# IMPROVING PERFORMANCE OF WIMAX NETWORKS USING MULTIPLE ANTENNAS

A THESIS

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*for the award of the degree*

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**Dedicated to**

**My Parents, and My Brother**

# THESIS CERTIFICATE

This is to certify that the thesis entitled **Improving Performance of WiMAX Networks using Multiple Antennas**, submitted by **Phani Krishna Penumarthi**, to the Indian Institute of Technology, Madras, for the award of the degree of **Master of Science (by Research)**, is a bona fide record of the research work carried out by him under my supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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***Let Noble Thoughts Come to you from All Directions*** – Rigveda

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# ABSTRACT

Due to the advent of smart phones in the market, multiple antenna technology is emerging as a competing feature for its performance maximization capabilities. Towards this direction, WiMAX standard supports $2-4$ number of antennas at each Mobile Station (MS). Utilizing the antennas efficiently to maximize performance of a network is an active area of research recently. WiMAX standard supports three Multiple Input Multiple Output (MIMO) techniques: Spatial Multiplexing (SM), Spatial Diversity (SD) and Collaborative Spatial Multiplexing (C-SM). C-SM technique proposes 2 MSs with one antenna each to transmit data in one time and frequency (OFDM) slot. In this thesis, we first study the maximum number of MSs that can share one OFDM slot for transmitting data, when each MS uses multiple (two) antennas for transmission. We show that in some real world scenarios, it is possible for many (as high as 10) MSs to share a slot for transmission. We propose a scheduling algorithm that determines which MSs can transmit data concurrently in each WiMAX frame.

On the other hand, SM and SD techniques either improve achievable capacity of the network or improve reliability of the transmitted data. Each MS uses a different MIMO technique based on the observed channel quality in the previous frame. In this thesis, we explore if a MIMO technique that maximizes reliability of the transmitted data and still improves the effective capacity of the network can be designed, between a transmitter and receiver equipped with multiple antennas. We show that it is possible to design a MIMO technique if atleast one of the streams transmitted, is received correctly at one of the antennas of the receiver.

# ABBREVIATIONS

| | |
|---|---|
| **AoA** | Angle of Arrival |
| **AWGN** | Additive White Gaussian Noise Channel |
| **BS** | Base Station |
| **CDD** | Cyclic Delay Diversity |
| **C-SM** | Collaborative Spatial Multiplexing |
| **D-PF** | Double Proportional Fair Pairing |
| **EGC** | Equal Gain Combining |
| **IA** | Interference Alignment |
| **ICI** | Inter Carrier Interference |
| **IN** | Interference Nulling |
| **ISI** | Inter Symbol Interference |
| **MCS** | Modulation and Coding Scheme |
| **MIMO** | Multiple Input Multiple Output |
| **MRC** | Maximum Ratio Combining |
| **MS** | Mobile Station |
| **OFDMA** | Orthogonal Frequency Division Multiple Access |
| **PDU** | Protocol Data Unit |
| **PMP** | Point to Multipoint Network |
| **RD** | Receiver Diversity |
| **SC** | Selection Combining |
| **SD** | Spatial Diversity |
| **SIR** | Signal to Interference Ratio |
| **SINR** | Signal to Interference Noise Ratio |
| **SM** | Spatial Multiplexing |
| **SNR** | Signal to Noise Ratio |
| **STC** | Space Time Code |
| **TD** | Transmit Diversity |

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## CHAPTER 1

# Introduction

## 1.1 WiMAX Networks

Worldwide Interoperable Microwave Access (WiMAX) Networks are one of the solutions that provide data rates up to 150 $Mbps$ in a wireless network, at distances in range of $3 - 5$ $Kms$. This long distance transmission is possible due to the usage of high transmitting power. WiMAX is the commercial version of the IEEE 802.16 Broadband Wireless Access standard. While initial versions of IEEE 802.16 standards supported for a mesh network also, the most recent standard supports only the centralized network, i.e., each Mobile Station (MS) is connected to a centralized entity, namely the Base Station (BS) and MSs can not communicate among themselves. This working mode is termed as Point to Multipoint (PMP) mode in WiMAX networks. WiMAX uses Orthogonal Frequency Division Multiple Access (OFDMA) technology to minimize interference at the physical layer. This eliminates the Inter Carrier Interference (ICI), Inter Symbol Interference (ISI) and the Multipath interference that can occur between a transmitter and receiver moving with high velocities.

**OFDMA Architecture**: Orthogonal Frequency Division Multiple Access (OFDMA) technique proposes to slice the entire bandwidth into a set of subcarriers, where the number of slices is dependent on the bandwidth allocated for transmission. Several of the subcarriers can be grouped together to form a sub-channel. Each sub-channel allocated along with duration of 102.8 $\mu s$ constitute an OFDM symbol. Two OFDM symbols constitute one OFDM slot. These slots are allocated to different MSs based on the requests of each MS in the previous frame. Scheduling these OFDM slots to different MS in each frame is the responsibility of the BS, which we will study in detail in Section 1.3.

Channel Allocation Strategies: Allocating several subcarriers to form a subchannel is studied under the name of channel allocation strategies. **BandAMC** strategy allocates contiguous set of $K$ subcarriers to form a subchannel. The value of $K$ is dependent

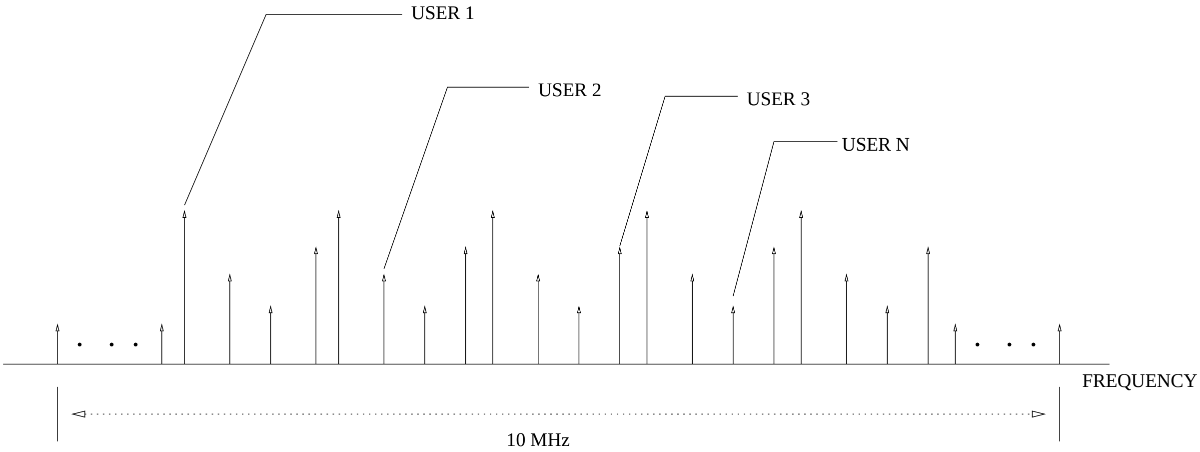

**Fig.** 1.1: Sample Allocation of Subcarriers to Mobiles using OFDMA Technique

on the coverage area, power and rate requirements of each MS. **Distributed** strategy allocates $K$ subcarriers orthogonal to each other to form a subchannel. Choosing subcarriers that are orthogonal to each other is dependent on the channel bandwidth. The most recent WiMAX standard [1] supports both continuous and distributed way of allocating subcarriers to sub-channels. The entire bandwidth is segregated into two bands: Mini-band and Sub-band. While Sub-bands constitute 4 continuous subcarriers, Mini-bands constitute 1 subcarrier. Sub-bands are frequency specific in nature, and are allocated to MSs that experience frequency selective fading in the channel. Mini-bands are allocated to a sub-channel such that each sub-carrier in a sub-channel observes same channel quality. Sub-bands and Mini-bands are optimally allocated to different MSs, based on the rate requests and channel qualities of each MS in the previous frame. Several works towards this direction attempt to maximize the effective capacity of the network. Some of the salient features OFDMA are as follows:

1. Frequency selective nature of the channel is almost mitigated, using distributed allocation of subcarriers to sub-channels.
2. Transmitter and Receiver complexity are improved.
3. Time and Frequencies are synchronized for the transmission between transmitter and receiver by differentiating sub-carriers in to pilot and data sub-carriers.

Pilot sub-carriers are used for synchronization, while data subcarriers are used for data transmissions.

**TDD Architecture**: WiMAX supports a Time Division Duplexing architecture for data transmissions. Time is divided in to several frames, with each frame constituting a duration of 5 $ms$. Each frame is further divided into uplink and downlink frames. The ratio of uplink to downlink duration can vary from $(1 : 1)$ to $(3 : 2)$. The entire bandwidth is allocated to several MSs for transmission both in downlink and uplink sub-frames. This bandwidth is allocated to each MS (in form of OFDM slots) based on the requests received from several MSs in the previous frame.

**Connection Oriented Network**: As the requirements of each MS can vary drastically, WiMAX supports several Quality of Service (QoS) classes to differentiate the rate requirements of different applications. Since one MS can have multiple applications pertaining to different QoS classes, WiMAX assigns a connection Identifier (connID) to each request. ConnIds are used for both requesting and allocating the OFDM slots to each MS, as per the requirements of each connection (thus, maintaining a connection oriented approach). WiMAX differentiates the traffic into five different classes namely RtPS (Real time Polling Service corresponding to video traffic), UGS (Unsolicited Grant Services corresponding to voice traffic), nRtPS (non-Real Time Polling Service corresponding to voice suppressed video traffic), BE (Best Effort corresponding to downloading data). WiMAX also supports using multiple antennas for transmission. Each MS can be equipped with up to 4 antennas. BS can be equipped with up to 16 antennas. Some of the antenna techniques to improve throughput of the network are discussed in the next subsection.

## 1.2 Multiple Antenna Techniques

WiMAX supports three MIMO techniques for transmission, named as MIMO A, MIMO B and MIMO C techniques. These techniques are typically segregated into two types: Closed loop and Open loop MIMO techniques. The techniques that use feedback mechanism to transmit data in accordance with the channel quality between a transmitter and receiver are typically considered as closed loop MIMO techniques. WiMAX standard imposes each MS to measure channel quality for each downlink transmission from the BS, and feedback the measured channel quality to the BS in the uplink duration (along with rate requests). Based on the received channel quality, BS determines the modulation and coding scheme and MIMO technique that MS has to encode/decode for transmissions. By using **MIMO C** technique, WiMAX supports beamforming vectors to be used for transmission.

Open loop MIMO techniques (**MIMO A and MIMO B**) that do not need specific feedback from the receiver are highly supported in WiMAX networks, due to their lower complexity. The supported MIMO techniques are mentioned below:

**MIMO A**: This technique is supported to improve reliability of data transmitted in each transmission. This improvement is possible by transmitting one stream of data across multiple antennas. The receiver performs a set of combining techniques (such as Maximum Ratio Combining, Selection Combining and Equal Gain Combining techniques) to retrieve the transmitted stream (with qualities better than stream received at each antenna separately).

**MIMO B**: This technique improves effective capacity of the channel between a transmitter and receiver. Each antenna at the transmitter transmits different streams of data for transmission. The receiver can decode each stream correctly if channel quality is very high. Hence, MIMO B techniques are applied only when measured channel quality is above the considered threshold (specific to the BS). Adaptively applying these MIMO techniques is a widely studied topic. A different problem that designs a new MIMO technique with required functionalities is studied in Chapter 3 of this thesis.

## 1.3 Scheduling Mobiles in a WiMAX Network

In this section, we provide an overview of how BS schedules different MSs to transmit data in each OFDMA frame. The sequence of steps involved in allocating OFDM slots to different MSs can be termed as follows:

1. An MS registers itself to a BS
2. Whenever an MS requires some data transfer, it requests a connection to the BS, providing the required Quality of Service details specific to that transfer
3. A connection Id is established between MS and the BS specific to each connection, depending on the availability of vacant slots at the BS
4. For each OFDMA frame, an MS requests the number of OFDM slots it requires to the BS along with details of the connection that requires the slots for transmission
5. The BS coordinates the requests of each MS for each allocated connection and allocates the OFDM slots to each MS
6. When an MS requests a new connection, based on the QoS parameters of the connection, BS provides a connection Identifier only when the QoS parameters of the connection can be satisfied

Each MS transmits or receives data from the BS in the allocated OFDM slots. Several algorithms proposed to schedule slots to different MSs are studied in Chapter 2 of this thesis.

## 1.4 Objective of the Thesis

The objectives of this thesis are two fold:

1. To address the problem of sharing a slot across many MSs in a WiMAX network. We determine the maximum number of MSs that can share a slot in WiMAX network, and propose a scheduling algorithm that executes at the BS to determine which MSs can transmit data in same slot satisfying the specific rate requirements.
2. To explore if a MIMO technique that maximizes performance of the network for **every** channel quality observed in the network can be designed.

## 1.5 Organization of the Thesis

The rest of the thesis is organized into three chapters followed by a list of references and publications as follows:

Chapter 2 discusses the problem of choosing several MSs that can transmit data in same OFDM slot for transmission, and still transmit data successfully at a mentioned rate. The proposed technique uses Interference Alignment technique for transmissions. A detailed study is provided to show that Interference Alignment vectors can be utilized in a WiMAX network. Evaluating the proposed technique in a typical WiMAX network shows that throughput of the network is enhanced by sharing a slot among many MSs.

Chapter 3 discusses the problem of designing a MIMO technique that can be assigned to each MS irrespective of the channel quality. However, the catch lies in maintaining reliability of the transmitted data same as that of Diversity (MIMO A) techniques and throughput of network similar to that of Multiplexing (MIMO B) techniques.

Chapter 4 summarizes the work carried out in this thesis and suggests directions for future work.

A few important technical reports, research papers, survey papers, and textbooks are listed in **References**. The publications based on the research work presented in this thesis are listed in **List of Publications**.

## CHAPTER 2

# Sharing a Slot Among Mobiles in WiMAX Networks

## 2.1 Introduction

Traditional wireless communication protocols eliminate interference due to multiple transmitters by allocating different frequencies and/or times for each transmission (Frequency or Time Division Multiple Access). With the advent of advanced antenna technologies, it is possible for several MSs to share a slot. This concept, when used with OFDMA technology at the physical layer, is named as Collaborative Spatial Multiplexing (C-SM) in IEEE 802.16 networks [1]. And it supports 2 MSs to share a slot for the uplink transmissions. The BS decides the MSs that can share a slot for the next time frame (of 5 $ms$ duration), depending on the requests received from each MS, and the observed channel quality of each MS during the previous frame. This scheduling of MSs at the BS is termed as Pairing which considers only one antenna at each MS. However, the sudden emergence of smart-phones with multiple (2) antennas at each MS can toggle the performance of existing multiple antenna techniques, due to increase in the values of interference in the network. Hence, the problem of determining the maximum number of MSs that can share a slot in a scenario where each MS has mobility speeds upto 120 $Kmph$ and uses 2 antennas for transmission all the time becomes interesting.

The dependency of this problem on the MIMO technique applied at each MS (which is decided by the BS) is an important parameter to maximize performance (throughput) of the network. Two contrasting MIMO techniques are Spatial Multiplexing (SM) and Spatial Diversity (SD). SM techniques improve the number of streams of data transmitted ($\leq \min(N_t, N_r)$) between a transmitter with $N_t$, and receiver with $N_r$ number of antennas. Diversity techniques improve the reliability of the transmitted data, either by transmitting or receiving variants of the same data across several antennas. Diversity embedded space time codes [2] show that different diversity and rate values can be achieved for different streams of data by optimally utilizing SM and SD techniques. However, in this thesis we consider only SM and SD techniques for evaluation, as these techniques are considered fundamental and constitute all other techniques proposed in the literature.

### 2.1.1 Motivation

Interference Alignment (IA) is a technique in which several interfering user pairs with single antenna transmit and receive data successfully, by aligning their transmissions along pre-determined vectors [3]. It is proved that all user pairs ($K$) in a decentralized network can transmit data for half of the time in the network (independent of $K$). However, this technique can not be directly applied to a Point-to-Multipoint (PMP) network, due to the requirement of enormous computing power to generate IA vectors at the BS (centralized location). While algorithms to generate IA vectors for each user-pair in a distributed network are available for different channels [4], these algorithms are not applicable in a PMP network, as all the receiving antennas are located at same location. A sample PMP network consisting of a BS with $N_r$ antennas, and each MS equipped with $N_t$ antennas can look similar to that of Fig. 2.1. IA technique, when complemented with Interference Nulling technique is utilized efficiently in [5] to share a slot across multiple MSs in an IEEE 802.11 $n$ network. The authors of [5] show with testbed results that a user-pair with more number of antennas than the current number of spatial streams transmitted in the network, can share the same slot for transmission. However, such a study is unavailable in a PMP network. Peters and Heath Jr. [6] study multiple antenna interference channels and propose a greedy algorithm to partition available users into several groups such that users in a group use IA to transmit data in a single slot, while users across groups use TDMA mechanism to transmit data across different slots. They model users pairs in the network as a connected graph, and partition the graph based on the position information of each transmitter and receiver in the network and provide fairness on rate requirements achieved among users. They model overhead of using IA in the network, and show

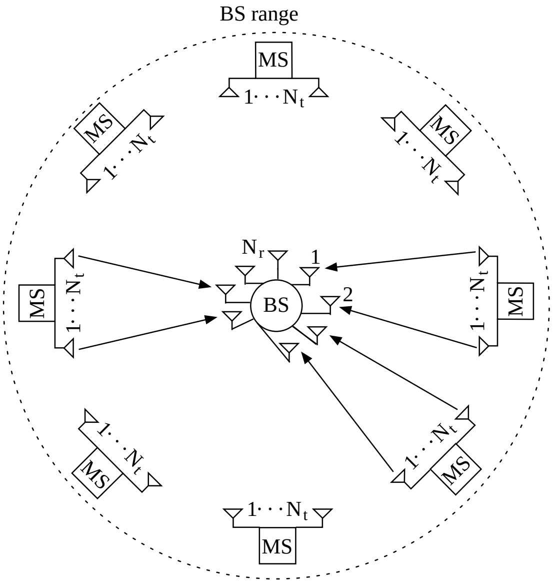

**Fig.** 2.1: Several MSs Sharing a Slot in a PMP Network

that the achievable sum transmission rate will become zero as more number of users share a slot.

While many studies [7–10] propose algorithms to allocate a slot to several MSs (pairing schemes) such that the frame is utilized optimally, they do not question why only two MSs share a slot in a WiMAX network. Also, these techniques assume that each MS is equipped with only one antenna.

### 2.1.2 Contributions

The main contributions of this chapter are as follows:

1. We find the maximum number of MSs that can share an OFDM slot, when each MS is equipped with 2 antennas and uses a known MIMO technique for transmissions. We use Signal to Interference Ratio (SIR) as a parameter to verify if a constant rate can be attained at each MS.
2. We propose an algorithm to schedule MSs in a typical WiMAX network, wherein each OFDM slot is optimally utilized by allocating to maximum number of MSs possible. Challenges and solutions to determine IA vectors with in the limited

time are also discussed in detail.

Overall, we propose a working design to use IA technology in WiMAX networks. To the best of our knowledge, this is the first study towards utilizing IA technique in WiMAX networks.

### 2.1.3 Organization

Section 2.2 provides the relevant background required to analyze the problem considered in this chapter. Section 2.3 presents the system model considered, while Section 2.4 deals with finding the maximum number of mobiles that can share a slot in a PMP network. In Section 2.5, we study the challenges to utilize IA vectors in a WiMAX network. In Section 2.6, we propose a scheduling algorithm that schedules MSs based on the channel quality and MIMO technique of each MS participating in the share. In Section 2.7, we conclude the work and provide directions for possible work in the future.

## 2.2 Background

**Interference**: The chief factors contributing to the term *interference* in a PMP network can be classified in two ways:
a) Interference due to mobility of MS: The most common problems of frequency, time synchronization, Carrier and Doppler frequency offsets can be described in the form of Inter Carrier Interference (ICI). Since OFDMA is used, Inter Symbol Interference (ISI) and interference due to signals taking multiple paths to reach the destination are almost eliminated by choosing the guard time appropriately. ICI can be eliminated in the network by transmitting same symbol redundantly along a set of adjacent subcarriers [11–13]. A disadvantage of such techniques is that the subcarriers are wasted.
b) Interference due to multiple antennas: Several antennas using same slot for transmission will cause interference at the receiving antenna. Choosing or Scheduling different MSs such that interference can be mitigated at the receiving antennas is the responsibility of the BS. Some of the ways of reducing interference at the receiving

antenna are beam-forming, Interference Nulling (IN), and IA. Beam-forming eliminates interference by transmitting data along a particular vector depending on the channel quality between the transmitting and receiving antennas. IN enables a second transmitter to transmit data using the same slot without interfering with the ongoing transmission. Generating IN vectors is dependent only on channel quality between second transmitter and first receiver.

**Interference Alignment**: This concept, introduced through a seminal paper by Viveck and Jafar, in [3] proves that all the $K$ user pairs in an interference channel can transmit and receive data correctly for half of the time. Interestingly, it considers each user to be equipped with only one antenna. Data is transmitted at each antenna along a pre-determined vector. Antenna at the receiver is configured such that it receives data along only one vector (dependent on transmitting IA vector and channel coefficient between transmitting and receiving antennas). Generating IA vectors is dependent on the channel quality between **every** transmitter and the receiver.

Example: Two antennas of an MS '$T$' transmit data along two vectors $\overrightarrow{W_1}$ and $\overrightarrow{W_2}$, as shown in Fig. 2.2. Appropriate antennas at the BS receive data along vectors $\overrightarrow{W_1^H}$ and $\overrightarrow{W_2^H}$,

where $W_1^H, W_2^H$ are designed such that $W_1 \times W_1^H = 1$ and $W_1 \times W_2^H = 0$, and $W_2 \times W_1^H = 0$ and $W_2 \times W_2^H = 1$. Designing these IA vectors for different channels [4, 14, 15] has been a thoroughly studied topic. The streams received at antennas $2T, 2T+1$ as shown in Fig. 2.2 can be taken as:

$$\begin{aligned} y_{2T} &= W_1 x_1 H_{1,2T} W_1^H + W_2 x_2 H_{2,2T} W_1^H \\ y_{2T+1} &= W_1 x_1 H_{2,2T+1} W_2^H + W_2 x_2 H_{2,2T+1} W_2^H \end{aligned} \tag{2.1}$$

**Signal to Interference Ratio**: For a received signal to be interference free, the value of SIR should be above a threshold $\beta$, where $\beta$ is dependent on the bit transmission rate. The SIR for a signal can be defined [16] as

$$SIR = \frac{S}{I} \tag{2.2}$$

where $S$ is the power of the required signal at the receiver and $I$ is the power of interfered signal at the receiver. $\beta$ can be taken as $2^R - 1$, where $R$ is the required

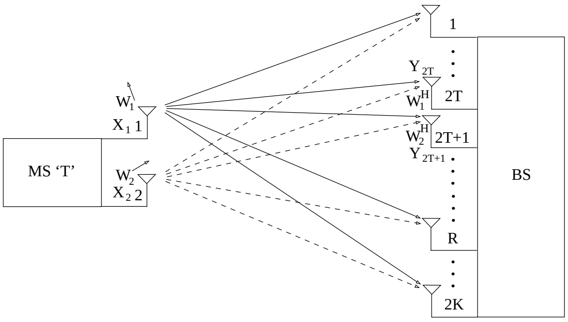

**Fig.** 2.2: Interference Alignment Used in Up-link Transmission

rate of transmission in $bps/Hz$ [17].

## 2.3 System Model

Let '$K$' MSs share the same OFDM slot for transmitting to the BS. Each MS is equipped with 2 antennas and the BS is equipped with $M(\geq 2K)$ antennas. An antenna at each MS transmits the data that is aligned along a vector, beamed to a specific antenna at the BS. In other words, alignment vectors specific to each antenna of the MS are transmitted by the BS for each frame. The overhead of transmitting these beam vectors in each frame is presumed to be negligible when compared to the achievable data rates. The data received at antenna $i$ of the BS, similar to Equation 6 in [18], can be written as

$$y_i(s) = \sum_{j=1}^{2K} d_{ij}^{-\rho} W_j H_{ij} x_j(s) W_i^H + n_{ij} \tag{2.3}$$

where $W_j$ is the beam-formed (weighted) vector along which data is transmitted,
$W_i^H$ is the inverse of the beam-formed matrix used at the BS,
$x_j(s)$ is the data transmitted across antenna $j$ on subcarrier $s$,
$H_{ij}$ is the channel coefficient between the transmitted antenna $j$ and received antenna $i$,
$n_{ij}$ is the Additive White Gaussian Noise associated with the channel,
$d_{ij}$ is the distance between antenna $i$ and antenna $j$,

and $\rho$ is the path loss exponent of the channel. The ICI in a channel using OFDM is mainly due to adjacent subcarriers [18]. Also, assuming the channel to be frequency flat fading, Equation 2.3 can be modified as follows:

$$\begin{aligned} y_i(s) = &\sum_{j=1}^{2K} d_{ij}^{-\rho} W_j H_{ij} x_j(s) W_i^H + \sum_{j=1}^{2K} d_{ij}^{-\rho} W_j H_{ij} x_j(s-1) W_i^H \\ &+ \sum_{j=1}^{2K} d_{ij}^{-\rho} W_j H_{ij} x_j(s+1) W_i^H + n_{ij} \end{aligned} \tag{2.4}$$

Equation 2.4 assumes that ICI occurs every time in the network. ICI in the network [19] is considered to occur at a probability equal to be a random number uniformly generated in the range of $[0, 0.1]$.

The SIR of $i^{th}$ stream at antenna $i$ on a OFDM slot using subcarrier $s$ can be determined as

$$SIR = \frac{\left|W_i W_i^H H_{ii}(s)\right|^2}{\sum_{l=s} \sum_{\substack{j=1 \\ j \neq i}}^{2K} \left|W_j W_i^H H_{ij}(l)\right|^2 + \sum_{\substack{l=s-1 \\ l=s+1}} \sum_{j=1}^{2K} \left|W_j W_i^H H_{ij}(l)\right|^2} \tag{2.5}$$

From the concept of IA, it is obvious that

$$W_j W_i^H = \left\{ \begin{array}{ll} 1 & \text{if } i = j \\ 0 & \text{otherwise} \end{array} \right\}$$

Hence, $W_j W_i^H$ is always binary (i.e., 0 or 1). However, due to the factors such as imperfections in measured channel conditions and highly varying nature of the channel the IA vectors may not remain fixed even for 20 $ms$ (same as time duration of a typical super frame in WiMAX networks [1]) time frame, $W_l \times W_m^H$ will not be zero all the time and is considered to have minute errors in evaluations.

Different MIMO techniques can be achieved by varying the transmitted data $x_j(l)$ across different antennas with alignment vectors $W_j$. We consider both multiplexing and diversity techniques in this work. A thorough study on the consequences of using different MIMO techniques is provided in the next section. For the numerical results, initially we place all MSs adjacent to each other. Since each MS shares approximately the same channel to the BS, the SIR estimate remains same for several MSs (Note:

Distance remains the same for all MSs). Later SIR value of each MS is made to be independent of other MSs, representing a more realistic scenario.

## 2.4 System Analysis

We devote this section to determine the maximum number of MSs that can share an OFDM slot in a PMP network. For this section alone, we assume that IA vectors are computed and communicated to each MS participating in the share. This assumption is to ensure the focus remains on the number of MSs in the share and not on inherent complexities to use IA technique. In the subsequent section, we determine different ways to compute IA vectors correctly according to parameters of the considered network. Also, the SIR expressions for different MIMO techniques are specified and independent analysis is provided for two MIMO techniques: Spatial Multiplexing and Spatial Diversity (with Selection Combining receiver). However, this study can be extended to other receiver combining techniques also. The maximum MSs that can share a slot is limited to that number, where the average SIR falls below the threshold $\beta = 3$ (pertaining to R = 2 $bps/Hz$).

### 2.4.1 Spatial Multiplexing

When each MS utilizes Multiplexing technique, both antennas transmit different data along different IA vectors. Considering $2K$ antennas at the BS receive data from 2 antennas of the $K$ MSs, the data received at any two antennas ($l$ and $m$) of the BS from an associated MS can be written as

$$\begin{aligned} y_l &= \sum_{j=1}^{2K} d_{jl}^{-\rho} W_j H_{jl} x_j W_l^H + n_{jl} \\ y_m &= \sum_{j=1}^{2K} d_{jm}^{-\rho} W_j H_{jm} x_j W_m^H + n_{jm} \end{aligned} \tag{2.6}$$

The SIR of data received at antenna $l$, for the data transmitted at antenna $i$ can be written as

$$SIR = \frac{\left|W_i H_{il} W_l^H\right|^2}{\sum\limits_{\substack{j=1\\ j\neq i}}^{2K} \left|W_j H_{jl} W_l^H\right|^2} \tag{2.7}$$

We also know that ICI in the network is inevitable, and occurs randomly in the range of $[0, 0.1]$. Assuming the probability of occurrence of ICI in the network as $\alpha$, SIR for the signal received at antenna '$l$', transmitted across an OFDMA slot using sub-carrier '$s$' can be written similar to Equation 2.7 as in Equation 2.8.

$$SIR_l(s) = \frac{\left|W_i H_{il}(s) W_l^H\right|^2}{\sum\limits_{\substack{j=1\\ r=s-1\\ r=s+1}}^{j=2K} \alpha \left|W_j H_{jl}(r) W_l^H\right|^2 + \sum\limits_{\substack{j=1\\ j\neq i}}^{j=2K} \left|W_j H_{jl}(s) W_l^H\right|^2} \tag{2.8}$$

where $\alpha \in [0, 0.1]$. Using ICI reduction techniques can further reduce $\alpha$, and thus can improve SIR values of the required signal, at the cost of wasting the most precious bandwidth. Hence, we study assuming that the ICI occurs in the network with a uniform probability in the range of $[0, 0.1]$ [19].

To provide a theoretical insight, we verify if SIR(s) term in Equation 2.8 can fit in any of the existing, well-studied probability distributions. Study in that direction leads to the following conclusions:

- $H_{ij}$ is a circularly symmetric Gaussian random variable. This is because the real and imaginary parts of the complex term to generate $H_{ij}$ are generated from an identical and independent distribution [20] in the range of $[0, 1]$.
- Clearly, $H_{ij}^2$ follows a chi-square distribution with 1 degree of freedom [21].
- Similarly, $\sum\limits_{j=1, j\neq i}^{j=2K} H_{ij}^2$ follows a chi-square distribution with $2K - 1$ degrees of freedom.

It can be seen that both numerator and denominator of the SIR(s) term follows chi-square distribution with 1 and $6K - 1$ degrees of freedom. Hence, $(6K - 1 * SIR(s))$ follows F distribution with $(1, 6K - 1)$ degrees of freedom. However, this derivation does not take $\alpha$ and errors due to IA vectors into consideration.

The immediate aim in this section is to find the maximum number of MSs that can share a slot such that a minimum rate requirement is maintained at each MS. For a minimum rate requirement, the maximum number of MSs that can share a slot is computed using standard F distribution tables (with 99% significance), and is mentioned in Column 3 of Table 2.1. While calculation steps for the rate requirement of 2 $bps/Hz$ are given in detail, values for other rate requirements are directly mentioned for reading elegance.

**Table** 2.1: Number of MSs that can Share a Slot Using Different MIMO Techniques

| Minimum Rate Requirement (in $bps/Hz$) | $\beta$ | Number of MSs (K) | |
|---|---|---|---|
| | | Using Multiplexing Technique | Using Diversity Technique with SC Receiver |
| 2 | 3 | $\Pr(SIR \geq 3) \geq 0.99$<br>$\Pr((6K-1) * SIR \geq 3 * (6K-1))$<br>$\geq 0.99$<br>$K \leq 1$ | 3 |
| 3 | 7 | 1 | 2 |
| 4 | 15 | 1 | 1 |
| 5 | 31 | 1 | 1 |

### 2.4.2 Spatial Diversity

When each MS utilizes Diversity technique for transmission, same data is transmitted across different antennas along same IA vectors. The SIR of data received at antennas

$l$ and $l+1$, for the data transmitted at antennas $i$ and $i+1$ can be written as

$$\begin{aligned} SIR_l &= \frac{\left|W_i(H_{il}+H_{(i+1)l})W_l^H\right|^2}{\sum\limits_{\substack{j=1\\ j\neq i,i+1}}^{j=2K}\left|W_jH_{jl}W_l^H\right|^2}, \\ SIR_{l+1} &= \frac{\left|W_i(H_{i(l+1)}+H_{(i+1)l})W_l^H\right|^2}{\sum\limits_{\substack{j=1\\ j\neq i,i+1}}^{j=2K}\left|W_jH_{jl}W_l^H\right|^2} \end{aligned} \tag{2.9}$$

The above expressions utilize the fact that two antennas transmit data aligned on one vector $W_i$ and receive across two antennas along same vector $W_i^H$.

$SIR_{eff}$:

In case of Receiver Diversity (RD) techniques, multiple antennas receive same signal transmitted across different antennas. Data is received at each antenna using a Zero Forcing receiver, and SIR is computed at each antenna. Once SIR at each antenna is computed, a Selection Combining (SC) receiver is used to determine SIR of the received data. For an SC receiver, $SIR_{eff}$ can be expressed as:

$$SIR_{eff} = \begin{cases} SIR_l & \text{if } SIR_l \geq SIR_{l+1}, \\ SIR_{l+1} & \text{otherwise.} \end{cases} \tag{2.10}$$

By proving that $SIR_{eff}$ follows F distribution with $(1, 3K-1)$ degrees of freedom, number of MSs in the share can be obtained similar to that of Multiplexing case. The calculated values are shown in Column 4 of Table 2.1.

Thus, it can be observed that more than two MSs can share a slot for transmission (under favorable conditions), and that number is dependent on the MIMO technique employed at each MS in the share. Since a 2 *bps*/*hz* is a reasonable rate requirement in next generation networks such as WiMAX networks, we prove that sharing a slot among multiple ($\geq 2$) MSs is indeed possible. Surprisingly, the analysis proved that only one MS can share a slot if each MS uses Multiplexing technique while three MSs can share using Diversity technique. We validate this analysis using simulations in the next subsection.

### 2.4.3 Model Validation

In this section, we validate the analytical findings presented in 2.4.1 and 2.4.2 via extensive simulations. Using MATLAB, we simulate a MIMO channel in which four MSs share an OFDM slot. Each MS is equipped with two antennas each, and transmits data across both the antennas with the same power. Antenna correlations at each MS and correlation between different MSs is also modeled while modeling the MIMO channel. The channel quality of each MS is assumed to be different. The beam vectors corresponding to the channel quality of each MS are computed using $Max - SINR$ algorithm [22]. Different MIMO techniques are achieved by changing the alignment vectors at each antenna before transmission. For instance: Multiplexing is achieved when data at each antenna is aligned across different vectors and Diversity is achieved when two antennas of an MS transmit across same alignment vector. Also, SC receivers are employed at the BS to retrieve data without errors. We compute SIR values at different antennas of the BS, and plot a Quantile-Quantile (QQ) plot with SIR values generated at those antennas via simulations in Figs. 2.3, 2.4.

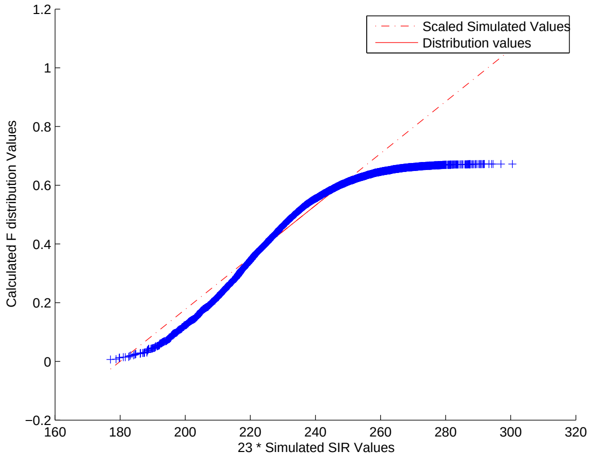

**Fig.** 2.3: Simulated Versus Analytical SIR Values in Multiplexing Case

An S-shaped curve in the plots (in Multiplexing and Diversity cases) denotes that the observed SIR values follow an F distribution with shorter tails. Hence, we conclude that the SIR values at each antenna can be approximated to the derived F distribution.

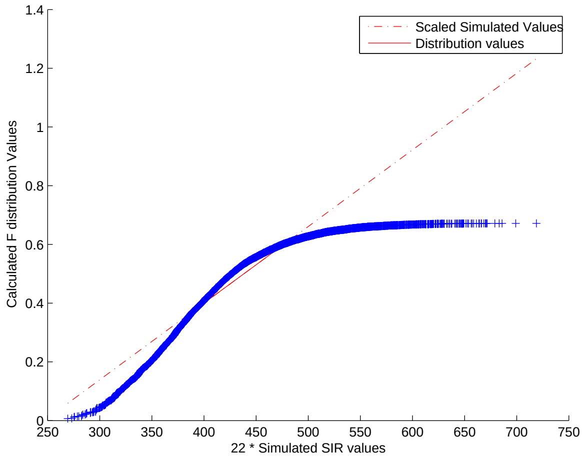

**Fig.** 2.4: Simulated Versus Analytical SIR Values in Diversity Case with Selection Combining Receiver

The errors in this approximation are primarily due to the inherent randomness in the occurrence of ICI in the network and possible mis-alignment (frequent channel quality variations caused due to high mobility) of IA vectors between the transmitter and receiver. We do not consider modeling mobility in this analysis due to its complicated nature. Hence, the model is only an approximate and is not exact.

### 2.4.4 Experimental Validation

We consider only one slot is being used for transmission by all MSs in the network and increase the number of MSs in the network from 1 to 20. The authors in [23] propose a transmitter centric algorithm after realizing that the uplink interference in a multi-user system is highly fluctuant. Since each MS receives different SIR values for each transmission, we calculate SIR of required signal at each antenna of the BS, and plot the average SIR across all antennas observed at the BS. This average SIR is used to determine the achievable transmission rate (in $bps/Hz$) for each MS in the network. For the sake of numerical calculations, we assume the channel coefficients to be uniformly distributed Gaussian random variables with zero mean and unit variance while noise is circularly symmetric and uniformly distributed with zero mean and 0.1

variance.

Initially, we compute the maximum number of MSs that can share a slot when channel conditions are identical for each MS. Later, we compute the same with channel conditions being completely independent for each MS. Also, an SC receiver is used at the BS when Diversity techniques are employed.

We consider 2 $bps/Hz$ as a norm in the analysis because it is highly visible in WiMAX networks, even at lower Modulation and Coding Schemes [Table 1.1 in [24]].

### 2.4.5 Numerical Results

When the number of MSs that share a slot is 1, the SIR value is maximum for all the four studied scenarios: Each MS with 1 (2) antennas and ICI can (not) be mitigated completely. As the number of MSs sharing a slot increases, the interference in the network also will increase, and a reduction in SIR value can be observed. The maximum MSs that can share a slot is limited to that number, where the average SIR falls below the threshold $\beta = 3$ (pertaining to R=2 $bps/Hz$). Also, note that $\beta$ is calculated from Section 2.3). The graphs are plotted with 95% confidence interval after performing $10,000$ iterations. Since $\beta$ is dependent on rate requirement of each MS, number of MSs that share a slot depends on rate requirement of each participating MS.

When an MS with one antenna transmits only one stream of data, SIR value would be maximum as there is no interference in the network. Fig. 2.5 provides the results for the scenario where all MSs have same channel quality while Fig. 2.6 provides results when the channel quality of each MS is independent of other MSs. Also, unless mentioned, the results are analyzed for a constant rate requirement of 2 $bps/Hz$ and $\beta = 3$.

As can be observed from Fig. 2.5, more than 10 MSs can share a slot if each MS is equipped with only one antenna and ICI is mitigated completely. However, a maximum of 7 MSs can share a slot when channel quality of each MS is independent of the other, as can be observed from Fig. 2.6. Hence, the number of MSs that share a slot depends on channel quality of each MS participating in the share.

Though multiplexing techniques multi-fold the achievable transmit rates depending

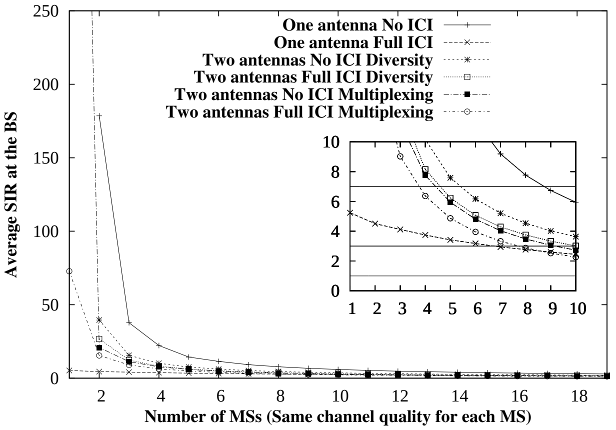

**Fig.** 2.5: Average SIR Determined at Different Antennas of the Receiver Versus Number of MSs Sharing a Slot

on number of antennas used for transmission, prior work showed that using multiplexing techniques improves performance of the network only in high SIR regions [1]. Thus, it can be misleading to consider that every MS uses multiplexing techniques for transmission. We observed that diversity techniques attain more SIR values compared to that of multiplexing techniques reiterating this notion. Hence, it becomes noteworthy that in a real world scenario, the number of MSs that share a slot also depends on the MIMO technique employed by each MS sharing the slot.

In Fig. 2.5, we observed that more than 6 MSs can share a slot for transmission when ICI is not mitigated. However, this number reduces significantly as the channel conditions vary for each MS, as seen in Fig. 2.6. Also, it can be observed from Fig. 2.6 that the SIR values remain almost same when the number of MSs sharing a slot is above 8, irrespective of the number of antennas at each MS and ICI mitigation in the network. This confirms that the upper bound for the number of MSs that can share a slot is bounded to 8 if we plan to exploit MIMO techniques available at each MS.

We can also observe that when 2 MSs with one antenna share an OFDM slot for transmission, the SIR value remains close to the threshold $\beta$, conforming to the C-SM specifications in WiMAX standards [1]. However, we observed that more MSs can share a slot when each MS is equipped with multiple antennas. A maximum of 7 MSs can

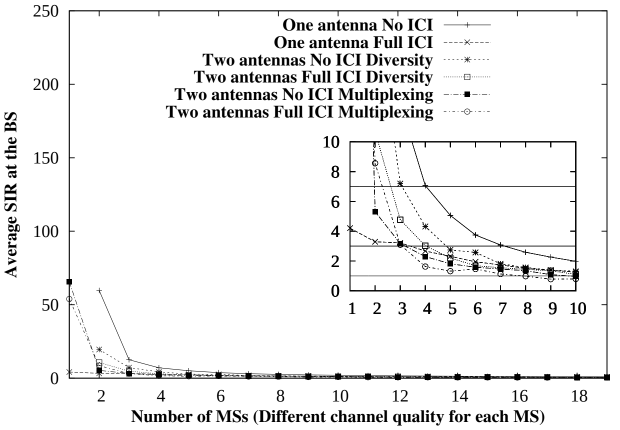

**Fig.** 2.6: Average SIR Determined at Different Antennas of the Receiver Versus Number of MSs Sharing a Slot

share an OFDM slot for a constant rate requirement of 2 $bps/Hz$ in the best possible settings. Consequently, a BS must need at least 14 antennas to receive data from each MS participating in the share. Thus, we provide a lower bound on the number of antennas required at the BS in a PMP network, such that rate requirements of each MS is satisfied. However, the number MSs sharing a slot is completely dependent on channel characteristics, rate requirements, and number of antennas at each MS participating in the share.

Though we showed that more than two MSs can share an OFDMA slot in a PMP network, several assumptions taken for granted in the above study need to be revisited, as they are non-trivial to be applicable in a standard WiMAX network. A few such important assumptions are discussed in the next section, and we show that they are indeed applicable in a WiMAX network.

## 2.5 IA Vectors Computation

Section 2.4 assumes that IA vectors are computed and communicated to each MS in the network. However, it is not trivial to calculate IA vectors in the network, as the available algorithms are computationally intensive and highly complicated in nature.

For example, the distributed algorithms proposed in [4, 22] take enormous time (need approximately $10,000$ iterations) to converge as the number of MSs in the network increases. Hence, we devote this section to determine the IA vectors in a WiMAX network with in one frame duration.

Before we delve in to the challenges of finding IA vectors in a network, we present an illustration to determine if we can ever schedule MSs satisfying the requirements mentioned in the above section.

## Illustration

A total of $10 - 50$ MSs are deployed in the network randomly, moving at speeds of 120 $Kmph$. The Angle of Arrival (AoA) of the signals from each MS are noted at the BS for each super frame. The distance of each MS is estimated at the BS in the initial connection establishment phase itself. Based on the speed of mobile, the relative difference in AoA and distance are calculated for each frame. This AoA, when considered based on the $H$ values of each MS, can be considered as Correlative Angle between two users [8]. In this setting, we find out the maximum number of MSs that can share a slot in one OFDM slot, with each MS equipped with two antennas. Each MS uses a MIMO technique randomly for each iteration. Though this is not an idealistic measure, just for this illustration this assumption is considered. While

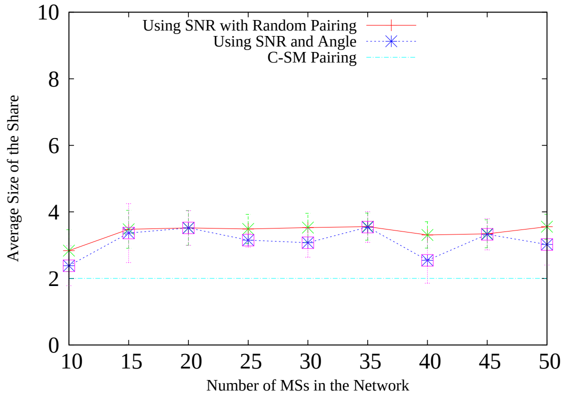

**Fig.** 2.7: Number of Mobiles Sharing a Slot a total of 3 MSs share a slot when each MS uses SM technique, a value of 4 is used when SD is used. A total of $100,000$ Monte-carlo iterations are performed and the number of MSs that can share a slot is calculated in each iteration. The results are compared using random pairing with SNR technique. The number of MSs sharing a slot is observed to be 3 when SNR with random pairing is used. Similar observation is visible when SNR with AoA pairing is used. We used a minimum of 60 degree difference between the AoA values of two MSs participating in the share, similar to that of a typical sectored antenna system [25].It is clearly visible from Fig. 2.7 that it is definitely possible to locate MSs with the required parameters. Also, we observed that this number is higher than the number (2) that C-SM technique provides in a typical WiMAX network. As this study is done for a single slot (time), extending this study to several OFDMA slots in a typical WiMAX frame is expected to provide more performance improvements and is further studied.

## Challenges

Important challenges of using IA in a WiMAX network can be named as follows:

- Precise Channel Quality Estimation
- Average time and complexity to compute IA vectors
- Delayed IA vectors relevance

For the sake of computing IA vectors between BS and several MSs, we consider a distributed numerical approach (Max-SINR) algorithm proposed in [22], based on the principle, “The wireless channel exhibits the property of reciprocity alignment”. In other words, the alignment vectors computed for a channel can simply be reciprocated when the transmitter and receiver are swapped, i.e., the alignment vectors are dependent on the channel values and not on the direction of the transmission. This assumption in a WiMAX network is acceptable, as the BS measures the channel quality of each MS once in each frame, only in the fast feedback channel [1, 26]. In a typical WiMAX network, the channel is estimated using techniques such as blind estimation and channel sounding [27, 28] wherein the MS transmits a known signal to the BS, and the BS determines the error in the received signal to determine the quality of the channel. Since the channel quality is measured only in one direction and is used for determining the IA vectors across both the directions, the above assumption of reciprocity looks reasonable. Also, it has been proved that reciprocity of the channel is visible in a TDD frame structure [15], similar to that of a WiMAX network. Each step involved in generating IA vectors according to the Max-SINR algorithm can be summarized as follows:

Step 0: Generate initial precoding vectors randomly
Step 1: Find interference plus noise covariance matrix
Step 2: Find receiver combining vectors
Step 3: Reverse the link and use receiver combining vectors as precoding vectors
Step 4: Find interference plus noise covariance matrix
Step 5: Find receiver combining vectors
Step 6: Reverse the link and use receiver combining vectors as precoding vectors
Step 7: Goto Step 1 until precoding and receiver vectors converge

The IA vectors calculated are dependent only on $H$ matrix, corresponding to the impact of each MS at several antennas of the BS. In a slow fading channel, the variations in the elements of $H$ matrix across few super frames will be minimal (as we do not consider sudden frequency specific disruptions in the network). In this scenario, we provide mechanisms to overcome the mentioned challenges in the following subsections.

### 2.5.1 Channel Estimation Precision

The duration of a typical MAC frame in a WiMAX network is 5 $ms$. Each MS typically transmits the channel quality to the BS once in each frame in Frame Control Header (FCH) slot. IEEE 802.16 $m$ standard specifies that four frames will constitute a super frame (one in 20 $ms$), and use one FCH slot, thus utilizing the available OFDM slots for transmitting data optimally. The Modulation and Coding Schemes (MCS) used by each MS are updated according to the channel quality updated for each 5 $ms$ frame. Also, we show later that IA vectors can be computed in 20 $ms$ time. Hence, IA vectors generated from the channel estimated in the previous frame can be used for transmission in the current frame.

### 2.5.2 Average Time to Compute IA Vectors

The numerical approach described in Max-SINR algorithm optimized to the current scenario is as follows: The algorithm (Step 0) considers generating random IA vectors and updating them constantly such that the IA vectors converge after several iterations. This converging value is dependent on the channel gain vectors of each MS participating in the share. Given the fact that the channel quality of each MS does not vary drastically for adjacent super frames (of 20 $ms$ duration due to slow fading channel), we use the IA vectors calculated in the previous frame as initial vectors to generate IA vectors for the next frame.

**Corollary 2.5.1** *The IA vectors converge early, when the initial random vectors are same as IA vectors generated for the previous frame.*

Since the channel quality varies minimally in two adjacent frames (since we consider a slow fading channel), as long as the pairing set remains same, the IA vectors of the set also vary accordingly. Hence, it becomes logically appropriate to choose the initial vectors as IA vectors in the previous frame.

**Validation**:

We verified this proposition in a decentralized network with 10 users, with each user requiring to transmit 2 streams of data at any instance. We found that by considering the IA vectors used in the previous frame, the average time consumed to generate IA vectors almost reduced to one third of the time taken when initial vectors are generated randomly.

For a set of $10,000$ iterations, $Max-SINR$ algorithm takes 190 *seconds* [1] to compute IA vectors for each MS participating in the share. However, we observed that $Max-SINR-Optimized$ algorithm takes only 65 *seconds* to compute IA vectors. Hence, $Max-SINR-Optimized$ algorithm is indeed implementable in a WiMAX network, as the algorithm consumes only 0.6 $ms$ to generate IA vectors for every MS participating

---

[1] On an Intel(R) Core(TM) i7 CPU 920 @ 2.67 $GHz$

in the share.

**Example**: Due to frequent channel quality exchange between each MS and the BS, the SNR values of each MS recorded at the BS vary continuously, *not* in a step wise manner. Also, MSs are paired based on the SNR and values of H matrix. Hence, the IA vectors calculated for MSs participating in the share will vary differentially during the subsequent frame. Let $MS_1, MS_2, MS_3$ share a slot in time $t_1$. During time $t_2$, the SNR values of each MS vary differentially with few variations in H matrix[2]. If all the MSs participating in the share remain same at time $t_2$ also, we optimize the Max-SINR algorithm to use IA vectors used at time $t_1$ as initial random vectors. Evaluation showed that the computation time indeed reduced to almost one-third compared to the normal computation time.

### 2.5.3 Delayed IA Vectors Relevance

As mentioned in Section 2.2, each MS transmits the channel quality to the BS once for each super frame [29]. This also means that the BS can transmit IA vectors to each MS participating in the share once in every 20 $ms$. However, the challenge remains if the IA vectors communicated will remain intact for the next 20 $ms$ frame. A simple block diagram to determine IA vectors in a typical WiMAX network is shown in Fig. 2.8. $C1$ to $S1$ at the BS denotes the instantaneous channel quality is converted to the channel quality measured statistically. This is done at the BS to ensure that the channel quality of each MS is always continuous and does not show high fluctuations in adjacent frames. Since, we consider a slow fading channel IA vectors will remain intact for the channel coherence time, which is 30 $ms$ for a mobility of up to 30 $Kmph$ at each MS. Hence, the IA vectors are relevant for the next frame duration.

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[2] generated by the mentioned three MSs sharing slot in the previous frame

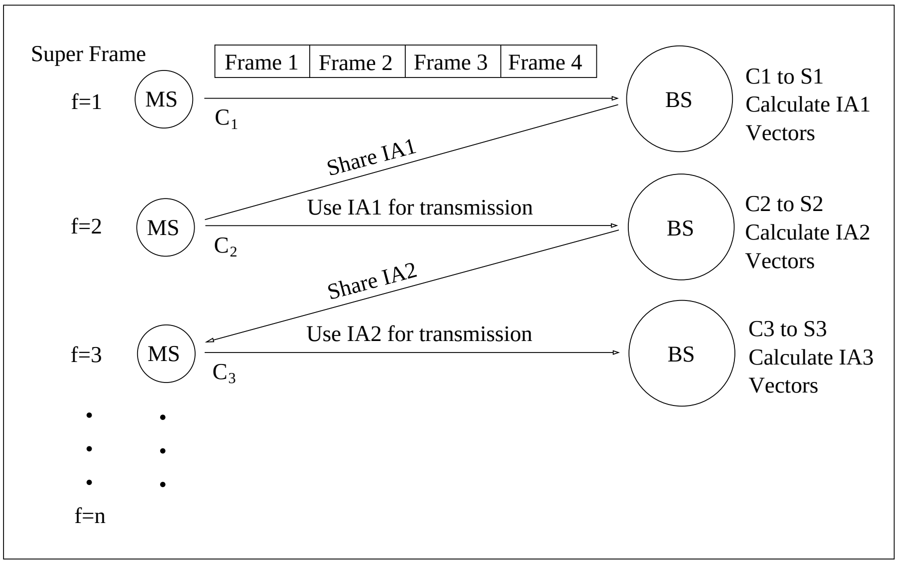

**Fig.** 2.8: Working Solution to Find IA Vectors

## 2.6 Proposed Algorithm to Schedule MSs

### 2.6.1 Related Work

In this subsection, we evaluate some of the basic algorithms that pair several (two) users in same slot.

**Random Pairing**: All MSs are ordered according to their SNR values [30]. An MS with highest SNR value is allocated the slot. Among the remaining MSs, one MS is randomly picked and allocated to the same slot. The process repeats for other OFDM slots at the BS, for each frame. A few disadvantages of this pairing scheme are:

1) The physical layer parameters of MSs, such as SNR, channel quality are not considered.

2) The rate constraints of each MS are not considered.

**Double Proportional Fairness Pairing (D-PF)**: This scheme assigns rank to each MS based on the ratio of required transmission rate to the average transmission rate achieved. Similar to the above, the first MS$_i$ allocated is the MS with highest SNR value. Before choosing the MS to be paired, the utility for each MS$_k$ defined as

$$U_{ik} = \frac{R_i + R_k}{\overline{R_i} + \overline{R_k}} \tag{2.11}$$

where $R_i, R_k$ is the rate required in the next frame, $\overline{R_i},\ \overline{R_k}$ is the average transmission rate achieved by MSs $i, k$ is determined. The MS that provides the maximum utility is paired with the MS$_i$ for the OFDM slot 1.

A notable point of D-PF [7] is that D-PF is proposed for each MS equipped with single antenna. The authors claim that the pairing algorithm can be extended to more than two MSs also. However, allocating MSs with multiple antennas will induce more interference, which needs to be considered in pairing. Towards this direction, we propose a scheduling algorithm as in Algorithm 1 in which we consider the presence of multiple antennas, interference and correlation angle between MSs sharing the slot.

The algorithm determines an MS with highest SNR value and assigns the slot to it. A set of $C$ MSs that can share the same slot are generated using CA-SUP technique [8]. These $C$ MSs are given as input to MAX-SINR-Optimized algorithm to determine $\tau$ MSs that can share the slot. This algorithm also determines the IA vectors to be used by each MS participating in the share. The value of $\tau$ is 3 if this MS uses a SM technique to transmit data, 4 when SD technique is used for transmission. In our scenario, the value of $C$ depends on the total number of MSs that can share that slot. This number $C$ should be large enough to provide a chance for other MSs to share the slot, and small enough for $Max-SINR-Optimized$ algorithm to converge in a reasonable amount of time. The $C$ MSs are given as inputs to $Max-SINR-Optimized$ algorithm: With the initial values of IA vectors taken as the IA vectors used in the previous frame (BS has the sufficient data). We iterate until $\tau$ MSs converge to IA vectors. The same is represented in Algorithm 1. It is proved in [22] that the $Max-SINR$ algorithm converges for any arbitrary initial values of precoding vectors. Hence, the proposed algorithm $Max-SINR-Optimized$ converges, with a worst case scenario where the number of iterations for convergence is same as that of $Max-SINR$ algorithm.

**Algorithm 1** Proposed Algorithm

```
Input: $SNR$ of each MS
H Matrix: $(N * N_t) \times N_r$ size
$N_t$: Number of antennas at each MS
$N_r$: Number of antennas at BS
$N$: Number of MSs in the network
$M_i$: $MIMO$ Technique at each MS
$O$: Set of $OFDM$ slots to be allocated
Start:
Sort MSs based on $SNR$ values
for each $OFDM$ Slot Ø
    1. $allocated\_MS_{\emptyset}$ //Holds the MSs allocated to a slot
    2. Find MS with largest $SNR$ and is unallocated
    3. Allocate $allocated\_MS_{\emptyset}$ slot to MS$_i$ with highest $SNR$ value
       //Match MSs for this MS$_i$ Starts
    4. Find $C$ candidate MSs (that use $M_i$ technique for transmission) based on CA-SUP algorithm (2.3 in [8])
    5. Find IA vectors with $C$ MSs as input using Max-SINR-Optimized algorithm
    6. Allocate $allocated\_MS_{\emptyset}$ to $\tau$ MSs determined from Max-SINR-Optimized algorithm //Match MSs for this MS$_i$ Ends
end for
return $allocated\_MS$ //Set of $allocated\_MS_{\emptyset}$ for each $OFDM$ slot Ø
End
Max-SINR-Optimized:
    1. Step 1: $V_i^{[k]} = V_i^{[IA_{Prev-frame}]}$
    2. Continue from Step 2 as mentioned in Section V.C in [22]
    3. If values of $\tau$ MSs converge, exit
    4. return IA vectors of converged MSs
```

### 2.6.2 Simulation Results

We use standard network simulator (ns-3) to evaluate performance of the proposed algorithm. A standard WiMAX network is simulated with each MS equipped with 2 antennas. However, only one antenna is used for transmission when D-PF and random pairing techniques are used. We do not consider using the best antenna for the transmissions, and consider each MS is equipped with only one antenna when using D-PF and random pairing techniques. For the purpose of simulations, we considered $C$ to be 10. This is because of the following reasons: a) If $C$ is very large, the time taken by $Max - SINR - Optimized$ algorithm to converge may be high enough that generated IA vectors will become irrelevant. b) We need to provide atleast $2 \times \tau$ MSs to generate IA vectors for $\tau$ MSs, inorder to provide sufficient chance for MSs to share a slot. Since $\tau$ can be 3 or 4, $C > 8$. Thus $C = 10$ is a reasonable value to consider for this set of simulations. A few important simulation parameters are mentioned in Table 2.2.

**Table** 2.2: Simulation Parameters

| **Parameter** | **Value** |
|---|---|
| Number of Antennas at MS | 2 |
| Carrier Frequency | 2.4 $GHz$ |
| Channel Bandwidth | 10 $MHz$ |
| OFDM Symbol Duration | 102.86 $\mu s$ |
| UGS Traffic | Constant Bit Rate - 64 $Kbps$ |
| Confidence Interval | 95% |
| Simulation Time | 500 *seconds* |

As we can observe from Fig. 2.9, there is substantial improvement in throughput of the network when the proposed scheduling scheme is used. This is because more number of MSs are sharing each OFDM slot using the proposed scheme. We also observed that D-PF and random pairing achieved similar throughput in the network. This is because we considered only Unsolicited Grant Service (UGS) traffic in the

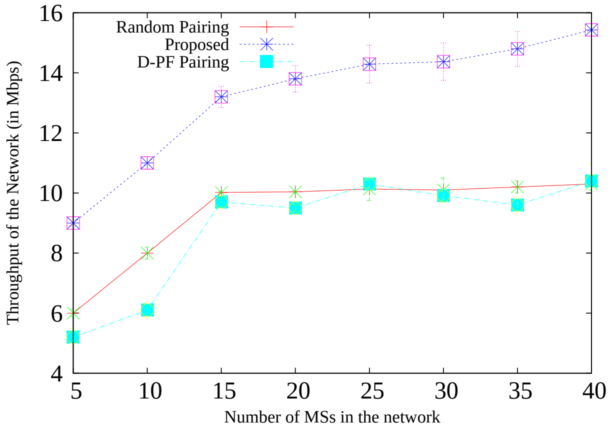

**Fig.** 2.9: Measured Throughput of the Network

network. The proposed algorithm assumes a constant rate requirement at each MS for transmissions. As other traffic classes such as Real Time Polling System (rTPS), non-real Time Polling System (n-rTPS), Best Effort (BE) transmit data at different rates in different frames, we do not consider them for the evaluations. Also, the MIMO technique applied at each MS is dependent on instantaneous SNR values.

## 2.7 Summary

In this chapter, we studied the effect of increasing the number of MSs that share a slot in a PMP network using both analysis and simulations. For a constant rate requirement of 2 $bps/Hz$, we observed (both in theory and simulations) that more than 2 MSs can share a slot when each MS is equipped with multiple antennas, which is in stark contrast to the current wireless network standards [1], which allow only 2 MSs to share a slot for transmission. The number of MSs sharing the slot is shown to vary for different rate requirements at each MS and different MIMO techniques applied at each participating MS. Once the number of MSs that can share a slot is determined, finding which MSs can share each slot in a typical WiMAX network is discussed and an algorithm is proposed to schedule MSs in each frame. We found that performance of the network is significantly improved by using the proposed scheduling algorithm. Studying the network for different rate requirements at each MS remains to be an open problem, and can be considered for future work.

## CHAPTER 3

# MIMO Enabled Efficient Mapping of Data in WiMAX Networks

## 3.1 Introduction

The set of MIMO techniques applicable in a WiMAX network are presented in chapter 1. In this chapter, we provide a detailed description of the existing MIMO techniques in a wireless network. Spatial Multiplexing (MIMO B in chapter 1) is a MIMO technique in which several streams of data (which is minimum of the number of antennas available at the transmitter and the receiver) can be transmitted simultaneously using multiple antennas. A typical transmitter and receiver equipped with 2 antennas using Multiplexing technique for transmission is shown in Fig. 3.1. The throughput of a system using multiple ($K$) antennas for transmission is theoretically $K$ times the throughput achieved using a single antenna. Interference occurs in these kind of techniques and can be eliminated if high channel quality is observed between the transmitter and receiver.

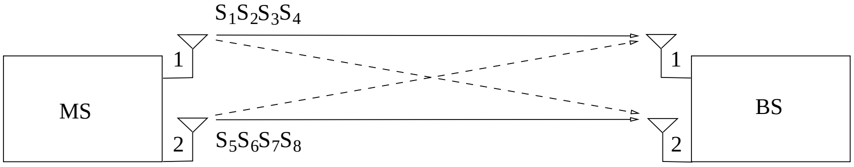

**Fig.** 3.1: Spatial Multiplexing Technique

Spatial Diversity techniques improve the reliability of transmitted data. Transmit Diversity is a technique in which the same data (with different transmission characteristics) is transmitted on more than one antenna simultaneously. A typical transmitter and receiver using transmit diversity technique to transmit data is shown in Fig. 3.2. Based on the spacing between the transmitting antennas, constructive interference occurs at the receiving antenna and the SNR of the transmitted signal is maximized.

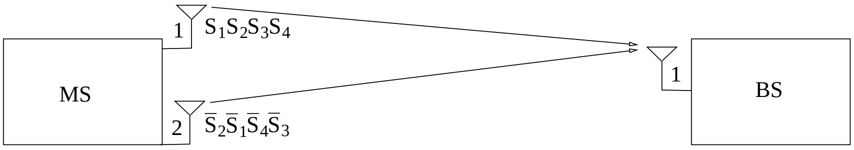

**Fig.** 3.2: Transmit Diversity Technique

Receiver Diversity is a technique in which a signal is received across multiple antennas, and one of the receiver combining techniques among Maximum Ratio Combining, Selection Combining and Equal Gain Combining [31] is used to maximize the Signal to Noise Ratio (SNR) of the required transmitted signal. A typical transmitter and receiver using receiver diversity technique to transmit data is shown in Fig. 3.3. Since SNR of the required signal is maximized, errors in the signal are reduced.

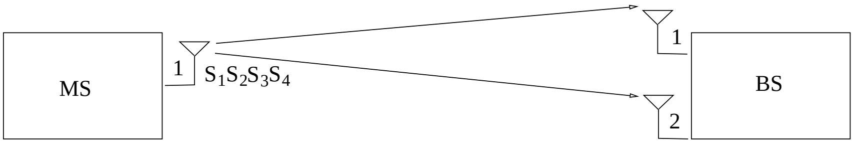

**Fig.** 3.3: Receiver Diversity Technique

Thus the reliability of the transmitted data is improved by using multiple antennas at the receiver. The concept of Receiver Diversity is efficiently used to improve reliability of the transmitted data in a Wireless Local Area Network (WLANs). The authors of [32] use Path Diversity technique to improve loss resilience of the transmitted data by enabling multiple Access Points (APs) to receive the data transmitted by a single client. A frame recombining scheme is used at each AP to recover transmitted frame from a set of possibly erroneous frames, thus improving the reliability of the transmitted frame.

The MAC Protocol Data Units (MPDU's) in a WiMAX Network are scheduled for each frame based on the number of OFDM slots and the MIMO techniques allocated to each MS in each frame. These MIMO techniques are adaptively assigned to each MS depending on the channel quality. Since, the reliability of the transmitted data and the achieved throughput of the network are highly dependent on the MIMO technique used, adaptively assigning the MIMO technique to each MS is an active area of research recently. Recently, it is shown that MIMO techniques can be adaptively assigned to each MS based on the channel conditions, condition number and Quality of Service requirements of each MS [1].

The problem that we study in this chapter can be termed as "Can we propose a MIMO technique that can maximize the achievable throughput with out compromising the reliability of transmitted data?" In other words, the reliability of transmitted data should be same as that of diversity techniques, but the throughput should be maximized. Switching the MIMO techniques adaptively [33] depending on the instantaneous channel quality is a completely different problem not studied in this thesis. However, adaptive MIMO switching does not always provide optimal performance in high mobility regions due to the unexpected variations in the channel. In this scenario, proposing a MIMO technique that works independent of channel quality and remains optimal is a challenge that we study in this chapter.

Considering the above problem in-hand, we design a transmission technique that works independent of the channel conditions and still improves performance of the network. The proposed technique should be time invariant in nature. We achieve this by proposing an optional error correction mechanism at the receiver, which is enabled when atleast one of the transmitted signals is received without errors. The advantage of the proposed technique is that the choice of an appropriate MIMO technique to be used at each MS is reduced to the basic choice of whether to use multiple antennas or not for the transmission.

In the next section, we describe the proposed technique in detail. This technique is applicable only when one of the two transmitted streams of data is received (in)correctly. The performance of the proposed technique is evaluated in Section 3.3. Section 3.5 summarizes the contributions of this work.

## 3.2 Proposed Technique

### 3.2.1 Assumptions

The following assumptions are made for solving the mentioned problem:

- The channel quality observed for each transmitted stream remains constant for the entire duration of one OFDMA frame, and varies between different streams. Example: If a signal $x$ transmitted along a channel with quality $h$ is received as $y$, A transmitted signal $x$ is related to the received signal $y$ as

  $$y = h * x + n \tag{3.1}$$

  where $h$ represents the channel quality perceived by the transmitted signal $x$, and $n$ is the noise induced in the signal $x$ during the ongoing transmission. Each MS transmits the channel quality observed in the previous frame to the BS, once in each OFDMA frame. This channel quality is considered a constant at the BS for each transmitted stream and OFDMA frame. By considering Equation 3.1 to hold for all the OFDM slots used by an MS for transmission, the signal received during each OFDM slot can be identified as

  $$\forall i \in [1, m],\, y_{[i]} = h * x_{[i]} + n$$

  where $i$ represents the OFDM slot. In essence, the value of $h$ is independent of $i$, for each transmitted stream in each OFDMA frame. This also assumes that the channel gain is independent of the frequency at which the data stream is transmitted (Additive White Gaussian Noise Channel).

- When an MS transmits data across two antennas, each stream obtains different SNR values at the BS [34]. In a deployed cellular network, it can be deduced that the difference in the SNR values of the signals from two antenna will differ by at least 3 $dB$. The difference is also dependent on SNR levels. As the SNR values increase, so does the difference. When the SNR value of an MS is close to the accepted threshold value at the BS, it can be assumed that one stream of data is received with SNR $\geq$ threshold (non-erroneous), and the other stream with SNR $<$ threshold (erroneous). It is at this SNR region that we solve the mentioned problem. The receiver combining techniques [31] are used at each antenna before the proposed technique is utilized at the receiver.

Based on the above assumptions, we propose a technique that improves the functionality of both the transmitter and receiver to solve the mentioned problem. Details of the functionalities overloaded at the receiver and transmitter using the proposed technique are explained in detail in Section 3.2.2 and Section 3.2.3.

### 3.2.2 Proposed Technique at the Transmitter

We propose a technique that improves reliability of the entire transmitted data even though only the first few OFDM slots transmit data redundantly. This is possible when atleast one of the streams is received correctly at the receiver. The details of the proposed technique at the transmitter can be mentioned as follows: When an MS is allocated $n_{ofdm}$ slots to transmit in one OFDMA frame, MS transmits variants of same data across two antennas in $t_{ofdm}$ slots. The technique is enabled only when one stream transmitted from an MS is received with SNR higher than the threshold and other stream is received with SNR lower than the threshold. This redundancy in the transmitted data (in form of signals in $t_{ofdm}$ slots) will be used by the optional error correction mechanism proposed at the BS.

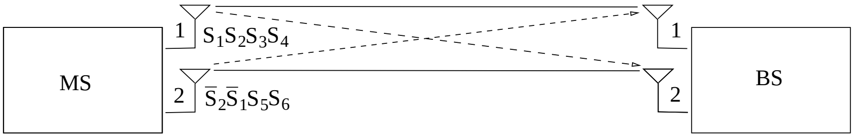

**Fig.** 3.4: Data Transmitted in the Proposed Technique

The data transmitted at an MS in 4 OFDM slots across two antennas with $t_{ofdm} = 2$ is shown in Figure 3.4. The first two OFDM slots across both the antennas transmit variants of same data. Different data is transmitted in remaining OFDM slots.

In this scenario, the probability of occurrence of error in the transmitted packet can be calculated as follows:
In an IEEE 802.16 network, the packet error ratio of a Protocol Data Unit (PDU) transmitted using OFDM symbols is termed in [35] as

$$p_{pdu} = 1 - (1 - p_{ofdm})^{n_{ofdm}} \tag{3.2}$$

where $p_{ofdm}$ denotes the probability of receiving an erroneous OFDM symbol and $n_{ofdm}$ is the number of ofdm symbols required to transmit the PDU.
When a PDU can be transmitted in a single frame using $n_{ofdm}$ symbols across two antennas, the packet error probability of PDU in Eq. (3.2) can be modified as

$$p_{pdu} = 1 - [(1 - p_{ofdm1})^{k_1} \times (1 - p_{ofdm2})^{k_2}] \tag{3.3}$$

where $k_1$ and $k_2$ are the number of OFDM symbols transmitted, $p_{ofdm1}$ and $p_{ofdm2}$ denote the probability of receiving an erroneous OFDM symbol transmitted from antenna 1 and 2, respectively; sufficient condition being $k_1 + k_2 = n_{ofdm}$.

With out loss of generality, we assume that the data transmitted from a single antenna will receive equal interference for all the OFDM slots used at that antenna (Assumption 1). In a single frame (of 5 $ms$ duration), the probability of an error occurring in $k_i$ OFDM symbols transmitted from an antenna is same as error occurring in a single OFDM symbol. Based on this assumption, Eq. (3.3) can be modified as

$$p_{pdu} = 1 - \ [(1 - p_{ofdm1}) \times (1 - p_{ofdm2})\ ] \tag{3.4}$$

Eq. (3.4) assumes that the receiver (BS) does not incorporate any error correction mechanism. By enabling an appropriate error correction mechanism at the BS and providing $t_{ofdm}$ symbol redundancy in the data being transmitted from both antennas, Eq. (3.4) can be modified as

$$\begin{aligned} p_{pdu} &= \overline{X}\ Y\ (1 - \mathbb{P}(\chi_1 = k_1 - t_{ofdm} | \nu_2 = k_2)) \\ &\quad + X\ \overline{Y}\ (1 - \mathbb{P}(\chi_2 = k_2 - t_{ofdm} | \nu_1 = k_1)) + \ \overline{X}\ \overline{Y} \quad where \\ X &= (1 - p_{ofdm1}), Y = (1 - p_{ofdm2}),\ \overline{X} = (p_{ofdm1})\ and\ \overline{Y} = (p_{ofdm2}) \end{aligned} \tag{3.5}$$

where X and Y denote the probability of receiving the signals from antenna 1 and 2 without errors, while $\overline{X}$ and $\overline{Y}$ is the probability of receiving signals with errors. $\mathbb{P}(\chi_1 = k_1 - t_{ofdm} | \nu_2 = k_2)$ is the probability of correcting the erroneously received $k_1$ OFDM symbols transmitted from antenna 1 when $k_2$ OFDM symbols from antenna 2 are received without error. Similarly, $\mathbb{P}(\chi_2 = k_2 - t_{ofdm} | \nu_1 = k_1)$ can be defined. This correction probability is dependent on the correction mechanism used at the BS. Clearly, the probability that the erroneous stream remains erroneous is less than the probability of occurrence of error. However, the techniques used at the receiver to mitigate error will have a high impact on the performance of the network. We propose a technique that works at the receiver (after the receiver combing techniques are performed at each antenna), which is explained in detail in the next subsection.

### 3.2.3 Proposed Technique at the Receiver

The flow diagram for decoding the signals received at two antennas of the BS is shown in Fig. 3.5. The SNR of each signal is checked for acceptance based on the threshold value. When one of the streams is received with SNR $\geq$ Threshold and the other stream is received with SNR $<$ Threshold, the proposed technique is utilized. When both the signals are received with SNR below the Threshold, both signals are rejected.

The proposed technique assumes OFDM technology at the physical layer, typical to that of a WiMAX network. This assumption is in stark contrast to the Alamouti coding technique that works independent of any physical layer technology used. We determine the error signal that differentiates the signals of erroneous stream and non-erroneous stream in the first $t_{ofdm}$ slots. The error signal is the signal when convolved with an erroneous stream of signals, will improve the SNR of the stream[1]. Also, the error signal determined from the redundant data in $t_{ofdm}$ OFDM slots can be used for correcting the data in the remaining OFDM slots of the erroneous stream[2]. Now, determining the error in erroneous stream is carried out by using Kalman filter to

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[1] Mentioned in Theorem 1 at the Appendix of this chapter

[2] Mentioned in Theorem 2 at the Appendix of this chapter

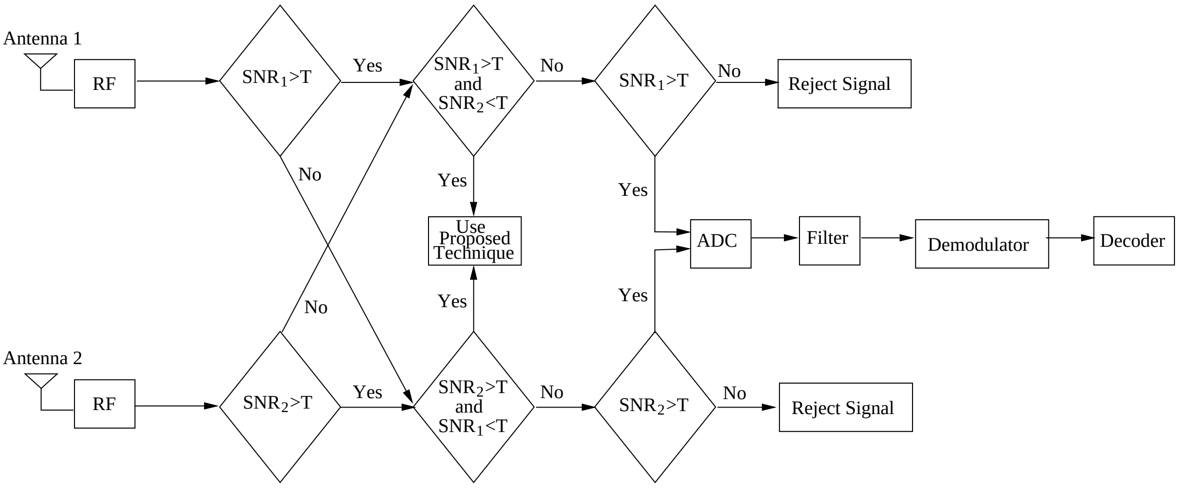

**Fig.** 3.5: Signal Flow at the Receiver

estimate the error for each sub-carrier in the remaining OFDM slots. Determining the error signal is carried out separately at the receiver for each sub-carrier in the first $t_{ofdm}$ slots, and error signal is estimated for the remaining OFDM slots. The details of the Kalman filter estimation in determining the error signal are mentioned below:

Kalman filter [36–38] efficiently estimates the noise in the received signal by measuring the noise from the previously received signals, and is adaptive in nature. For each iteration, Kalman filter updates the estimated value and estimates the values accurately, stabilizing with time. A variation of Kalman filter applied at sub-carrier level [39] considers using of OFDM symbols for transmitting data. The per sub-carrier Kalman update recursively estimates the error for a set of sub-carriers in a each time slot. Several iterations are possible for each OFDM symbol, and the estimated values are accurate after 40 iterations [3]. Hence, per sub-carrier Kalman filter is apt for detecting error in the proposed technique and we use Kalman filter to efficiently estimate the difference between the erroneous and non-erroneous streams. Details of Kalman filter parameters mapped to the proposed technique are tabulated in Table 3.1.

Once the error signal is estimated for each sub-carrier used by the MS for transmis-

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[3] Observation 1 mentioned at the Appendix of this chapter

**Table** 3.1: Mapping of Kalman Filter Parameters at the Receiver

| Parameter | Description | Relevant Parameter in the Technique |
|---|---|---|
| x | State Vector Estimate | Error Estimate |
| H | Observation Matrix | Data in Non-erroneous Stream |
| Z | Observation Vector | Data in Erroneous Stream |
| A | State Transition Matrix | Identity Matrix |
| B | Input Matrix | Null matrix |
| u | Input Control Vector | Null matrix |
| v and w | Gaussian Noise | Gaussian Noise |

sion, the error correction mechanism can be explained as follows: The error correction mechanism is triggered only when one of the streams is received with errors and the other is received without errors (SNR $<$ Threshold). Assuming that data is transmitted redundantly in $t_{ofdm}$ OFDM slots at each antenna, data in the first OFDM slot at each antenna is given as input to the Kalman filter. Each OFDM slot is split into several sub-carriers (48 in WiMAX), and Kalman filter is used to estimate the error for each sub-carrier, as explained in Fig. 3.6. As the number of sub-carriers in one OFDM slot (48) is greater than 40, the estimated value converges and we can estimate the error for the remaining sub-carriers. Thus, error in the erroneous stream compared to non-erroneous stream is estimated. The error determined in first OFDM slot remains constant, and can be used to correct data in the remaining OFDM slots [4]. The data in the remaining OFDM slots of the erroneous stream is convolved with the error signal, and data is corrected.

**Optimal $t_{ofdm}$ Number**:

An MS utilizes multiple antennas only when the number of slots allocated is higher than a threshold value (8 in simulations), which is dependent on the SNR values of the received signals. The optimal number of OFDM slots $t_{ofdm}$, in which data is to be transmitted redundantly across different antenna is determined as below. The es-

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[4] Mentioned in Theorem 2 at the Appendix of this chapter

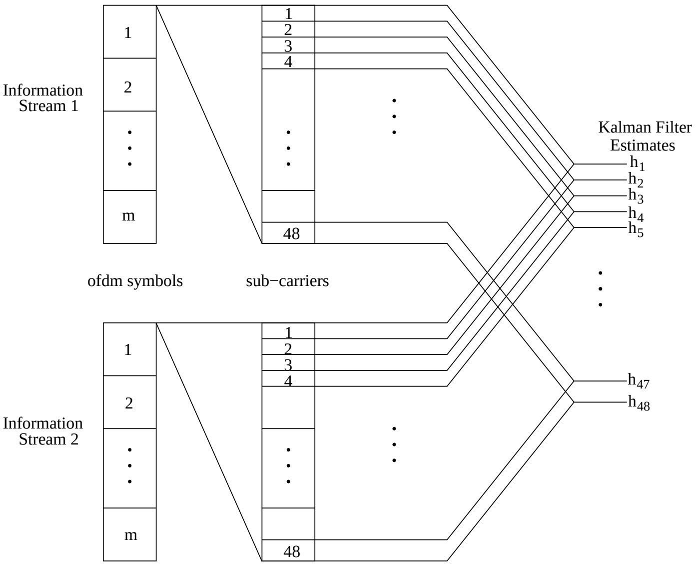

**Fig.** 3.6: Proposed Error Detection Mechanism at the Receiver

timated error is accurate after 40 iterations[5]. Since 48 sub-carriers available in an OFDM slot provide iterations $\geq 40$, the error estimated using the first OFDM slot is sufficient to determine the error efficiently. Hence, transmitting data redundantly in $t_{ofdm} = 1$ slot is optimal to maximize performance of a WiMAX network.

## 3.3 Evaluating the Proposed Technique

We use a standard network simulator (ns-2) and apply a WiMAX patch provided by NIST [40] to evaluate the proposed technique. The simulations are conducted at 3.5 $GHz$ carrier frequency with a bandwidth of 7 $MHz$, and each OFDM symbol constitutes 102.8 $\mu s$ and uses QPSK 3/4 modulation technique. Each MS and also the BS is equipped with two antennas for transmission. A constant bit rate (CBR) traffic is generated at each MS with a constant packet size of $1,500$ $bytes$. We compare the proposed technique with Alamouti technique and a technique that uses single antenna for transmission, by measuring the throughput and reliability of the data transmitted in the network. Here, the term reliability is defined as the ratio of number of packets

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[5] Observation 1 at the Appendix of this chapter

received successfully to the number of packets transmitted. We also assume that for a single OFDMA frame of 5 $ms$, data transmitted across each antenna will have constant channel coefficient and noise terms at each receiving antenna.

As shown in Fig. 3.7, the throughput of the network increases until the number of MSs reaches a value of 20, as sufficient traffic is induced in the network. The throughput in the Alamouti coding technique is close to the throughput of single antenna technique even though it uses 2 antennas, because the entire data is transmitted redundantly across the second antenna. However, since the reliability is high for the data transmitted using Alamouti technique, throughput is slightly higher in Alamouti technique compared to that of using single antenna technique for transmission. Since, the number of redundant OFDM slots in the proposed technique is only 1, an improvement in the throughput of the network is visible in the simulations. We measure the observed reliability of the data transmitted in the network. As can be seen in Fig. 3.8, Alamouti coding technique maintains the highest reliability value while the single antenna technique maintains the lowest. This is because the data is entirely replicated at another antenna in Alamouti coding technique. The reliability of the transmitted data in the proposed technique matches with Alamouti technique when the number of MSs in the network is less than 20, and maintains value in between the values of Alamouti and single antenna technique. This improvement in reliability is due to the usage of Kalman filter at the receiver to determine and eliminate error in the erroneously received signal. However, the proposed technique works only when one

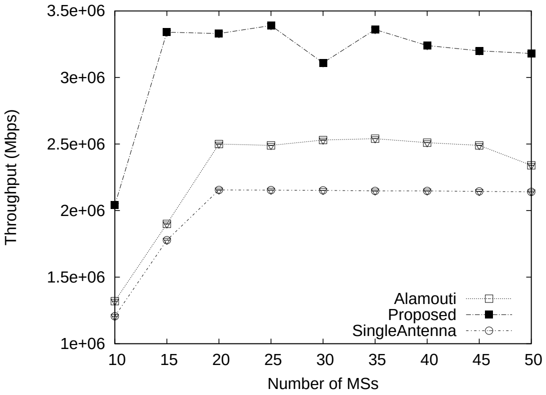

**Fig.** 3.7: Throughput of the Network Versus Number of MSs in the Network

SNR $<$ Threshold and another SNR $\geq$ Threshold. Hence, the value of reliability is not always same as Alamouti technique.

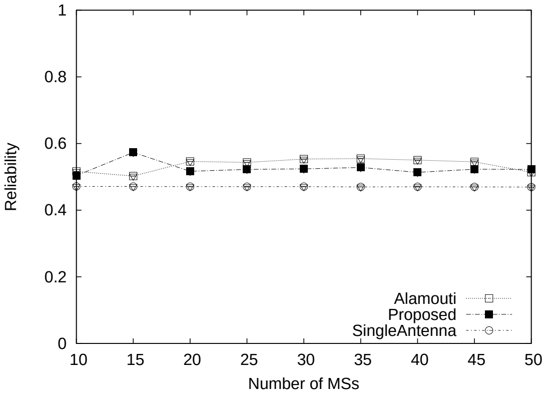

**Fig.** 3.8: Reliability of the Transmitted Data Versus Number of MSs in the Network

## 3.4 Drawback of the Proposed Technique

The technique is proposed under the assumption that irrespective of the signal processing techniques over an existing signal, the domain of the noise term in the processed signal remains in the same domain as the preprocessed (existing) signal[6]. However, this assumption is highly idealistic in nature and is considered practically impossible. Solving the mentioned problem when this assumption is relaxed (close to realistic conditions) remains as a challenge and can be considered as future work.

## 3.5 Summary

In this chapter, we proposed a transmission technique across multiple antennas that exploits the usage of OFDM technology in WiMAX networks. We showed that by transmitting redundant data in $t_{ofdm}$ $(= 1)$ number of OFDM slots at different antenna of an MS and using efficient error correction mechanism at the receiver (BS), the reliability of the transmitted data can be improved. While other techniques that improve the reliability have considerable reduction in achievable throughput, proposed

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[6] Mentioned in Theorem 1 at the Appendix of this chapter

technique maintains the reliability by reducing the throughput marginally compared to that of other MIMO techniques. We use extensive simulations and show that our proposed technique performs better than other MIMO techniques.

### 3.5.1 Appendix

**Theorem 1**: In any network with a frame size of 5 $ms$ using OFDM symbols for transmission, when two streams $I_1$ and $I_2$ transmitted from a single terminal (MS) are received at two antennas of another terminal (BS), we can correct one erroneous signal if the other signal is received without errors.

**Proof**: The channel gain for a stream of data transmitted from an antenna in a 5 $ms$ frame is constant [1] irrespective of the fading distributions. Let stream $I_{1(2)}$ has a channel gain of $h_{1(2)}$ with Gaussian noise as $n_{1(2)}$. Here, $n_{1(2)}$ is the Circularly Symmetric Gaussian Random Variable taken from $(0, N_{\sigma^2})$, where $N_{\sigma^2}$ is average noise value $< 1$. Let $I_1$ stream is received without errors (SNR $\geq$ Threshold) and $I_2$ stream is received with errors (SNR $<$ Threshold). Let stream $I_1$ is transmitted with signals $d_1, d_2, d_3$ and stream $I_2$ is transmitted with signals $d_1, d_4, d_5$ across 3 OFDM slots. The transmission of signals across the channel can be written as

$$s_1^1 = h_1 * d_1 + n_1 \tag{3.6}$$

$$s_1^2 = h_2 * d_1 + n_2 \tag{3.7}$$

Calculating $d_1$ from Eq. (3.6) and substituting in Eq. (3.7),

$$s_1^2 = h * s_1^1 + n, \tag{3.8}$$

where $h = h_2/h_1$ and $n = n_2 - n_1 * h_2/h_1$. Hence, by convolving the erroneous stream ($I_2$) signals with $h^{-1} = (h_2/h_1)^{-1}$, the channel gain is shown to be same as that of stream $I_1$. It is to be noted that the noise also is improved by the same factor. However, since noise term $n_{1(2)}$is the Circularly Symmetric Gaussian variable, the noise value remains in $(0, 1)$. Hence, the power of noise is improved marginally compared to the channel gain. Since the channel gain is improved with marginal change in power of the noise, the SNR of the stream $I_2$ increases. Also, the channel gain in $I_2$ is improved to that of $I_1$ with minor variations in noise. Hence, the error in stream $I_2$ is corrected.

**Theorem 2**: The error ($h$ in Theorem 1) that we determine for erroneous stream $I_2$ using the first OFDM slot remains constant for all the remaining OFDM slots, and can be utilized to improve the quality of the received signal.

**Proof**: Following from Eq. (3.7), we can determine $s_4^2$ with data transmitted as $d_4$ to be

$$s_4^2 = h_2 * d_4 + n_2 \tag{3.9}$$

Now, convolving $s_4^2$ with $h^{-1} = (h_2/h_1)^{-1}$ gives

$$s_4^2 * h^{-1} = (h_2 * d_4 + n_2) * (h_1/h_2) = h_1 * d_4 + n_2 * h_1/h_2 \tag{3.10}$$

Since the channel gain is improved to $h_1$, the quality of the received signal is improved. Also, the value of $h$ is achieved only from the first OFDM slot and the same $h$ is used to improve the quality of the remaining OFDM slots. Hence, the quality of the received signal is improved by determining the $h$ from the first OFDM slot and applying for the remaining OFDM slots.

**Observation 1**: The value of the estimate from the Kalman filter converges after 40 iterations (estimates).

We generate the plot using MATLAB, by transmitting integers as the correctly and wrongly received signals and estimated the value of error signal. As we know that the data is transmitted in form of constellations for each modulation type, we denote that

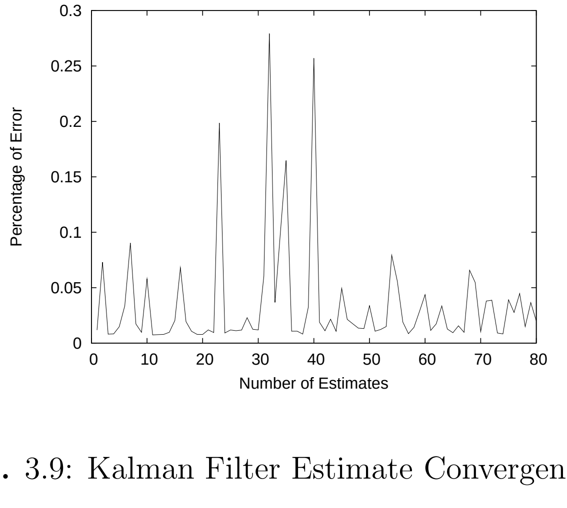

**Fig.** 3.9: Kalman Filter Estimate Convergence the data in each constellation (bits) can be represented as integers. In a constellation, the probability of converting adjacent point is high compared to others [41]. Thus, we assume that we get different integers for different constellations. The approximate error percentage is as plotted in Fig. 3.9. As can be seen, the initial estimates constitute an error estimate of up to 30%, and as the number of estimates crosses 40, the error percentage remains stable at $1\% - 5\%$.

# CHAPTER 4

# Conclusion

In this thesis, we studied two important problems that arise by using multiple antennas in a WiMAX network. First, we studied the problem of determining the maximum number of MSs that can share a slot in a Point-to-Multipoint network. We showed (using both analysis and simulations) that more than 2 number of MSs can share a slot in a centralized network, depending on several parameters such as number of antennas used for transmission, MIMO technique applied, and rate requirements of each MS. This was shown to be possible by applying Interference Alignment technique for transmitting data. We showed that the performance of the network is improved by allocating one OFDM slot to multiple MSs, that can transmit data concurrently without errors. Studying the mentioned problem network for different rate requirements at each MS remains to be an open problem, and can be considered for future work. The problem is studied for a network in which each MS is equipped with either 1 or 2 number of antennas. However each MS may not have same number of antennas in a real network. Studying the problem for a network in which each MS is equipped with varying number of antennas can be considered for future work.

Second, we proposed a MIMO that exploits the usage of OFDM technology in WiMAX networks. We showed that by transmitting data redundantly across multiple antennas in $t_{ofdm}$ (= 1) OFDM slots and using efficient error correction mechanism at the receiver, the reliability of the transmitted data can be maximized with considerable improvement in throughput of the network. Using extensive simulations we showed that the proposed technique performs much better than other MIMO techniques. This study is based on the assumption that data from atleast one of the antennas of the transmitter is received correctly at the receiver. A study that relaxes this assumption can be an interesting piece of work for further progressive research in this direction.

# REFERENCES

[1] "IEEE Standard for Local and Metropolitan Area Networks Part 16: Air Interface for Broadband Wireless Access Systems," *IEEE Std 802.16-2009 (Revision of IEEE Std 802.16-2004)*, pp. 1–2082, May 2009.

[2] S. Diggavi, A. Calderbank, S. Dusad, and N. Al-Dhahir, "Diversity embedded space-time codes," *IEEE Transactions on Information Theory*, vol. 54, no. 1, pp. 33–50, Jan. 2008.

[3] V. Cadambe and S. Jafar, "Interference alignment and degrees of freedom of the K-user interference channel," *IEEE Transactions on Information Theory*, vol. 54, no. 8, pp. 3425–3441, Aug. 2008.

[4] M. Shen, A. Host-Madsen, and J. Vidal, "An improved interference alignment scheme for frequency selective channels," in *Proceedings of IEEE International Symposium on Information Theory*, 2008, pp. 559–563.

[5] K. C.-J. Lin, S. Gollakota, and D. Katabi, "Random access heterogeneous MIMO networks," in *Proceedings of ACM Special Interest Group on Data Communication*, 2011, pp. 146–157.

[6] W. S. Peters and J. W. R. Heath, "User partitioning for less overhead in MIMO interference channels," *CoRR*, vol. abs/1007.0512, 2010.

[7] X. Chen, H. Hu, H. Wang, H. hwa Chen, and M. Guizani, "Double proportional fair user pairing algorithm for uplink virtual MIMO systems," *IEEE Transactions on Wireless Communications*, vol. 7, no. 7, pp. 2425–2429, July 2008.

[8] M. Peng, W. Wang, and H.-H. Chen, "Multiuser pairing-up schemes under power constraints for uplink virtual MIMO networks," *Mobile Network Applications*, vol. 15, no. 2, pp. 298–309, Apr. 2010.

[9] Y. Rui, H. Hu, H. Yi, and H.-H. Chen, "Robust user pairing algorithm under channel estimation errors for uplink virtual multiple-input multiple-output systems," *IET Communications*, vol. 6, no. 3, pp. 318–323, Apr. 2012.

[10] N. Aggarwal, R. S. Manickam, and C. S.R. Murthy, “Cross-layer user pairing for CSM in IEEE 802.16 networks,” *IEEE Communications Letters*, vol. 15, no. 5, pp. 515–517, May 2011.

[11] Y. Zhao and S.-G. Haggman, “Intercarrier interference self-cancellation scheme for OFDM mobile communication systems,” *IEEE Transactions on Communications*, vol. 49, no. 7, pp. 1185–1191, July 2001.

[12] K. W. Park and Y. S. Cho, “An MIMO-OFDM technique for high-speed mobile channels,” *IEEE Communications Letters*, vol. 9, no. 7, pp. 604–606, July 2005.

[13] D. Petrovic, W. Rave, and G. Fettweis, “Intercarrier interference due to phase noise in OFDM - Estimation and suppression,” in *Proceedings of IEEE Vehicular Technology Conference*, 2004, pp. 2191–2195.

[14] P. Mohapatra, K. Nissar, and C. Murthy, “Interference alignment algorithms for the K user constant MIMO interference channel,” *IEEE Transactions on Signal Processing,*, vol. 59, no. 11, pp. 5499–5508, Nov. 2011.

[15] J. Shi, Q. Luo, and M. You, “An efficient method for enhancing TDD over the air reciprocity calibration,” in *Proceedings of IEEE Wireless Communications and Networking Conference*, 2011, pp. 339–344.

[16] M. Haenggi and R. K. Ganti, “Interference in large wireless networks,” *Foundations and Trends in Networking*, vol. 3, no. 2, pp. 127–248, Feb. 2009.

[17] R. Vaze, “How many transmit antennas to use in a MIMO interference channel,” *CoRR*, vol. abs/1105.6170, 2011.

[18] M. Garcia and C. Oberli, “Intercarrier interference in OFDM: A general model for transmissions in mobile environments with imperfect synchronization,” *EURASIP Journal on Wireless Communications and Networking*, vol. 3, no. 9, pp. 101–111, Nov. 2009.

[19] T. Yucek and H. Arslan, “Carrier frequency offset compensation with successive cancellation in uplink OFDMA systems,” *IEEE Transactions on Wireless Communications*, vol. 6, no. 7, pp. 3546–3551, Oct. 2007.

[20] R. G. Gallager, “Circularly-Symmetric Gaussian random vectors,” 2008, preprint. [Online]. Available: www.rle.mit.edu/rgallager/documents/CircSymGauss.pdf

[21] A. Papoulis and S. Unni Krishnan Pilali, *Probability, Random Variables and Stochastic Processes*. Tata McGRAW-HILL, 2002.

[22] K. Gomadam, V. Cadambe, and S. Jafar, “A distributed numerical approach to interference alignment and applications to wireless interference networks,” *IEEE Transactions on Information Theory*, vol. 57, no. 6, pp. 3309–3322, June 2011.

[23] Y. Li, G. Zhu, and S. Zhang, “Transmitter centric scheduling in multi-cell MIMO uplink system,” in *Proceedings of IEEE International Conference on Communications*, 2010, pp. 1–6.

[24] L. Cottatellucci, G. He, and S. Gault, *Information Theoretic Capacity of WiMAX*. Wiley and Iste, 12 2009. [Online]. Available: http://www.eurecom.fr/publication/2960

[25] A. Nascimento, J. Rodriguez, S. Mumtaz, A. Gameiro, and C. Politis, “Dynamic resource allocation architecture for IEEE 802.16e: Design and performance analysis,” *Mobile Network Applications*, vol. 13, no. 3-4, pp. 385–397, Aug. 2008.

[26] W. Xiaoyi and W. Lilei, “A new mathematical model for analyzing CQI channel allocation mechanism in IEEE 802.16 systems,” in *Proceedings of IEEE International Conference on Circuits and Systems for Communications*, May 2008, pp. 177–181.

[27] T. Kwon, H. Lee, S. Choi, J. Kim, D.-H. Cho, S. Cho, S. Yun, W.-H. Park, and K. Kim, “Design and implementation of a simulator based on a cross-layer protocol between MAC and PHY layers in a WiBro compatible IEEE 802.16e OFDMA system,” *IEEE Communications Magazine*, vol. 43, no. 12, pp. 136–146, Dec. 2005.

[28] Y.-W. Huang and Y. Li, “802.16 uplink sounding via QPSK Golay sequences,” *IEEE Communications Letters*, vol. 14, no. 7, pp. 593–595, July 2010.

[29] R. Cohen and G. Grebla, “Efficient allocation of CQI channels in broadband

wireless networks," in *Proceedings of IEEE International Conference on Computer Communications*, Apr. 2011, pp. 96–100.

[30] K. Balachandran, D. Calin, N. Gopalakrishnan, J. H. Kang, A. Kogiantis, S. Li, L. Ozarow, S. Ramakrishna, A. N. Rudrapatna, and R. Sun, "Design and performance analysis of collaborative spatial multiplexing for IEEE 802.16e-based systems," *Bell Labs Technical Journal*, vol. 13, no. 4, pp. 97–117, 2009.

[31] D. Brennan, "Linear diversity combining techniques," *Proceedings of the IEEE*, vol. 91, no. 2, pp. 331–356, Feb. 2003.

[32] A. Miu, H. Balakrishnan, and C. E. Koksal, "Multi-radio diversity in wireless networks," *Wireless Networks*, vol. 13, no. 6, pp. 779–798, Dec. 2007.

[33] M. Tran, D. Halls, A. Nix, A. Doufexi, and M. Beach, "Mobile WiMAX downlink performance analysis with adaptive MIMO switching," in *Proceedings of IEEE Mobile WiMAX Symposium*, 2009, pp. 147–151.

[34] P. Moberg, A. Osseiran, and P. Skillermark, "Cost comparison between SISO and MIMO deployments in future wide area cellular networks," in *Proceedings of IEEE Vehicular Technology Conference*, 2009, pp. 1–5.

[35] C. Hoymann, "Analysis and performance evaluation of the OFDM-based metropolitan area network IEEE 802.16," *Computer Networks*, vol. 49, no. 3, pp. 341–363, Oct. 2005.

[36] M. H. Hayes, *Statistical Digital Signal Processing and Modeling.* Wiley, 1996.

[37] J. R. Treichler, C. R. Johnson, Jr., and M. J. Larimore, *Theory and Design of Adaptive Filters.* Wiley-Interscience, 1987.

[38] G. Welch and G. Bishop, "An Introduction to the Kalman Filter," University of North Carolina, Chapel Hill, NC, USA, Tech. Rep., 1995.

[39] W. Chen, "Time- frequency- selective channel estimation of OFDM systems," Ph.D. dissertation, Drexel University, Pennsylvania, USA, 2005.

[40] NIST. (2009, Feb.) IEEE 802.16 module for NS-2. [Online]. Available: http://www.antd.nist.gov/seamlessandsecure/pubtool.shtml#tools

[41] S. Sen, S. Gilani, S. Srinath, S. Schmitt, and S. Banerjee, “Design and implementation of an approximate communication system for wireless media applications,” in *Proceedings of ACM Special Interest Group on Data Communication*, 2010, pp. 15–26.

# LIST OF PUBLICATIONS

1. Phani Krishna P, Saravana Manickam R, and Siva Ram Murthy C, "MIMO Enabled Efficient Mapping of Data in WiMAX Networks," in *Proceedings of the 13th International Conference on Distributed Computing and Networking*, 2012, pp. 397-408.
2. Phani Krishna P and Siva Ram Murthy C, "On Bounding the Number of Mobiles Sharing a Slot in a Point-to-Multipoint Network," *Accepted for Presentation at the 15th ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems*, 2012.
3. Phani Krishna P and Siva Ram Murthy C, "Scheduling Mobiles with Multiple Antennas to Share a Slot in WiMAX Networks," *Communicated to the IEEE Transactions on Wireless Communications*, August 2012.

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