EFFECTS OF UE SPEED ON MIMO CHANNEL CAPACITY IN LTE

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With the introduction of 4G LTE, multiple new technologies were introduced. MIMO is one of the important technologies introduced with fourth generation. The main MIMO modes used in LTE are open loop and closed loop spatial multiplexing modes. This thesis develops an algorithm to calculate the threshold values of UE speed and SNR that is required to implement a switching algorithm which can switch between different MIMO modes for a UE based on the speed and channel conditions (CSI). Specifically, this thesis provides the values of UE speed and SNR at which we can get better results by switching between open loop and closed loop MIMO modes and then be scheduled in sub-channels accordingly. Thus, the results can be used effectively to get better channel capacity with less ISI. The main objectives of this thesis are: to determine the type of MIMO mode suitable for a UE with certain speed, to determine the effects of SNR on selection of MIMO modes, and to design and implement a scheduling algorithm to enhance channel capacity.

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CHAPTER 1

INTRODUCTION

1.1 History of Mobile Communications

Wireless communication is a rapidly changing technology. Multiple factors drive this change, and required data rates, number of users, and required channel bandwidth are constantly increasing at exponential rates. As a result, the technology moves rapidly from one generation to the next. As of now, there have been 5 generations [1].

1.1.1 Zeroth Generation

The Zeroth generation of mobile communication was a pre-cell mobile phone communication technology. In this generation, mobile phones were usually kept in a suitcase or mounted in a vehicle. The main technologies that were used in this generation for communication were PTT (Push to Talk), MTS (Mobile Telephone System) and IMTS (Improved MTS).

1.1.2 First Generation

First generation mobile phones were the first cell phones. These were analog and could only provide voice calls. The main technologies that were used in this generation were FDMA (Frequency Division Multiple Access), NMT (Nordic Mobile Telephone) and AMPS (Advanced Mobile Phone System). This generation was the first to use modulation in cell phones. The main issues with this generation were no security, high power consumption and heavy signal distortion.

1.1.3 Second Generation

Digital wireless communications started being used in 2G (Second Generation). Cellular phones became smarter and started providing more services such as short messaging services, digital video calling, and mp3 downloads. The main technologies that were used in second generation were GSM (Global System for Mobile Communications), TDMA (Time Division Multiple Access), and CDMA (Code Division Multiple Access). 2G alleviated some issues that were present in previous generations. It consumed less battery power and improved voice clarity. Noise reduction techniques were applied and it was more secure. However, with the number of users increasing rapidly and their demand for more data at a higher rate, 2G techniques were unable to keep pace as they were built mainly for voice data and had slower transmission rates.

1.1.4 Third Generation

To provide higher data rates and use the same network for voice as well as non-voice data, 3G (Third Generation) networks were built. With cell phones becoming even smarter, users needed more non-voice data in comparison to voice data. The main improvements of 3G are enhanced audio, video streaming, much better data speed, video calls, web browsing at higher speeds, global roaming, emails, and navigation systems. The main technologies used in 3G are W-CDMA (Wide-band Code Division Multiple Access) or UMTS (Universal Mobile Telecommunications System), EDGE (Enhanced Data rates for GSM Evolution) and CDMA2000. W-CDMA was upgraded to HSPA (High Speed Packet Access) and then into HSPA+. 3G is also more secure in comparison to previous technologies. However, 3G has some drawbacks. It requires high bandwidth, a high spectrum-licensing fee, and a very large amount of capital to setup its infrastructure.

1.1.5 Fourth Generation

With the number of users increasing rapidly, the International Telecommunications Union specified the requirements for the standards for 4G (Fourth Generation) in March 2008. Most of these requirements are based on higher data rates, VoIP (Voice over IP), and increasing the channel quality. The main standards in 4G are Mobile WiMAX, which is based on the IEEE standard 802.16 and LTE (Long Term Evolution), which is a 3GPP standard. Both of these standards do not meet the ITU 4G standards but still were considered by vendors as 4G. The latest upgrades in these standards are Mobile WiMAX release 2 and LTE-A (LTE-Advanced). The main features that are used in these standards are MIMO (Multiple Input Multiple Output), OFDMA (Orthogonal Frequency Division Multiple Access), SC-FDMA (Single Carrier- Frequency Division Multiple Access), link adaptation, femtocells, and channel dependent scheduling.

1.2 Problem Description and Motivation

In this work, we analyze the effects of UE (User Equipment) speed on channel capacity and how the high speed and feedback delay affect link adaptation. We focus on finding a way to mitigate the effects of UE speed on channel capacity. We also focus on implementing an algorithm that can assign a UE to a particular transmission mode based on the channel conditions so that the ICI (Inter Channel Interface) can be mitigated and that channel capacity can be increased for the system. We assume constant values for parameters such as transmit power, feedback delay, PMI (Precoding Matrix Index) period, and UE distance from the base station. We also observe varying parameters such as Doppler shift, SNR (Signal to Noise Ratio) and UE speed. By varying these values, we observe the variation in the channel capacity in both Open Loop and Closed Loop Spatial Multiplexing MIMO modes. Open Loop Spatial Multiplexing has no PMI feedback while Closed Loop spatial multiplexing does.

In this work we try to achieve the following objectives:

(1) Determine the effect of UE speed on MIMO mode selection.

(2) Determine the effect of SNR variation on channel capacity.

(3) Determine the effect of UE speed on sub-band scheduling.

(4) Design a UE scheduling algorithm to get the improved output.

(5) Verify the algorithm through simulation.

The goal of the algorithm is to analyze the effects of user speed on the channel capacity with and without feedback, and schedule users in different sub-channels based on the results.

1.3 Contributions

The contributions of this work are:

(1) To determine the type of MIMO mode suitable for a UE with a certain speed.

(2) To determine the effect of SNR on selection of MIMO modes.

(3) To design and implement a scheduling algorithm to enhance channel capacity.

1.4 Organization

Chapter 2 describes the MIMO modes related to spatial multiplexing in LTE. It explains the difference between MIMO modes and under what conditions one is preferred over another. It discusses the traditional scheduling algorithms used in sub-channel scheduling and why they are used. It also introduces Doppler shift and different fading models in wireless communications.

Chapter 3 describes the related work that has been done in this area.

Chapter 4 describes signal transmission and the effect of UE speed and SNR variations on a signal and the effect on MIMO mode selection. It explains the impact of speed on sub-channel scheduling. It also describes the algorithm for selection of a sub-channel based on the channel capacity of the UE as relative to UE speed and SNR.

Chapter 5 presents the conclusion and future direction for our work.

CHAPTER 2

LONG TERM EVOUTION

Mobile telecommunication is expanding exponentially and with that demand for higher data rates and better channel quality is growing. With the launch of smartphones, tablets and multiple other devices, which use wireless mobile communications, the demand will keep increasing with time. Now mobile communication is being used for web browsing, VoIP, social networking, video streaming and downloading multi-media. To meet the demands, new standards are being developed to support the next generation of mobile communications and meet the demands of higher data rates and better channel quality while increasing the capacity as the number of users also increases.

One of the standards that was developed to meet these requirements is called Long Term Evolution or LTE. LTE was started in 2004 by 3GPP and it replaced UMTS. LTE was fully implemented in 2010. There have been multiple releases of LTE. Release 10 was named LTE-Advanced and meets the requirements for fourth generation mobile communications. A few specifications of LTE are as given below:

(1) It supports TDD and FDD.

(2) It provides high data rates on the uplink and downlink side.

(3) It provides spectrum flexibility as it operates between 1.5 to 20 Mhz.

(4) It requires much less time to connect to a user.

(5) The QoS (Quality of Service) has increased so that users have better signal connectivity and a higher bit rate.

With LTE, there were many new technologies that were introduced to meet these requirements. These technologies [1] are:

(1) OFDM (Orthogonal Frequency Division Multiplexing),

(2) SC-FDMA (Single Carrier- Frequency Division Multiple Access),

(3) MIMO (Multiple Input Multiple Output),

(4) FDE (Frequency Domain Equalizer),

(5) Link Adaptation, and

(6) Channel Dependent Scheduling.

2.1 OFDM

Orthogonal Frequency Division Multiplexing is the technique used in LTE for signal transmission and reception. OFDM has almost the same functions that any other multiplexing technique has: it allows the base station to transmit and receive signals from multiple mobiles at the same time. The main concept behind OFDM is to transmit the data stream in parallel channels using FDM. By sending multiple streams on sub-channels instead of a single stream, it helps in reducing the effects of ISI and reduces the error rate. One consideration in OFDM is that the sub-carriers need to be sampled at sub-carrier frequencies. In LTE, OFDM is only used on the downlink. There are several steps included in the OFDM downlink transmission in LTE. First, the signal is modulated, then the modulated signal is sent to a Serial to Parallel Converter. The output signal then goes through an IFFT (Inverse Fast Fourier Transform) operation and then goes through a Parallel to Serial Converter. Then a cyclic prefix is added and the signal is passed through a Digital to Analog converter.

In LTE, OFDM sub-carrier spacing is 15 KHz if the mobile is stationary. If the mobile is moving however, the Doppler shift will offset the signal spacing in some of the sub-carriers, increasing loss. Because of the shift, the sub-carriers will interfere with other sub-carriers, and thus there will be no orthogonality between the signals. To keep the signals from being affected by Doppler shift, there are certain conditions that need to be considered. One condition is:

$$\delta f \ll f_D \tag{1}$$

where δf is the sub-carrier spacing and f_D is the Doppler frequency. Another parameter we need to consider is delay spread. We need to select a symbol duration, which can mitigate the effects of ISI. For this to happen, this condition needs to be satisfied:

$$T \gg \tau \tag{2}$$

where T is the symbol time and τ is the delay spread.

2.2 MIMO

MIMO (Multiple Input Multiple Output) is a technology where multiple antennas are deployed at both the transmit and receive sides. This allows the use of multi path propagation to increase the capacity. The history of MIMO can be traced back to the 1970s when a few research papers were published about multi-channel digital transmission systems and crosstalk between wire pairs in cable bundles. Some of the techniques mentioned in these papers were very helpful in MIMO development. Finally, in 1996, Greg Raleigh proposed that multi-path propagation could be used to transmit multiple streams independent of each other using co-located antennas and multi-dimensional signal processing. MIMO has been divided into three categories: Precoding, Diversity Coding, and Spatial Multiplexing.

2.2.1 Precoding

Precoding is multi-stream beamforming. The primary goal of precoding is to remove spatial crosstalk in MIMO channels. In MIMO, multiple antennas at both sides can be used to get array gain or diversity gain. In beamforming, the same signal is sent from each transmit antenna so that the input matrix has unit rank. The transmitted signal is the original signal multiplied by a complex valued scaling factor, which collectively is known as the precoding matrix.

$$r = HPs + n \tag{3}$$

where H is channel matrix, P is precoding matrix, n is noise, r is the received signal, and s is the original signal to be transmitted.

Precoding is used when either the channel condition is bad or the difference between the number of transmitters and receivers is high. When the channel condition is bad, there is no spatial multiplexing gain as the channel capacity is a function of SNR:

$$\frac{C}{B} = \log_2\left(1 + \frac{S}{N}\right) \tag{4}$$

where C is the channel capacity and B is bandwidth and $\frac{S}{N}$ is signal to noise ratio.

In this case, it is better to use multiple receivers and transmitters for beamforming which improve the signal-to-noise ratio.

Alternatively, when the difference between the number of transmitters and receivers is high, the excess antennas can be used for beamforming with the use of precoding. This is because the channel data rate for spatial multiplexing is defined based on the minimum of N_R and N_T.

2.2.2 Diversity Coding

Diversity coding, also known as Space-Time coding, is used in cellular communications as well as wireless LANs. The main goal of diversity coding is to reduce noise and interference, thus increasing the channel quality. There are three types of diversity coding, Diversity Reception, Diversity Transmission, and Delay Diversity.

Diversity Reception typically includes only one transmitter but multiple receivers. It is a reliable technology, but alone does not provide expected results such as higher data rates and channel bandwidth.

Diversity Transmission typically involves multiple transmitters to a single receiver. One of the most reliable diversity transmission techniques is space-time block coding. Space-time codes can be developed to find a sequence of matrices that accomplish specific optimality criteria. A space-time block-coding scheme is a tradeoff between complexity of decoding, error performance, and information rate. Alamouti [2] proposed one of the first space-time codes. It was designed for two transmit antennas. According to this coding technique, only one receiver and two transmitters can achieve the best results.

Delay Diversity is a technique in which the symbol transmitted is the same but at different time instances so that every transmission has different fading profile. This technique converts spatial diversity into frequency diversity by transmitting a symbol from one transmitter at time t_1 where $t_1 - t_0$ is equal to one symbol period.

2.2.3 Spatial Multiplexing

As opposed to diversity techniques, the main goal of spatial multiplexing is to achieve higher transmission data rates. Therefore, in an $\mathrm{N_T}$ x $\mathrm{N_R}$ spatial multiplexing system, where $\mathrm{N_T}$ is number of transmit antennas and $\mathrm{N_R}$ is number of receive antennas, the peak data rate is proportional to the minimum of $(\mathrm{N_T}, \mathrm{N_R})$, because this is also the maximum number of parallel signals being transmitted at a particular time. This technique is not as reliable as diversity coding, but it does provide much better data transmission rates by comparison. There are two primary types of encoding techniques used with spatial multiplexing, Horizontal Encoding (HE) and Vertical Encoding (VE). In spatial multiplexing, a signal is divided into several signals. These signals are then transmitted through different transmitters simultaneously in the same frequency channel, which is divided into sub-channels in parallel. Then at the receiver, these signals are combined using CSI (Channel State Information). This technique will be explained in detail in the next chapter.

2.3 SC-FDMA

SC-FDMA is Single Carrier-Frequency Division Multiple Access. This is used in LTE Uplink. The reason OFDM is not used is that it has a high PAPR (Peak to Average Power Ratio) in its transmitted signals. The PAPR maximizes where sub-carriers collide, and it becomes 0 where they cancel each other. These variations can create complications for the power amplifier of the transmitter. For a linear amplifier, power output is proportional to the input power. The downlink has large transmitters, which can avoid the issue of high PAPR by using amplifiers that are close to linear. But in the uplink, UEs are very small and that option is typically not available. Thus OFDM cannot be used in the uplink. SC-FDMA is not used in downlink, because the signal is being transmitted to multiple UEs simultaneously, and that is not possible because it is a single carrier transmission.

2.4 Frequency Domain Equalizer

FDE (Frequency Domain Equalizer) is used in the OFDM downlink instead of a CP (Cyclic Prefix) because it is more efficient. FDE is a digital filter, which works in the time domain and is used to remove the multi-path of a channel. FDE is more efficient than CP because it does not require extra bits in the transmission. These extra bits consume energy as well as time during transmission and are of no use after the signal is received. FDE provides higher transmission rates and less data loss in comparison to CP. The disadvantages of using FDE with OFDM are ISI (Inter Symbol Interference) and a greater complexity than CP.

2.5 LTE MIMO Modes

In the LTE downlink, there are 7 primary MIMO modes [3], which are used for data transmission under different circumstances. These modes were introduced in release 8:

(1) Transmission Mode 1 (Single Transmit Antenna).

(2) Transmission Mode 2 (Transmit Diversity).

(3) Transmission Mode 3 (Open Loop Spatial Multiplexing).

(4) Transmission Mode 4 (Closed Loop Spatial Multiplexing).

(5) Transmission Mode 5 (Multi-User MIMO).

(6) Transmission Mode 6 (Closed Loop Spatial Multiplexing with Single Layer)

(7) Transmission Mode 7 (Beam-forming).

There are 3 more transmission modes which were introduced in later releases, 9 and 10. These modes are:

(8) Transmission Mode 8 (Dual Layer Beam-forming).

(9) Transmission Mode 9 (Closed Loop Spatial Multiplexing with Single Layer).

(10) Transmission Mode 10 (Coordinated Multipoint)

2.6 Link Adaptation

Link Adaptation [4] is a technique used to improve the channel quality in 3G and 4G standards. It is also known as channel aware scheduling. It is used to change specific parameters according to varying channel conditions. The main parameters that are changed are the modulation technique, precoding matrix, coding scheme, transmission power, and the number of layers being used. By changing these parameters according to varying channel conditions, bandwidth efficiency increases over a wider range of conditions. Link Adaptation relies on three measurements: CQI, RI, and PMI.

2.6.1 CQI

CQI (Channel Quality Index) measures downlink channel quality and specifies the modulation technique and coding rate to match the channel quality. There are two types of CQI. The first is wideband CQI, which specifies the modulation technique and coding rate for the entire system's bandwidth. The second is sub-band CQI, which specifies the modulation technique and coding rate for a specific sub-band.

2.6.2 PMI

PMI (Precoding Matrix Index) estimation is only used in closed loop spatial multiplexing. In closed loop spatial multiplexing, a codebook is used in which all the possible precoding matrices are listed with an index. The PMI is calculated using various algorithms and is transmitted back to the transmitter which selects the precoding matrix relevant to that PMI. Similar to CQI, PMI also has two types, Wideband PMI and Sub-band PMI.

2.6.3 RI

RI (Rank Index) is used for rank estimation. It represents the number of transmission layers that can be used in a spatial multiplexing system. There are several algorithms to calculate the preferred RI of a channel matrix. These algorithms consider a multitude of values including SINR, channel throughput, and the Eigen values of the channel matrix, to calculate the best RI for a particular system.

2.7 Subcarrier Scheduling

Subcarrier scheduling [4] is a very important part of LTE. The UE scheduler is a critical part of the downlink, and assigns a particular user to a particular sub-channel depending on multiple factors. The scheduler assigns a sub-channel to a user for a single TTI (Transmission

Time Interval) based on current channel conditions. For each TTI the channel conditions are evaluated and the TTIs are assigned. Every sub-channel has different channel conditions, so if a UE with poor CSI is allocated to a sub-channel with poor SNR and high fading, the resulting transmission signal will be lost. In the same way, if there is a UE with really good CSI that is allocated to a sub-channel with the best channel conditions, then that sub-channel will be underutilized. UE schedulers seek to obtain a balance of sub-channel quality and assigned users. There are two types of schedulers: channel aware schedulers and channel unaware schedulers.

2.7.1 Channel Aware Schedulers

Channel Aware Scheduling is a channel dependent scheduling technique which uses the channel state information to schedule a UE to a particular sub-channel and allocate the consecutive subcarriers available in that sub-channel according to that UE's condition. In this way, the best frequency and channel for that particular UE is selected and this is how frequency selective gain is achieved. By using favorable subcarriers for a UE based on their CSI instead of selecting the predefined subcarriers without having the knowledge of CSI, the scheduler improves overall performance. In this approach, band adaptive modulation and coding sub-channelization techniques or frequency localized mapping are used. The main problem with this scheduling scheme is that it requires the use of CSI for selecting the subcarriers. If the CSI is highly variable in time, the channel conditions will change before scheduling can happen, causing improper scheduling. In this case, a channel unaware scheduler is required. Some channel aware schedulers are: Maximum Throughput, Proportional Fairness Scheduler, Throughput to Average Scheduler, and Exponential Proportional Fairness Scheduler.

2.7.2 Channel Unaware Schedulers

Channel Unaware Schedulers provide frequency diversity gain. In these schedulers, the UE is allocated to sub-carriers, which are spread throughout the sub-channel. This type of scheduler uses sub-carriers with independently faded paths, which may not have similar path gains and fading. The main problem with this scheduling scheme is that UEs are assigned to a sub-carrier irrespective of their specific channel conditions. In this approach, diversity sub-channelization or frequency distributed mapping is used. Channel Independent Schedulers are those schedulers, which do not use any channel conditions. Some channel unaware schedulers are: First-In-First-out, Round Robin, Blind Equal Throughput, Weighted Fair Queuing, Earliest Deadline First and Largest Weighted Delay First. These algorithms are based on the assumption that channel is time invariant and there is no error.

2.8 Doppler Effect

Doppler effect [5] is a phenomena caused by Doppler Shift. It happens when the transmitter is moving with respect to the receiver. In telecommunications, this happens when a UE moves at a given speed with respect to the base station. This shift affects the frequency of the transmitted and received signal such that the received signal will be different than the transmitted signal. Due to the Doppler Shift, the main problems that arise in a channel are ISI (Inter Symbol Interference) and Multi-path fading. In this work, we focus on the effects of Doppler Shift. If the original carrier frequency is f_c, the speed at which a user moves is v, and the speed of light is c, the Doppler frequency (f_D) is:

$$f_D = f_c \frac{v}{c} \tag{5}$$

$$f_D = \frac{\frac{v}{c}}{f_c} \tag{6}$$

$$f_D = \frac{v}{\lambda_c}\,. \tag{7}$$

Here, λ_c is the carrier wavelength. If the coherence time is T_c, then the relation is:

$$T_c = \frac{0.3}{2f_D} \tag{8}$$

from eq. 5,

$$T_c = \frac{0.3}{2f_c\frac{v}{c}} \tag{9}$$

$$T_c = \frac{0.3c}{2f_c v}\,. \tag{10}$$

So, we can say that if f_c is constant then the following relation holds:

$$T_c \alpha \frac{1}{v}\,. \tag{11}$$

2.9 Fading

In wireless communications, according to [5], fading is a common phenomenon. It is the degradation of a signal over both time and frequency. Fading is usually a non-additive signal disturbance. The main factors leading to fading are:

(1) Multi-path Propagation: Multi-path propagation is when a signal follows two or more paths to reach the receiver. This can be constructive or destructive interference in the signal. This type of propagation also causes a phase shift in the signal because of the delay between different paths taken to the receiver.

(2) Mobile Speed: If the transmitter or receiver is moving at different relative speeds then there can be fading or random frequency modulation as explained above due to the Doppler effect. This can affect the signal quality greatly.

(3) Mobility of Surrounding Objects: In a system, if the surrounding objects of a

transmitter or receiver are moving at a speed greater than the transmitter or receiver, Doppler shift will occur. This type of Doppler shift will dominate the system over the Doppler shift caused by the difference in speed of only the transmitter and receiver.

(4) Signal Bandwidth: The signal bandwidth must be less than the channel bandwidth as specified by the coherence bandwidth, otherwise the received signal will be distorted.

In wireless communications there are two primary types of fading, shadow fading and multi-path fading. Shadow fading happens over long distances because of a phenomenon known as shadowing. Shadowing occurs when obstacles appear in the transmission path that obstruct the signal and cause power fluctuations at the receiver.

Multi-Path fading is typically the result of multi-path propagation. Multi-path propagation occurs when the transmitted signal reaches the receiver by multiple paths. This can happen because of several reasons, such as reflection from a building, mountain, or other physical object in the path of the transmission. This can cause errors and degradation of the signal. Each path that the signal takes can have a different fading profile. In this work we focus on multi-path fading which is common in telecommunication systems. Fading due to multi-path is also called small scale fading because it happens over a very short period of time. In this type of fading, the quality degrades rapidly and amplitude fluctuations are high. The main effects of multi-path fading are:

(1) The signal strength fluctuates rapidly over a short time period.

(2) The Doppler shift varies on the multi-path signals causing random frequency modulation.

(3) Time Dispersion.

2.9.1 Types of Small-Scale Fading

There are two sets of parameters on which fading is dependent. These are:

(1) Channel parameters (Doppler Effect), and

(2) Signal Parameters (Multi-path Propagation Effect).

Based on these parameters, there are four types of fading. These are:

(1) Flat Fading,

(2) Frequency Selective Fading,

(3) Fast Fading, and

(4) Slow Fading.

2.9.2 Fading due to Multipath Delay

There are two type of fading which occur because of multipath delay spread (part of the multi-path propagation effect), flat fading and frequency selective fading. The main parameters of this fading are mean access delay, rms delay spread, and excess delay spread.

2.9.2.1 Flat Fading

Flat fading occurs when all of the frequencies in the channel are affected due to the multi-path. There are some conditions for this fading to occur. If the bandwidth of transmitted signal is less than the coherence bandwidth of the channel, then flat fading will occur. Also, if the symbol duration is greater than the rms delay spread then this fading occurs. In the equations below, B_s is signal bandwidth, B_c is coherence bandwidth, T_s is symbol duration, and σ_τ is rms delay spread. Thus fading occurs when:

$$B_s \ll B_c \tag{12}$$

and

$$\sigma_\tau \ll T_s . \tag{13}$$

2.9.2.2 Frequency Selective Fading

In frequency selective fading, multi-path propagation affects only selected frequencies of the channel to varying degrees. The effects of this fading cannot be overcome by maintaining the overall amplitude. OFDM is able to mitigate this fading because the data is spread over a large channel bandwidth making the effects negligible. The main conditions for this fading to occur are:

$$B_s \gg B_c \tag{14}$$

and

$$T_s \ll \sigma_\tau \, . \tag{15}$$

2.9.3 Fading due to Doppler Effect

Based on the value of the Doppler frequency or Doppler spread, fading due to Doppler effect is divided in two parts. Velocity is the main factor to determine if this type of fading will occur in the channel.

2.9.3.1 Fast Fading

Fast fading is when the impulse response of a channel varies during the symbol duration. This is due to reflections from other objects and the speed of the transmitter or receiver. This causes frequency dispersion. In the following equations, B_s is signal bandwidth, B_D is Doppler spread, T_s is symbol duration, and T_c is coherence time.

The main conditions for this fading to occur are:

$$T_s \gg T_c \tag{16}$$

and

$$B_s \gg B_D \, . \tag{17}$$

2.9.3.2 Slow Fading

In slow fading, the impulse response of the channel varies at a much slower rate in comparison to the transmitted symbol. The channel conditions remain static over one or more transmission time intervals. The main conditions for slow fading are:

$$T_S \ll T_c \qquad (18)$$

and

$$B_C \gg B_D . \qquad (19)$$

CHAPTER 3

LITERATURE REVIEW

In this chapter, we discuss the related work that has been done in this area of UE speed and channel scheduling. I have selected 7 papers (all accepted by IEEE).

3.1 Scheduling Exploiting Frequency and Multi-User Diversity in LTE Downlink Systems

In this paper [6], the authors describe a new type of scheduling algorithm that uses Frequency Diversity and Frequency Selective Scheduling. The algorithm switches between them based on the variance in the Channel Quality Index (CQI). They define a threshold value for CQI variance, and based on this value, they define two sets of users. Users with CQI variance greater than the threshold are referred to as high mobility users, and users with CQI variance lower than the threshold value are referred to as low mobility users. The authors do not mention the specific velocities at which the threshold value is obtained. They do however refer to another paper for the threshold value of CQI variance. They use a feedback period of 2ms and a feedback delay of 5ms. However, the authors do not explain these values and the reason behind them.

3.2 Performance Analysis of Closed and Open Loop MIMO in LTE

The authors of this paper [7] have provided a detailed comparison of the performance of open loop and closed loop MIMO schemes for OFDM based LTE systems. They create a scheduling algorithm that uses CQI and RI to switch from Transmit Diversity Mode to Spatial Multiplexing MIMO mode. The authors have selected a fading model with only low mobility (less than 15km per hour). They also mention that for a low SINR, transmit diversity performs better than spatial multiplexing. According to the paper, in an ideal lossless environment, the closed loop MIMO mode approximately provides a 20% increase in spectral efficiency. The authors also explain the difference between open loop and closed loop MIMO modes in spatial multiplexing, but do not provide an algorithm to switch between them.

3.3 User Classifications and Scheduling in LTE Downlink Systems with Heterogeneous User Mobilities

This paper [8] is similar to the paper in section 3.1. The authors use a frequency selective and frequency diversity scheduler based on user's mobility. According to the authors, the algorithm can be used to maintain diversity as well as scheduling gain. Also, it is not necessary to determine the exact speed of the user, only if a user is in the particular range. They do not however explain the values that define this range. The range is used to define users in two categories: High Mobility Users and Low Mobility Users. They also use the data rate of a particular user to calculate throughput and then compare this value to a threshold. The authors have used the inaccuracy of CSI, which occurs with high mobility of users, to calculate the frequency selective gain. They use RI and CQI for observing the variations in CSI. However, they do not consider the PMI, which is used to select the Precoding Matrix and if selected incorrectly does affect the channel capacity directly in closed loop spatial multiplexing. Lastly, they switch the scheduling algorithm based on user velocity.

3.4 The Impact of MS Velocity on the Performance of Frequency Selective Scheduling in Mobile WiMAX IEEE 802.16e

This paper [9] focuses on the effects of a Mobile Station's velocity on the performance of frequency selective scheduling in WiMAX IEEE 802.16e. In this paper, the authors discuss the frequency selective scheduling and how it works in OFDM based WiMAX system. They explain the effects and necessity of the availability of perfect channel estimation information at a base station so that a particular user can be scheduled using frequency selective scheduling. They also explain how frequency selective scheduling outperforms frequency diversity scheduling if a user has normal speed. They compare the performance of two scheduling algorithms as user speed increases. They have also calculated the threshold value of speed after which the frequency diversity scheduler outperforms the frequency selective scheduler. They also describe the slot types they use in this work and the values that they have considered. This work is heavily cited, but does not consider switching MIMO modes, only scheduling algorithms.

3.5 Mobility Based MIMO Link Adaptation in LTE-Advanced Cellular Networks

In this work [10], the authors evaluate the performance of different MIMO modes in LTE downlink. They propose considering mobility as a type of link adaptation with SNR feedback. In this paper, they use different modulation and coding schemes on MIMO systems and varying velocity to analyze the difference in throughput for Alamouti Transmit Diversity, Spatial Multiplexing and Beam-forming MIMO modes. According to the authors, link adaptation is achieved by adjusting the modulation and coding techniques based on the CSI, which they measure using the average SNR. They propose a new link level simulator that uses and measures the LTE features at varying mobile speeds. Based on these results they propose a new link adaptation scheme.

3.6 Shannon Capacity and Symbol Error Rate of Space-Time Block Codes in MIMO Rayleigh Channels with Channel Estimation Error

This paper [11] focuses on the channel estimation errors in STBC (Space-Time Block Coding) and how they affect the Shannon Capacity and Symbol Error Rate in MIMO Rayleigh channels. The authors describe a channel estimation error model in which they show how they estimate the channel and the effects of incorrect channel state estimation, especially on effective SNR. They also analyze the closed loop expression of STBC ergodic capacity and calculate the closed loop form of symbol error rate in STBC based MIMO channel. They conclude that, with the introduction of channel estimation errors, the capacity loss increases as diversity gain loss increases. They do not however specify if the work was done only for an LTE or WiMAX system. They use MIMO and have shown that with increasing the number of antennas in MIMO, the STBC results in more channel estimation errors.

3.7 Fading Channels: Information-Theoretic and Communications Aspects

The authors of this paper [12] focus on fading channels, and the information-theoretic and communications features of these channels. They have explained various types of possible CSI scenarios and fading models and then they calculate the channel capacity of the fading channels. The authors work on both SISO (Single Input Single Output) and MIMO. They also work on equalization schemes for fading multi-path channels. According to the authors, using information theoretic tools to analyze fading channels is useful and provides a better understanding of these channels to make them more efficient. They also explain that information theoretic models can be useful to practically implement these techniques. Lastly, they conclude that interference cancellation techniques and iterative decoding can be very useful in multiple access methods.

CHAPTER 4

PROBLEM FORMATION

We have discussed briefly the research problem in Chapter 1, and now we explain the problem in detail. First, we discuss the signal models used and the effect of user speed on channel capacity therein. Next, we explain the effects of imperfect CSI at the transmitter as well as the chosen performance criteria for maximizing the total capacity. Other benefits of choosing these criteria will also be described. Finally, we will formulate the problem, solve it and show the results.

4.1 System Model

In this system, there are N_T transmit antennas and N_R receive antennas. There are K independent sub-carriers with a bandwidth B_C. There are two options for sub-channelization (discussed in Chapter 2):

(1) Channel Aware Sub-Channelization

(2) Channel Unaware Sub-Channelization

If we use frequency selective scheduling gain, then we can transmit all of a single user's data through a single sub-carrier, and if we use frequency diversity scheduling gain, then we can divide the user's data into K parts and transmit each through a separate sub-carrier. For a particular sub-channel k, the received signal as reported in [1] , is:

$$r_k(t) = H_k(t)s_k(t) + n_k(t) \tag{20}$$

where $H_k(t)$ is the channel vector of k^{th} sub-channel at time t, $s_k(t)$ is the transmitted signal vector at time t through sub-channel k, and $n_k(t)$ is the noise in sub-channel k at time t.

4.2 Spatial Multiplexing

Spatial Multiplexing is one of the main techniques of transmission in OFDM LTE. It is used in both open and closed loop MIMO. Although it is not as reliable as Transmit Diversity, it provides higher data rates for a larger number of users. If multiple antennas exist at both the transmitter and receiver, parallel data streams can be created. For a system where $N_R = 2$ and $N_T = 2$, the received signals are:

$$r_1 = H_{11}s_1 + H_{12}s_2 + n_1 \tag{21}$$

$$r_2 = H_{21}s_1 + H_{22}s_2 + n_2 \tag{22}$$

where s_1 and s_2 are the transmitted signals from the two transmit antennas, r_1 and r_2 are the received signals, and n_1 and n_2 are the total noise received. H_{ij} is the channel element, which is the effect of phase shift and attenuation on transmitted symbols as they travel from transmit antenna j to receive antenna i.

In equations 21 and 22, all of the terms are complex valued. In the transmitted signals s_i, the received signals r_i, and the noise terms n_i, the real and imaginary parts are the amplitudes of the in-phase and quadrature components respectively. Similarly, in each of the channel elements H_{ij}, the magnitude represents the attenuation of the signal, and the phase represents the phase shift. To estimate the channel element for a received signal, one transmitter transmits a reference signal while the other transmitter transmits nothing. This process is repeated for each transmitter. Thus, the receiver is able to estimate the channel matrix H_{ij}.

Once the channel estimate H_{ij} has been established, the receiver can now estimate the transmitted signals s_i. There are several ways to do this, but the simplest is to use a zero-forcing detector, which assumes no noise or interference and is ideal when the channel is noiseless. Using the zero-forcing method, the equations are modified as follows:

$$r_1 = \widehat{H_{11}}s_1 + \widehat{H_{12}}s_2 \tag{23}$$

$$r_2 = \widehat{H_{21}} s_1 + \widehat{H_{22}} s_2 \ . \tag{24}$$

Here, $\widehat{H_{ij}}$ is the estimation made by receiver of the channel matrix H_{ij}. Solving for s_i, produces:

$$\widehat{s_1} = \frac{\widehat{H_{22}} y_1 - \widehat{H_{12}} y_2}{\widehat{H_{11}}\widehat{H_{22}} - \widehat{H_{21}}\widehat{H_{12}}} \tag{25}$$

$$\widehat{s_2} = \frac{\widehat{H_{11}} y_1 - \widehat{H_{21}} y_2}{\widehat{H_{11}}\widehat{H_{22}} - \widehat{H_{21}}\widehat{H_{12}}} \ . \tag{26}$$

Here, $\widehat{s_1}$ and $\widehat{s_2}$ are the estimated values of the original transmitted signals s_i at the receiver. Using this method, two signals have been transmitted at the same time and in the same sub-carriers, which has resulted in doubling the overall data rate.

In the case of Spatial Multiplexing with a precoding matrix, the received signal, as shown in [6], is:

$$r(t) = H(t)P(t)s(t) + n(t) \tag{27}$$

At time t, r(t) is the received signal, H(t) is the channel matrix, P(t) is the precoding matrix, and n(t) is the added noise.

Channel variation, which can be used to calculate the channel estimation error, is represented by the equation:

$$\widehat{H}(t) = \rho H(t) + \sqrt{(1 - \rho^2)} W(t) \tag{28}$$

At time t, W(t) is an independent and identically distributed error matrix with a mean of 0 and unit variance, and $\widehat{H}(t)$ is the estimated channel matrix. Here, $\rho = 1$ means that there is no channel estimation error.

$$\rho = J_0(2\pi f_c \frac{v}{c} \tau) \tag{29}$$

Where J_0 is the zeroth order Bessel function of the first kind [13], f_c is the carrier frequency as mentioned in the previous chapters, v is the UE speed, and τ represents the correlation time for the channel.

The mean square error (E) between the original channel matrix and the estimated channel matrix is:

$$E = \mathbb{E}\left[\left|\hat{H} - H\right|^2\right] \tag{30}$$

From eqs. 28 and 29, we can derive E as:

$$E = 2(1 - \rho) \tag{31}$$

or

$$\rho = 1 - \frac{E}{2} \ . \tag{32}$$

The model of the channel delay is typically accomplished by using a Jakes model. According to the Jakes model [13], channel variations are due to the movement of the mobile receiver with respect to time, and the channel correlation is proportional to $J_0\left(2\pi f_c \frac{v}{c} \tau\right)$. Thus, the outdated channel estimates will be used by the receiver to estimate the precoding matrix and sent back to the transmitter. This correlation is calculated by the feedback time or the PMI feedback period.

The MIMO modes associated with spatial multiplexing in LTE can be divided into two categories:

(1) Open Loop Spatial Multiplexing.

(2) Closed Loop Spatial Multiplexing.

Next, we will briefly introduce these spatial multiplexing techniques and then we will discuss the effects of user speed on user scheduling in the sub-channels and MIMO modes.

4.2.1 Open Loop Spatial Multiplexing with Cyclic Delay Diversity

Open loop spatial multiplexing is a well-known MIMO technology, which is used worldwide in wireless communications systems. PMI feedback is unavailable with this technique and thus it typically requires only one fixed value precoding matrix, selected from a predefined set, also known as a codebook, for two transmit antennas. When there are four transmit antennas, the index used to select the precoding matrix from the codebook is cyclically rotated for each instance of a data transmission on both the transmitter and receiver. In LTE transmission mode 3, there is always a delay included when sending a signal to each antenna. This delay is known as CDD (Cyclic Delay Diversity), and is used to create artificial diversity. In open loop spatial multiplexing, only the CQI and RI are available. The rank index for open loop varies from highest rank possible to minimum of 2 layers. There are many ways to calculate RI, but the three most commonly used methods are:

(1) Capacity based Rank Adaptation,

(2) SNR based Rank Adaptation, and

(3) Eigen Value of Channel Matrix based Rank Adaptation.

When the rank index results in only a single layer, it means that the transmission may occur in only one layer. At that time, the transmission switches from Spatial Multiplexing to Transmit Diversity. In this case, SFBC (Space Frequency Block Coding) is used in LTE mode 3 and both SFBC and FSTD (Frequency Switched Transmit Diversity) are used in LTE mode 4.

In open loop spatial multiplexing, the general equation for a received signal is:

$$\mathrm{r} = \mathrm{HPs} + \mathrm{n} \tag{33}$$

where r is received signal, H is channel matrix, P is precoding matrix, s is transmitted original symbol and n is noise. If the rank index is 2, then there will be 2 layers for transmission, and the layer mapper will select two symbols, s_1 and s_2, to be transmitted through the layers simultaneously. Next, the antenna mapper will take one symbol for each antenna and transmit it. In this scenario, the received signals are:

$$r_1 = H_{11}Ps_1 + H_{12}Ps_2 + n_1 \tag{34}$$

$$r_2 = H_{21}Ps_1 + H_{22}Ps_2 + n_2. \tag{35}$$

If we take one reference signal and transmit it through both antennas, we can then estimate the channel matrices. And after applying an estimation method, such as zero-forcing [4], equations (11) and (12) become:

$$r_1 = \widehat{H_{11}}Ps_1 + \widehat{H_{12}}Ps_2 \tag{36}$$

$$r_2 = \widehat{H_{21}}Ps_1 + \widehat{H_{22}}Ps_2. \tag{37}$$

From these equations, we can estimate the transmitted signals as:

$$\widehat{s_1} = \frac{\widehat{H_{22}}y_1 - \widehat{H_{12}}y_2}{(\widehat{H_{11}}\widehat{H_{22}} - \widehat{H_{21}}\widehat{H_{22}})P} \tag{38}$$

$$\widehat{s_2} = \frac{\widehat{H_{11}}y_2 - \widehat{H_{21}}y_1}{(\widehat{H_{11}}\widehat{H_{22}} - \widehat{H_{21}}\widehat{H_{21}})P}\,. \tag{39}$$

If the rank index is one, then the layer mapper will select a single symbol, s_1, and the antenna mapper will transmit it through both antennas. Thus, the received signals are:

$$r_1 = (H_{11} + H_{12})Ps_1 + n_1 \tag{40}$$

$$r_2 = (H_{21} + H_{22})Ps_1 + n_2. \tag{41}$$

Here, there are two measurements of the transmitted symbol and these can be combined in a diversity receiver to recover the transmitted data. In the case of open loop spatial multiplexing, the precoding matrix will be fixed for each transmission and the signal will be:

$$r(t) = H(t)Ps(t) + n(t). \tag{42}$$

If a system has N_T transmit antennas and N_R receive antennas and the number of transmission layers N_L is min (N_R, N_T), then r will be an $N_R \text{ X } N_L$ matrix. Because open loop spatial multiplexing has only CQI and RI available, the SNR of open loop spatial multiplexing is:

$$SNR = \frac{1}{N_T}\left(\frac{S}{N}(H\,H^*)\right) \tag{43}$$

where $\frac{S}{N}$ is the SNR before detection. Thus, the SNR variation in open loop spatial multiplexing is:

$$SNR_{variation} = H\,H^* \tag{44}$$

And also, the channel capacity of open loop spatial multiplexing is:

$$C = \log_2(1 + SNR) \tag{45}$$

or

$$C = \log_2\left(\frac{1}{N_T}\left(\frac{S}{N}(HH^*)\right)\right). \tag{46}$$

4.2.2 Closed Loop Spatial Multiplexing

The increase in required data rates and throughput drive rapid change in the technology of mobile phones. The required peak data rates are difficult to achieve. Spatial Multiplexing can accomplish that data rate if perfect CSI is available at the transmitter. The main difference between Open Loop and Closed Loop Spatial Multiplexing is the availability of PMI feedback in closed loop. Spatial multiplexing is only used if the rank index is 2 or more, otherwise it will revert back to transmit diversity. In closed loop spatial multiplexing systems there is a precoding matrix codebook. The receiver sends feedback to the transmitter which includes the index of the matrix in the codebook that is used in the next transmission. The research topic of precoding matrix codebook selection has attracted many researchers in the past few years. Research in this area has concentrated on attempting to find the most efficient Precoding Matrix codebook that is compatible with a wide variety of systems. The use of a precoding matrix and equalization techniques improve capacity, reduce interference, and reduce noise in a wireless transmission. PMI selection techniques currently used in LTE [4] include:

(1) Min MMSE Geometric Mean Criteria Based PMI Selection,

(2) Max Post Processing SNR Criteria Based PMI Selection, and

(3) Min-MMSE Arithmetic Mean Based PMI Selection.

According to [2], the Min-MMSE Arithmetic Mean Based PMI selection provides the best results in LTE.

In closed loop spatial multiplexing, for a system with N_T transmit antennas and N_R receive antennas, the received signal is:

$$r = Hx + n \tag{47}$$

where r is the N_R x 1 received vector, x is the N_T x 1 transmitted vector, H is the N_R x N_T channel matrix, and n is the Additive White Gaussian Noise (AWGN) with N_R x 1 independent and identically distributed (i.i.d.) elements with a mean of 0 and a σ^2 variance.

To achieve better results and a multiple layer transmission, a precoding matrix should be applied to the transmitted symbol. This transmitted signal is:

$$x = Ps \tag{48}$$

where P is an N_T x L unitary precoding matrix, L is the number of transmission layers available, and s is the Lx1 transmitted symbol. Thus, the received signal is:

$$r = HPs + n\ . \tag{49}$$

If a system has N_T transmit antennas and N_R receive antennas and the number of transmission layers is N_L, which is $\min(N_T, N_R)$, then r will be a N_R x N_L received vector. Because closed loop spatial multiplexing has PMI, CQI and RI feedback, the SNR of closed loop is:

$$SNR = \frac{1}{N_T}\left(\frac{S}{N}\right)(PH(PH)^*) \quad (50)$$

where $\frac{S}{N}$ is the SNR before detection, and the * denotes the complex conjugate. The SNR variation in closed loop spatial multiplexing is:

$$SNR_{variation} = PH(PH)^* \quad (51)$$

On the receivers' end, as mentioned in [3], the Min-MMSE trace criterion based PMI selection is used:

$$PMI_x = \underset{PMI_x \in P}{\arg\min}\{Tr[MSE(H_x P)]\} \quad (52)$$

where x = {1,2,3…,N_L}, and N_L is the number of transmission layers available.

$$PMI_x = \underset{PMI_x \in P}{\arg\min} \sum_{N_R-1}^{N_R}[MSE(H_x P)] \quad (53)$$

In equation 53, the arithmetic mean is taken on each layer and the most suitable precoding matrix index is selected. This index is transmitted back to the base station to be used in the next transmission.

PMI feedback has two types, periodic and aperiodic. With an aperiodic PMI feedback, the PMI is transmitted back at a variable time period and is only used when the channel conditions are stable. If the channel is changing rapidly, then a periodic feedback transmits after every frame (usually 1ms in LTE) or as configured by the higher layers. After the base station receives the CSI, it analyzes the channel conditions and uses the PMI to look for the related precoding matrix in the codebook and uses it in the next transmission for that UE. In this way the desired SNR can be achieved which will mitigate the effects of noise. In closed loop, the received signal is:

$$r(t) = H(t)Ps(t) + n(t). \quad (54)$$

In closed loop spatial multiplexing, the precoding matrix is an important aspect of increasing the SNR. If N_T is 2 and N_R is 2, then the channel will consist of 2x2 dimensions where 2 signals are transmitted and received. Therefore, the precoding matrix will also be a 2x2 dimensional matrix. The channel matrix, H(t), is:

$$H(t) = \begin{pmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{pmatrix} \quad (55)$$

and the received signal vector is:

$$\begin{bmatrix} r_1 \\ r_2 \end{bmatrix} = \begin{bmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{bmatrix} \begin{bmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{bmatrix} \begin{bmatrix} s_1 \\ s_2 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \end{bmatrix}. \quad (56)$$

Once the signal is received, it will be used for channel estimation. The periodic PMI will be generated using one of the techniques previously mentioned for the next frame being transmitted. In this way, the PMI is based on the channel matrix of the current frame and the SNR value at that particular moment. If the channel matrix at time t is H(t), the precoding matrix is P(t), and the SNR is constant, then the channel capacity [5] for closed loop spatial multiplexing will be:

$$C = \log_2(1 + SNR) \quad (57)$$

and using equation 50,

$$C = \log_2\left(1 + \frac{1}{N_T}\left(\frac{S}{N}\right) PH(PH)^*\right). \quad (58)$$

4.3 CSI: Effect of Information on Capacity

In this section, we discuss the available information and its effect on the channels capacity. Then, we calculate the performance of the channel based on the mutual information between transmitter and receiver. In information theory, channel capacity is different from the capacity due to mutual information. The channel capacity is the upper bound on the information transmitted reliably through a communication channel.

According to Shannon's theory for point-to-point communication from [8], the channel capacity of a DMC (Discrete Memory-less Channel) is:

$$C = \max_{p(x)} I(X;Y) \tag{59}$$

where $p\left({}^{y}/_{x}\right)$ is the maximum rate at which data can transmit reliably. According to the theorem, the information can be transmitted with $P_e \rightarrow 0$ if the rate of transmission R is less than channel capacity C. Here, P_e is the error probability. If the condition is reversed and the transmission rate R becomes greater than channel capacity C, then the error probability P_e divaricates from 0. If the CSI is available only at the receiver, then according to information theory, the channel capacity will be:

$$C = \max_{p(x)} I\left(X; {}^{Y}/_{V}\right) \tag{60}$$

where Y and V are outputs if the state is ergodic. If perfect CSI is available, then the capacity is:

$$C = \sum_s p(s) \max_{p(x)} I\left(X; {}^{Y}/_{S}\right) \tag{61}$$

4.4 Switching Algorithm

The variation in the channel matrix estimation does not have a large impact on open loop spatial multiplexing since the precoding matrix is a fixed value and there is no PMI feedback. Therefore, we need not consider any precoding matrix index generator. In closed loop spatial multiplexing, we use a PMI generator and feedback is sent at a certain period. If the channel conditions have changed in that time period or the estimated channel matrix is different from true channel matrix, then the PMI becomes less effective and will affect channel capacity negatively. Also, with incorrect CSI, closed loop spatial multiplexing will not have the advantage of Link Adaptation. In this case we must calculate the value of SNR and the UE speed at which the PMI becomes ineffective and therefore open loop becomes a better choice. We have included SNR in this calculation because the correlation also depends on signal strength. This algorithm calculates the threshold level at various points and then selects a scheduling technique accordingly.

4.4.1 Pseudo Code

The switching algorithm that is developed and used in this work is:

Initialization: $U_{CAS} = 0$.

$U_{CUS} = 0$:

for all k such that $1 \leq k \leq U$ and $k \in U$ do

If $SNR_k \leq SNR_{th}$ then

If $V_k \leq V_{th}$ then

$U_{CAS} = U_{CAS} \cup k$

else

$U_{CUS} = U_{CUS} \cup k$

else

$U_{CUS} = U_{CUS} \cup k$

end if

end for

4.4.2 Threshold Algorithm

Calculation of the threshold value of SNR and speed is:

Initialization: $SNR_{th} = 0$.

$V_{th} = 0$:

for all S such that $1 \leq S \leq 25$ and S ∈ SNR do

for all V such that $1 \leq V \leq 50$ and V ∈ Vel do

if $C_{ol} = C_{cl}$

$SNR_{th} = SNR_{th} \in S$

$V_{th} = V_{th} \in V$

end if.

end for

end for

The first algorithm uses the threshold values stored by the second algorithm. There is a single speed value for each SNR. If we know the SNR of the channel, then we can use the second algorithm to get the related threshold value of the speed where the channel information becomes ineffective, and thus we can perform scheduling based on these results. In this way, we can get better output from a channel by using both spatial multiplexing modes.

4.5 Results

Analysis of the algorithm has been conducted for channel capacity of both open loop and closed loop spatial multiplexing for varying values of SNR and UE speed. The results are plotted below, and in figures 4.1 to 4.11, the values of SNR and UE speed at the point when the channel capacity of open loop spatial multiplexing crosses the closed loop spatial multiplexing channel capacity are taken as the threshold values for the switching algorithm.

Table 4.1 Threshold Values of SNR and Speed

Threshold SNR Values (dB)	Threshold Speed Values (MPH)
25	0
22	5
19	10
16	15
12	20
11	25
9	30
8	35
7.5	40
7	45
6.5	50

Table 4.1 summarizes the threshold values of SNR and speed where open loop performs better than closed loop. For example, the table shows that if the SNR is 22dB and the UE speed is at least 5 MPH, open loop will have a greater capacity than closed loop.

The overall results shown in this section reveal that a higher capacity is achieved by using open loop instead of closed loop when the UE speed increases. Meaning, that open loop has a much greater tolerance for bad channel conditions when the UE speed is higher. This tolerance exists because at higher UE speeds the PMI feedback overhead grows exponentially with the UE speed, causing closed loop spatial multiplexing performance degradation. However, in some cases the capacity of open loop is higher than closed loop at a very good channel quality for very low

UE speed. Hence we can see that for bad channel conditions, PMI still performs and keeps the channel capacity of closed loop better than open loop spatial multiplexing until a certain value of UE speed is reached. In the table, we can see that the SNR value of 25 dB is the threshold value for UE speed 0 MPH, but for a UE speed of 50 MPH, the SNR value at threshold is 6.5 dB. Hence we can say that for a certain SNR range, even at very high velocity, closed loop performs better than open loop. Figure 4.1 to Figure 4.11 show the plots that vary the UE speed from 0 to 50 MPH and graph for capacity w.r.t. SNR of open loop and closed loop spatial multiplexing. The convergence of the two modes is the threshold, beyond which open loop performs better than closed loop in terms of channel capacity.

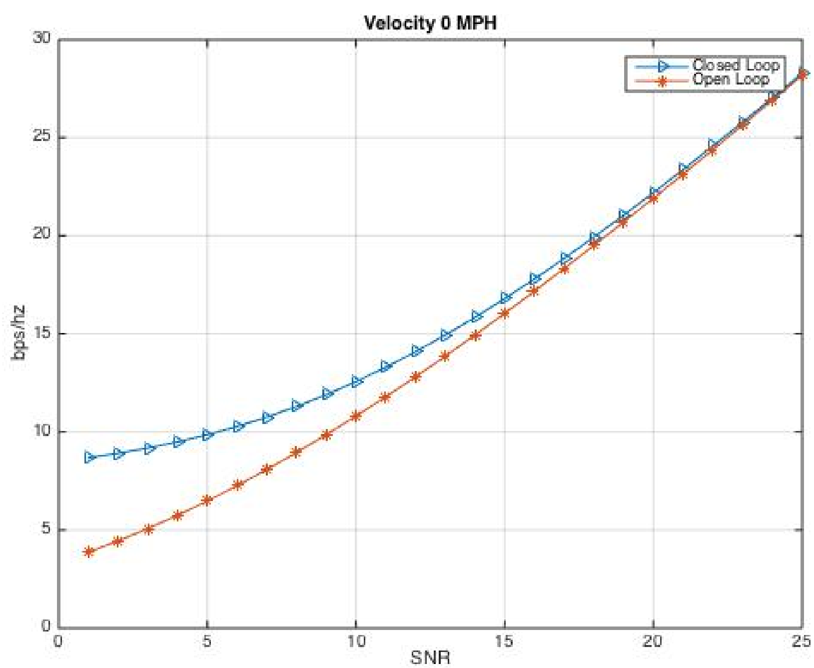

Figure 4.1 Plot with UE speed set to 0 MPH

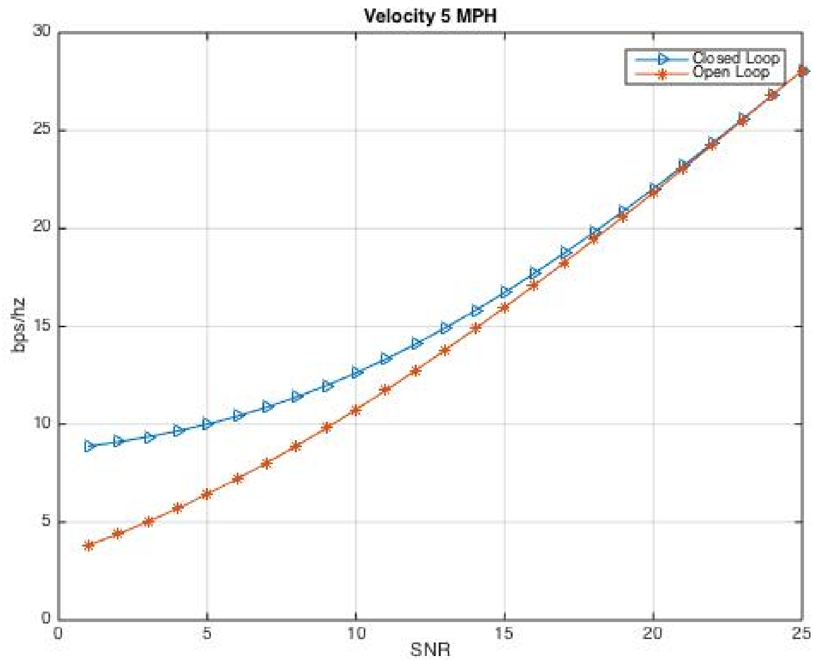

Figure 4.2 Plot with UE speed set to 5 MPH

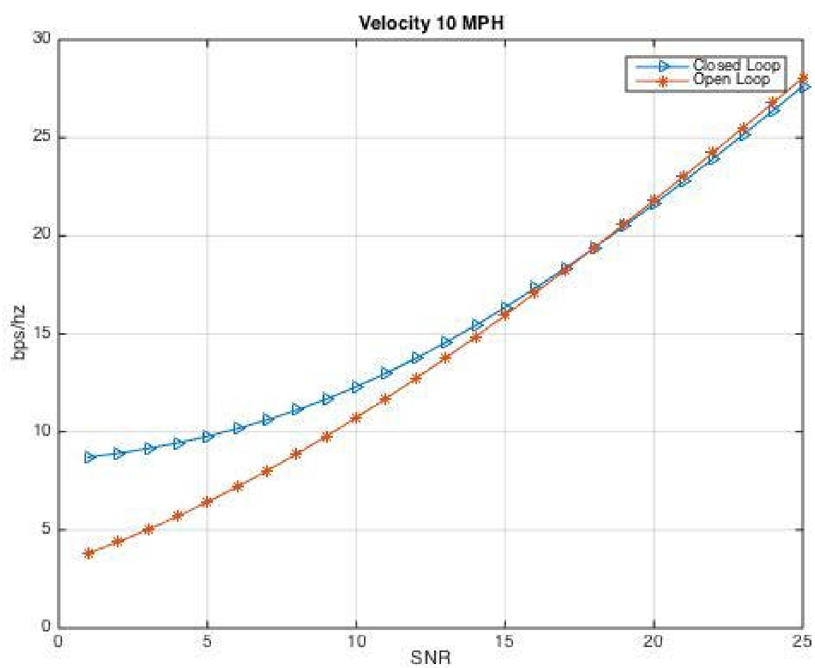

Figure 4.3 Plot with UE speed set to 10 MPH

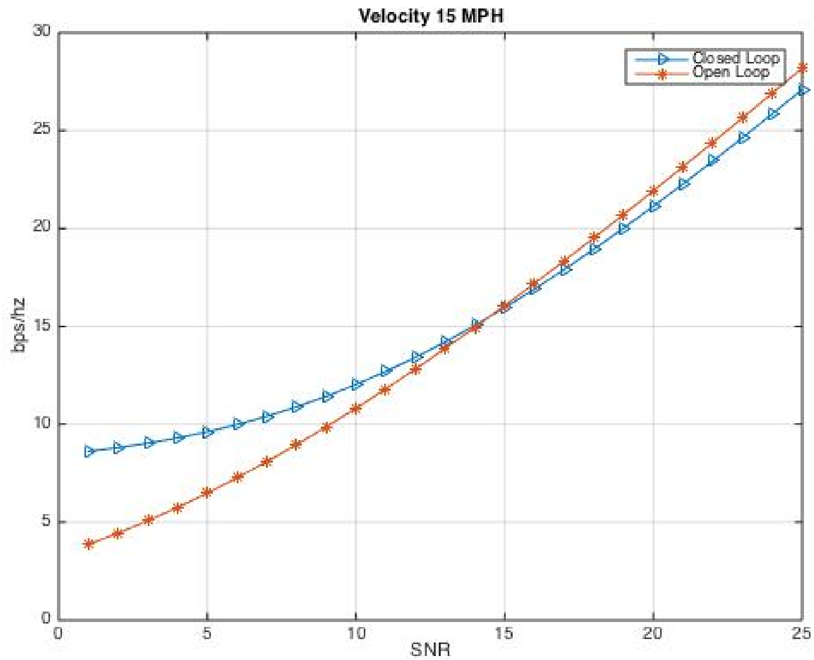

Figure 4.4 Plot with UE speed set to 15 MPH

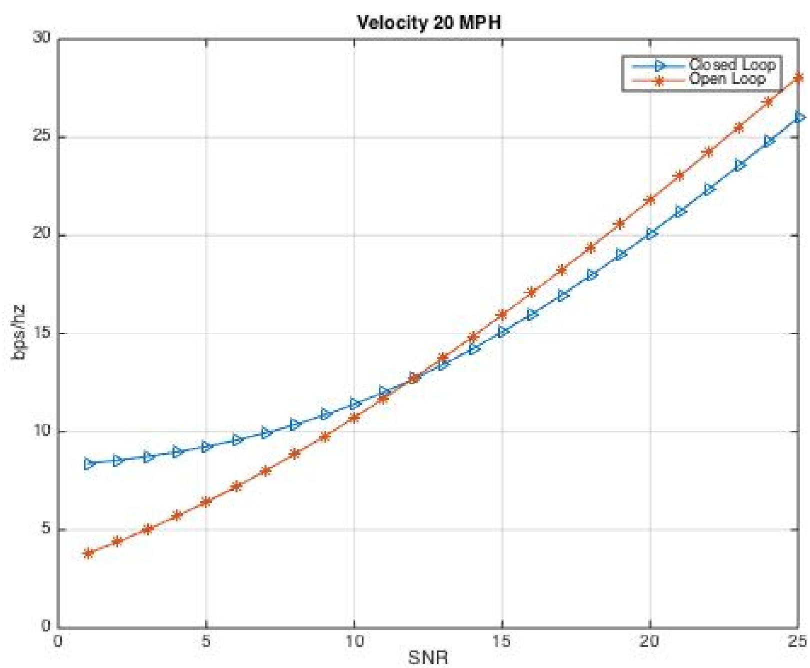

Figure 4.5 Plot with UE speed set to 20 MPH

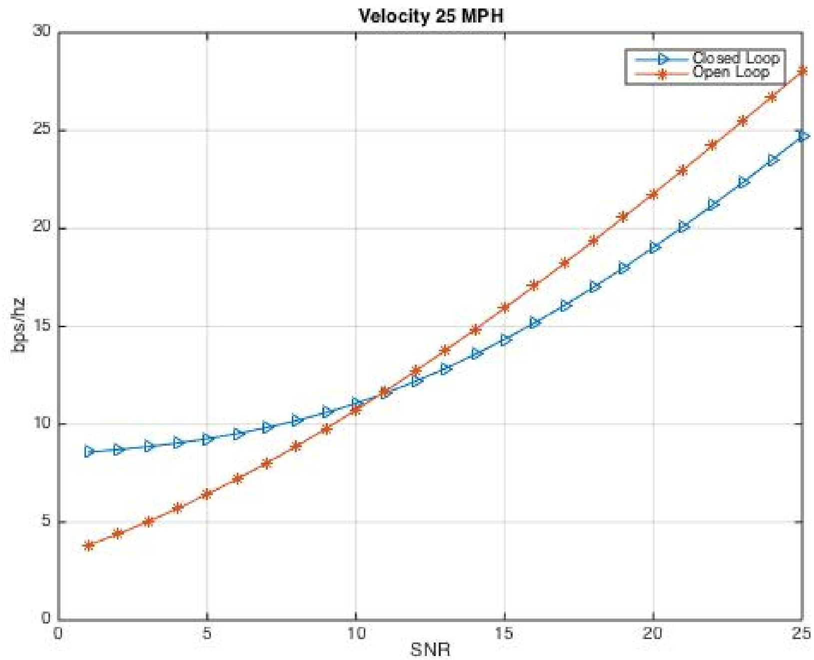

Figure 4.6 Plot with UE speed set to 25 MPH

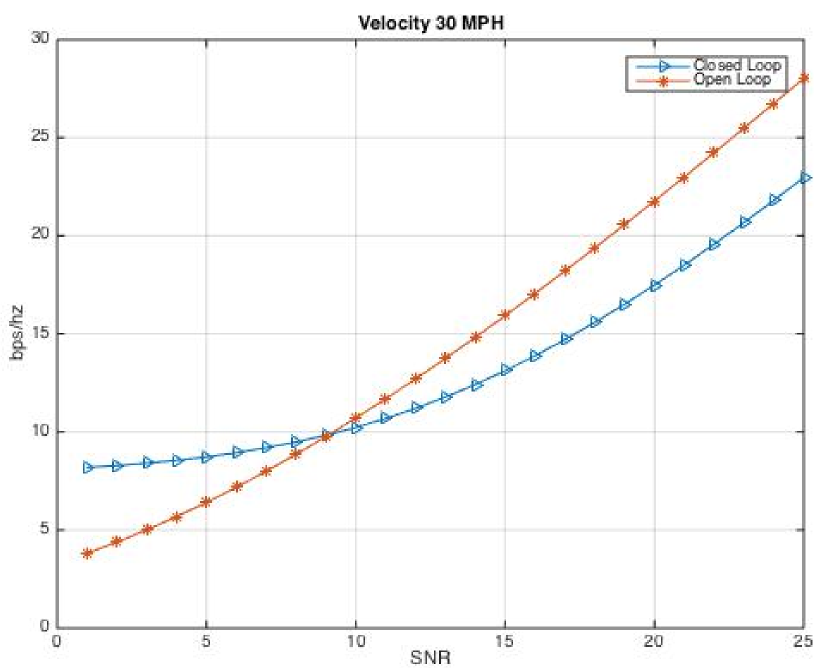

Figure 4.7 Plot with UE speed set to 30 MPH

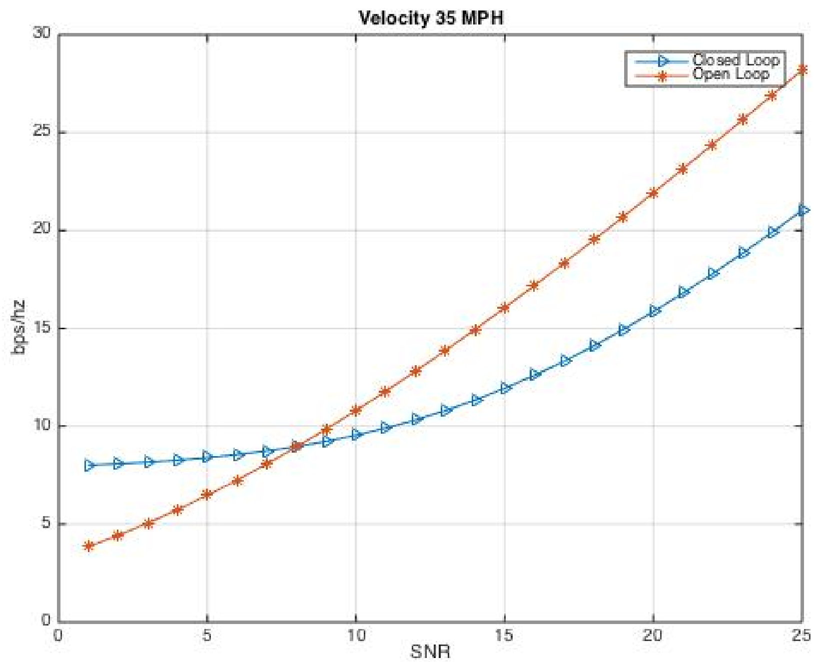

Figure 4.8 Plot with UE speed set to 35 MPH

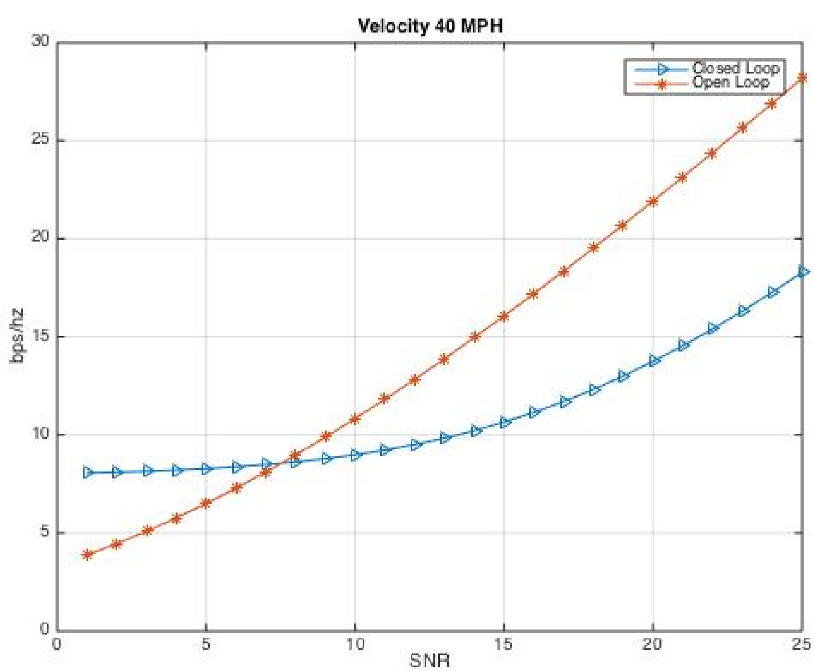

Figure 4.9 Plot with UE speed set to 40 MPH

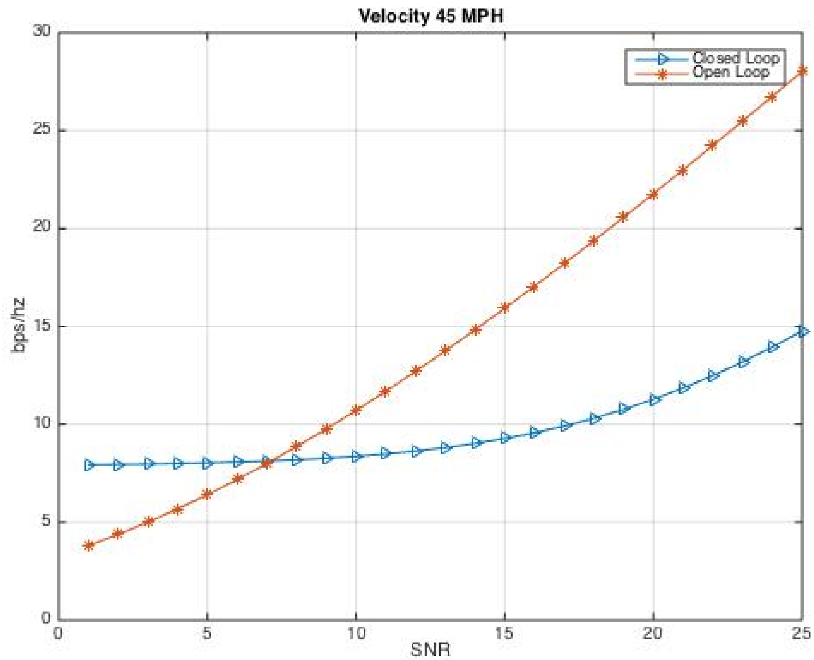

Figure 4.10 Plot with UE speed set to 45 MPH

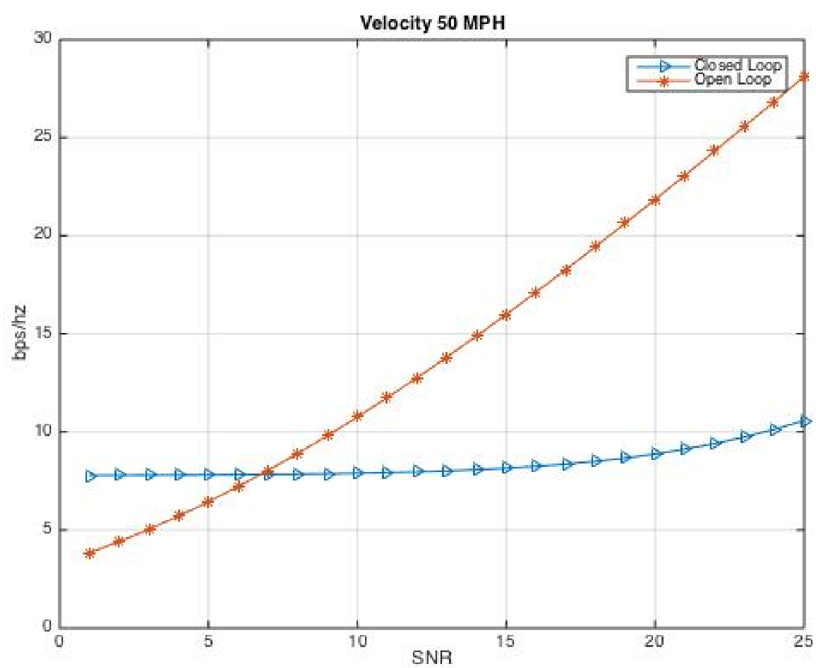

Figure 4.11 Plot with UE speed set to 50 MPH

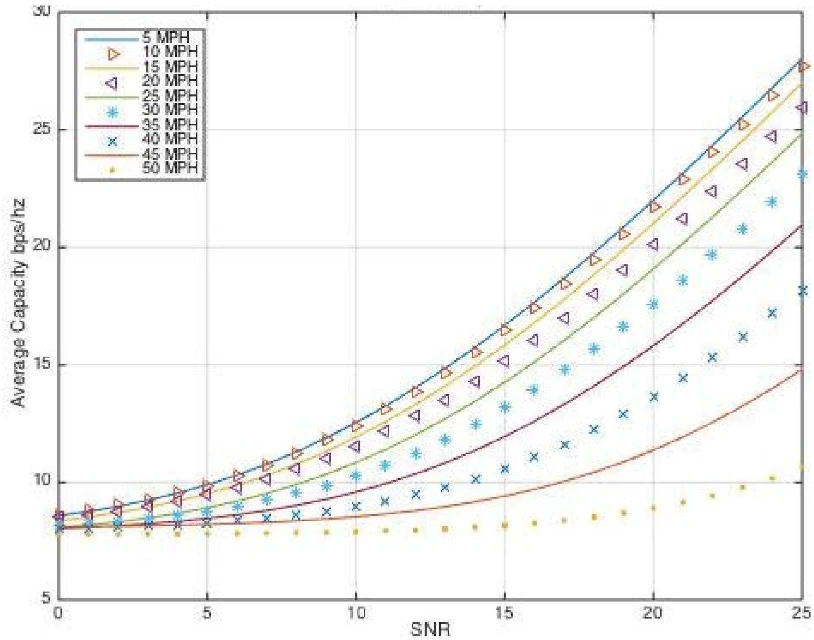

Figure 4.12 Plot with UE speed variation for closed loop

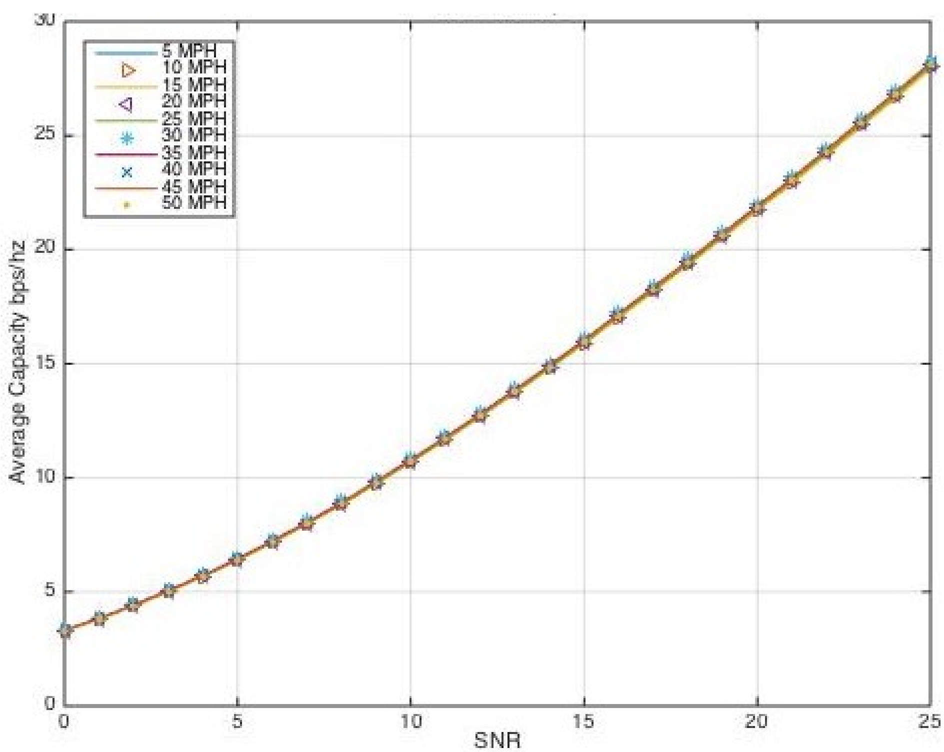

Figure 4.13 Plot with UE speed varying for open loop

Figure 4.12 is a plot showing the capacity variation for different values of UE speed and varying SNR for closed loop spatial multiplexing. Similarly, Figure 4.13 shows this plot for open loop spatial multiplexing.

In Figure 4.12, we can see the effects of UE speed variations on the channel capacity of closed loop spatial multiplexing because of the PMI feedback delay caused by channel correlation. With increasing UE speed, the channel capacity decreases for closed loop for SNR values. In Figure 4.13, we can see that there is no effect of UE speed variation on channel capacity of open loop spatial multiplexing because PMI is not available in open loop spatial multiplexing.

CHAPTER 5

CONCLUSION AND FUTURE WORK

In this chapter, we conclude with the results that have been achieved and we also describe possible research areas and directions for future work.

5.1 Conclusion

Channel state information is used in MIMO to increase the capacity of the wireless channel as well as the signal to noise ratio. Link adaptation in LTE uses Channel State Information (CSI), which is primarily the Channel Quality Index (CQI) and the Rank Index (RI). The CQI is used to control the modulation and coding schemes used in the communications channel while the RI is used to control the number of layers, which subsequently determines the number of parallel transmissions, thus allowing the change between transmit diversity and spatial multiplexing. After the introduction of the Precoding Matrix in spatial multiplexing, another variable was added to the CSI, which is the Precoding Matrix Index (PMI). We analyzed the effect of incorrect PMI on the channel capacity of closed loop spatial multiplexing. We calculate the correlation time for various UE speeds and the PMI feedback delay, which allows us to calculate the channel capacity. The results demonstrate that both SNR and mobility play equally important roles in maintaining the channel capacity of closed loop spatial multiplexing. We determine the values at which open loop spatial multiplexing becomes more effective than closed loop spatial multiplexing and consider these as switching points. These points are also used to switch between channel aware and channel unaware scheduling schemes. Based on our results, we show that the resulting capacity is greater than the capacity of open loop and closed loop systems individually.

5.2 Future Work

Wireless communication is a vast topic, full of research opportunities. There are multiple areas that can be researched in the future to make this technology more efficient. Here we describe two such areas:

(1) In this thesis, we have worked on a two-antenna transmitter and receiver system. It could be beneficial to extend this work to include increasing the number of antennas that exist in LTE, such as 4x4 and 4x8 systems. Obtaining good results would allow for a more complete analysis on the effect of the algorithm on current MIMO systems.

(2) We can also investigate calculating the PMI differently, which would take into account the UE speed and transmit back the PMI feedback based on the correlation time. The PMI feedback is usually transmitted after each frame. If the channel estimation is done considering the UE speed and the precoding matrix index is then sent back to the transmitter, then closed loop spatial multiplexing may become more efficient.

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