps [8]. This technology is apt for applications such as video over mobile wireless devices, backhaul for WLAN last mile wireless networks and other broadband wireless access services. The study of service quality over WiMAX is discussed in [9]. In this report, the dynamic problems by temporary allowing traffic to flow in a reserved channel are discussed. The service quality in 802.16e is divided into five classes.

1. UGS (Unsolicited Grant Service) - requires strict delay specifications and is designed to support real-time applications (with strict delay requirements). Mostly, applications that deal with fixed-size data packets at periodic intervals such as T1/E1 and VoIP without silence suppression, are classified with UGS service. This service requires three specifications from the users - the minimum reserved traffic rate, grant interval and the tolerated jitter. The unsolicited grant interval specified by the subscriber is used as the base period to closely follow the packet arrival pattern such that the offset does not exceed the tolerated jitter specification. The UGS connection grants are based on the minimum reserved traffic rate and do not require bandwidth requests.
2. rtPS (real time Polling Service) - is also designed to support real-time applications but requires lesser stringent delay specifications compared to UGS. Mostly, applications

that deal with variable-size data packets at periodic intervals, such as Moving Pictures Expert Group (MPEG) video and VoIP with silence suppression, are classified with this service. This service requires two specifications from the users - the minimum reserved traffic rate, the maximum latency and an optional unsolicited polling period. Since the size of arriving packets with rtPS is not fixed, they are required to notify the BS of their current bandwidth requirements. The BS periodically grants unicast polls to rtPS connections.

3. nrtPS (non-real time Polling Service) - is designed to support applications that do not have any specific delay requirement and with variable bit rate. Some applications that use this service are bandwidth-intensive such as File Transfer Protocol(FTP). nrtPS service requires the minimum reserved traffic rate parameter and these connections are reserved a minimum amount of bandwidth. The BS grants unicast requests less frequently as compared to rtPS connections. In case, the specifications are not satisfied, contention request opportunities are allowed to be used.
4. BE (Best Effort) - These connections are required to contend for bandwidth request opportunities. There is no throughput or delay requirement specified with these service requests. The grant opportunities are based on the available bandwidth and current network load. Common applications associated with this service are www and telnet.

A detailed explanation on QoS over WiMAX and their performance evaluation is done in [10]. Since the service classification of applications are performed for enhancing quality, it is required to design a scheduler with priority based on QoS. The requirements of such a scheduler and a simple design is explained in [11]

The quality of service in WiMAX suffers from two main problems - lack of flow resolution and lack of dynamic response [9]. Every service flow in WiMAX is associated with

a connection id(CID). The CID is the key assigned to every connection setup by the base station with subscriber stations. A mobile terminal might request multiple connections and services. Thus, in order to ensure service quality, flow resolution is required. This calls for a QoS based transmission scheduler.

Salient features of IEEE 802.16 include adaptive modulation scheme from 64-QAM to QPSK, OFDM technology, directional antennas and transmit and receive diversity. IEEE 802.16 networks manage channel bandwidth efficiently as described in [12]. The most important feature of WiMAX is Adjacent Modulation and Coding (AMC). AMC aims at maximizing the data rate by probing the air transmission and adjusting transmission parameters to channel variations.

## **1.2 Scheduling in OFDMA based wireless networks**

An integral medium access control (MAC) layer process is transmission scheduling which decides the allocation of resources such as bandwidth, channel access, set of sub-carriers and time slots to every subscriber during every scheduling time instance. The standard [13] does not specify a scheduler and leaves it open for vendors to implement custom scheduling algorithms.

Scheduling is an active area of research in IEEE 802.16 networks. The MAC structure of the IEEE 802.16e contains three layers which are Convergence Sublayer (CS), Common Part Sublayer (CPS) and the Security Sublayer. The 802.16e MAC works based on a Request-Grant Mechanism. The Subscriber stations (SS) make bandwidth (BW) requests using a separate MAC header subfield. The MAC is connection oriented and the Base Station (BS) accepts connections after initial ranging that defines the power level of operation and the timing offset. The Uplink Channel Descriptor (UCD) and the Downlink Channel Descriptor (DCD) contain the channel information as depicted in the MAC frame. A

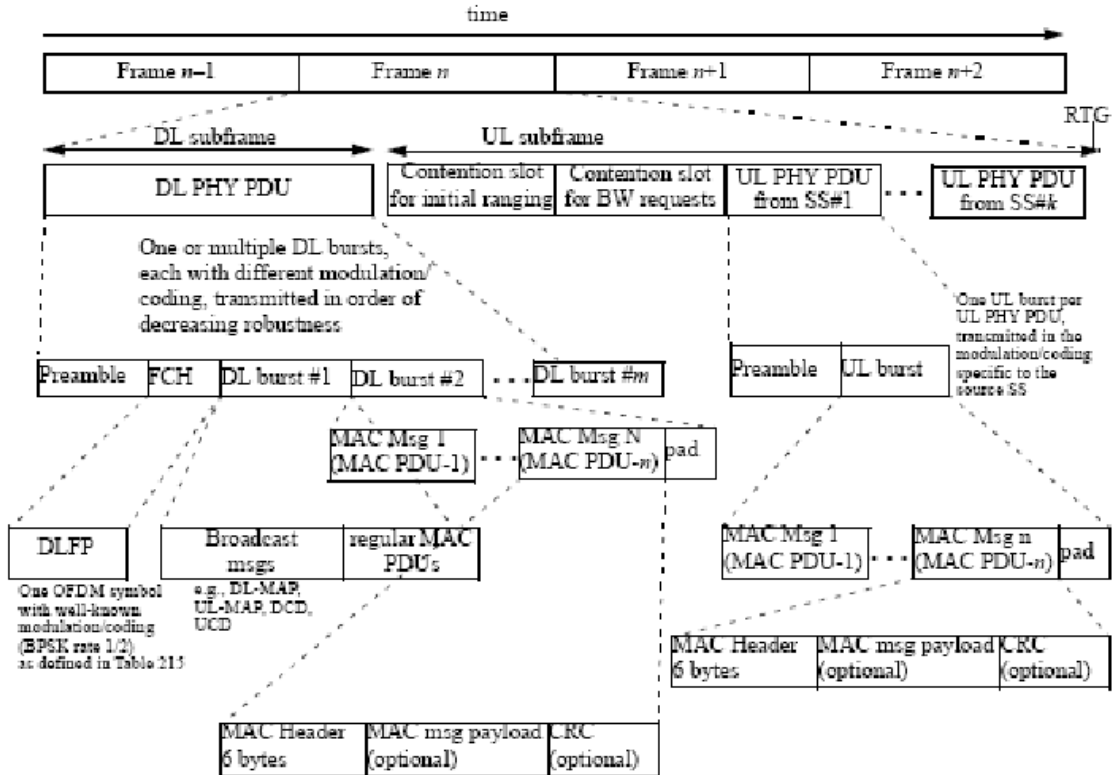


Figure 1.2: IEEE 802.16e OFDMA TDD frame structure

detailed explanation of the role of OFDMA in 802.16e based wireless networks is described in [14]. The TDD based OFDMA frame structure as defined in the WiMAX standard [13] is shown in Figure 1.2.

Sub-channelization in OFDMA networks refers to the grouping of sub-carriers into sub-channels. These sub-channels are assigned to the users based on a static or dynamic procedure. The process of mapping subcarriers to sub-channels is called permutation. But, in wireless networks, the channel properties such as channel to interference plus noise ratio (CINR), maximum achievable data rate etc. change instantaneously. Properties of channels and their subcarriers such as carrier to interference plus noise ratio (CINR), power levels, bit error rate (BER) can affect the data rate and channel utilization. Hence, allocation of

channels to mobile users must be done based on instantaneous channel properties. Such assignment is called as distributed subcarrier assignment.

The mapping of subcarriers into sub-channels is called permutation. The basic objective of permutation mechanisms that define the combinations grouping subcarriers into sub-channels is to increase the frequency reuse ratio. There are two types of permutation - contiguous and diversity. Permutation refers to the random formulation using which the sub-carriers in an OFDMA system are grouped into sub-channels. Diversity permutation methods are used during poor channel conditions as they draw sub-carriers in random and group them. Since the wireless channel conditions vary with respect to time and mobility and result in poor signal quality, diversity methods are popular. The two types of diversity permutation are:

1. FUSC (Fully Used Sub-Channelization) - the pilot subcarriers are first permuted and then the remaining data subcarriers are grouped into sub-channels.
2. PUSC (Partially Used Sub-Channelization) - the used subcarriers are grouped into subchannels and then the pilots are allocated in each subchannel.

Scheduling in 802.16e networks is based on the service flow priority. The types of service flows are unsolicited grant service (UGS), extended real time polling service (ertPS), non-real time polling service (nrtPS), real time polling service (rtPS) and best effort (BE) in decreasing order of priority. The scheduler must be designed by considering the instantaneous variations in channel properties. Our aim is to design a scheduler based on the distributed subcarrier assignment in order to maximize throughput. The scheduler assigns a subset of subcarriers to a user that corresponds to a proportional fairness constraint. User transmissions are scheduled based on priority of service flows.

These issues form the basis of designing schedulers for WiMAX based wireless networks. The first scheduling algorithm is designed for OFDMA based WiMAX networks and is based

on graph theoretic approaches. The second algorithm is designed for WiMAX WLAN hybrid networks and aims at throughput improvement by assigning appropriate schedules based on dynamic user requirements. The design of these algorithms are discussed in subsequent chapters.

### 1.2.1 Hybrid Automatic Repeat Request

Automatic Repeat request (ARQ) is a mechanism in which error detection and retransmission principles are employed to reduce the number of packet transmission errors in the network. An improved version of the ARQ mechanism is the hybrid ARQ mechanism that efficiently uses both the error correction and detection modes to further reduce packet transmission errors.

WiMAX uses simple stop and wait or sliding window protocol through which the sender can transmit a certain number of packets (window size) without expecting an acknowledgement from the receiver. The ARQ at the receiver end detects if there are any errors in the received frame. If an error is found, a request for retransmission is initiated.

If the receiver receives an out-of-sequence packet, it sends a negative ack requesting the sender to transmit the missed packet. On receiving the negative ack, the sender retransmits blocks of data that were lost and moves the sliding window forward when service data unit (SDU) blocks are acknowledged. However, in stop and wait protocol, every packet has to be acknowledged and there is no necessity for a negative ack. The OPNET Modeler was used which supports a stop and wait protocol in which the window size is one.

There is a trade-off between error correction and error detection techniques. In error detection, for every error, a retransmission is initiated. Hence, this technique requires more time to resolve an error. But, the advantage of this method is that it adds only a couple of bytes to the frame. Hence, this method would prove to be efficient in bad channel conditions



also. In contrast, error correction transmits a frame with certain error correction bits. The receiver can rebuild the original message even if it is corrupted by using the error correction bits. But, error correction adds a considerable overhead to the original frame - almost equivalent to the size of the frame. Hence, this method requires a fairly good channel to operate efficiently.

There are two types of hybrid ARQ. Type I HARQ adds both Error Detection (ED) and Forward Error Correction (FEC) information to each frame. This type uses both error correction and detection techniques that is independent of the channel quality. If channel quality is good, the errors are corrected at receiver end. Otherwise, a request for retransmission is sent. Hence, this type proves to be useful for any channel condition. But, this type uses more overhead as both error handling techniques are used.

Type II HARQ transmits either error detection or forward error correction bits. This type switches between the two error handling techniques and thus comparatively uses lesser overhead. In this type, the forward error correction bits are only transmitted on subsequent retransmissions when needed. Type I suffers capacity loss during strong signal condition while Type II does not. Some modifications include adding a part of the message to the subsequent message in order to recover the message from the erroneously received frame efficiently. Other modifications of type II use chase combining and code combining techniques. A detailed analysis over these schemes are introduced and described in [15]

The final chapter provides an overview of other literature in this line of research. Then, the improved HARQ mechanism is introduced. The later sections describe the simulation setup and the results are explained.

## CHAPTER 2

### A GRAPH THEORETIC SCHEDULING ALGORITHM FOR WiMAX BASED WIRELESS NETWORKS

#### 2.1 Introduction

WiMAX is an OFDMA-based wireless metropolitan area networking technology. The MAC layer scheduling for uplink and downlink transmissions plays an important role in affecting the performance of such networks. The assignment of subcarriers to the different users is an important ingredient of MAC layer scheduling algorithms. In this chapter, a new distributed subcarrier assignment algorithm suitable for WiMAX networks is described. In OFDMA based networks, the bandwidth is divided into narrow divisions called sub-carriers. These sub-carriers are modulated individually and assigned to users. The transmissions are scheduled in time and every combination of sub-carrier and time offset is called a channel resource. The described algorithm allocates these resources based on the instantaneous channel properties like signal to interference and noise ratios experienced by users. Since the properties of the wireless medium dynamically change with time and the mobility of the user, static assignment of subcarriers may result in reduced throughput. The scheduling algorithm presented here avoids such inefficiencies by intelligently assigning the channel resources. The algorithm comprises two successive greedy heuristics that maximize throughput per user. It makes use of a bi-partite graph model and an opportunistic matching of subcarriers to users. The effectiveness of the algorithm is studied using NS2 simulations and a variety of traffic scenarios. The resulting throughput with the new scheduler is shown to be superior to that from a round robin scheduler.

## 2.2 Related Work

The major problem associated with wireless networks is the instantaneous change in the channel state due to mobility of the users. This might cause significant throughput performance degradation. When the transmission of these users are scheduled to use the same sub-carrier set for all instances, the change in channel state will result in under-utilization of channel resources. Hence, a static scheduler proves to be ineffective, especially for mobile users. Pseudo random dynamic schedulers [16] can solve this problem to some extent, but they will not adapt effectively to the changes in channel state. Hence, an effective solution is to employ graph theoretic approaches for dynamic scheduling.

Dynamic scheduling can be interpreted as a graph theoretic partitioning problem where the goal is to determine an efficient mapping of subcarriers and time symbols to the users. This mapping can appropriately schedule transmissions of all users and thus reduce medium access delays and utilize the channel to its maximum. The effects of infrequent channel measurements and a dynamic scheduler design for such networks is discussed in [17]. The authors introduce poly-matching where the resource allocation is represented as a matching problem in a bi-partite graph with users and subcarriers as the two entities. Our work uses this representation and we define a matching problem that considers the subscribers bandwidth requests and service flow classifications.

Designing medium access schedulers has been an active area of research and various dynamic adaptive scheduling algorithms have been proposed. The number of symbols on uplink transmissions can be scheduled based on the congestion control mechanism at the TCP layer. Such a mechanism is described in [18]. Scheduling is an important phenomenon in orthogonal frequency division multiple access (OFDMA) in which users are assigned subsets of subcarriers. Users average signal-to-noise ratio can be used to decide the number of sub-carriers assigned as described in [19]. The article also compares two different types

of greedy algorithms. Our work is also based on greedy algorithms but looks into physical channel properties and assigns subcarriers based on a deciding factor. A general technique of allocating upstream channel resources in any broadband wireless access networks is described in [20]. This chapter explains a scheduler at the base-station that assigns uplink opportunities. A mathematical modeling of time-varying channel and multi-user diversity properties applied to optimal opportunistic scheduling is discussed in [16].

Queuing based scheduling is another efficient criterion for assigning subcarriers to users. One such method applied to variable bit rate video applications is described in [21]. The objective of our research is to design an algorithm to assign sufficient subcarriers to users and schedule their transmission based on service priority. The algorithm is a sequence of two separate greedy operations. One of these operations aims at maximizing each users throughput by assigning the subcarriers that are best suitable for that user. The other operation maximizes the whole networks efficiency by allowing the user that has maximum channel properties over a particular subcarrier to utilize that subcarrier. Finally, a mismatch management is performed in order to obtain a net solution.

### **2.3 Double Greedy Scheduling Algorithm**

The main idea behind the scheduler design is to assign subsets of subcarriers to users based on physical channel properties. The main objectives behind hybrid scheduler design are to maximize throughput using distributed subcarrier assignment, to assign a number of subcarriers to a user that corresponds to a proportional fairness constraint, to schedule user transmissions based on the priority of service flow and to design an optimal scheduler that considers the instantaneous variations in channel properties and also maximizes individual user throughput. The first step in designing such scheduler is to allocate sub-carriers to users based on a deciding factor ( $df$ ). The  $df$  is a function of inter-cell interference, channel state

information (CSI) (this is defined in Frame Control Header (FCH) in WiMAX) in terms of pathloss (in db), data rate, SNR and BER. Then, the number of time slots assigned to each user based on the bandwidth requested by each user is determined. The proportional fairness criterion is introduced in order to account for fairness among users for a considerable amount of time. Now, a bipartite graph is drawn, where the user connections and subcarriers are taken as the vertices of the two partitions. The dfs are taken as weights on the edges.

The users are arranged according to the service flow priority. An opportunistic greedy algorithm is performed on the subcarriers. Here, every subcarrier vertex selects edges with higher df. The degree of each subcarrier vertex is the number of symbols (units of time). Adjacency matrix is a matrix in which each entry is the number of edges adjacent to a subcarrier vertex and a user vertex. Initially, the subcarrier adjacency matrix -  $adj-sc$  is formulated. Then, an opportunistic greedy algorithm on the users is performed. Here, every user vertex selects edges with higher df. The degree of each user vertex is the number of time-slots allowed for that user. The user adjacency matrix -  $adj-u$  is formulated.

Finally, the final adjacency matrix is formulated by performing an element by element OR operation i.e.  $adj = adj-sc \text{ OR } adj-u$ . The user mismatches and subcarrier mismatches are determined and time slots are assigned based on an adjustment algorithm. All other connections are pseudo randomly assigned with the available subcarriers. The pseudo code of the algorithm is shown in Figure 2.1.

```

Start
Read df [N][M], lim_u[N], K
Initialise - each element of deg_sc [] to K, adj_sc, adj_u and adj to zero.
//deg_sc [j] is the degree of vertex j.
sub_greedy ()
{
    for j = 0 to M-1 AND deg_sc [j] < K
    {
        l = max_col(df j)
//returns the row index for maximum element in column j of array df
        if deg_u[l] < lim_u[l]
        {
            increment adj_sc [l][j]
            update deg_u
        }
    }
}
zero each element of deg_u and deg_sc
usr_greedy ()
{
    for i = 0 to N-1 AND deg_u[i] < lim_u[i]
    {
        l = max_row(df i)
//returns the column index for maximum element in row i of array df
        if deg_sc [l] < K
        {
            increment adj_u [i][l]
            update deg_sc
        }
    }
}
final()
{
    adj = adj_u OR adj_sc
//perform an element by element OR operation
    mismatch(adj_u, adj_sc)
//call mismatch procedure to obtain the final map.
}
}

Where,
N - Number of users
M - Number of sub-carriers
K - Number of time symbols in a scheduling instance
lim_u - Array containing the degree limit of each user based on bandwidth
request
deg_sc - array containing the degree of each sub-carrier vertex
deg_u - array containing the degree of each user
adj_sc - adjacency matrix obtained from sub-carrier greedy operation
adj_u - adjacency matrix obtained from user greedy operation
adj - final adjacency matrix

```

Figure 2.1: Pseudo code of the double greedy scheduling algorithm

### 2.3.1 Scheduler Design Details

The first step is to allocate sub-carriers to users based on a deciding factor (df). The number of sub-carriers depends upon the bandwidth requested by a user connection. Each service flow request is translated by the WiMAX MAC as a connection. This function is performed by the service specific convergence sublayer of WiMAX MAC. The proportional fairness criterion is introduced in order to account for fairness among users for a considerable amount of time.

The scheduler assumes that the channel quality index is available at each scheduling period. A deciding factor (df) is computed using the relation :-

$$df_{ij} = CINR_{ij} Pwr_{ij} PL_{ij}$$

where, CINR Carrier to Interference plus Noise ratio Pwr Transmission Power level (in dB) PL pathloss (in dB) and and scaling constants j Subcarrier index

$$No\ of\ subcarriers_i = BWR_i * pf_i$$

where,  $BWR_i$  bandwidth requested by user i.  $Pf$  proportional Fairness criterion

Then, a mapping bipartite graph is drawn where the user connections and subcarriers are taken as the vertices of the two partitions as shown in Figure 2.2.

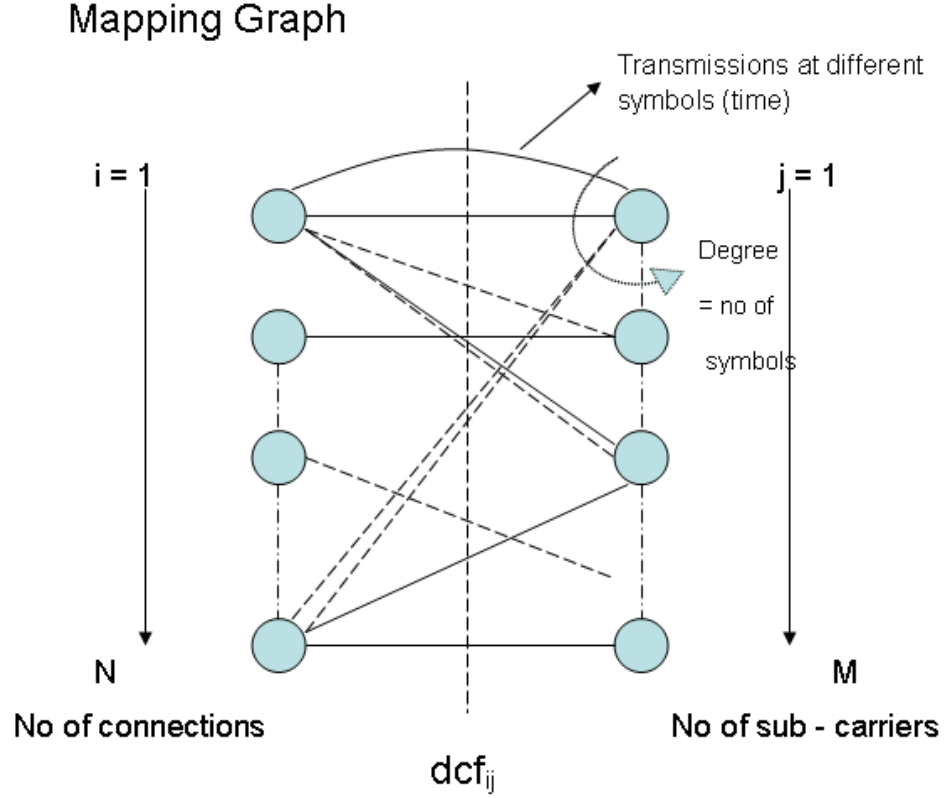


Figure 2.2: The bipartite representation of users and subcarriers

The deciding factors are taken as weights on the bipartite edges. An opportunistic greedy algorithm is executed on the subcarriers. In this operation, every subcarrier vertex selects edges with the next highest deciding factor. The degree of each subcarrier vertex is the number of time symbols. This is done in such a way that the degree on the user vertices do not exceed respective bandwidth request indices stored in the array  $deg_u(i)$ .

The next step is to perform a greedy operation on the users. After the greedy subcarrier assignment operation, the user transmissions are arranged based on service priority in the order of UGS, ertPS, nrtPS, rtPS and BE. This makes the cross-layer scheduler comprehensive, proportionally fair and also throughput efficient. Now, for every user the best set of subcarriers is chosen such that the user vertex degree does not exceed the respective entry



in the  $deg_u$  array. Also, care is taken to ensure that the degree on each subcarrier vertex does not exceed beyond the maximum number of time symbols. The adjacency matrices are computed during these processes.

Now, there may be many mismatches. A mismatch graph is drawn with excess edges as solid edges. Every connection vertex that requires a subcarrier assignment is connected with all subcarrier vertices with broken edges as shown in Figure 2.3.

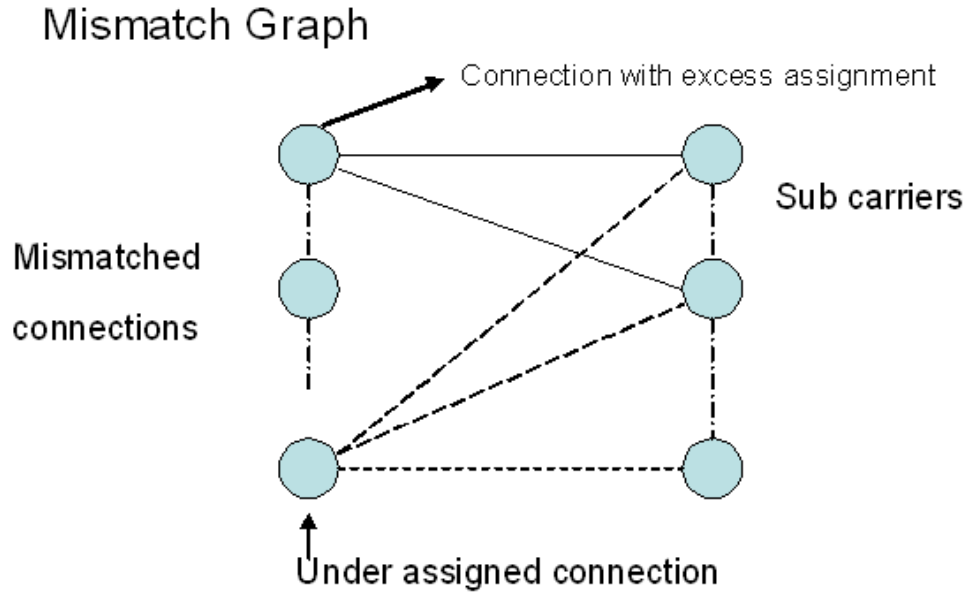


Figure 2.3: Graph representing the mismatched user connections and subcarriers

At every subcarrier vertex, excess edges of lesser deciding factor are removed and newer edges with limits on degrees of this subcarrier vertex and other connection vertices are drawn. Thus, the degree of each vertex in both graph partitions are maintained within their respective constraint values. The mismatches are such that the sum of all mismatch vectors is zero. Since the degree of each vertex during both operations are unaltered, the number of edges of the final bipartite graph during both operations remain the same. An edge is drawn between any two vertices and in any simple graph, the total number of edges

is half of the total number of vertices. Hence, the total number of edges remain the same as the total number of vertices remain the same. All connections other than those addressed by the double greedy algorithm are randomly assigned with the available subcarriers.

## 2.4 Simulation and Results

The algorithm was implemented using the WiMAX patch for NS2 simulator provided by National Institute of Standards and Technology (NIST) [22]. An external executable of the double greedy algorithm was linked with the scheduler developed by NIST. Various scenarios were simulated using the original round robin and modified double greedy scheduler and the efficiency of the algorithm was determined. The simulator settings are described in Table 2.1

Table 2.1: Simulation Parameters

Parameter	Value
Packet Size	1500 bytes
Packet gap length	0.001 s
Downlink to uplink traffic ratio	0.3
OFDM cyclic prefix	0.25
Frequency of operation	2412 MHz

The simulation setup consisted of an 802.16 base station and a sink node connected to it using a duplex link. The simulated network was hierarchical with the WiMAX base station on top of the hierarchy. The mobile subscriber nodes were placed randomly in a grid of 1100X1100. Application traffic was initiated among the nodes and the sink and all traffic were routed through the base station. The results obtained are explained as follows.

### 2.4.1 Application traffic over UDP

UDP agents were setup on the mobile nodes and the sink node and CBR application was used. The average throughput was measured and plotted by running the simulation for different number of WiMAX nodes. It can be noted that the throughput in the case of the double greedy scheduler is about 40Kbps greater than that of the round robin scheduler as shown in Figure 2.4.

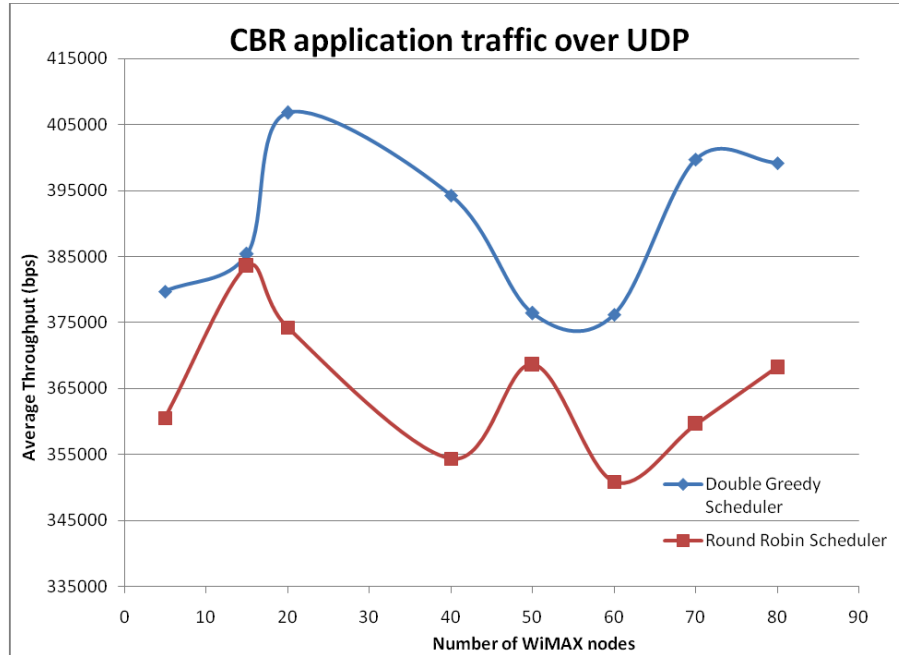


Figure 2.4: Throughput variation over number of nodes for CBR traffic over UDP

Similarly, it was found that the double greedy algorithm yields better throughput for Pareto application traffic as shown in figure 2.5. Pareto traffic has a distribution in which the probability that  $X$  is greater than some number  $x$  is

$$Pr(X > x) = (x/xm)^{-k}$$

For larger number of WiMAX nodes, the double greedy algorithm behaves similar to the round robin as the limit on the number of subcarriers used is a constant value. Hence

there are not enough resources to match all requirements and so, the scheduler assigns the available sub-carriers to users requesting better service quality and higher priority. This is similar to the round robin mechanism.

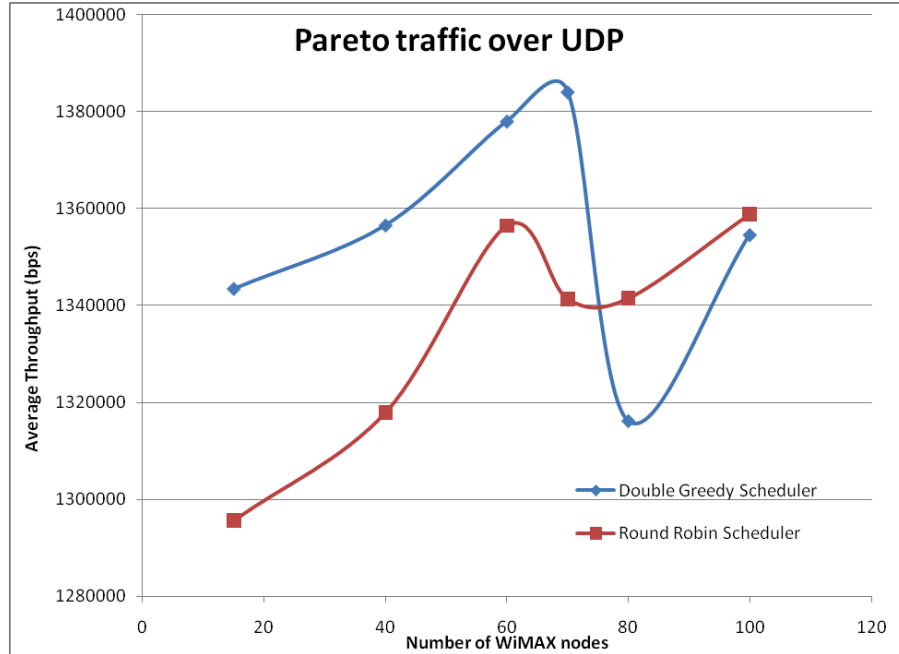


Figure 2.5: Throughput variation over number of nodes for Pareto traffic over UDP

#### 2.4.2 Application traffic over TCP

The second simulation is to employ TCP agents and run FTP application over them. In this case, the measured throughput in the double greedy scheduler is much greater than that of a round robin scheduler. The throughput improvement in this case is well pronounced than using application traffic over UDP. The main reason is that UDP is based on best effort packet delivery while TCP works on congestion avoidance. In this case, the congestion window keeps on incrementing during the congestion avoidance phase. This is because every subscriber is scheduled to access a particular sub-carrier at a time and so

there are no collisions. Hence we can see that TCP congestion window increases with round trip time as shown in Figure 2.6.



Figure 2.6: Congestion window vs time for FTP application over TCP

Thus, the number of packets in a connection depends almost entirely on the receiver advertised flow control window size (rwnd). This is because in a TCP connection the effective window size is the minimum of congestion window size (cwnd) and receiver advertised flow control window size. Since cwnd keeps on increasing due to no congestion, after some time the rwnd entirely decides the throughput.

Thus, more packets are allowed to be pumped through the medium and hence an increase in the throughput can be noted. Using the double greedy scheduler, the MAC delays are reduced and hence the round trip times (RTT) remain fairly constant at a lower value. The TCP retransmission timeout (RTO) value depends upon RTTs consistency. In the double greedy scheduling case, constant RTO and smaller MAC delays lead to less retransmission. Thus, we can see that TCP remains in congestion avoidance. The throughput

performance for FTP application and CBR traffic over TCP connections is determined and plotted. It can be seen from figures 2.7 and 2.8 that the double greedy scheduler yields better throughput than the round robin scheduler.

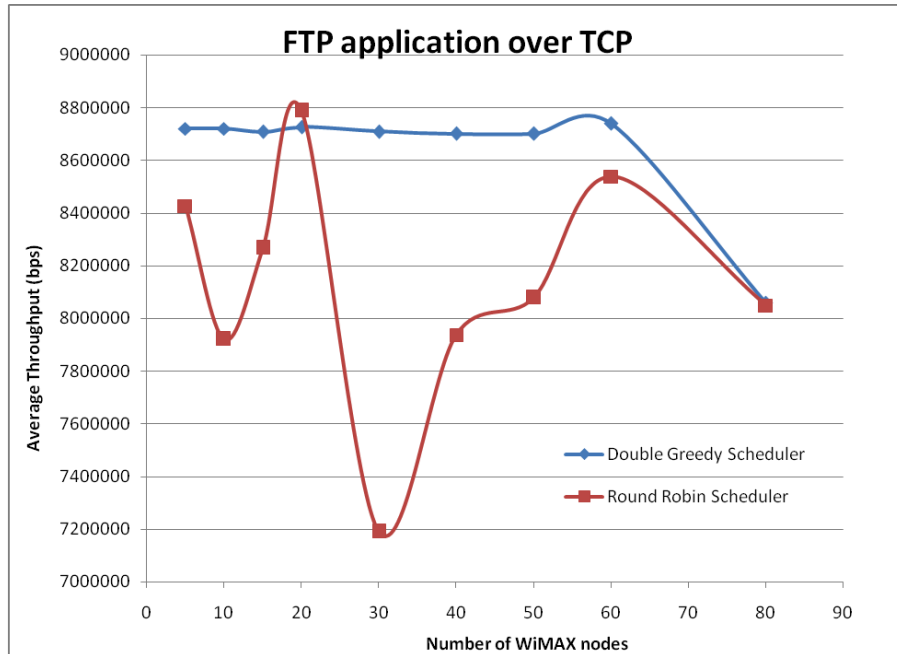


Figure 2.7: Throughput variation over number of nodes for FTP application over TCP

The scheduler performance is oblivious to the transport layer protocols. In this work, the classic TCP model was used. It was found that the scheduler improves per-user average throughput for both TCP and UDP agents. The primary function of the scheduler is to reduce medium access delay and in both TCP and UDP protocols, lesser medium access delay would yield better throughput. For constant bit rate applications, the packet size used was 1500 bytes in 0.001 seconds with a data rate of 12Mbps.

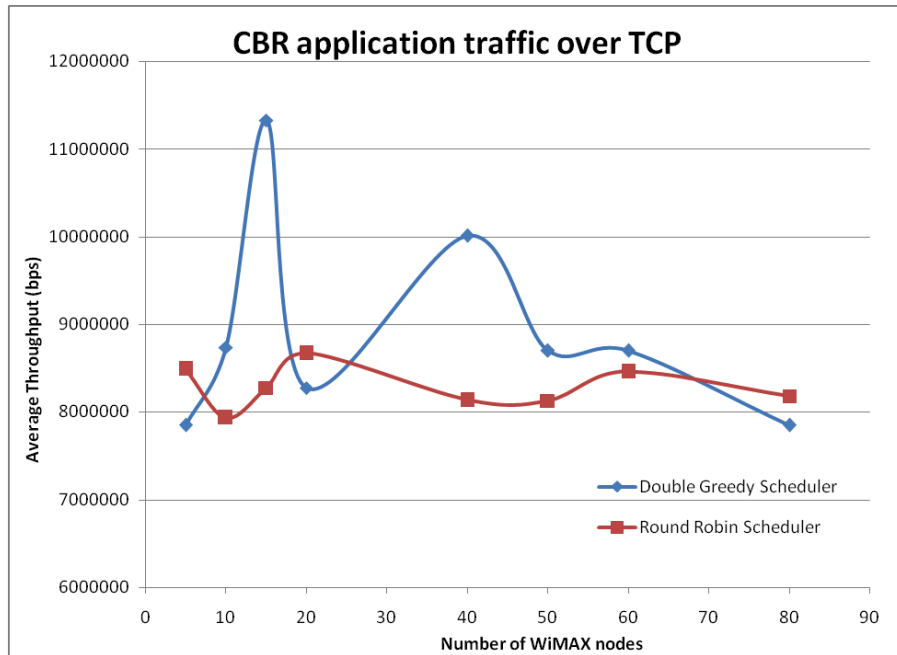


Figure 2.8: Throughput variation over number of nodes for CBR application traffic over TCP

In real-time, users may employ different types of traffic. For example, a voice over IP (typically CBR traffic over UDP connections) user might experience poor service quality due to the increase in overall network traffic. It is important to study the effect of increase in TCP users on the users running VOIP applications. It is interesting to note that the double greedy scheduler yields better throughput compared to the round robin scheduler, for nodes running CBR application over UDP when the number of nodes running TCP traffic is increased as shown in Figure 2.9.

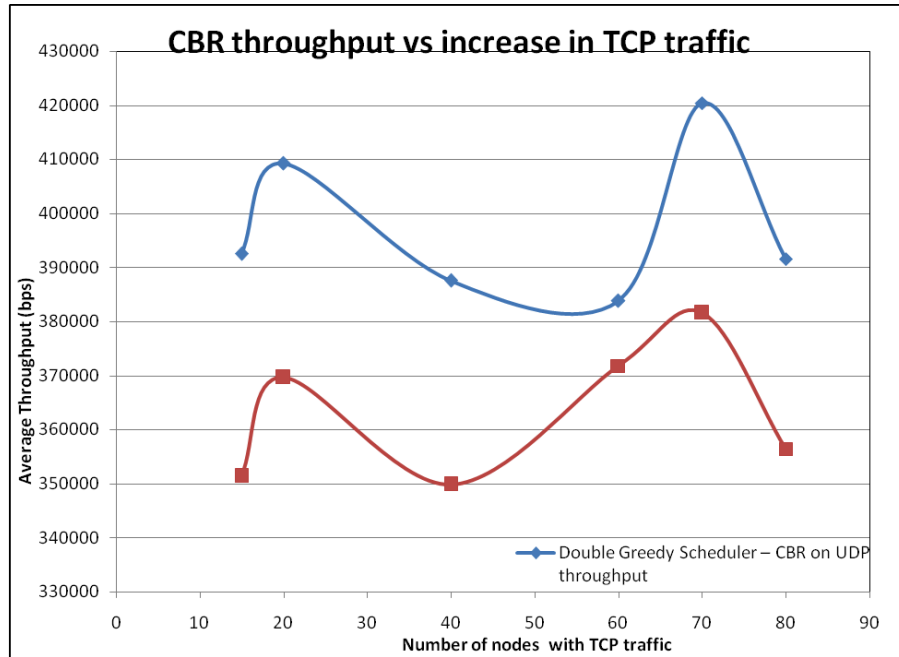


Figure 2.9: Throughput of UDP users over number of nodes running TCP traffic

Munkre’s assignment algorithm also known as the Hungarian algorithm [23] is an algorithm that provides optimal solution to matching problems. However, it has a running time in the order of  $O(n^3)$ , where  $n$  is the number of users. The Double Greedy scheduler is simple and has a running time of  $O(n^2)$ . The throughputs were measured for similar settings as described before. The average throughput is the average of every packet’s individual throughput. The overall throughput is a measure of the number of packets sent over the entire session. The average throughput and the overall throughput was compared. It was found that Double Greedy scheduler yields the best overall throughput as shown in Figure 2.10.



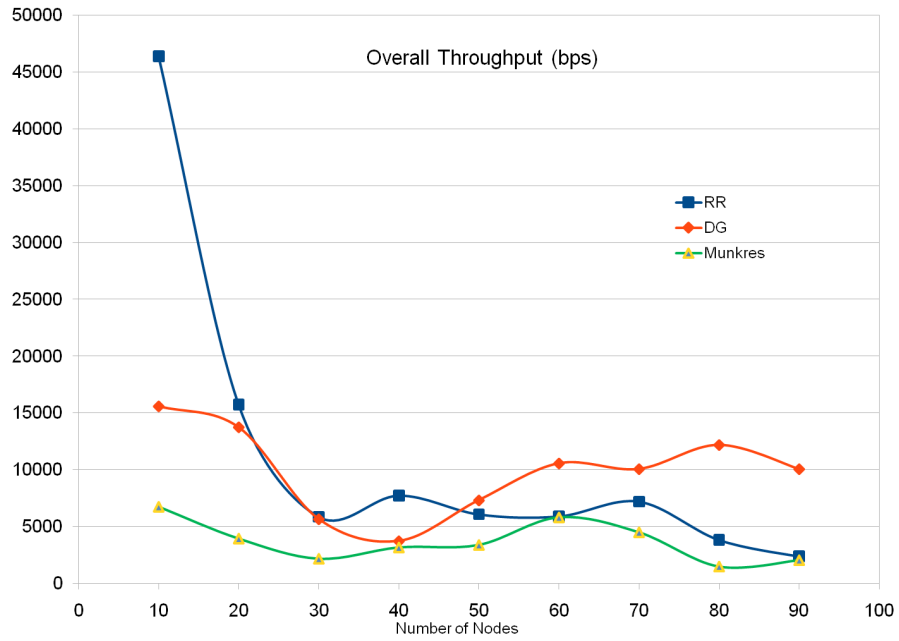


Figure 2.10: Overall Throughput of UDP users over number of nodes running TCP traffic

Munkre's assignment based scheduler could yield better average throughput for lesser number of nodes as shown in Figure 2.11. The munkres C++ implementation found in [24] was used. This was ported on NS2 and the elements of the cost matrix was determined by inverting every element of the df matrix.

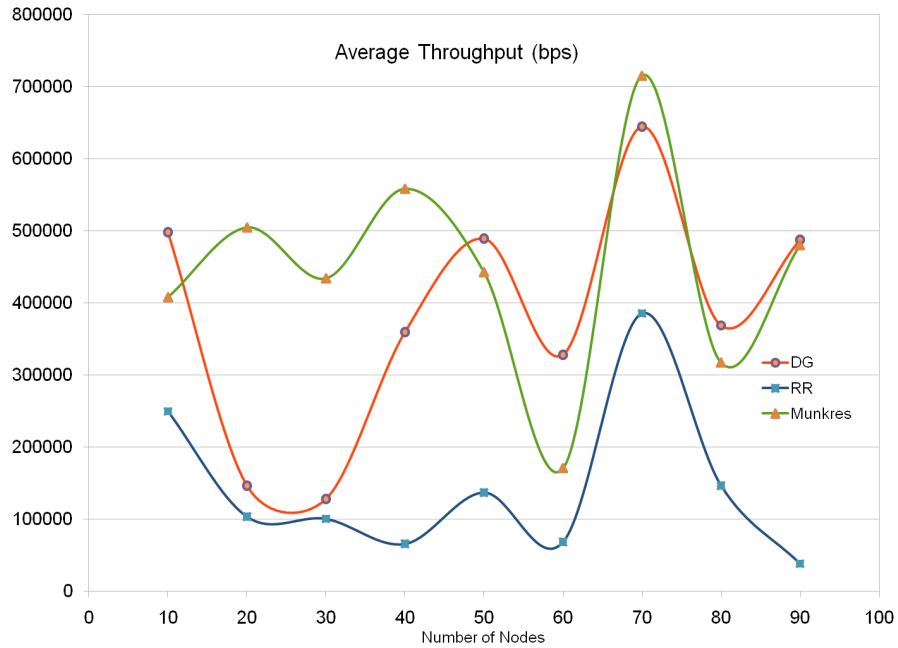


Figure 2.11: Average Throughput of UDP users over number of nodes running TCP traffic

## 2.5 Future Work

The future work in this line of research includes efficient computational techniques to increase the speed of operation. There are various graph theoretic algorithms and implementing these techniques for scheduling would be interesting. Famous graph theoretic algorithms such as Kernighan-Lin [25] can be employed for matching the two bi-partite vertices.

## 2.6 Conclusion

An efficient algorithm to schedule user transmissions in an OFDMA based wireless network was designed and implemented. The algorithm works on two successive opportunistic greedy modules that assign a set of subcarriers to users. Such assignment leads to high average throughput per user and also makes the best use of the available subcarriers.

Moreover, the priority of service flows is considered in assignment. Thus, this scheduler proves to be a comprehensive solution for OFDMA based wireless networks.

## CHAPTER 3

### A SCHEDULING ALGORITHM FOR WIRELESS HYBRID NETWORKS

#### 3.1 Introduction

Hybrid wireless networks can be conceived by combining suitably interfaced 802.11 access points (APs) and WiMAX (802.16) backhaul. Integration of heterogeneous wireless networks has been an interesting research topic. One such integration mechanism is described in [26]. However, integrating such networks requires considering factors such as throughput fairness, capacity, average user delay etc. One of the major problems associated with 802.16/802.11 networks is the increased communication delay experienced by 802.16 users. In this chapter, a plausible solution is described to address this problem. Containing such delay is important in maintaining quality of service for VoIP applications, for example. This delay can be substantially decreased by a strategic reduction in the number of active 802.16 subscribers in the network. WiMAX connections at any point of time, that are currently serviced by the base station is referred to as active subscribers. This chapter deals with realizing such delay reduction by rerouting traffic thru lightly loaded 802.11 APs. For doing so, a schedule has to be generated using an algorithm. A scheduling algorithm was designed and its effect on the overall network performance, using end to end packet delay as a metric, was analyzed. For this purpose CBR traffic were used over UDP connections. NS-2 simulations using CBR traffic show significant improvement in end-to-end packet delay.

### 3.2 Related Work

The effect of different scheduling algorithms on the packet delay and performance degradation due to increase in the number of subscribers is discussed in [27]. A hybrid network can be conceived by a network of 802.11 networks with an 802.16 backhaul network as shown in figure 3.1. A methodology to extend the coverage of 802.11 networks by reducing handoff probability based on signal strength variations in a hybrid network is presented in [28]. Hence, the overall network performance can be improved by scheduling transmissions of various heterogeneous users in a wireless hybrid network. This forms the crux of the problem that this research aims to solve. The throughput capacity of hybrid wireless networks and the effects of the number of nodes and base stations are analyzed in [29]. Most of these approaches concentrate on the performance degradation due to increase in the number of 802.16 subscribers. This report examines the potential of reducing the effective number of 802.16 users on the network performance. Thus, by reducing the number of active users, the contention in the network can be minimized and hence average individual throughput can be improved.

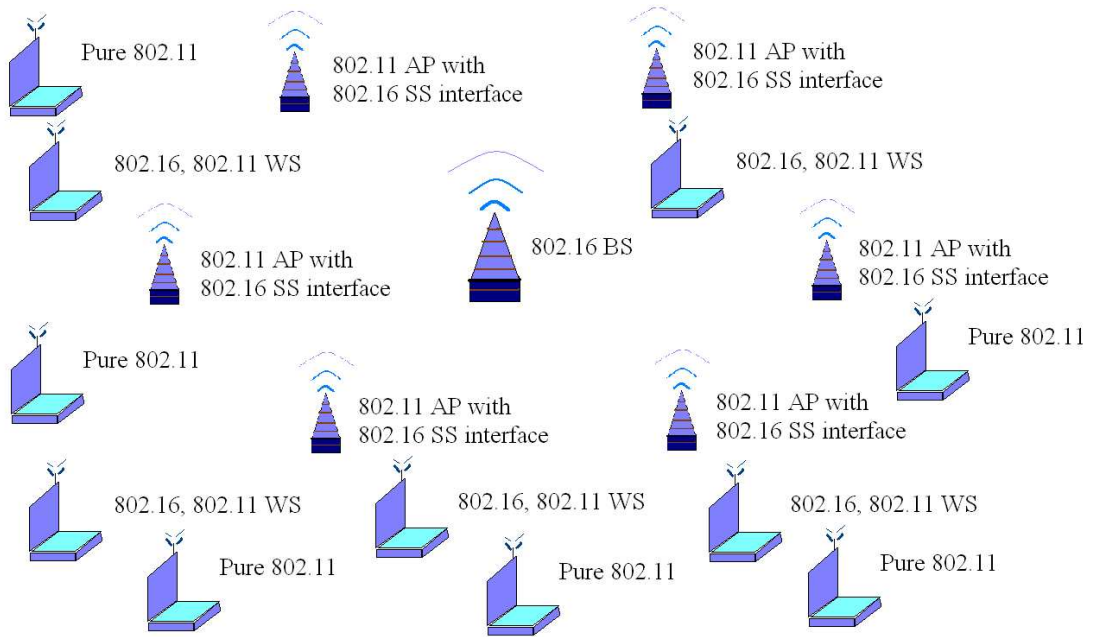


Figure 3.1: Topology of a hybrid network with 802.11 WLANs with an 802.16 backhaul

### 3.3 Scheduling Algorithm

The main idea behind the scheduling algorithm is to allocate time slots to 802.16 subscribers based on their distance from the gateway. Typically, users placed farther away from the base station take up more time for data transmissions. This is because, the propagation delay is large with longer distances. Hence, the scheduler allocates resources for one user with larger data rather than several users with lesser data. This transmission aggregation process reduces contention in ranging, connection establishment and capabilities negotiation processes. Thus, the scheme can improve the overall average user throughput by enabling more frequent channel access.

The main idea is to allow those workstations, farther away from the 802.16 BS, to forward their packets through an 802.11 AP. An important consideration is the traffic support provided by the 802.11 AP. The 802.16 BS knows the bandwidth requested by an

802.11 AP and hence can decide whether the route through the 802.11 AP will be optimal. For example, let the bandwidth requested by an 802.11 AP be only 100 kbps while it can request up to a maximum of 5 Mbps. Now, suppose that an 802.16 subscriber farther away from 802.16 BS but closer to the 802.11 AP requests 64kbps. Then, this 802.16 subscriber can forward its packets through the 802.11 AP in order to aid the 802.16 BS in serving all its active subscribers with sufficient time slots.

The scheduling algorithm aims at modifying the basic steps of operation of the 802.16 BS. The MAC management messages that are used to pass control messages between the 802.16 BS and SS are described in [2]. Initially, it is required to acquire the information on the list of 802.11 APs. Threshold values of service parameters such as delay in VOIP applications are determined and will be used in deciding the route for the workstations packets. The 802.16 BS broadcasts a downlink map message (DL-MAP), downlink channel descriptor (DCD) and uplink channel descriptor (UCD) with sync information that lists out the available channels. The SS listens for this information in a defined frequency list while operating in the licensed band. When the SS is synchronized with a downlink channel, it initiates the initial ranging process by sending a ranging request (RNG-REQ) MAC management message to the BS. The 802.16 BS collects and processes all the RNG-REQ messages and sends a ranging response (RNG-RESP) to the subscribers. Capability negotiation, where the SS sends a capability request with a list of supported modulation levels, coding rates and schemes is performed. At this juncture, the scheduling algorithm requires the BS to analyze bandwidth and service requests by all 802.16 subscribers and assign alternate routes through 802.11 APs for those subscribers requiring services lesser than the threshold parametric values. This process is hooked into the basic WiMAX operation. The BS updates the threshold values based on the aggregate service requested by the 802.11 APs. The BS broadcasts updated map messages to the new set of 802.16 subscribers. This

is followed by authentication by which an SS gets registered with the BS. The main steps of the algorithm are illustrated using Figure 3.2. The average overhead delay incurred by assigning routes through 802.11 APs will be lesser than that caused at the 802.16 BS for ranging large number of 802.16 subscribers. The main advantage offered by this scheduling algorithm is a comprehensive decision on an 802.16 subscribers interface selection made by the 802.16 BS to improve the overall network performance.

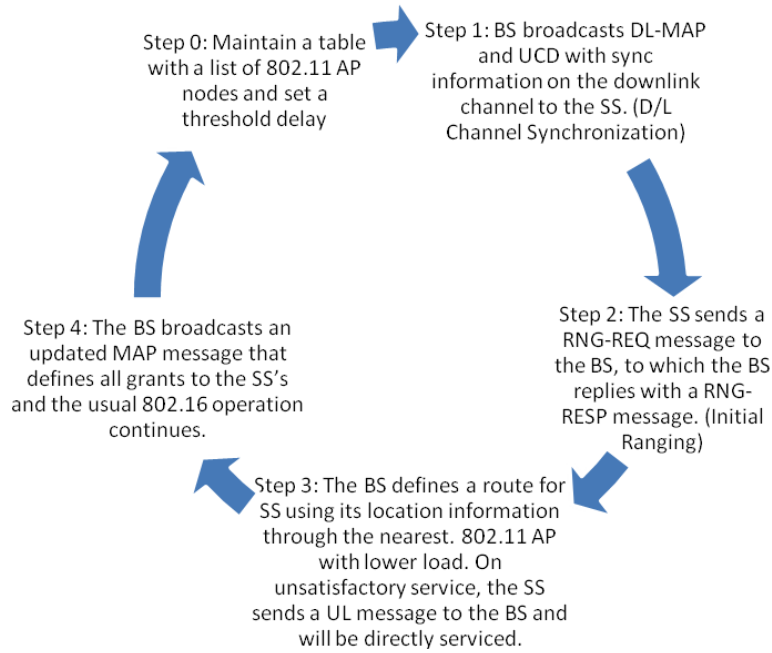


Figure 3.2: Steps of network operation based on the scheduling algorithm

### 3.4 Simulation Setup

The simulation was performed using NS-2 simulator provided by Communication technology lab, Intel Corporation. The topology constitutes an 802.16 BS and a group of subscribers scattered randomly around the BS. The workstations are employed with WiMAX interface. The simulation parameters are listed in table 1.



Table 3.1: Simulation Parameters

Parameters	Value
TDD Frame Duration	5 ms
TDD Ratio	2
Control Signals rate	10 Mbps
Burst rate	50 Mbps
Contention Slot duration	0.0001
Data Slot duration	0.0005
Number of contention slots	7

The frame duration is set to 5 ms as in the case of OFDMA. The TDD ratio defines the number of downlink (D/L) frames to the number of uplink (U/L) frames. The control signals rate refers to the transmission rate of the preamble, D/L map and U/L map. The number of contention slots for the BS is set as 7. The average packet end-to-end delay was estimated for one fixed subscriber. The algorithm was simulated by increasing the number of subscribers by 1 for every 5 new users and the packet size for 5 subscribers were increased by 512 bytes. This is similar to aggregating five user transmissions on to an 802.11 access point and increasing the bandwidth requested by this 802.11 AP/802.16 SS device.

### 3.5 Results

The number of unsuccessful packets was found to increase with the number of 802.16 subscribers in the network as shown in Figure 3.3. This increase is due to the contention between the 802.16 SS to obtain access over the ranging channel. The 802.16 subscribers can get access to the wireless channel for data transmission only if they are successful in ranging with the base station. The algorithm design and results can be found in [30].

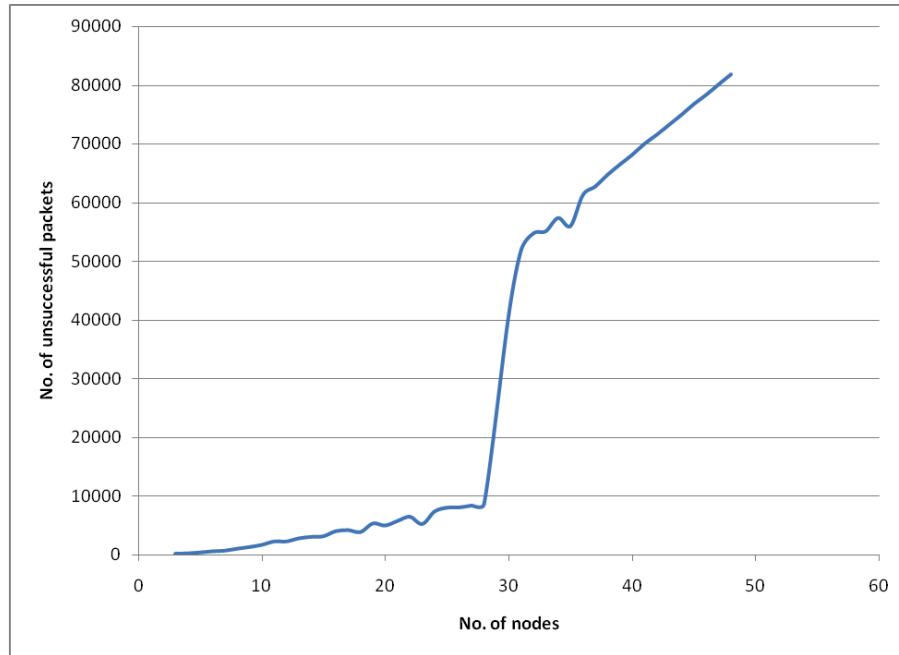


Figure 3.3: Number of unsuccessful packets vs. number of nodes

If there are more users contending for ranging with the base station, the probability of a subscriber to get access to the channel is reduced. Thus, in order to assign frequent channel access to the users, the base station can request data aggregation on one intermediate node. This is the basic idea of the scheduling algorithm. This algorithm was implemented in NS2 and the delay plots over number of users were obtained. These plots confirm the improvement achieved by the algorithm. The delay was found to be reduced by around 40ms for a total of 50 workstations in the hybrid network. For lesser number of nodes, the improvement is not very pronounced as there are enough resources to handle all connections. However, as the number of nodes increase, the algorithm proves to be efficient by assigning frequent channel access as shown in the figure 3.4.

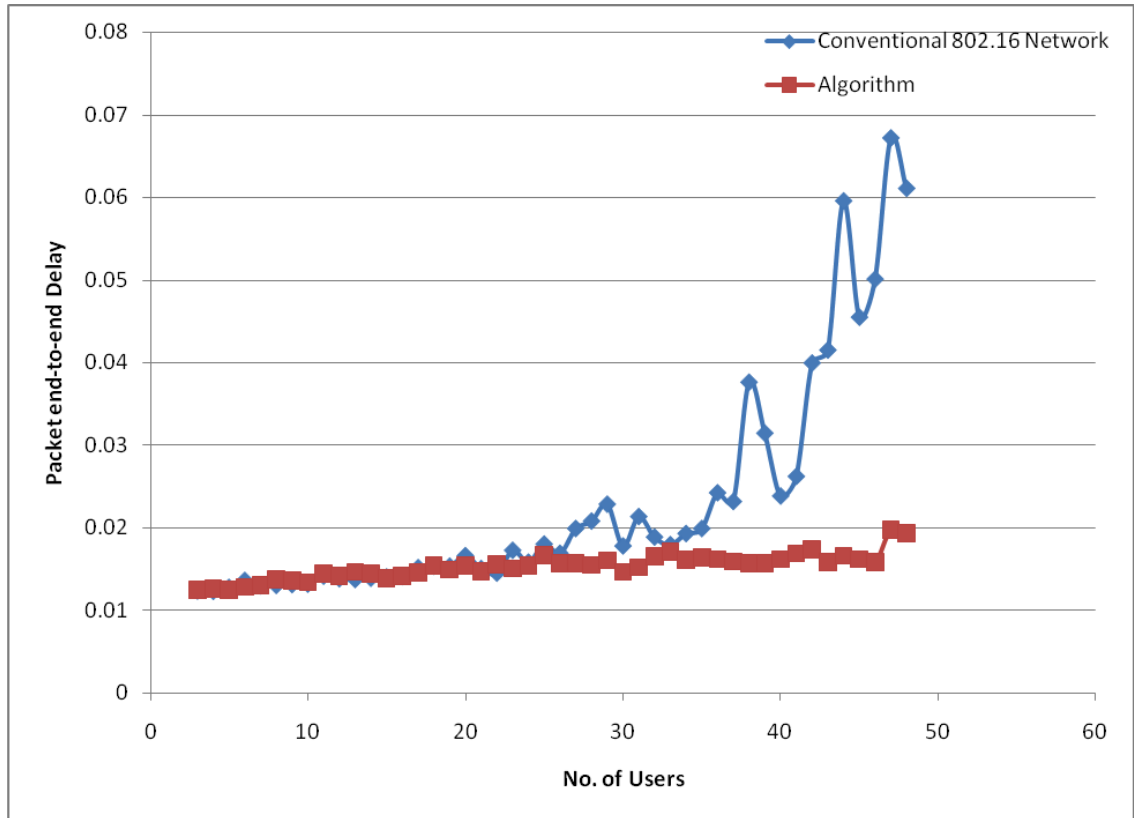


Figure 3.4: Delay vs. number of users in CBR traffic over UDP connections

### 3.6 Conclusion and Future Work

It can be concluded that the network performance degrades due to increase in number of 802.16 users in hybrid 802.16/802.11 networks. A comprehensive solution to this problem would be to assign schedules for lightly loaded 802.11 users with 802.16 interfaces based on their position with respect to the 802.11 APs. The efficiency of the algorithm in a scenario with a variety and different mixes of traffic applications can be determined. It will be interesting to consider the handoff schedules for mobile users. Future work in this direction includes modification of the scheduling algorithm to suit mobility and heterogeneous traffic.

## CHAPTER 4

### AN EFFICIENT HARQ RETRANSMISSION ALGORITHM IN OFDMA BASED WIRELESS NETWORKS

#### 4.1 Related Work

Hybrid automatic repeat request (HARQ) is an efficient method to handle error correction and detection mechanisms. It enhances the reliability of the packets from source to destination. Various methods have been proposed to enhance ARQ methods for wireless networks. The performance of a selective repeat ARQ method for wireless ATM networks is described in [31]. It is shown that retransmissions improve the link quality and has no significant effect on the end-to-end delay. The sequencing of packets is required to be properly maintained especially when using ARQ based error recovery. Hence, all packets that are correctly received after an erroneous packet need to be retained until this packet has been retransmitted correctly. This is called as re-sequencing delay and the methods described in [32] aim to reduce such delays. These methods are important for applications such as video traffic that require proper sequencing. Our method also addresses similar problems but aims at maintaining the overall data rate and sequencing. A classical method to improve bandwidth in an ARQ based system is to retransmit only the re-coded data packet. Estimation of channel conditions in these cases is very important [33]. We make use of channel estimations in our method in order to selectively retransmit the erroneous data packets using sub-carriers best suited for these packets. Physical layer improvements using MIMO antennas and space time architecture for enhancing HARQ performance is

discussed in [34]. ARQ techniques have been widely exploited in WiMAX and their performance analysis is provided in [35]. The WiMAX standard [13] makes use of two important technologies HARQ and OFDMA. It is important to analyze the HARQ schemes when applied to OFDMA systems. Such analysis is performed in [36] in which it was found that type II HARQ offers best throughput performance. In OFDMA based systems, each user can be assigned a set of subcarriers based on dynamic channel variations. We make use of this fact to assign suitable subcarriers for HARQ retransmission purposes. Error recovery and packet retransmission in multicast services over OFDMA systems are cumbersome and uses up a lot of downlink resources. A method to minimize these issues is described in [37]. Some improvements over TCP handle link layer retransmissions efficiently. The effect of local retransmissions in wireless networks on TCP is discussed in [38]. The link layer retransmission handling explained in [39], aims to improve throughput by introducing timestamp and avoids out-of-segment packets. We employ similar technique in our research and apply the timestamp method to packet retransmissions alone in OFDMA based systems. The scheduling of these packets in time is also based on the timestamp value. This research area has been active in the past few years. A hybrid ARQ mechanism designed for frequency selective fading channels is discussed in [40]. The authors use a turbo equalizer modification to achieve better exploitation of channel diversity and improved frame error rates. Our approach also exploits channel diversity in order to appropriately schedule the HARQ retransmissions. The following section introduces and describes the proposed improvement.

## 4.2 HARQ Improvement

In this research, we introduce an improvement to the conventional HARQ scheme. We concentrate on using the channel diversity by scheduling retransmissions effectively.

We assume that the variation of channel properties such as signal to noise, distortions and interference ratios is random in nature. Hence, the HARQ transmissions and retransmissions are scheduled based on this variation. By selecting a random sub-channel for the HARQ frames, we can observe a throughput enhancement. This is due to the fact that the HARQ scheme uses different sub-channels during different channel conditions. This scheme can prove to be efficient especially for WiMAX nodes whose transmissions are spatially and temporally diverse.

Another improvement to the HARQ scheme is to use timestamps to indicate the importance of a frame. If a frame retransmission is out-of-sequence by several packets such that it is close to unnecessary, then this packet would not be needed. In such cases, these retransmissions can be avoided by discarding those packets at the sender end. A simple flowchart of this modification at the base station is shown in figure 4.1

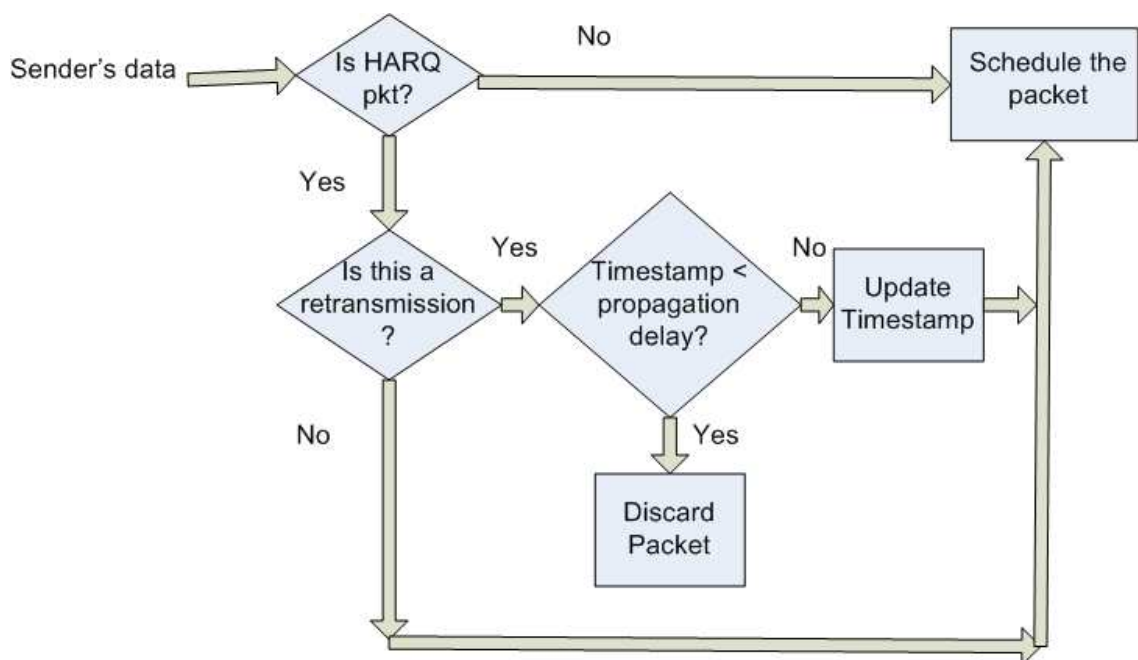


Figure 4.1: HARQ modification in base station

### 4.2.1 Code Implementation

This scheme was simulated using the OPNET Modeler (r) wireless suite. A stop and wait based HARQ scheme is implemented in the node's process models. A base station's uplink and downlink HARQ transmission handling procedures were modified to suit the improvement. In the conventional HARQ implementation, the base station selects a particular HARQ channel. In the improved version, we assign a random sub-channel based on a uniform distribution for HARQ transmissions and retransmissions. The modifications were performed in the base station MAC control procedure.

### 4.3 Simulation Parameters

The simulations were performed using the OPNET modeler. The scenario consists of WiMAX base-station, an application server and four WiMAX subscriber stations as shown in figure 4.2. One of the nodes - node 2 was equipped with HARQ mechanism. All the nodes were placed randomly within a distance of 500 meters from the base station. Different applications were used and results were generated. The common parameters used for the simulations are listed in table 4.1. The maximum power refers to the total transmission power that a node can output over the entire channel bandwidth. The actual transmission power is scaled down based on the fraction of bandwidth used by a node.

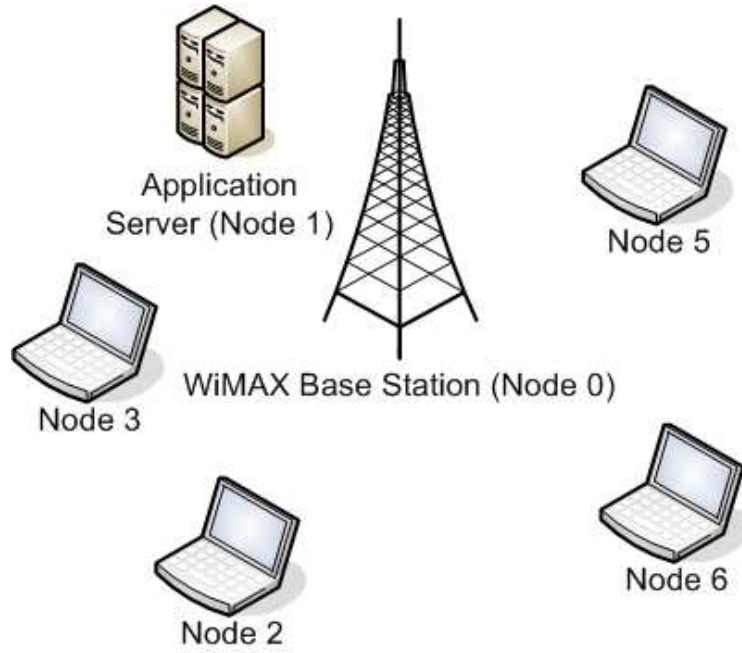


Figure 4.2: Simulation Scenario

The power density attributes are defined in the base station. They refer to the amount of power in a single sub-channel. These attributes including the transmission power decide the number of sub-carriers that can be scheduled for a particular user. The objective is to study the effect of HARQ and its performance in poor channel conditions. This is achieved by introducing packet errors through certain mechanisms. The classical freespace model was used to introduce packet errors due to physical layer effects. In addition to this, packet errors can be introduced by using the PDU dropping probability attribute in the server node. The CQICH period refers to the amount of frames after which the subscriber station would transmit the CQI (Channel Quality Indicator) back to the base station. The CQI is a measure of channel properties such as signal to noise, distortions and interference ratios. A subscriber station waits for  $2^p$  frames to transmit the CQI, when the CQICH period is  $p$ . The request retries attribute refers to the number of times the subscriber station would



try to retransmit the CDMA based bandwidth request for a particular connection before dropping the packet. As per the WiMAX standard [13], this value is set to be 16.

Table 4.1: Common Simulation Parameters

S. No.	Simulation Parameters	Value
1	Max. Pwr. Density received power tolerance	-90 dBm/sub-channel
2	Min. Pwr. Density received power tolerance	-60 dBm/sub-channel
3	Max. transmission power	0.5 W
4	Pathloss model	Free space
5	Modulation and coding	QPSK 3/4
6	CQICH period	3
7	Request Retries	16
8	Server PDU dropping probability	0.10

The HARQ parameters that were used by node 2 is listed in table 4.2. The maximum number of HARQ retransmissions of an HARQ encode MAC PDU on a HARQ channel is set as 4 before the PDU is discarded. The maximum number of HARQ UL channels is defined to be 8 in the standard [13] and the maximum number of DL channels is 16. The buffer size constant is used to calculate the size of the buffer in bits associated with one HARQ channel as per the formula -

$$\text{Buffer size (bits)} = \text{floor} (512 \times 2^{k/4})$$

The explicit ACK delay refers to the number of frames the sender must wait in order to get an explicit acknowledgement from the receiver on the given HARQ channel. In WiMAX, explicit acks are used in DL flows and implicit acks are used in UL flows.

Table 4.2: HARQ Simulation Parameters

S. No.	Simulation Parameters	Value
1	Max. HARQ retransmissions	4 packets
2	No. of HARQ U/L channels	8
3	No. of HARQ D/L channels	16
4	Buffer Size constant (K)	20
5	Explicit Ack Delay	1 frame

The simulations were performed on video and VoIP application traffic and the obtained results are explained in the following section. Both these applications use UDP as their transport protocol which is based on best effort delivery.

#### 4.4 Results

The simulations were performed under two conditions - the conventional HARQ and the modified HARQ version. In the first sub-section, the results of conventional HARQ performance is described. In the second sub-section, the performance improvement by using the modified HARQ scheme over the conventional HARQ for VOIP application traffic is discussed. In the third sub-section, video application was employed and the performance improvement was deduced.

#### 4.4.1 HARQ

HARQ was enabled on node 2 and some important characteristics of HARQ can be seen. For instance, the HARQ transmission rate is directly related to the achieved throughput. Figure 4.3 shows the average throughput in bps and figure 4.4 depicts the average HARQ transmission rate in packets per second. The nodes used VOIP application and the scheduling service was based on best effort mechanism. We can see a better throughput initially and then it becomes constant. The initial high throughput is because of lesser congestion in the beginning. This characteristic was found to be similar in the improvement case also.

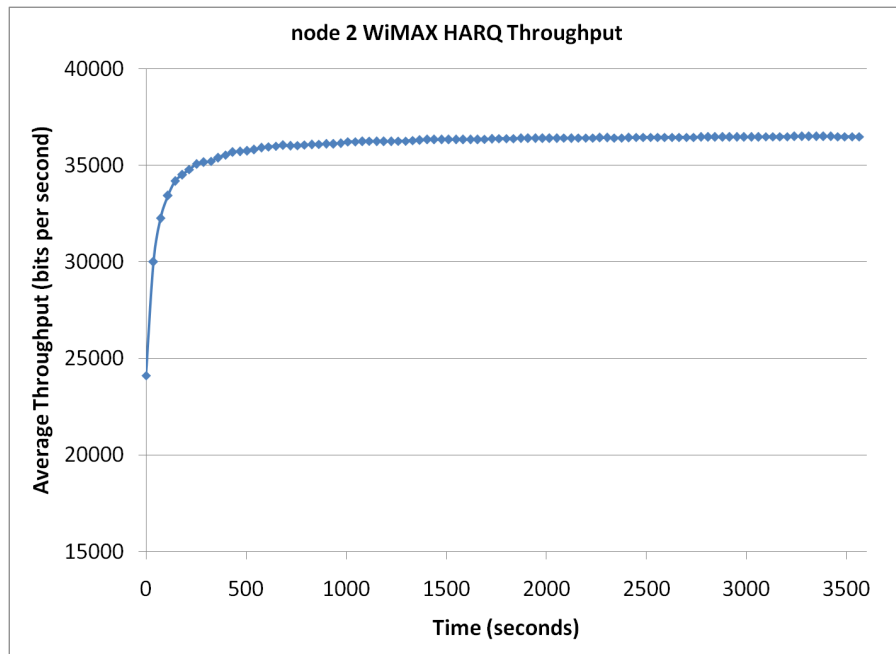


Figure 4.3: Throughput improvement using HARQ

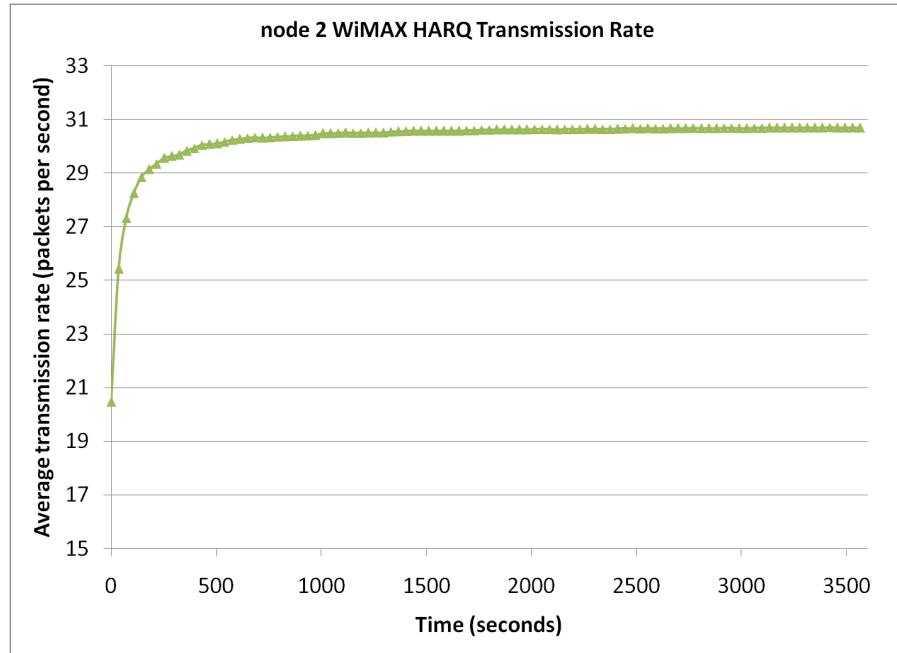


Figure 4.4: HARQ transmission rate

#### 4.4.2 VOIP application

By using conventional HARQ, the throughput improvement on node 2 is shown in figure 4.5 . Voice over IP application parameters were chosen to PCM quality as designated by the OPNET Modeler. One frame was allowed to be sent in a single packet and the delay in compressing and decompressing a voice packet was set to be the default value of 0.02 seconds. The scheduling service associated with this flow is based on best effort mechanism. It can be seen that initially there is significant throughput improvement but as time progresses, node 2 throughput is comparable to the others. This is primarily because of higher congestion in the network as time progresses and packet losses due to the use of same sub-channel over a considerable period of time.

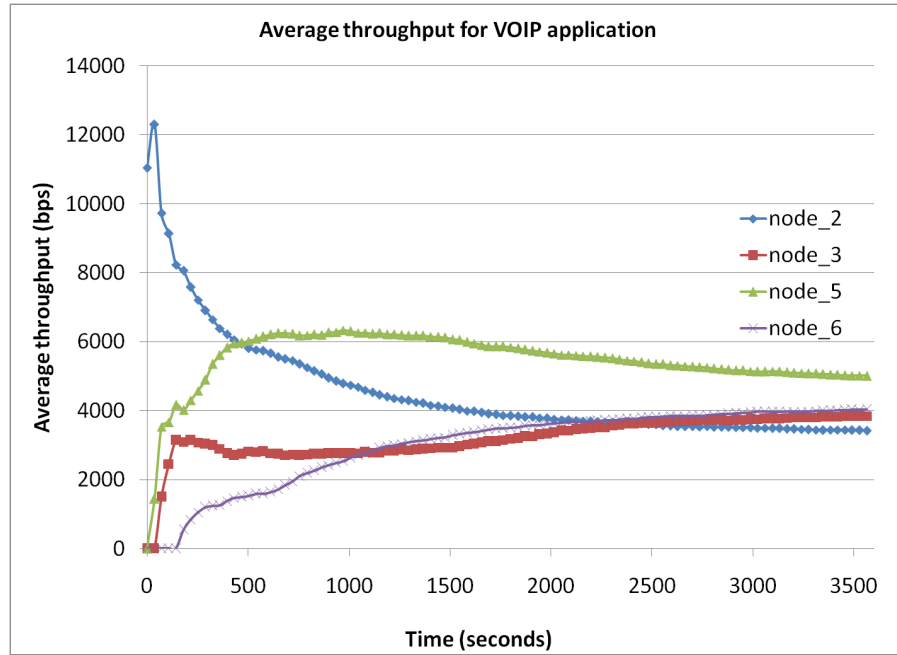


Figure 4.5: Voip application throughput using conventional HARQ mechanism

The improvement in HARQ mechanism was performed and simulated. The improvement yielded better throughput for node 2 as shown in figure 4.6. The throughput of other nodes were comparatively lessened but the improvement in node 2 throughput is significant. The comparison of the HARQ improvement and classical version is shown in figure 4.7. It can be seen that the average throughput using the improved HARQ scheme is much higher than the conventional scheme. The throughput variation is high initially and becomes constant as time progresses. This variation is because initially the congestion of frames in the network is less while congestion increases as time progresses. We can also observe that the reduction in throughput is comparatively lesser. This is because the improved HARQ scheme selects the HARQ transmission sub-channel in random fashion. Hence, the congestion in a random sub-channel varies in a random fashion. Thus, by addressing a random problem with a random solution, we are able to obtain better performance.

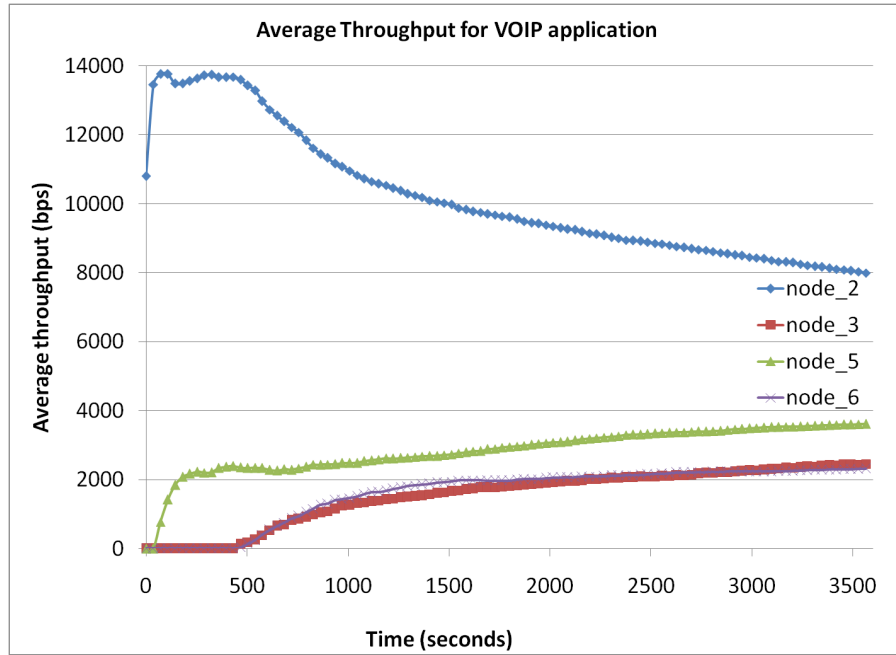


Figure 4.6: Voip application throughput using improved HARQ mechanism

The improvement also results in lesser packet end to end delay which is the major service quality parameter in VOIP applications. This is depicted in figure 4.8.

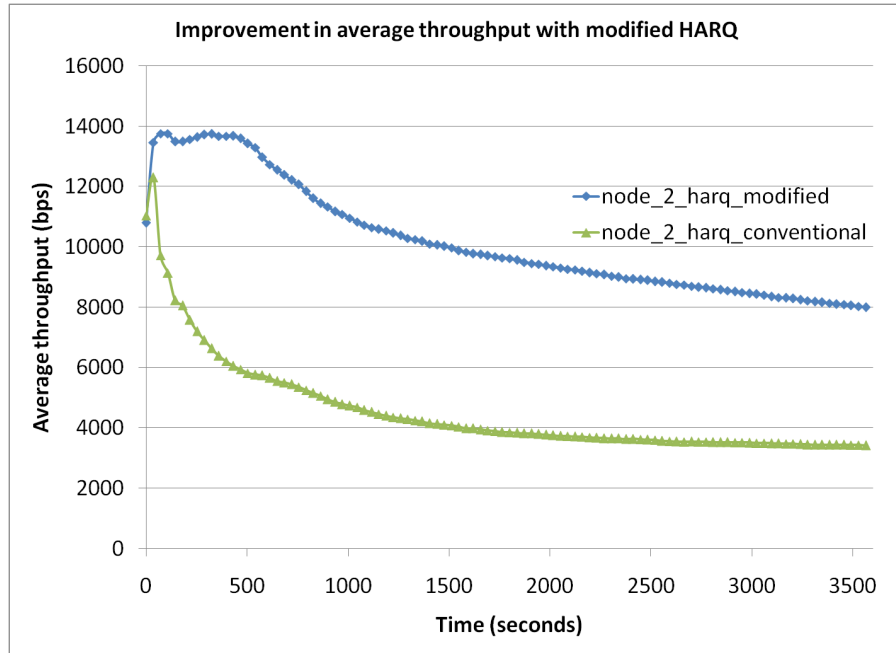


Figure 4.7: Voip application throughput of improved and conventional HARQ mechanism on node 2

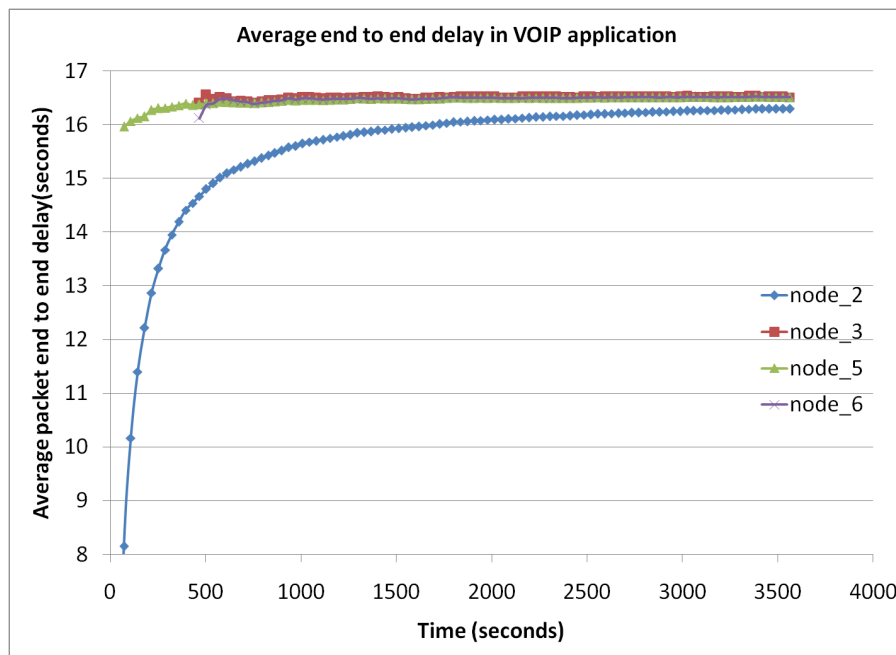


Figure 4.8: Average packet end to end delay in improved HARQ mechanism on node 2

The average overall packet delay variation over time for both improved and conventional HARQ schemes is shown in figure 4.9. We can observe that the delay variation is almost the same. However, the initial delay in the improved version is lesser comparatively. The improved HARQ scheme proves to improve network performance by providing higher throughput with a slightly lesser delay.

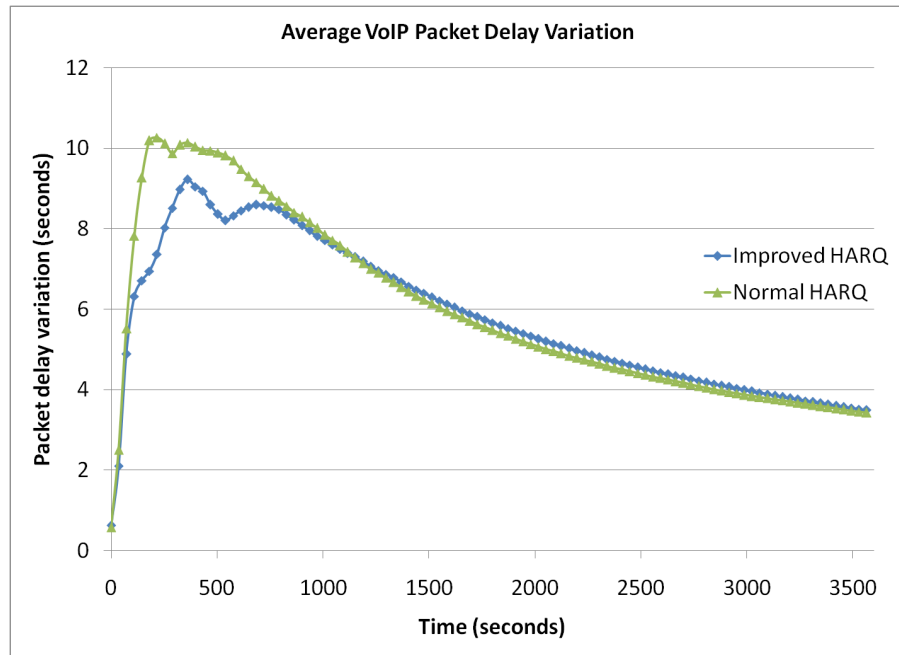


Figure 4.9: Overall VoIP average packet delay variation

#### 4.4.3 Video Application

Video application was used and the performance was evaluated. The video application parameters were chosen to VCR quality as defined by OPNET Modeler. The frame inter-arrival time was chosen to be the default value of 30 frames per second with a frame size of 352X240 pixels. The video throughput analysis using the conventional HARQ scheme is shown in figure 4.10. The throughput reduction as time progresses can be explained with high initial congestion and use of same HARQ sub-channel. Since, the scheduling service



is based on best effort mechanism, as time progresses all nodes except node 2 achieves comparable throughputs. Node 2 gets better throughput because of HARQ mechanism.

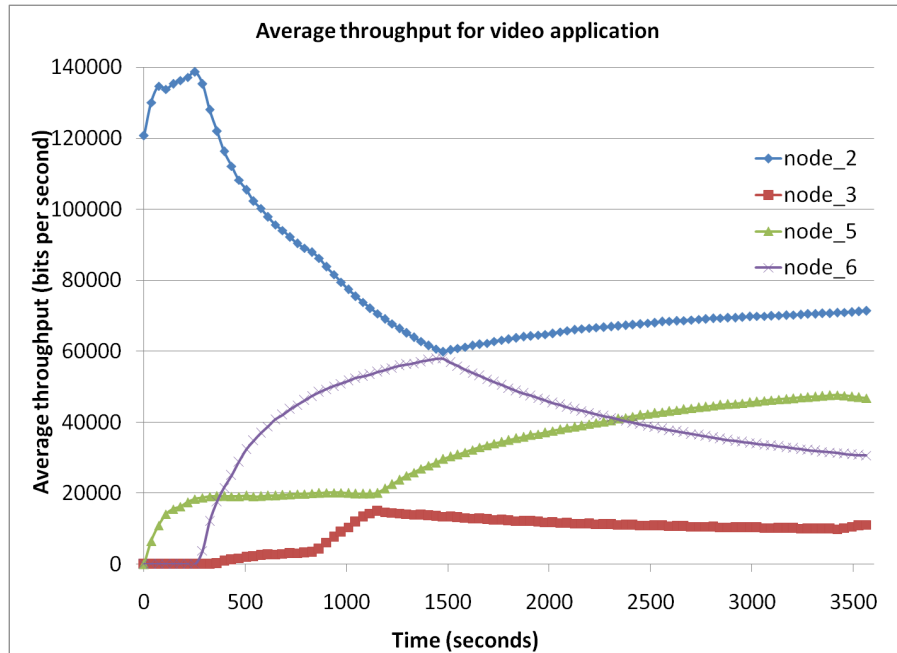


Figure 4.10: Video application throughput of conventional HARQ mechanism on node 2

It was found that the HARQ improvement yielded better throughput for this application also as shown in figure 4.11. Here, the throughput is much higher than the other nodes. Comparatively, this mechanism yields higher throughput for the node employing HARQ than the other nodes because of using a part of the entire bandwidth for HARQ transmissions. Better utilization of channel bandwidth is important in video applications as more error-free packets can be sent through the network. The number of packets destroyed in both schemes for video application traffic is compared as shown in figure 4.12. Lesser number of packets are destroyed in the improved version. This is due to efficient usage of channel resources and lesser errors. These results comprehensively prove the advantage of the improved HARQ scheme.

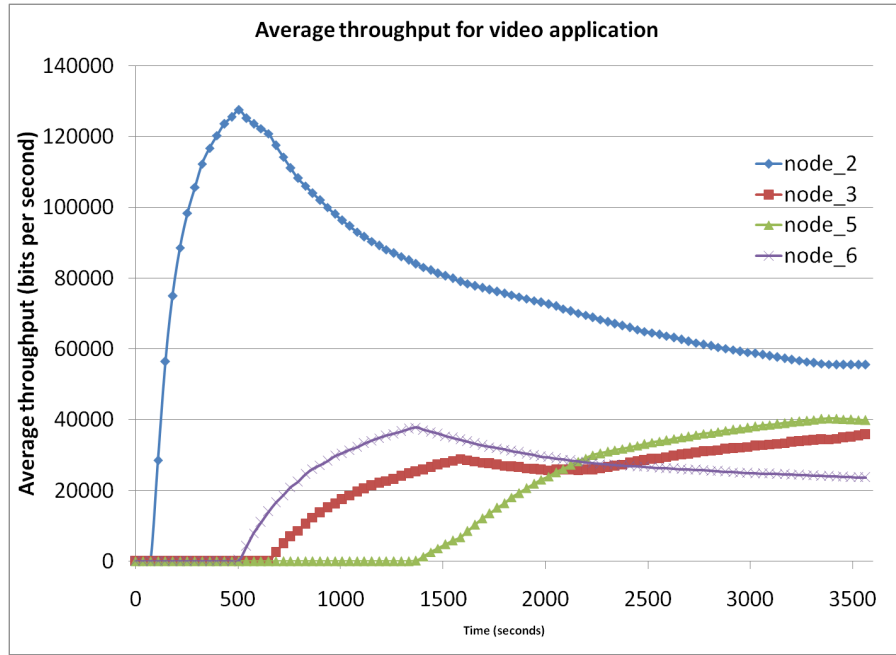


Figure 4.11: Video application throughput of improved HARQ mechanism on node 2

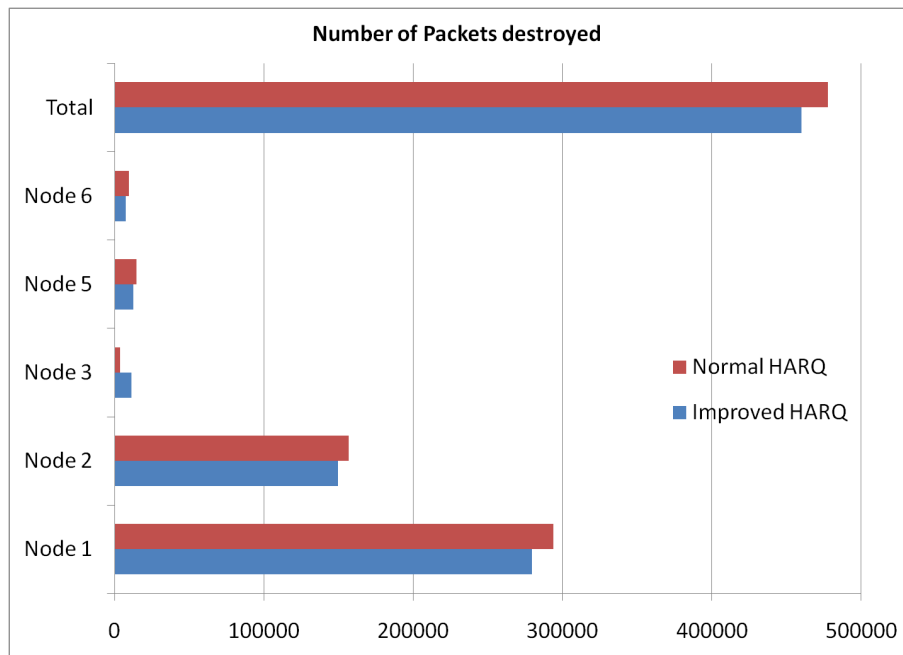


Figure 4.12: Number of packets destroyed

#### **4.5 conclusion**

HARQ mechanism employed along with OFDMA is an important advantage in WiMAX networks. The channel diversity exploitation can be done by using OFDMA and the HARQ retransmissions can be scheduled accordingly. HARQ can be used to reduce packet errors in the network. Scheduling HARQ retransmissions is important and determining whether a retransmission is necessary is required. These measures in unison can improve the overall network performance. This fact has been proved by scheduling appropriate HARQ transmissions and retransmissions in a random sub-channel at a particular scheduling period of time. The results prove the significant throughput and delay improvements in VoIP and video application traffic.

#### **4.6 Future Work**

The future work in this line of research includes analyzing the effect of this algorithm on the other HARQ types. The modification of the packet format and related analysis would be interesting. The efficiency of the algorithm when applied at the subscriber end is also a direction to be considered.

## CHAPTER 5

### CONCLUSION

WiMAX, officially termed as IEEE 802.16, is the latest wireless standard developed for metropolitan area networks. It can be applied as backhaul or last mile networks. The most important feature in WiMAX is the transmission scheduler employed in layer 2. The medium access method in WiMAX is based on a Request/Grant mechanism. In WiMAX operation, the data transmission by a user with a particular frequency is scheduled in time. The base station is responsible for making this scheduling decision. Three types of networks were analyzed and performance enhancement and the importance of scheduling was studied.

In the first scenario, the problem of varying channel conditions over time and mobility was addressed. It was found that transmission scheduling based on instantaneous channel properties like signal to noise ratio could yield significant throughput improvement. In order to perform this task, graph theoretic algorithms were used. Two successive greedy heuristics were used to map the sub-carriers and time slots to users. The mismatches in this typical bi-partite matching problem were handled and the algorithm was implemented in NS2 simulator. The results showed significant overall throughput improvement over the round robin scheduler and Munkre's assignment algorithm based scheduler.

In the second scenario, the 802.11 nodes were connected to the internet using a WiMAX back haul network. The 802.16 base station was assumed to be the gateway. In this hierarchical network, it was found that the 802.16 subscribers suffered detrimental throughput when there are too many nodes contending for connection with the base station. This problem was tackled by assigning alternate routes for packets originating from 802.11 users

requesting lower service quality. NS2 simulator was used and it was found that the packet end-to-end delay, a service quality metric for VOIP users was lesser and average network performance was improved.

Hybrid automatic repeat request is an important phenomenon in WiMAX networks. Scheduling HARQ transmissions in OFDMA based networks is an important task for wireless medium that contributes to high packet losses. We can observe that HARQ improves the average throughput by using appropriate error handling techniques. Assigning appropriate sub-carriers for these HARQ transmissions can further reduce the packet errors. Hence, it proves to be an efficient method for HARQ in OFDMA networks. This algorithm was compared and contrasted with the normal HARQ technique and the results show significant improvement in average throughput and packet end to end delay for common applications such as video and VoIP.

These solutions clearly indicate the importance of scheduling in WiMAX based wireless networks and performance enhancement by using efficient scheduling techniques. Three important applications of WiMAX networks were considered and solutions for significant issues were implemented and analyzed.

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