DEVELOPMENT OF A PILOT ALLOCATION PROTOCOL TO MITIGATE THE EFFECT OF PILOT CONTAMINATION IN MASSIVE MULTIPLE INPUT MULTIPLE OUTPUT SYSTEM

BY

SAIDU WAZIRI MUHAMMAD

DEPARTMENT OF COMMUNICATIONS ENGINEERING,

FACULTY OF ENGINEERING,

AHMADU BELLO UNIVERSITY,

ZARIA, NIGERIA

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BY

Saidu Waziri MUHAMMAD, B. ENG. ELECTRICAL (ABU), 2009

P15EGCM8046

mw.waziri@gmail.com.

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DEPARTMENT OF COMMUNICATIONS ENGINEERING,

FACULTY OF ENGINEERING,

AHMADU BELLO UNIVERSITY,

ZARIA, NIGERIA

JULY, 2018

DECLARATION

I declare that the work in this dissertation entitled "Development of a Pilot Allocation Protocol to Mitigate the Effect of Pilot Contamination in Massive Multiple Input Multiple Output System" was carried out by me in the Department of Communications Engineering. The information derived from literature has been duly acknowledged in the text and list of references provided. No part of this dissertation was previously presented for award of another degree or diploma at this or any other institution.

Saidu Waziri MUHAMMAD _____

_____

(Student) Signature Date

CERTIFICATION

This dissertation entitled"**DEVELOMENT OF A PILOT ALLOCATION PROTOCOL TO MITIGATE THE EFFECT OF PILOT CONTAMINATION IN MASSIVE MULTIPLE INPUT MULTIPLE OUTPUT SYSTEM**" by Saidu Waziri MUHAMMAD meets the regulations governing the award of degree of Master of Science (M.Sc.) in Telecommunications Engineering by Ahmadu Bello University, Zaria and approved for its contribution to knowledge and literary presentation.

Prof. B. G. Bajoga	_____	_____
(Chairman, Supervisory Committee)	Signature	Date
Dr. A. M. S. Tekenyi	_____	_____
(Member, Supervisory Committee)	Signature	Date
Dr. M. B. Abdulrazaq	_____	_____
(Member, Supervisory Committee)	Signature	Date
Dr. A.D. Usman	_____	_____
(Head of Department)	Signature	Date
Prof. S.Z. Abubakar	_____	_____
(Dean, School of Postgraduate Studies)	Signature	Date

DEDICATION

This dissertation is dedicated to Almighty Allah alone, my sustainer and my helper, the Lord of the worlds, master of the day of judgement, the most Beneficent and the most Merciful.

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Saidu waziri MUHAMMAD

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ABSTRACT

Pilot Contamination (PC) has been considered as a majorlimiting factor of Time Division Duplexing (TDD) Massive Multiple-Input Multiple-Output (M-MIMO) systems, as itsaturates the signal to interference plus noise ratio (SINR) saturated. Similarly, several mitigation techniques such as Eigenvalue decomposition, cooperative Bayesian channel estimation, blind equalization technique, time staggering pilot, smart pilot assignment, etc. proposed in literature to address PC issue have limitations. These proposed methods are either based on initializing all pilot sequences allocated for training as requested by users or require coordination among neighboring cells. Either process is found to be difficult as synchronizing different levels of the network (micro, nano, and pico-cells) and possibly many cells is not only difficult but a huge task of highly computational complexity that requires coordination among neighboring cells. Therefore, this research work developed a Pilot Allocation Protocol (PAP) decontamination technique. The developed scheme was based on sectional pilot sequence initialization and sharing which allocate more than one user to share the same orthogonal pilot sequence within a cell. As a result of the sharing, intra cell interference was created, which in turn suppresses inter cell interference between users sharing the same pilot sequence and mitigate the effect of PC. Simulation was carried out using MATLAB 2016Rb and the performance of the developed PAP technique was then compared with conventional; and; Soft Pilot Reuse and Multi-Cell Block Diagonalization (SPR and MBD) schemes utilizing average Uplink (UL) and Downlink (DL) cell throughputs, and Bit Error Rate (BER) as performance metrics. Results obtained showed that, PAP technique had a better average UL and DL cell throughputs over the conventional; and; SPR and MBD schemes with an improvement of 2 b/s/Hz and 3b/s/Hz when the number of BS antennas considered was set at 64, 20.5 b/s/Hz for uplink and 20.3 b/s/Hz for

downlink when the number of BS antennas was set at 250, and 20.2 b/s/Hz for uplink and 19 b/s/Hz for downlink when the number of BS antennas was setat 256, when Zero Forcing(ZF) detector/precoder was adopted while when Matched Filter(MF) detector/precoder was used, the developed PAP technique had an average uplink and downlink cell throughputs improvement of 1.5 b/s/Hz for both UL and DL when the number of BS antennas considered were set at 64, 8.1 b/s/Hz for both UL and DL at 250 BS antennas, and 8.1 b/s/Hz for both UL and DL when the number of BS antennas was set at 256 BS.

TABLE OF CONTENTS

DECLARATION ii

CERTIFICATION iii

DEDICATION iv

ACKNOWLEDGEMENT v

ABSTRACT vii

TABLE OF CONTENTS ix

LIST OF FIGURES xiii

LIST OF TABLES xv

LIST OF APPENDICES xii

LIST OF ABBREVIATION xvi

CHAPTER ONE: INTRODUCTION

1.1 BACKGROUND OF RESEARCH 1

1.2 PROBLEM STATEMENT 2

1.3 SIGNIFICANCE OF RESEARCH 3

1.4 AIM AND OBJECTIVE 3

1.5SCOPE OF RESEARCH 4

CHAPTER TWO: LITERATURE REVIEW

2.1 INTRODUCTION **5**

2.2 REVIEW OF FUNDAMENTAL CONCEPTS **5**

2.2.1 Multiple Input Multiple Output (MIMO) 5

2.2.1.1 Limitations of MIMO **7**

2.2.2 Massive MIMO **8**

2.2.2.1 Benefits of M-MIMO **8**

2.2.2.2 Challenges of M-MIMO **11**

2.2.3 Pilot Contamination **12**

2.2.3.1 Sources of Pilot Contamination **12**

2.2.4 Pilot Decontamination Techniques **15**

2.2.4.1 Pilot Sequence Reuse and Power Allocation Techniques **17**

2.2.5 Pilot Allocation Protocol (PAP) Technique **22**

2.2.6 Pilot Information Recovery (User Separation) **24**

2.2.6.1 Uplink Transmission **27**

2.2.6.2 Downlink Transmission **28**

2.2.6.3 Linear processing schemes **29**

2.2.6.4 Linear Receivers (in the UPLINK) **29**

2.2.6.5 Maximum Ratio Combining Receiver **30**

2.2.6.6 Zero Forcing **32**

2.2.6.7 Minimum Mean Square Error **32**

2.2.6.8 Linear Precoder (in the DOWNLINK) **32**

2.2.7 Comparison of Wireless Channel Model **34**

2.2.8Channel Modelling in Time Division Duplex **27**

2.2.8.1 Uplink Transmission **28**

2.2.8.2 Downlink Transmission **28**

2.2.8.3Linear Processing Schemes **28**

2.2.8.4 Linear Receivers (in the UPLINK) **29**

2.2.8.5 Linear Precoders (in the DOWNLINK) **29**

2.2.8.6 Zero Forcing **30**

2.2.9 Review of Similar Works **31**

CHAPTER THREE: MATERIALS AND METHODS

3.1INTRODUCTION **39**

3.2 MATERIALS USED FOR THE RESEARCH WORK **39**

3.3 METHODOLOGY **39**

3.4 DEVELOPMENT OF PILOT ALLOCATION PROTOCOL (PAP) CHANNEL MODEL **40**

3.4.1 Channel Model **44**

3.4.2 Base Parameters (Initialization) **44**

3.4.3 User Equipment Parameters (Initialization) **45**

3.5ENHANSEMENT OF UPLINK (UL) AND DOWNLINK (DL) AVERAGE CLL THROUGHPUTS 46

3.5.2 Signal Detection **48**

3.5.3 UL SINR and Average UL Cell Throughput Determination **49**

3.5.4 DL SINR and DL Average Throughput Determination **49**

3.6 PERFORMANCE METRICS **50**

3.6.1 Uplink (UL) and Downlink (DL) throughput **50**

3.6.2 Bit Error Rate **50**

CHAPTER FOUR RESULTS AND DISCUSSION

4.1 INTRODUCTION **52**

4.2 ENHANCED UL AND DL THROUPUTS BASED ON THE DEVELOPED PILOT ALLOCATION PROTOCOL **52**

4.3 RESULTS DISCUSSION **53**

4.4 SUMMARY OF RESULTS **60**

4.5 VALIDATION **62**

CHAPTER FIVE: CONCLUSION ANDRECOMMENDATION

5.1 INTRODUCTION **64**

5.2CONCLUSION **64**

5.3 SIGNIFICANT CONTRIBUTION **65**

5.4 RECOMENDATIONS **66**

REFERENCES

APPENDIX A1
COMPLETE MATLAB CODE OF PILOT ALLOCATION PROTOCOL TECHNIQUE **70**

APPENDIX A2
COMPLETE EQUATIONS DERIVATION OF LINEAR DETECTION/PRECODING TECHNIQUES **76**

LIST OF FIGURES

Figure 2.1: MIMO System model **6**

Figure 2.2: Massive MIMO Schematic Diagram **8**

Figure 2.3: Reciprocity in M-MIMO System **11**

Figure 2.4: Training Phase **13**

Figure 2.5: Pilot Contamination**14**

Figure 2.6: Multi-Cell Architecture **15**

Figure 2.7: Uplink Transmission with all Users Transmitting at Maximum Power **15**

Figure 2.8: Pilot Reuse of 1 and 1/3**21**

Figure 2.9: Pilot Distribution Scheme for SPR-MBD **22**

Figure 2.10: Flowchart based on SPR-MBD Scheme **23**

Figure 2.11: Multi-Cell Architecture based on SPR-MBD Technique **24**

Figure 2.12: Mu-MIMO **27**

Figure 3.1: Multi-Cell Architecture Based on the Developed PAP Technique **41**

Figure 3.2: Flowchart Implementation of the Developed PAP Technique **43**

Figure 4.1: Uplink Rate against Number of BS Antennas with ZF for Conventional, SPR-MBD, and PAP Schemes **53**

Figure 4.2: Downlink Rate against Number of BS Antennas with ZF for Conventional, SPR-MBD, and PAP Schemes **55**

Figure 4.3: Uplink Rate against Number of BS Antennas with MF for Conventional, SPR-MBD, and PAP Schemes **56**

Figure 4.4: Downlink Rate against Number of BS Antennas with ZF for Conventional, SPR-MBD, and PAP Schemes **58**

Figure 4.5: A plot of BER performance of the PAP scheme with ZF**59**

Figure 4.6: A plot of BER Performance of the PAP Scheme with MF **60**

LIST OF TABLES

Table 3.1: Model Parameters used. **48**

Table 4.1: Average UL and DL Cell Throughput Tabular Result for the Developed PAP, SPR-MBD and Conventional Schemes with ZF and MF Detection/Precoding at 64, 250 and 256 BS Antennas. **62**

LIST OF ABBREVIATION

ACRONYMS	DEFINATIONS
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BS	Base Station
CE	Channel Estimation
CS	Conventional Scheme
CSI	Channel State Information
CMT	Cosine Modulated Multitone
DL	downlink
EE	Energy Efficiency
FDD	Frequency Division Duplex
FBMC	Filter Bank Multi Carrier
ICI	Inter Cell Interference
IID	Identically Independent Distribution
I/Q	Imbalance Quadrature
MATLAB	Matrix Laboratory
MBD	Multi-Cell Block Diagonalization
MF	Matched Filter
MIMO	Multiple Input Multiple Output
M-MIMO	Massive Multiple Input Multiple Output
MMSE	Minimum Mean Square Error
MRC	Maximum Ratio Combination
MRT	Maximum Ratio Transmission

NBSA	Number of Base Station Antennas
OFDM	Orthogonal Frequency Division Duplex
PAP	Pilot Allocation Protocol
PC	Pilot Contamination
RF	Radio Frequency
SE	Spectral Efficiency
SNR	Signal to Noise Ratio
SPR	Soft Pilot Reuse
TDD	Time Division Duplex
UL	Uplink
UT	User Terminal
ZF	Zero Forcing

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND OF RESEARCH

In today's world, the use of mobile devices is increasing exponentially and is not limited to just sending and receiving calls. Next generation communication systems, also known as fifth generation (5G) networks, have been recognized as having the prospect of providing solutions to the issue of capacity constraints of today's networks (Jose *et al.*, 2009). It can also address the problems associated with existing communication systems, concerning their reliability for multimedia applications, full coverage distance area, link reliability, latency, and energy efficiency (Larsson *et al.*, 2014). Higher channel counts Multiple-Input Multiple-Output (MIMO) also known as Massive MIMO (M-MIMO) technology is at an advantageous position to deal with these constraints (Vardhan *et al.*, 2016a). M-MIMO system has been identified to have the potential to cater for the high capacity demand, for wireless mobile communication networks in 2020 and beyond (Benmimoune *et al.*, 2015).

In spite of the prospects of the M-MIMO technology, it has some key challenges such as (Tebe *et al.*, 2015):

i. Finding an appropriate way to communicate the Channel State Information (CSI) for communication between a transmitter and a receiver to trigger pre-coding.
ii. Channel estimation based on the assumption of having full knowledge of the CSI, which is practically impossible due to a large number of antennas.
iii. Trade-off between Spectral Efficiency (SE) and Energy Efficiency (EE).
iv. Link reliability in relation to channel estimation error.
v. Pilot contamination in a multi-cell scenario.

In an attempt to address these problems in relation to the reliability of the communication channel, channel estimation error and PC of a multi-cell M-MIMO, various techniques have been proposed in literature (Frenger *et al.*, 2014); (Tai *et al.*, 2015); and (Liu *et al.*, 2017). Similarly, looking into the problems of channel state estimation error and PC in a multi-cell scenario, an integer linear programming and heuristic dynamic programming algorithms were used by Benmimoune *et al.*, (2015). Downlink (DL) transmit power model was derived using Zero Forcing (ZF) and Maximum Ratio Transmission (MRT) pre-coding schemes Tebe *et al.*, (2015).

However, not all the problems mentioned above have been exhaustibly addressed, as many of the approaches were subjected to some assumptions which are inconsistent with the practical scenario. Therefore, a lot still needs to be done in order to improve the performance of these techniques to accommodate additional parameters in their system models, which represent a more realistic and practical network framework. Some of the areas that need improvement are: channel estimation due to the PC issue to improve CSI, reducing computational complexity in the mitigation techniques used in addressing PC and finally, the assumption of perfect CSI in a multi-cell scenario.

1.2 PROBLEM STATEMENT

To achieve the full benefits of M-MIMO, accurate estimation of the CSI is required at each base station. The M-MIMO networks operating in Time-Division Duplex (TDD) mode can have their expected capacity reduced to a large extent as a result of pilot contamination. M-MIMO uses orthogonal pilots to train the transmitter or receiver to acquire an estimate of the channel state information of users.The number of orthogonal pilots needed are limited compared to the number of users. This is why cells use the same pilots (Non-Orthogonal), resulting in pilot contamination. To mitigate pilot contamination, suggestions are made to

use collaboration between cells so that they transmit their pilots at different times and therefore there is no inter-cell interference from non-orthogonal pilots. This is found to be difficult as synchronizing different levels of the network (micro-, nano-, and pico-cells) and possibly many cells are a huge task. Another suggestion is to randomly change the orthogonal code of pilots so that the interfering signals randomly changes and therefore has averaging effect rather than summing effect. Since the random change happens only once in a coherence time, the interference is bound to remain from the same sources for a significantly long time. Therefore, orthogonal pilot sequence re-use within the same cell, which can create intra-cell interference and suppresses Inter Cell Interference (ICI) and Pilot Contamination (PC) is suggested. This makes it easy to either coordinate orthogonal pilot allocation or training using different hardmad matrix codes.

1.3SIGNIFICANCE OF RESEARCH

The significance of this research work is to develop a pilot allocation protocol decontamination scheme, so as to mitigate the effect of Pilot Contamination (PC) in M-MIMO system operating in Time Division Duplex (TDD) mode. The pilot allocation protocol will be developed based on sectional pilot sequence initialization and sharing to mitigate the effect of PC to the barest minimum and improve the performance of M-MIMO. A significant mitigation of PC would paveway to an improved CSI estimation and also, to reap the benefits of M-MIMO technology in terms of spectral efficiency, energy efficiency, increased robustness and reliability, multiplexing gain and cost reduction in radio frequency (RF) power components.

1.4AIM AND OBJECTIVES

The aim of this research work is to develop a pilot allocation protocol (PAP) decontamination scheme to mitigate the effect of pilot contamination (PC) in order to

enhance the performance of cell edge users in terms of uplink and downlink throughputs as well as Bit Error Rate (BER).

The objectives of this research are as follows:

i. To develop a pilot allocation protocol (PAP) based on sectional pilot sequence Initialization and sharing in order to mitigate the effect of PC.
ii. To enhance both the uplink (UL) and downlink (DL) throughputs of cell edge users using the developed model in item (i).
iii. To compare the results obtained from the developed PAP with those of Zhu *et al.* (2016)as a means of validation using uplink and downlink throughputs and bit error rate as performance metrics.

1.5 SCOPE OF RESEARCH

This research work is focused on the development of a pilot allocation protocol decontamination scheme in Massive Multiple Input Multiple Output (M-MIMO). This is with the view to mitigate the effect of pilot contamination in order to improve the performance of M-MIMO system in terms of average cell throughput and bit error rate.

CHAPTER TWO

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter is divided into two parts. The first part discusses the fundamental concepts and theoretical background pertinent to the research. The second part presents critical review of the relevant literature in this particular area of research. These two components will aid in the understanding of the possible approach to take in the resolution of the problem in question and also pave a way for improvement in order to achieve better results.

2.2 REVIEW OF FUNDAMENTAL CONCEPTS

This sub-chapter presents a review of the concepts fundamental to the proposed research work. The review outlines the important principles and relevant theoretical model equations, methods and tools relevant to this research area and problem, in particular.

2.2.1 Multiple Input Multiple Output (MIMO)

The multiple input multiple output (MIMO) technology is a scheme that exploits a significant array of antennas (maximum of 8 antennas at both transmitter and receiver ends to send multiple copies of signals to and from them, through a wireless medium concurrently (Vardhan *et al.*, 2016a). The scheme is depicted in Figure 2.1. Present-day communication systems require great data rate, improved security, and vast coverage area in a limited frequency spectrum environment. MIMO system is a multipath propagation model that converges on the spatial diversity and spatial multiplexing and has been identified to cater for these needs (Larsson *et al.*, 2014). Increases the data rate by conveying several information signals in parallel via a single channel with the same transmit power by means

of spatial multiplexing (multiplexing of diverse parallel information signals in the space between the transmitter and receiver).

The multiple input multiple output system Model is depicted in Figure 2.1

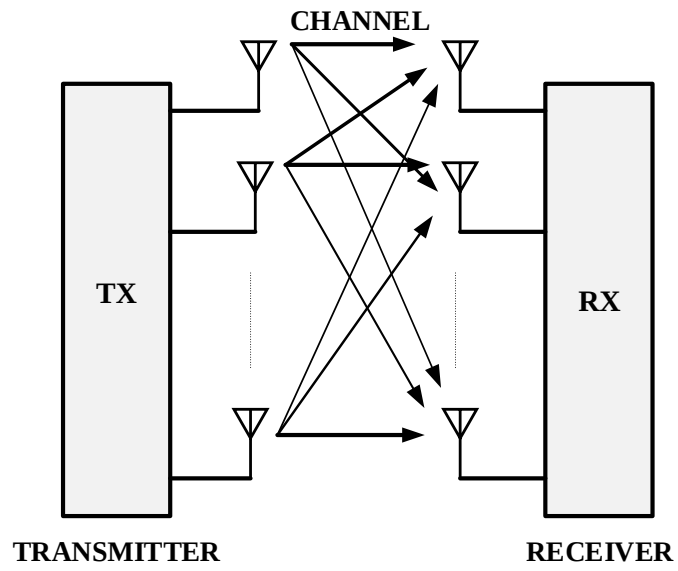


Figure 2.1: MIMO System Model (Vardhan *et al.*, 2016a)

Based on Figure 2.1, the received symbols over an Additive White Gaussian Noise (AWGN) could be expressed as (Vardhan *et al.*, 2016b);

$$Y = Hx + n \qquad (2.1)$$

where:

$x_1, x_2, x_3, x_4, ...x_m$ are transmitted symbols from the transmitting antennas (Tx) and $x = x_m$, and

X = Transmitting symbols vector

$y_1, y_2, y_3, y_4, ... y_n$ are received symbols by the receiving antennas (Rx)and $Y = y_n$, and

Y = Received symbols vector

H is channel coefficient matrix and n is additive white gaussian noise.

For n number of antenna configuration, equation (2.1) can be written in a matrix form as;

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ . \\ . \\ . \\ y_n \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & h_{13} & . & . & . & h_{1m} \\ h_{21} & h_{22} & h_{23} & . & . & . & h_{2m} \\ h_{31} & h_{32} & h_{33} & . & . & . & h_{3m} \\ . & & & & & & . \\ . & & & & & & . \\ . & & & & & & . \\ h_{n1} & h_{n2} & h_{n3} & . & . & . & h_{nm} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ . \\ . \\ . \\ x_n \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \\ n_3 \\ . \\ . \\ . \\ n_n \end{bmatrix} \quad (2.2)$$

2.2.1.1 Limitations of MIMO System

Despite the benefits MIMO technology has offered in wireless communications, it has been found to have the following limitations (Larsson *et al.*, 2014):

i. Underperformance due to the deployment of a few number of antennas in the conventional MIMO.
ii. It cannot substantially cater for the exponential data rate requirement of next generation wireless communications (5G).
iii. Large array of antenna elements cannot be accommodated due to physical limitations at the user equipment end.
iv. The number of antenna configuration in the conventional MIMO system cannot handle efficiently the high data requirements of the next generation wireless communications (5G)

2.2.2 Massive Multiple Input Multiple Output (M-MIMO)

To address the challenges associated with the traditional MIMO, a new approach into advanced channel count known as Massive MIMO (M-MIMO) has emerged as a promising technology. In this new technology, large number of antenna arrays at the Base Station (BS) is used to serve many user terminals (UTs), each having a single antenna, in the same time frequency resource as shown in Figure 2.2. M-MIMO technology is expected to deliver high data rates as well as enhanced link reliability, coverage, energy efficiency, spectral efficiency and has therefore attracted lots of research interest (Zhu *et al.*, 2015).

A typical arrangement or configuration of M-MIMO system is shown in Figure 2.2

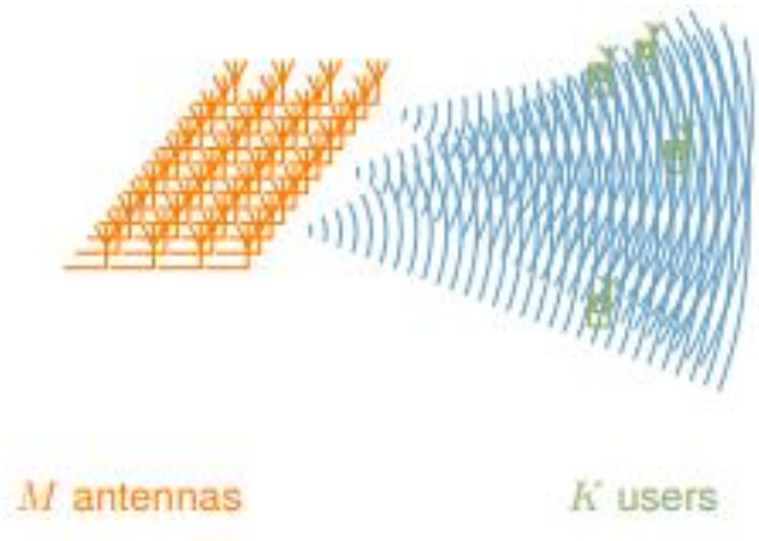


Figure 2.2: Massive- MIMO System Schematic Diagram (Vardhan *et al.*, 2016a)

2.2.2.1 Benefit of M-MIMO System

M-MIMO offers the following benefits (Yin *et al.*, 2013):

i. **Multiplexing gain:** Excessive spatial multiplexing employed in M-MIMO makes it possible to increase capacity 10 times more.

ii. **Energy efficiency:** The huge antenna arrays has the potential to reduce uplink and downlink transmit powers by means of coherent combination and to increase antenna aperture by concentrating power into smaller area. It offers increased energy efficiency in which uplink transmits power of each user terminal (UT) can be reduced inversely proportional to the number of antennas at the BS with no reduction in performance.

iii. **Spectral efficiency:** The large number of base station antennas in M-MIMO systems and multiplexing to a small number of users instead of beamforming to a single user offers spectral efficiency benefits.

iv. **Increased robustness and reliability:** The large number of antennas provides for more diversity gains that the propagation channel can offer. This in turn leads to an improved performance in terms of data rate or link reliability. Also, with excessive deployment of antennas at the base station, asymptotic studies based on random matrix theory demonstrates that both uncorrelated noise, fast fading, and intracell interference disappear.

v. **Simple linear processing:** Due to the huge deployment of antennas at the BS as compared to the few number of user antenna terminals, simple linear pre-coding and detection techniques gives results close to theoretical values in terms of throughput.

vi. **Cost reduction in radio frequency (RF) power components:** Because of the reduction in energy consumption,the large array of antennas allows for use of less expensive RF amplifiers within the range of milli-watt.

To realize the benefits of M-MIMO, each base station requires accurate estimation of the CSI and this can be done either through reciprocity, that is Time Division Duplex (TDD) or

feedback as in Frequency Division Duplex (FDD) schemes (Elijah *et al.*, 2016). TDD is preferred as a better mode to obtain timely CSI in wireless systems in place of FDD due to the fact that the estimation requirement of TDD can be done in one direction and used in both directions, while in FDD estimation and feedback are required for both forward and reverse directions (Guo *et al.*, 2017). Another reason for the choice of TDD over FDD, is that if you are training using FDD, that is from the BS to UE the number of pilots will be limited by the number of antennas which is huge and can consume the whole bandwidth for data transmission. Due to the popularity of FDD among existing networks (3G and 4G), it continues to attract more interest. The TDD scheme is based on reciprocity of downlink and uplink channels and has been considered to be a good choice because of these reasons. The forward channel is assumed to be equal to the transpose of the reverse channel and the needed information is obtained from transmitted pilots on the reverse link (Elijah *et al.*, 2016). Figure 2.3 shows an example of channel reciprocity in a M-MIMO system.

A reciprocity in M-MIMO system is depicted in Figure 2.3

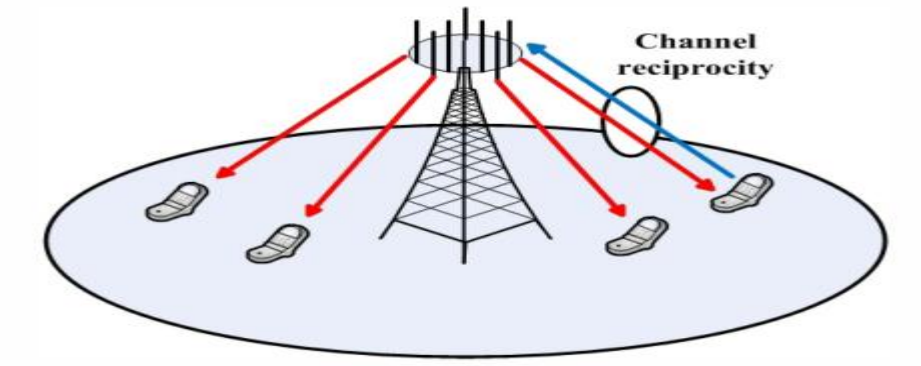


Figure 2.3: Reciprocity in M-MIMO System (Tebe *et al.*, 2015)

2.2.2.2 Challenges of M-MIMO System (Vardhan et al., 2016b):

i. Dealing with correlated channels is very difficult and almost practically impossible
ii. They require high cost radio frequency amplifiers.
iii. Constraint in antenna spacing based on the assumption that user channel is uncorrelated and orthogonal in nature.
iv. Channel computation is very complex due to overhead requirement of large antenna arrays at the base station, if the communication is assumed to be based on FDD transmission mode.
v. Channel estimation error due to hardware implementation leads to error in channel estimation and reduction in the capacity of the system.
vi. They use non-orthogonal pilots which can consequently create PC resulting in ICI, which in turn leads to the degradation of system performance.

Upon all these limitations mentioned, this research work will focus on addressing the problem of PC which occurs as a result of using non-orthogonal pilots in different cells, by

developing a pilot-based protocol allocation from the first principle with the view to mitigate the effect of PC in order to enhance M-MIMO system performance.

2.2.3 Pilot Contamination

A pilot symbol is defined as a sequence of data (information) of known characteristics that is known to both the transmitter and receiver. The value of the sequence inform of bits (hardmad matrix codes) is the characteristics of the sequence (Saxena, 2014). Due to the dense network deployment and limited orthogonal pilot sequences, multiple neighbor cells may use the same pilot sequence (non-orthogonal) and the pilot positions in pilot patterns of the multiple neighbor cells may overlap, which will directly affect the performance of the channel estimation. This is known as Pilot Contamination (PC) (Vardhan *et al.*, 2016b).

2.2.3.1 Sources of Pilot Contamination

The two major sources of PC and basic theory are discussed as follows:

i. Non-orthogonal pilot sequence: Considering a multi-cell where the same frequency is shared by all cells, intra-cell interference is assumed to be insignificant since the pilot sequence are considered to be mutually orthogonal. If a frequency reuse factor of 1 is used, then the pilot sequence will then be affected by ICI leading to PC from the neighboring cells. The individual BS correlates its received pilot sequence signals with its own orthogonal pilot sequence signal while all users in the other cells contribute to the PC (Ul mulk, 2015).

ii. Hardware impairments: Are impairments caused as a result of non-ideal behavior of the hardware components of a transceiver. The hardware components in radio frequency chain are susceptible to impairments such as phase noise, amplifier non-linearity, Quadrature Imbalance (I/Q) and quantization errors. It was proved

that the impairments affect the accuracy of the Channel Estimate (CE) which leads to PC as well as affect the performance of M-MIMO system (Vardhan *et al.*, 2016a).

Different pre-coding schemes, techniques of estimation, and methods of coordination having low complexity are required to address this issue of PC. Figure 2.4 and 2.5 illustrate the phenomenon of PC.

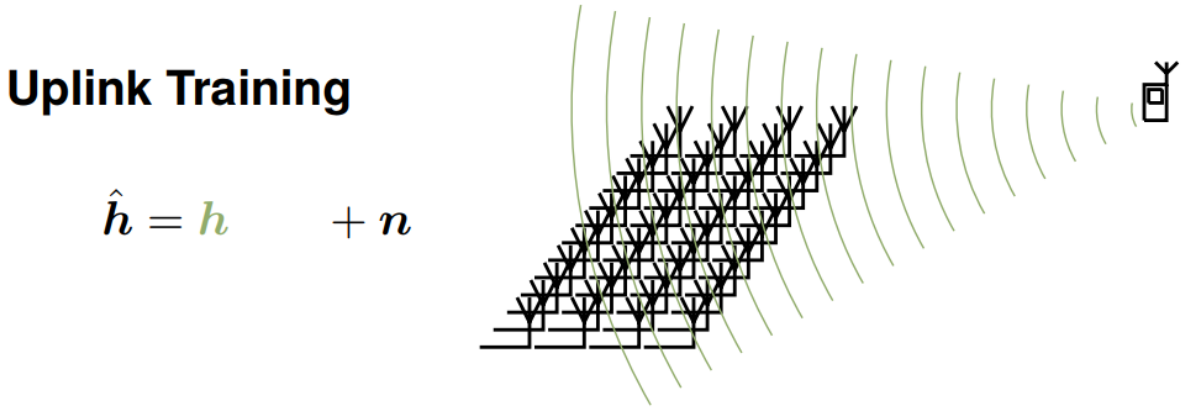


Figure 2.4: Training phase (Ul mulk, 2015)

By considering UL training, before the transmitter can send information to the receiver, the receiver sends information to the transmitter at the BS, but the transmitted symbols are known on both sides so that it could train the symbols. Based on this known and properties of its symbols, then the transmitter can estimate the unknown channel vector $h$added with some noise n of user1, which leads to the corrupted version of the right channel vector $\tilde{h}$ user1.

Figure 2.5: Depicts the scenario of Pilot Contamination (PC) using Uplink (UL) training

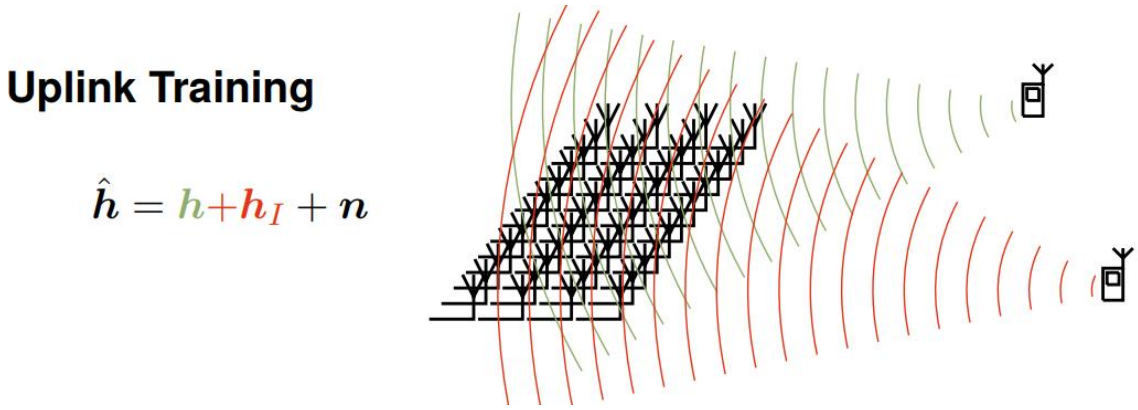


Figure 2.5: Pilot Contamination (Guo *et al.*, 2017).

However, at the same time there might be a second user (user 2) which also wants to have access to the BS and it also sends training symbols to the BS. If the BS at the transmitter is not aware of this it might happen that it considers the signal coming from the second user (user 2)as part of the original user (user 1), and that will have automatic effect on the downlink when the BS is transmitting data to the first user (user 1). Where h_1 is the channel vector of user 2, this effect is called Pilot Contamination (PC), because the interfering part of the channel vector of user 2 (h_1) contaminates the channel information of user 1. Multi cell Architecture of M-MIMO system is shown in figure 2.6.

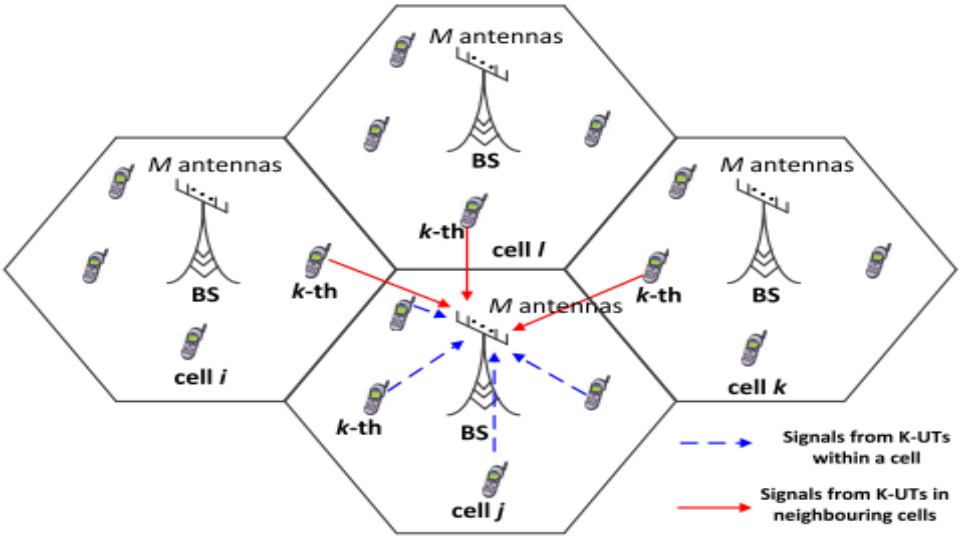


Figure 2.6: Multi Cell Architecture of M-MIMO System (Elijah *et al.*, 2016). Mathematically (Jose *et al.*, 2009).

$$\hat{h}_{22} = c_1 h_{12} + c_2 h_{22} + cw \quad (2.3)$$

$$a_2 = f\left(\hat{h}_{22}\right) = h_{22} a_2 + h_{12} a_2 \quad (2.4)$$

where:

h_{ij} is channel between the base station in the i^{th} cell and the user in the j^{th} cell.

$C_1 = C_2$ is constants that depends on propagation factors

a_2 *is transmitted vector of users*

w is additive noise

2.2.4 Pilot Decontamination Techniques

In an effort to address the problem of PC in a multi-cell architecture, different schemes have been proposed, which are grouped into (1) Pilot-based estimation approach and (2) Sub-space estimation approach (Elijah *et al.*, 2016). In the pilot-based approach, channels of users are estimated using orthogonal pilot sequence within the cell and non-orthogonal pilot sequence across the cells while in the sub-space estimation approach, the channels of users are estimated with limited or no pilots sequence as discussed here under.

i. **Eigenvalue Decomposition:** In this approach, the channel is estimated blindly from the received data. The scheme uses the asymptotic orthogonality of the channel vectors in very large massiveMIMO systems, where channel estimation to each user can be performed from the covariance matrix of the received signals (Ngo & Larsson, 2012).

ii. **Cooperative Bayesian Channel Estimation:** In this technique, the effect of pilot contamination is removed by using channel covariance matrices subject to satisfying certain conditions for example synchronization different levels of the network (micro-, nano-, and pico-cells when there is coordination among the cells (Ngo & Larsson, 2012).

iii. **Blind Technique:**The scheme is called blind in that no pilot data is required to find the appropriate subspace to mitigate pilot contamination problem. It is based on the large random matrices theory that predicts that as the size of the matrices increases, the eigenvalue spectra of the covariance matrices can be asymptotically decomposed into separate bulks (Müller *et al.*, 2014).

iv. **Pilot Sequence Hopping:** In this method, pilot decontamination is achieved without inter-cell coordination, where every user selects a new pilot sequence in each transmission time slot (Sorensen & de Carvalho, 2014).

v. **Blind Equalization Technique:** This method utilizes the blind equalization capability of Cosine Modulated Multitone (CMT), which is based on the property of a Filter Bank Multi Carrier (FBMC) called self-equalization which is extended to M-MIMO to mitigate channel estimation errors that occur as a result of pilot contamination. The technique is highly computationally complex due large number of iterations needed for it to converge (Farhang *et al.*, 2014).

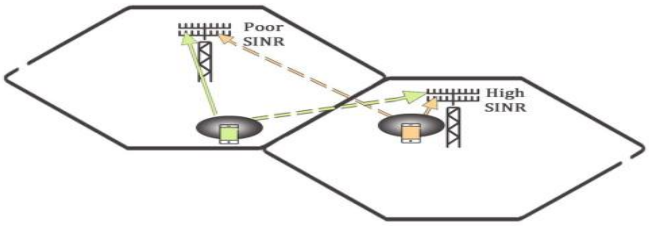
vi. **Time Staggering Pilot:** The scheme removes PC by making sure that the pilot transmission of the individual users exploiting the same pilot avoid overlap in time. The method is expensive and hard to achieve because of the need for a controller to manage the complex staggering of pilots in all cells by depending on tight corporation amongst the base stations (Elijah *et al.*, 2016).

vii. **Soft Pilot Re-use and Multi-Cell Block Diagonalization**: This pre-coding method divides the users into cell-center and cell-edge groups to mitigate PC. The technique cannot completely remove the ICI aided by PC by re-using same group of pilots. (Zhu *et al.*, 2016). In view of these discussions, this research will focus on pilot-based estimation mitigation technique sub-category which depends on pilot reuse and power allocation techniques as discussed here under.

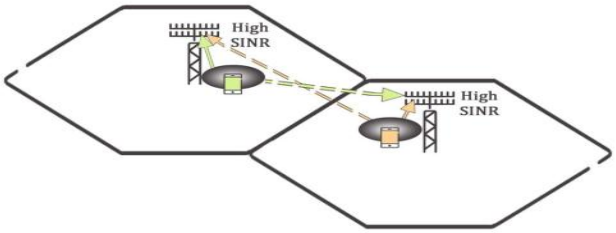
2.2.4.1 Pilot sequence re-use and power allocation techniques

i. Pilot Open Loop Control: The pathloss and transmit power of a User Terminal (UT) is determined by the average received power of a pilot sequence at the base station (BS). Terminals located close to the BS usually have a lower pathloss and a

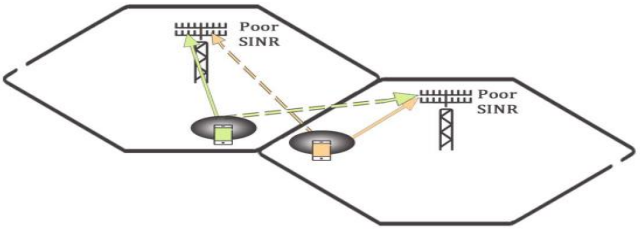
higher signal power while those located at the cell-edge usually have a higher pathloss and therefore a lower signal power (Ul mulk, 2015). This means, those terminals close to the BS enjoy a reduced pathloss, resulting in a better Signal to Interference plus Noise Ratio (SINR). The three different scenarios of pilot reuse at cell edge, close to serving BS and by close cell edge terminals are described in figure 2.6 (Saxena *et al.*, 2015). Figure 2.7 depict Pilot Reuse at Cell Edge, Pilot Reuse Close to Serving BS and Pilot Reuse by Close Edge Terminals.



(a)Pilot Reuse at Cell Edge and close to BS



(b) Pilot Reuse Close to Serving BS.



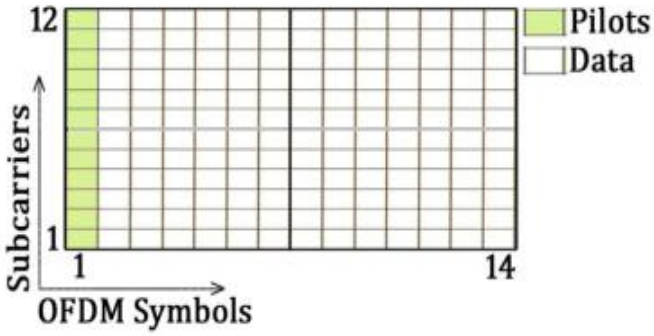
(c) Pilot Reuse by Close Edge Terminals.

Figure 2.7: Uplink Transmission with all Users Transmitting at Maximum Power (Saxena *et al.*, 2015).

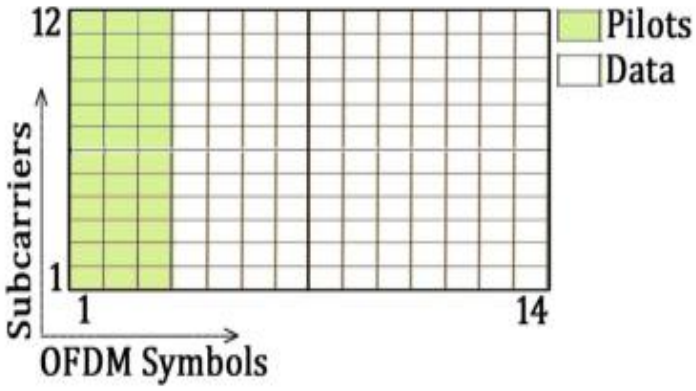
ii. **Less aggressive pilot reuse:** Full pilot reuse prompts most extreme inter cell interference (ICI) during channel estimation, which can be mitigated by using a less aggressive pilot reuse factor (Saxena, 2014). Pilot reuse is analogous to the traditional frequency reuse in the sense that terminals within the pilot reuse area can use just a small amount of the time frequency resources during the channel estimation phase (Zhang, 2015). Whereas, in the case of full pilot reuse, each terminal is allowed to use all the available resources for communication for the remaining coherence interval (Sohn *et al.*, 2017). The pilot reuse factor 1/U is the rate at which pilot resources may be reused in the network, where U is the quantity of cells that are allotted orthogonal pilot sequence. While using reuse factor of U>1 reduces the pilot contamination effect by allotting orthogonal pilot sequence to the neighboring cells. The total number of unique time frequency elements earmarked for pilot transmission are KU, where K is the quantity of terminals per cell. The trivial instance of pilot reuse is aggressive pilot reuse with U = 1. Considering some reserved K time-frequency indices for pilot sequence. The indices may be found any place inside the resource block without loss of simplification. K orthogonal pilot sequences are generated including these indices, that are distributed randomly at arbitrary or algorithmically among the terminals per cell. Since the cells are assumed to be synchronized, the pilot transmissions are synchronized crosswise over cells also. Considering a hexagonal cellular layout then the minimum reuse factor that can ensure orthogonal pilots in adjacent cells is 1/3. The resources used to implement this reuse factor will be three time the number of terminals, that is 3K. A pilot group is allocated to each cell in accordance with the reuse pattern and the terminals are assigned with the pilots as in the case of full pilot reuse. Clearly, a higher value of U

will eliminate Pilot Contamination (PC) but at the cost of more training overheads added by using the pilot resources, limiting the resources available for data within a coherence interval (Saxena *et al.*, 2015). The improved estimates are used for better forward and reverse links beamforming at the BS using spatial multiplexing to serve the terminals. Hence there is a tradeoff between the exact beamforming and data transmission afterwards, Figure 2.8 depicts full pilot reuse and 1/3 pilot reuse respectively (Ul mulk, 2015). Alternatively, there is another technique called Soft Pilot Reuse (SPR) that mitigate PC by assigning additional orthogonal pilot sequences to terminals at the cell-edge to improve their Signal to interference plus Noise Ratio (SINR).

Figure 2.8 showed the full pilot reuse and 1/3 pilot reuse



(a).



(b)

Figure2.8 Pilot Reuse of 1 and 1/3 (Ul mulk, 2015).

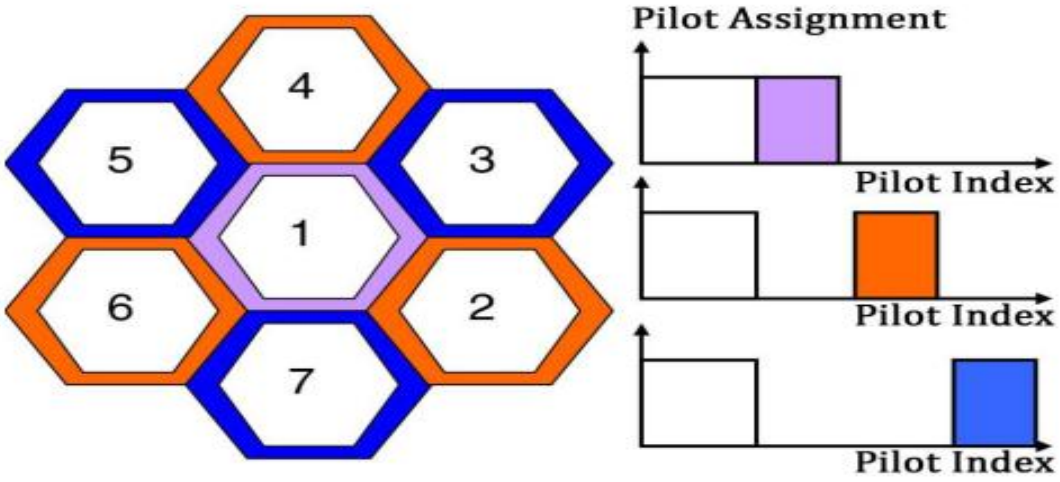


Figure 2.9: Pilot Distribution Scheme for Soft Pilot Reuse (Ul mulk, 2015).

2.2.5 Pilot Allocation Protocol (PAP) Technique

Motivated by the concept of pilot reuse and Soft Pilot Reuse (SPR) particularly, which allocates orthogonal pilot sequence to cell-edge users, we proposed Pilot Allocation Protocol (PAP) decontamination scheme for Time Division Duplex (TDD) mode Massive Multiple Input Multiple Output (M-MIMO) system based on sectional pilot sequence initialization (use of distinct hardmad matrix codes in the first three cells before re-use starts) and sharing with a pilot sequence reuse factor of 1/3 as shown in Figure 2.9 which can allocate more than one user to share same orthogonal pilot sequence within a cell which then creates Intra Cell Interference and mitigates the effect of Pilot Contamination (PC) by separating the users using distinct codes (hardmad matrix) unique to each of the interfering users. This means the cell in which the interfering User Terminal (UT) belongs to, has total control of

all the interfering UTs at the same time needs no communication to any other cell to control the interference as described in Figure 2.9.

Soft Pilot Reuse and Multi-Cell Block Diagonalization technique is showed in Figure 2.10

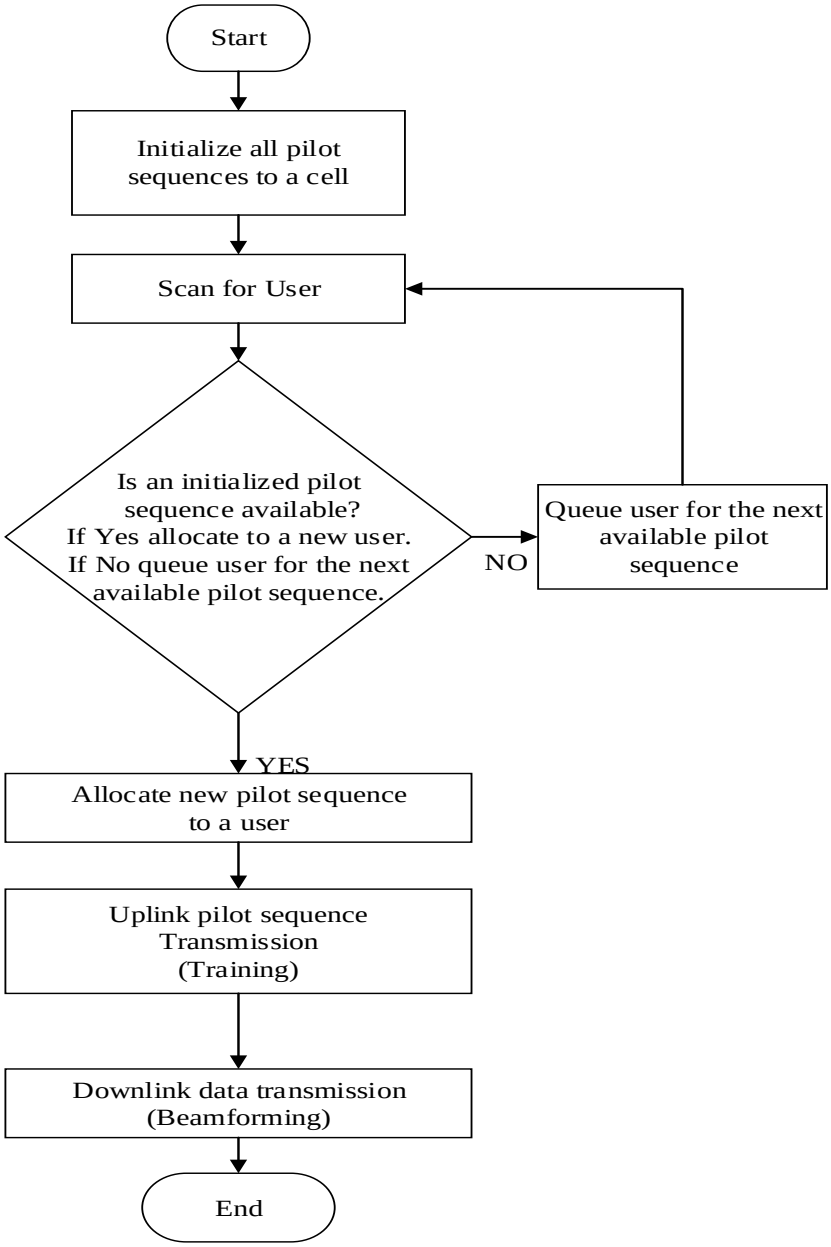


Figure 2.10: Flow chart based on Soft Pilot Reuse and Multi-Cell Block Diagonalization (SPR and MBD) Technique (Zhu *et., al 2016)*

A multi cell architecture based on SPR and MBD Technique is shown in Figure 2.11

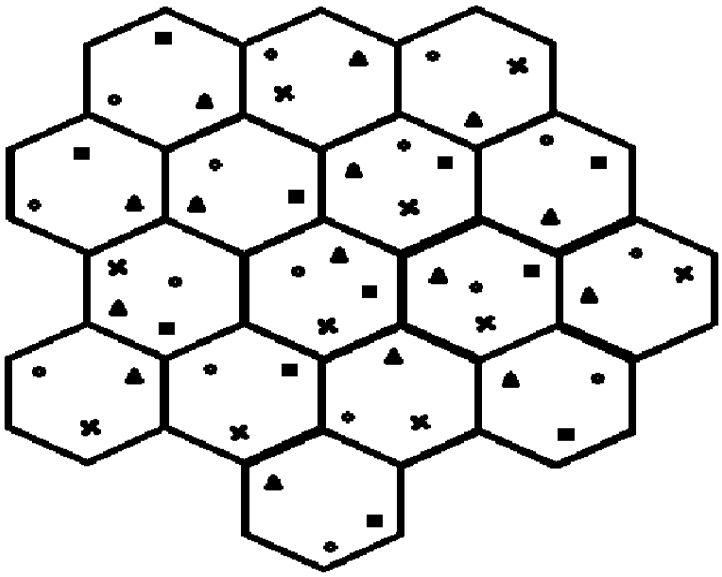


Figure. 2.11: Multi-Cell Architecture based on SPR and MBD Technique (Zhu *et al.*, 2016).

Figure 2.11: depicts a multi-cell architecture based on SPR and MBD, which allocates orthogonal pilot sequence to new users within the same cell. This leads to re-use of the same (non-orthogonal) pilot sequence in the neighboring cells thereby creating strong ICI that causes PC.

2.2.6 Pilot Information Recovery (User Separation)

The design of modern digital communications systems is heavily dependent on statistical approaches to recover information in the presence of noise and interference, and the mathematical sequenceused to achieve that is Hadamard Matrix (A multi Antenna design scheme of Hadamard matrices for wireless communication). It is a square matrix whose

elements are either 1 or -1 and having rows that are orthogonal to each other. Hadamard matrix has a special property of being an inverse of itself. To demonstrate how the information could be recovered using Hadamard matrix, suppose a channel with a known channel state information (CSI) given by matrix A:

$$A = \begin{bmatrix} -0.5 & 0.8 \\ 0.3 & -0.6 \\ 1.0 & 0.3 \end{bmatrix}$$

If two users are assumed, then the Hadamard matrix will be a 2 X 2 matrix given by:

$$B = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

A is the actual Channel State Information (CSI) of each channel between all users to all antennas (that is the type of modification that the channels under go before reaching the antennas at the Base Station (BS)) with variation in amplitudes sometimes or change in phase.The first raw of matrix B represents some bits of Hadamard matrix sent by user one u_1, in the first and second periods t_1 and t_2, while the second raw represents some bits of hardmard matrix sent by user two u_2 in the first and second periods, t_1 and t_2. Then the resultant signal that will reach the antenna is equal to the actual CSI multiplied by the bits of hardmard matrix which contained the training symbols, as shown in matrix C.

$$C = \begin{bmatrix} 0.3 & -1.3 \\ -0.3 & 0.9 \\ 1.3 & 0.7 \end{bmatrix}$$

However, matrix C does not represent the actual CSI.Therefore, to get the actual CSI, the inverse of the sent signals matrix is multiplied by the received signals which cancels the effect of the sent matrix to yield the actual CSI. In the case of Hadamard matrix however,

the same matrix is its own inverse, so the received signals at the antennas in the first period and second period are multiplied by the hardmad matrix and then divided by the its order to get the actual CSI as shown below.

$$\begin{bmatrix} 0.3 & -1.3 \\ -0.3 & 0.9 \\ 1.3 & 0.7 \end{bmatrix} \frac{1}{2}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} = \begin{bmatrix} -0.5 & 0.8 \\ 0.3 & -0.6 \\ 1.0 & 0.3 \end{bmatrix}$$

In practice, there will be little variation with the estimated value due to additive noise.

2.2.7 Comparison of Wireless Channel Models

Rayleigh channel: is a wireless communication channel model that is used to analyze the performance of radio propagation in mostly high dense urban areas (Zheng *et al.*, 2003). The properties of Rayleigh fading channel are summarized as follows:

i. It is used to describe the fading that occurs when multipaths propagation exist;
ii. Rayleigh fading channel can best be used in the absence of a nondominant signal (absence of direct line of sight);
iii. The statistical characteristics of Rayleigh fading channel makes it suitable for the analysis of the overall radio communications channel.'
iv. The power is exponentially distributed.

Rician fading channel: is a type of wireless communication that is similar to Rayleigh, except that it requires a strong dominant signal (line of sight). Due to this property, Rician fading channel is suitable for modeling satellite communications channel.

Nikagami fading channel: is a type of fading channel that was derived from Rayleigh model based on empirical measurements. When the fading factor $k = 1$, Nikagami distribution equals the Rayleigh distribution.

Based on the above and peculiar properties of fading channels, it is clear that Rayleigh fading channel behaves like Massive MIMO for the fact that the later exploits special diversity as well special multiplexing. These have informed the choice of Rayleigh fading channel as the model adopted in this dissertation.

2.2.8 Channel Modelling in Time Division Duplex

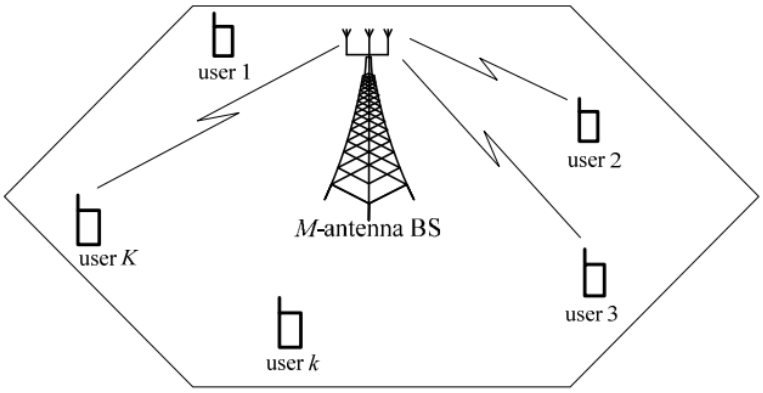


Figure 2.12 MU-MIMO System (Ul mulk, 2015)

Considering MU-MIMO, which consist of one BS and one K active users. The BS is equipped with$M$ antennas, while each user has a single antenna as shown in Figure 2.12. Assuming that all$K$ users share the same time-frequency resource and the BS and the users have perfect CSI. The channels are acquired at the BS and the users during the training phase.

Let $H \in \mathrm{C}^{M \times K}$ be the channel matrix between the K users and the M BS antenna array, where the K_{th} column *of* $\boldsymbol{H}$, denoted by h_k, represents the channel $M \times 1$ vectorbetween the K_{th} user and the BS. Assuming that the elements of $\boldsymbol{H}$ are identically independent distribution (iid) Gaussian distributed with zero mean and unit variance.

2.2.8.1 Uplink Transmission

Uplink transmission is the process whereby *K* users transmit signals to the BS. Let s_k, where $\mathrm{E}\left\{|S_k|^2\right\}=1$, be the signal that is transmitted from the K_{th} user. Since all *K* users share the same frequencies resource, the $M\times 1$ received signal vector at the BS is the combination of all signals transmitted from all *K* users.

$$y_{ul}=\sqrt{\rho_u}\sum_{k=1}^{K}h_k s_k+n \quad (2.5)$$

where, ρ_u is the average signal to noise ratio (SNR), $n\in \mathrm{C}^{M\times 1}$

2.2.8.2 Downlink Transmission

Downlink transmission is the process whereby the BS users transmit signals to all K users. Therefore, the sum capacity of the channel model as detailed in the Appendix A is given by:

$$C_{sum}=\max\log_2\det\left(I_M+\rho_d H^* D_q H^T\right) \qquad (2.6)$$

where, D_q is the diagonal matrix whose K_{th} diagonal element is qk. The sum capacity can be achieved using linear precoders such as Zero Forcing (ZF), Matched Filter (MF) and Minimum Mean Square Error (MMSE).

2.2.8.3 Linear Processing Schemes

To obtain optimal performance, complex signal processing schemes must be employed. The BS can use linear processing techniques (linear receivers in the uplink and linear precoders in the downlink, to reduce the signal processing complexity. However, if the number of BS

antennas tends to infinity, it is shown that the linear processing is nearly optimal (Vardhan *et al.*, 2016a). The details of Linear Processing Schemes are discussed in the following subsections.

2.2.8.4Linear Receivers (in the UPLINK)

With linear equalization schemes at the BS, the received signal y_{ul} is separated into K streams by multiplying it with an $M \times K$ linear equalization matrix, A:

$$y_{ul} = A^H y_{ul} = \sqrt{\rho}_u A^H H_s + A^H n \qquad (2.7)$$

Each stream is then decoded independently. From the aforementioned equation the K_{th} stream (element) of $\tilde{y}_{ul}$, which is used to decode S_k is given by:

$$\tilde{y}_{ul,k} = \underbrace{\sqrt{\rho_u a_k^H} h_k s_k}_{desiredsignal} + \underbrace{\sqrt{\rho_u} \sum_{k^i \neq k}^{k} a_k^H h_{k^i} s_{k^i}}_{\text{int}eruser\,\text{int}erference} + \underbrace{a_k^H n}_{noise} \qquad (2.8)$$

where: a_k denotes the K_{th} column of $\boldsymbol{A}$. The interference plus noise is treated as effective noise, and hence, the received signal to interference plus noise ratio (SINR) of the K_{th} stream is given by:

$$SINR_K = \frac{\rho_u \mid a^H h_k \mid^2}{\rho_u \sum_{K^i}^{K} \mid \mathrm{a}_k^H \, h_{k^i} \mid^2 + \| \, a_k \, \|^2} \qquad (2.9)$$

2.2.8.5 Linear Precoders (in the Downlink)

In the downlink, with linear precoding techniques, the signal transmitted from M antennas**, x** is a linear combination of the symbols intended for the k_{th} users. Let q_k, $\mathrm{E}\left\{ \mid q_k \mid^2 \right\} = 1$, be

the symbol intended for the k_{th} user. Therefore, the SINR of the transmission from BS to the k_{th} user is:

$$SINR_k = \frac{\alpha\rho_d \mid h_k^T w_k \mid^2}{\alpha\rho_d \sum_{k^i \neq k}^{k} \mid h_k^T w_{k^i} \mid^2 + 1} \qquad (2.10)$$

Three conventional linear precoders are maximum ratio transmission (MRT), zero forcing (ZF) (also called conjugate beamforming) and MMSE precoders. These precoders have similar operational meanings and properties as MRC, ZF, MMSE receivers, respectively. Thus, the final formulas for these precoders are:

2.2.8.6 Zero Forcing

The k_{th} column of the ZF receiver matrix satisfies:

$$\begin{cases} a_{zf,k}^H h_k \neq 0 \\ a_{zf,k}^H h_{k^i} = 0, \forall \mathrm{k}^i \neq k. \end{cases} \qquad (2.11)$$

The ZF receiver matrix, which satisfies the above equation for all *K*, is the pseudo-inverse of the channel matrix **H.** With ZF, we have:

$$\tilde{y}_{ul} = \left(H^H H\right)^{-1} H^H y_{ul} = \sqrt{\rho_u} s + \left(H^H H\right)^{-1} H^H n \qquad (2.12)$$

This scheme requires that $M \geq K$ (so that the matrix $H^H H$ is invertible). It can be observed that each stream (element) of y_{ul} in the previous equation is free of multi-user interference. The k_{th} stream is of y_{ul} is used to detect s_k:

$$\tilde{y}_{ul,k} = \sqrt{\rho_u s_k} + \tilde{n}_k, \qquad (2.13)$$

where: n_k denotes the k_{th} element $\left(H^H H\right)^{-1} H^H n$. Thus, the received SINR of the k_{th} stream is given by:

$$SINR_{zf,k} = \frac{\rho_u}{\left[\left(H^H H\right)^{-1}\right]_{kk}} \qquad (2.14)$$

$$W = \begin{cases} H^*, \ for MRT \\ H^*\left(H^H H^*\right)^{-1}, \ for ZF \\ H^*\left(H^T H^* + \dfrac{K}{\rho_d} I_k\right)^{-1}, \ for MMSE \end{cases} \qquad (2.15)$$

2.2.9 Review of Similar Works

This sub-section presents a review of some relevant works carried out and published by other researchers. This gives an indication of the extent of the work in this area of research and the techniques or mechanisms used to resolve the same problem, with this knowledge, a better tool and method are identified to give better results.

A solution to pilot sequence decontamination was proposed by**Sorensen & de Carvalho, (2014)**using pilot sequence hopping and modified Kalman's filter. The approach did not require inter-cell coordination to achieve decorrelation of orthogonal pilot sequence. Pilot sequence hopping was carried out at each transmission slot there by providing randomization of the decontaminated pilots. The major contribution of the paper was the fact that inter-cell coordination was not required and passed pilot signals were fully

exploited. The modified Kalman's filter was used to perform channel estimation across multiple time slots so that channel tracking and channel correlation were achieved. The result showed that the mean squared error obtained was much lower than the one obtained from conventional estimation at low user mobility. However, the work was restricted to estimation of a single channel coefficient (Reference cell in relation to other neighboring cells), therefore the channel is denoted by a complex scalar

A potential technology using massive MIMO beam forming as a tool for energy enhancement and improvement of the performance of radio networks was evaluated by **Frenger *et al.*, (2014)**. In the analysis, factors such as: user bit rate, geometry, area power, inter site distance, area power, discontinuous transmission ratio and the relative power consumption at the point of transmission were evaluated. The results were compared with the conventional three-sectorized arrangement and showed that the massive MIMO beam forming can significantly reduce network area/coverage, particularly if the gains are considered during network planning. It was reported in the paper that with 5db additional link budget achieved by massive MIMO beam forming, 50% network area power reduction could be achieved for a network designed for 10mbps cell edge user data target. However, the assessment presented in the paper was mainly based on rough assumptions and models. Several other vital second order effects (noise, interference, antenna configuration, etc.) were not captured. This clearly shows that the results present the efficacy of technology prospect, not an absolute evaluation of what should be expected.

Farhang *et al.*, (2014)looked into the problem of pilot contamination in cosine modulated multi-tone (CMT) based M-MIMO networks with the view to address the issue. The scheme takes the advantage of the special property of CMT, known as blind equalization property. It

was evident that when the technique was extended from single user to a large-scale cellular M-MIMO system, channel estimation error due to (PC) removed without any coordination among the different base stations or transmission of more training information. Furthermore, it was proved that the proposed solution performed equally good as or even better compared to MF having perfect CSI and also the output SINR of the proposed algorithm converges towards that of the MMSE solution which has a perfect knowledge of CSI of the various users within its neighboring cells. However, the scheme is highly computationally complex due to the high order statistical parameters needed to estimate the channels which could introduce serious error in the channels estimation.

A pilot contamination mitigation scheme based on Smart Pilot Assignment (SPA) to enhance the performance of users affected severely by PC was investigated in **Zhu *et al.*, (2015).** It is done, particularly, by taking into consideration the characteristics of the channels large-scale fading. The base station measures the ICI of the individual training sequences produced from the users having the same training sequence in neighboring cells. Contrary to the traditional way of allocating training sequences to users haphazardly, the SPA scheme allocates a training sequence that has the least ICI to a user with the poorest channel quality sequentially to enhance its performance. The scheme proves theoretically that the pilot allocation generated by it, is the answer to the optimization problem P^i in a greedy way that can approach the novel optimization problem P as the number of antennas tends to infinity. However, the scheme did not break away from the conventional way of initializing all training sequences for the training that leads to the re-use of the same training sequences in the adjacent cells, thereby causing ICI.

Tai *et al.*, (2015) proposed normalization and correlation-based algorithm having low complexity for energy efficiency maximization. They looked at the issue of RF transmit chain configuration with the view to maximize the energy efficiency under total power constraint under massive MIMO systems. In their work, norm and correlation-based algorithm for the optimization of energy was designed. The approach or technique uses selection matrix in order to take into account the effect of the channel columns and the relationship between them while ensuring less computational complexity. A number of assumptions were made, channel state information was assumed to be perfectly known, transmitter and receiver were assumed to have the same number of RF chains, channel was assumed to experience only flat and slow fading. The proposed algorithm showed superiority over norm-based correlation and correlation-based algorithm in-terms of energy efficiency. The problem with the algorithm was that it had high computational complexity when compared with other algorithm by counting the numbers of floating point operations and therefore reduces the performance of the algorithm due the tradeoff between complexity and performance.

A load adaptive algorithm in terms of number of antennas based on a daily load profile (DLP) to maximize downlink energy efficiency in MIMO systems was proposed by **Hossain *et al.*, (2015).** A multi cell system, nineteen cells (19 cells) was considered were each base station is provided with large number of antennas to serve many single mobile users. The maximum energy efficiency(EE), was formulated using gave theory frame work and it was found out that nineteen percent (19%) energy efficiency (EE) was achieved, which is more than the one obtained from the baseline system where base stations are being run with fixed number of antennas. Significant improvement in EE was obtained at a cost of reduction of

average user data rate at a very low user load. However, a stiff reference scenario was used to achieved that by a complete shutdown of all the antennas when a user is not being served by a base station. Although this approach can significantly reduce interference and result in high data rate but it may be practically impossible to achieve since not all antennas can be simultaneously shut down for a particular base station.

A novel scheme of reducing the amount of energy consumed to feedback all the channel state information to the base station was proposed in **Benmimoune *et al.*, (2015)** The scheme was based on transmit antenna selection for massive MIMO systems. Two things were achieved: reduction in energy consumption needed to feedback the channel state information systems and the reduction in complexity in selecting transmit antennal configuration. A routing feedback constant that minimized the energy consumption was found by formulating the problem as a least cost Hamiltonian path problem. An integer linear programming and leuristic dynamic programming algorithms were used to find the optimal solution to the formulated problem with low computational complexity. The paper was not limited to only power consumed for data transmission but also included energy due to feedback acquisition, as this increase significantly as the number of antennas increases. However, a perfect channel state information was assumed which is practically impossible, also, the fairness among the users in relation to their amount of feedback energy was not considered which could lead to serious error.

The effect of channel estimation errors on the energy performance for a single cell downlink Massive Multiple-Input Multiple-Output (M-MIMO) system, was investigated and analyzed in **Tebe *et al.*, (2015).** Downlink transmit power model was derived using zero forcing (ZF) and maximum ratio transmit (MRT) pre-coding schemes, under imperfect channel state

information (CSI). It has been established that the total downlink power decreases in respect with the certain minimum reliability value which depends on the number of base stations, antennas and mobile users. However, the analysis carried out was limited to a cell. There was also no justification as to the definite number of mobile users or antennas that could efficiently improve the reliability parameter for energy efficiency and this leaves serious research gap.

An in-depth survey of pilot contamination in M-MIMO system was presented in **Elijah *et al.*, (2016).** The paper gave an extensive detailed analysis of the effect of pilot contamination on the performance of M-MIMO systems in accordance with the established theories. Different mitigation techniques (pilot-based approach and sub-space-based approach) have been proposed. Research windows such as deployment platform, training overhead, channel reciprocity and computational complexity associated with pilot contamination have also been brought to the surface. The paper however, presented a broader or general review of the concept of pilot contamination and its possible effect on the performance of M-MIMO system. There was no evidence what so ever an attempt to address any of the issues militating against the performance or rather deployment of the M-MIMO system as highlighted therein.

The problem of pilot contamination in M-MIMO systems, for cell-edge and-cell center user terminals (UTs) was investigated In **Zhu *et al.*, (2016).** A novel scheme based on Soft Pilot Re-use (SPR) and Multi Cell Block Diagonalization (MBD) was used to address this issue. It has been established that users at the cell edge suffer from severe PC than their center cell counterparts, in view of this development SPR is used in enhancing the quality of service (QoS) of cell edge users by re-using a cell-center pilot group for all center-cell users and a

cell-edge pilot group for all cell edge users in the adjacent cells which is determined by their large-scale fading coefficients. The MBD pre-coding is utilized for a multi-cell scenario, to mitigate ICI and enhanced the QoS for cell-edge users. However, the enhanced rates of the UL and DL throughputs of the proposed scheme was achieved at the expense of more pilot sequence requirement for channel state information estimation as a trade-off with resources for data transmission within the coherence interval in comparison to conventional methods and also the scheme is still based on full pilot sequence initialization (pilot sequence re-use factor of 1) and reuse of non-orthogonal pilot sequence in different cells in multi-cell scenario which is the major source of PC.

Liu *et al.*, (2017) carried out an investigative study of the tradeoff between spectral efficiency and energy efficiency for massive MIMO systems having linear precoding and transmit antenna selection. The analysis of both circuit power consumption and large-scale fading were taken into account, the spectral efficiency and energy efficiency were optimized in terms of the number of transmit antennas and transmit power by formulating their tradeoff as a continues integer variable using multi objective optimization problem. The properties of parator (exponential) front for the energy efficiency and spectral efficiency were analyzed using mathematical relationship of energy efficiency and spectral efficiency. Weighted sum particle optimization and normal boundary swarm optimization were used to solve the optimization problem with the normal boundary swarm particle optimization given better performance in terms of parator optimal energy efficiency and spectral efficiency tradeoff. The analysis was limited to EE and SE tradeoff over transmit power and number of antennas with no consideration of the number of users, which also plays an important role on the EE and SE tradeoff. Despite being able to graphically show the parator fronts, the

corresponding optimal solutions were still not determined and this could lead to more power consumption hence reducing energy efficiency.

From the reviewed literature, it is evident that pilot contamination (PC) mitigation in Massive Multiple Input Multiple Output (M-MIMO) is an ongoing research challenge. Several decontamination schemes were proposed ranging from pilot based to sub-space but still there is a lot of open issues such as training overhead, deployment scenario, computational complexity and cost. This leaves a lot of gap for further research. It was also observed from the reviewed works that although less aggressive pilot reuse was used to reduce pilot contamination (PC) to a large extent none of the reviewed scheme considers pilot sequence sharing for training within one cell. This proposal seeks to consider sharing pilot sequence within a cell to many users in order to further suppress inter cell interference and PC.

CHAPTER THREE

MATERIALS AND METHODS

3.1 INTRODUCTION

In this chapter, the materials, methods, and procedures employed for the successful completion of this research work are discussed. The development of a Pilot Allocation Protocol (PAP) based on sectional initialization and sharing of pilot sequence to mitigate the effect of pilot contamination in massive multiple input multiple output system was simulated using MATLAB 2016Rb simulation environment.

3.2 MATERIALS USED FOR THE RESEARCH WORK

The materials used for this research work include; MATLAB 2016Rb communication toolbox, a Hewlett Packard mini laptop, and literature materials.

3.3 METHODOLOGY

The following methodology was adopted in carrying out the research work:

i. Development of a Pilot Allocation Protocol (PAP) based on sectional pilot sequence initialization and sharing to mitigate the effect of Pilot Contamination.The following step was followed.

a. A Pilot Allocation Protocol (PAP) based on sectional pilot sequence initialization and pilot sequence sharing was developed using a modified Rayleigh fading channel taking into consideration the PAP.

ii. Enhancement of both the average Uplink (UL) and Downlink (DL) cell throughputs for cell edge users.

a. PAP was implemented based on sectional initialization and pilot sequence sharing, which allocates pilot sequence to many users within a cell and their training was conducted using different codes (Hadamard matrix).
b. Users were grouped into cell center and cell edge based on their large-scale fading coefficient.
c. A signal detection scheme based on matched filter and zero forcing, for equalizing the signals was implemented.
d. The UL Signal to Interference plus Noise Ratio (SINR) of cell edge users was then calculated and the average UL cell throughput determined.
e. Repeat step (d) for the average DL cell throughput.

ii. Validation of the results was done by comparing the results obtained from the Pilot Allocation Protocol (PAP) technique and those of Zhu et al., (2016) in terms of average uplink and downlink cell throughputs and bit error rate as performance metrics.

3.4 DEVELOPMENT OF PILOT ALLOCATION PROTOCOL

The processes involved in the development of the pilot allocation protocol (PAP) model based on sectional and sharing of pilot sequence technique in TDD mode M-MIMO

system are discussed in the following subsections hereunder.Figure. 3.1 shows the flowchart of the developed PAP technique, in this scheme the orthogonal pilot sequences are divided into 3 groups and allocated to three different cells, that is to say that within each cell and at least the next neighboring cells the pilot sequence are orthogonal to each other, so when orthogonal pilot sequences within a particular group are exhausted by users, then sharing starts between users which then creates an intra cell interference between users sharing the same pilot sequence which are then separated (made orthogonal to each other) by employing a property of hadamard matrix as discussed in subsection 2.2.6, which assigns distinct codes to the interfering users sharing the same pilot sequence in each coherence interval as against discarding or queuing the users for the next available pilot sequence in the conventional; and; SPR and MBD techniques. The concept was able to mitigates the effect of pilot contamination to a large extent and also increase the number of users that can use the available resources without increasing the number of the orthogonal pilot sequences

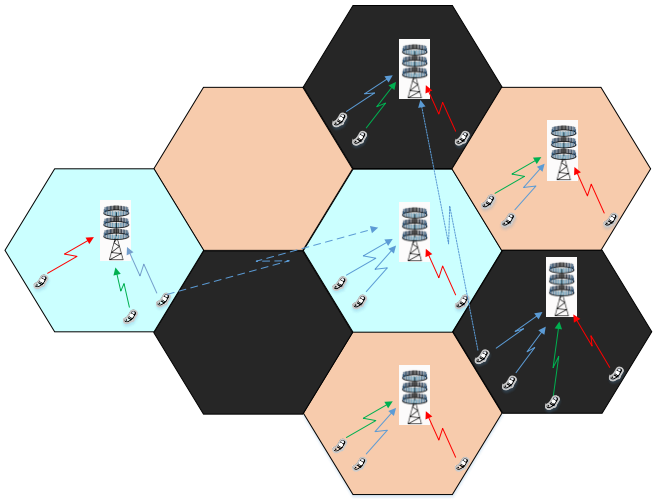


Figure. 3.1: Multi Cell Architecture Based on the Developed PAP Technique.

Figure 3.1 shows the pilot sequence allocation and sharing pattern of the developed PAP scheme based on sectional initialization and pilot sequence sharing between users drawn with Visio software, each color in Figure 3.1 represents a particular group (a section) of the total orthogonal pilot sequences while cells having the same colors uses the same type of orthogonal pilot sequences with a minimum reuse distance of one kilometer since the cell radius considered is 500m. furthermore the green, blue and red colored signals emanating from the user equipment's to the base stations represents the individual pilot sequences in each cell, users transmitting same color of signals are sharing the same pilot sequence but then are separated using distinct signs of hadamard matrix while the broken signals in blue colors represents interfering signals from far cells and they formed part of the additive white gaussian noise.

Figure 3.2 depicts the flow chart of the developed PAP technique

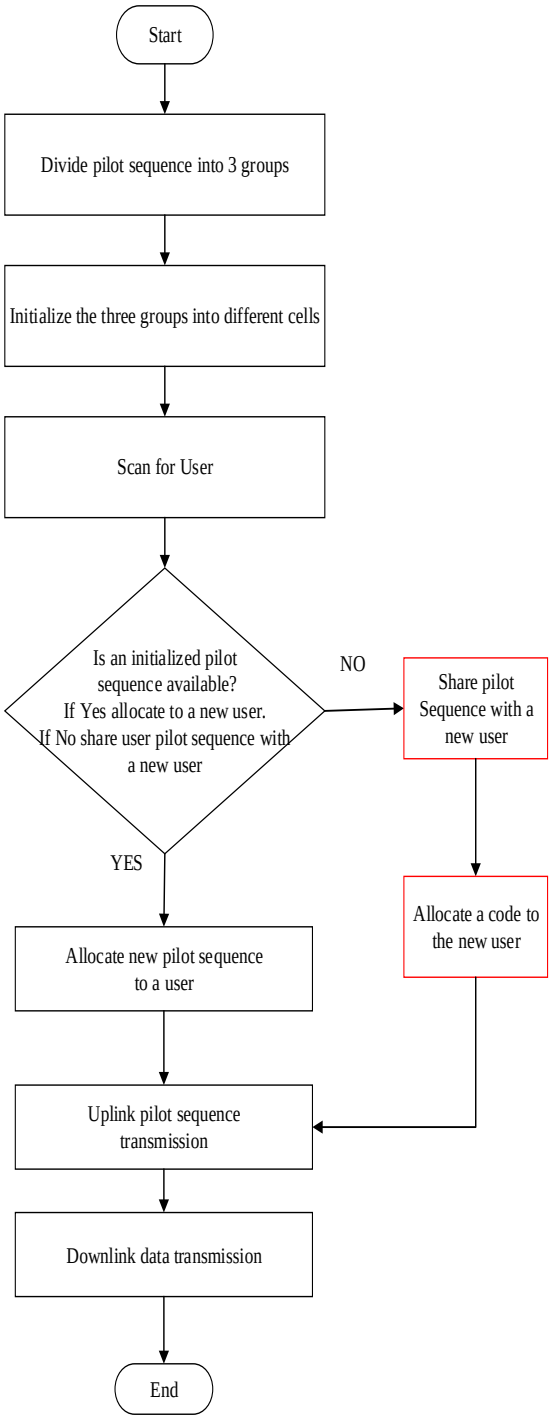


Figure 3.2: Flow chart Implementation of the Developed PAP Technique.

3.4.1 Channel Model

A multi-cell M-MIMO is considered, which is composed of *L* hexagonal cells, each having a central BS associated with *M* antennas to serve *K* (*K*<<*M*) single antennas. The channel is a modified Rayleigh fading MIMO channel. The terminals are located randomly within the cell area of the BSs, and the elements of the system matrix are assumed to be independent and identically distributed (iid) complex variables with zero mean and unit variance.

3.4.2 Base Station Parameters.

For base station (BS) the following parameters were assumed for initialization of pilot sequence: Number of base station antennas = 32 to 256, coherent interval = 64, number of training symbols = 16, downlink symbols = 32 and pre-coding option, 1 = zero forcing and 2 = matched filtering. In order to generate the Channel State Information (CSI) of users, Rayleigh fading channel is considered as a normally distributed random number with the assumption that the CSI should be normally distributed, the CSI of the individual users were first generated.

```
%Actual CSI of channel from each UE to each antenna
AcCSI=randn(UsEq.noUE, BStn.NoAn);
```

MATLAB code for the generation of the channel state information.

Also, in order to initialize the group of coherent intervals that will be processed together. Group of coherent intervals were initialized together.

```
%Previous Uplink Pilot Transmission
PrULp= AcCSI'*(UsEq.TrSy(:,(1+BStn.NoTS):(UsEq.noUE)))/sqrt(UsEq.noUE)....
            + power(10,-Snr/20)*randn(BStn.NoAn, BStn.NoTS);
```

MATLAB code for initializing group of coherent intervals.

```
%Passing through channel
```

Pre-coder which was determined from the estimated CSI either using matched filtering or zero forcing was used to multiply the data send to user equipment and the result was passed through the channel by multiplying with CSI to get the received data at the user equipment. MATLAB code is used for beam forming data to the user equipment. First line is for beamforming, first line in the loop is for adding interference and the second line is for varying CSI.

```
%Beamforming
DLdata = PreCoders*Block(:,1:BStn.bsDL);
DLRxdata = zeros(UsEq.noUE, BStn.bsDL);
for ii = 1:BStn.bsDL
DLRxdata(:,ii) = AcCSI*DLdata(:,ii);
AcCSI = AcCSI  + Var1*Var2(ii+BStn.NoTS)
```

MATLAB code for initializing group of coherent intervals.

3.4.3 User Equipment Parameters.

For user equipment (UE) the following parameters were assumed for initialization of pilot sequence: Number of user equipment = 2*Bstn.NoTs, number of uplink symbols = BStn.CoIn-Bstn.NoTS-Bstn.BsDL, transmitted power by UEs = UsEq.UPwr = once (UsEq.noUE, 1), training symbols from user equipment = UsEq.TrSy = hadamard (UsEq.noUE). Using the assumed parameters, the users sends their pilot sequences to the BS and then passed through the channel with noise added to it was then received at the BS. First line in the loop is for adding interferences, second line in loop varying the CSI and last line adding AWGN.

```
%Uplink Pilot Transmission from UE to BS for Training at BS
ULPilot = zeros(BStn.NoAn, BStn.NoTS);
for ii = 1:BStn.NoTS
ULPilot(:,ii) = AcCSI'*UsEq.TrSy(:,ii+Par*BStn.NoTS);
AcCSI = AcCSI + Var1*Var2(ii);
```

MATLAB code for uplink pilot transmission.

The data that the UE wants to send to the BS was also transmitted, the block of data was passed through the channel by multiplying it with the CSI which varies with time. A MATLAB code in Figure 3.5 is used for transmitting of uplink data from UE to BS, the first line in the loop is for adding interferences, second line in loop varying the CSI and last line adding AWGN.

```
Uplink transmission from UE to BS and reception at BS
ULdata = zeros(BStn.NoAn,UsEq.ueUL);
for ii = 1:UsEq.ueUL
        ULdata(:,ii) = AcCSI'*Block(:,ii+BStn.bsDL);
AcCSI    = AcCSI  + Var1*Var2(ii+BStn.NoTS+BStn.bsDL);
```

MATLAB code for transmitting uplink data from UE to BS.

3.5 Average Uplink and Downlink Cell Throughputs based on the Developed PAP Technique.

The performance of pilot decontamination scheme in terms of enhancing average Uplink (UL) and Downlink (DL) cell throughputs at the User Equipment (UE) is largely affected by the magnitude of Pilot Contamination (PC) inflicted on users sharing the same pilot sequence during UL pilot sequence transmission from UE to the Base Station (BS) for Channel State Information (CSI) estimation. Large magnitude of PC forms a major

performance bottle neck of M-MIMO system as it reduces its capacity to a large extent.In this research work, Pilot Allocation Protocol (PAP) technique based on sectional and pilot sequence sharing was used where users are sharing one pilot sequence as against one user using one pilot sequence in the Soft Pilot Reuse and Multi-Cell Block Diagonalization (SPR and MBD) technique. The effect of PC was mitigated and also the average UP and DL cell throughputs of users were significantly improved. Figure 3.6 showed the flow chart of the developed PAP technique based on sectional pilot sequence initialization and sharing. For the enhancement of the PAP technique, all the processes listed in the methodology i (a) and ii (a-b) were repeated for the two equalization schemes except for ii (c-e) which is different for Zero Forcing (ZF) and Matched Filter (MF) signal detection/precoding at the UL and DL, also the SINR of the individual cell edge users were calculated based on the signal detection/precoding scheme likewise the average UL and DL cell throughputs determination. The codes for signal detection based on ZF and MF is depicted in Figure 3.8 with option of channel type of 1 for ZF and channel type of 2 for MF. Using time division duplex once you are able to estimate your CSI for the uplink direction it is the same thing that will be used for downlink direction the only difference is how we do the precoding. The PAP protocol is just used for training once the training is finished and all the users are separated the data can now be beamformed to the different users no matter the number.It is worthy to note that the choice of the parameters presented in Table 3.1 on page 48 were selected based on consultation of literature and since the work of Zhu et., al (2016) was used to validate this research, parameters presented were adopted from their work, and varied based on the simulation and performance of the enhanced technique. Hence, the value of these parameters can be varied depending on the simulation.

Table 3.1: Model Parameters used

Parameters	**Units**
Number of cells L_{Total}	19
Number of antenna in BS M	$32 \leq M \leq 256$
Number of users in the i_{th} cell K_i	32
Number of pilot resource K_{cs}	10
Cell radius R	500m
Average transmit power at users ρ_p ρ_u	10dbm
Average transmit power at BS ρ_d	12dbm
Pathloss exponent α	3
Log normal shadowing fading σ_{show}	8db
Carrier frequency	2GHz
System bandwidth	10MHz
Minimum distance between user and BS	30m

3.5.1 Grouping of Users into Cell-Center and Cell-Edge

In order to classify users into cell-center and cell-edgetheir signal power strength was considered, the user with a high amplitude is considered cell-center and the user with low amplitude is considered cell-edge user

3.5.2 Signal Detection

From the training a precoder is determined and the received uplink data is multiplied with the precoder to equalize the data and remove interferences out from the data. A precoding option of 1, represents data equalization with zero forcing while a precoding option of 2,

represents data equalization with matched filtering. MATLAB code was used for the equalization of the uplink data.

```
%Equalisation
ULRxdata = PreCoder'*ULdata;
if(Chan.TyVa ~= 1)
AcCSI = AcCSI/sqrt(1+Chan.vCSI.^2);
```

MATLAB code for equalization of uplink data.

In order to get the estimate of the channel estimation we take the received pilot sequences in the form of matrix and multiply by the inverse of the training sequences which represents its own inverse in order to remove the effect of the training symbols and get the CSI by removing interferences.

```
% CSI estimation at BS
EsCSI= UsEq.TrSy*cPilot'/sqrt(UsEq.noUE);
```

MATLAB Code for finding estimated CSI

3.5.3 UL Signal to Interference plus Noise Ratio (SINR) Calculation and Average UL ThroughputDetermination

In order to calculate the average UL throughput of cell edge users the SINR of the cell edge users was first determined and then the average UL cell throughput was calculated. Equations 2.15 and 2.11 were used for the determination of SINR and throughputs of cell edge users

3.5.4 DL Signal to Interference plus Noise Ratio Calculation and Average DL Cell Throughput Determination.

In order to calculate the DL throughput of cell edge users the SINR of the cell edge users was first determined and then the throughput was calculated using equations 2.22 and 2.12 were used for the determination of SINR and throughputs of cell edge users.

3.6 Performance Metrics

In order to establish the fact that this research work has really contributed to the existing knowledge in the area of mitigating the effect of PC inflicted on users using the same pilot sequence in the adjacent cells, a performance metric need to be used so as to compare between SPR and MBD precoding technique and PAP technique to see which one outperform the other. The performance of the developed PAP decontamination scheme was evaluated using average uplink and downlink cell throughputs and Bit Error Rate (BER) as performance metrics.

3.6.1 Average Uplink (UL) and Downlink (DL) Cell Throughputs

Average Uplink and downlink Cell throughputs are used to measure the amount of data that is successfully conveyed from source to destination per unit time. Equations 2.15 and 2.22 were used for the average UL and DL cell throughputs calculation.

3.6.2 Bit Error Rate

Bit error rate in telecommunication transmission, is the measure of the percentage of bits that have errors relative to the total number of bits received in a transmission, usually expressed as ten to a negative power. For example, a transmission might have a BER of 10 to the minus 6, meaning that, out of 1,000,000 bits transmitted, one bit was in error.

```
%BITERR Compute number of bit errors and bit error rate.

QauntDL = DLRxdata;
QauntDL(QauntDL<=0) = 0;
QauntDL(QauntDL> 0) = 1;
```

```
QauntUL = ULRxdata;

QauntUL(QauntUL<=0) = 0;

QauntUL(QauntUL> 0) = 1;

QuantData = (1+Block)/2;

BER = [biterr(QuantData(:,1:BStn.bsDL),    QauntDL)/numel(QauntDL);...

biterr(QuantData(:,BStn.bsDL+1:end),QauntUL)/numel(QauntUL)];
```

MATLAB code for bit error determination.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 INTRODUCTION

In this chapter, the results obtained are presented and discussed based on sectional and sharing of pilot sequence pilot allocation protocol technique (PAP). Results obtained are also compared with the work of Zhu et al. (2016), for validation. Finally, the performance of PAP based on sectional and pilot sequence sharing was evaluated using (1) average Uplink (UL) and Downlink (DL) cell throughputs, and (2) Bit Error Rate (BER) as a performance metrics.

4.2 ENHANCED AVERAGE UL AND DL CELL THROUGHPUTS BASED ON THE DEVELOPED PILOT ALLOCATION PROTOCOL SCHEME

The simulation results obtained based on the model highlighted in Table 3.1 for the PAP technique are shown here under with the performance of the developed PAP technique highlighted in red and blue for UL and DL throughputs, for both the two precoding options, with option 1 = ZF and option 2 = MF. Also shown are the established results from the work of **Zhu *et al.*, (2016).** SPR scheme with ZF and MF is highlighted in green, conventional with ZF and MF is highlighted in violet for both UL and DL throughputs while SPR-MBD with ZF for DL is highlighted in black, also shown are the BER performance of the developed PAP technique highlighted in red and blue. The PAP channel model was developed based on Rayleigh fading channel, User Equipment (UE) velocity of 250km/h was considered and a delay spread in seconds of 1.5km (for 1.0km diameter). Maximum number of circles was set at 100 and 1/5 of the coherence

interval was used for training while the bandwidth for data transmission was shared equally for both UL and DL.

4.3 RESULTS

Figure 4.1 shows the Uplink (UL) Throughput against the Number of Base Station (BS) Antennas for the developed PAP, SPR and conventional schemes when Zero Forcing (ZF) detector was used, with number of BS antennas ranging from 60 to 256 antennas and 50% of the bandwidth for data transmission allocated to UL data transmission.

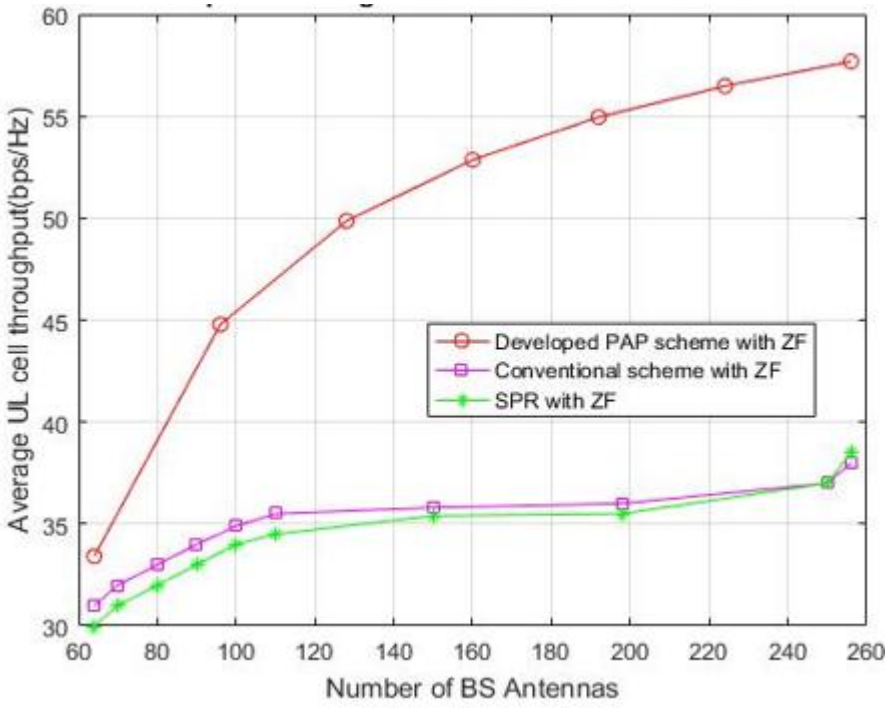


Figure 4.1: Uplink Rate against Number of BS Antennas for the three Schemes

From simulation results in Figure 4.1. When the number of BS antennas is at 64, the conventional and SPR schemes offer an average UL throughput of 31 b/s/Hz and 30 b/s/Hz while the developed PAP offers an average UL cell throughput of 33 b/s/Hz improvement, which is 2 b/s/Hz and 3 b/s/Hz more than the conventional and SPR schemes when ZF detector was used. At 250 BS antennas both the conventional and SPR schemes offers an

average cell throughput of 37 b/s/Hz while the developed PAP offers an average UL cell throughput of 57.5 b/s/Hz, which is 20.5 b/s/Hz more than the conventional and SPR schemes. This shows that the performance improvement of the interfering users (cell edge) users of the developed PAP schemes is better than that of the conventional and SPR schemes as the number of BS antennas increases. It can be seen that when the number of BS antennas was set at 256 the conventional and SPR schemes offers an average cell throughput of 37.5 b/s/Hz and 37.8 b/s/Hz while the developed PAP offers an average UL cell throughput of 42.5 b/s/Hz, which is 5 b/s/Hz and 4.7 b/s/Hz more than the conventional and SPR schemes. The PAP scheme out performs SPR scheme which has a better performance than the conventional scheme and hence further proved that the performance improvement of the interfering users (cell edge users) of the PAP is better than that of the SPR scheme as the number of BS antennas increases.

Figure 4.2: shows the Downlink (DL) Throughput against the Number of Base Station (BS) antennas for the developed PAP, SPR-MBD, SPR and conventional scheme all with ZF precoder, with number of BS antennas ranging from 60 to 256 antennas and 50% of the bandwidth for data transmission allocated to DL data transmission.

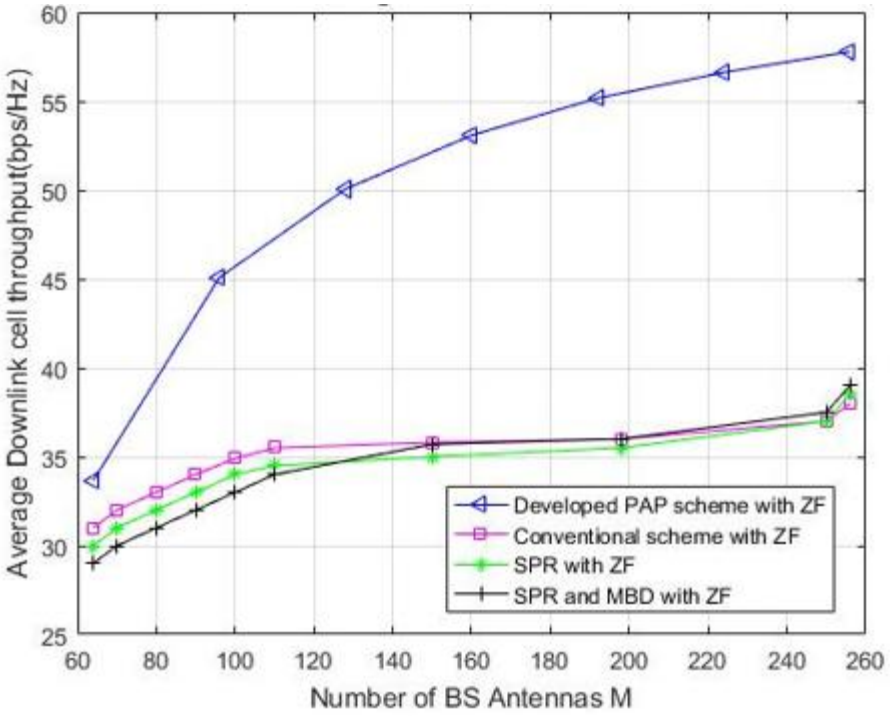


Figure 4.2: Downlink Rate against Number of BS Antennas for the four Schemes

The same analysis of UL holds for the DL, for the conventional; SPR and the developed PAP schemes when a ZF precoder was used except for the SPR-MBD precoding scheme which offers an average DL cell throughput of 37.2 b/s/Hz and 39 b/s/Hz when the BS antennas was set at 250 and 256 respectively.

Figure 4.3: shows the Average Uplink (UL) Cell Throughput against the Number of Base Station (BS) antennas for the developed PAP, SPR and conventional scheme when a Matched Filter (MF) detector was used, with number of BS antennas ranging from 60 to 256 antennas and 50% of the bandwidth for data transmission allocated to DL data transmission.

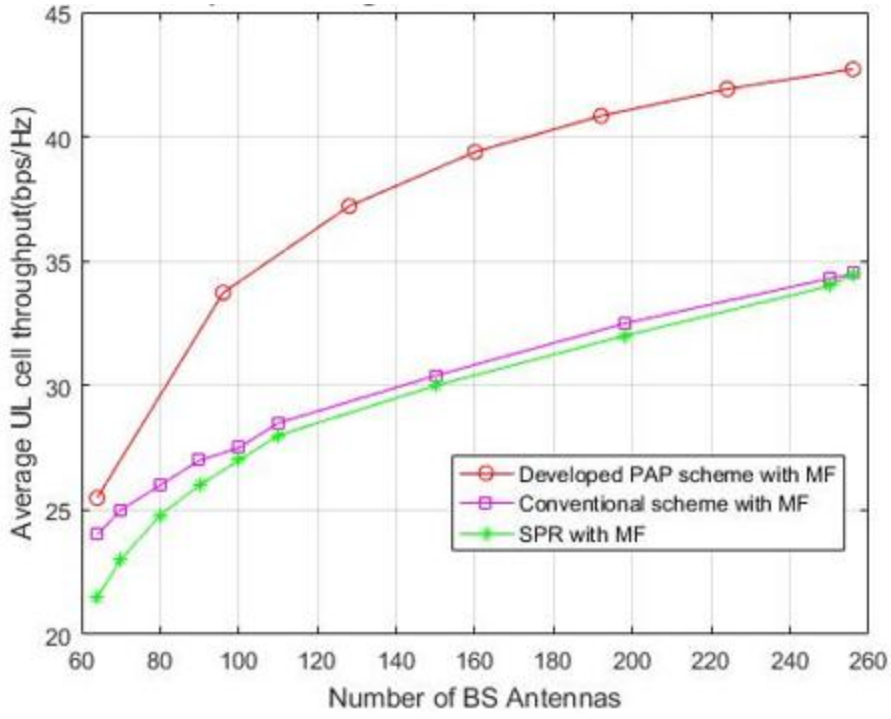


Figure 4.3: Uplink Rate against Number of BS Antennas for the three Schemes

It can be seen from Figure 4.3, thatwhen the number of BS antennas is at 64, the conventional and SPR schemes offer an average UL throughput of 24 b/s/Hz and 21.5 b/s/Hz while the developed PAP offers an average UL cell throughput of 25.5 b/s/Hz improvement, which is 1.5 b/s/Hz and 4 b/s/Hz more than the conventional and SPR schemes when a Matched Filter (MF) detector was used. At 250 BS antennas both the conventional and SPR schemes offer an average cell throughput of 34.5 b/s/Hz while the developed PAP offers an average UL cell throughput of 42.5 b/s/Hz, which is 8 b/s/Hz more

than the conventional and SPR schemes. At 256 BS antennas the conventional and SPR schemes offers an average cell throughput of 34.5 b/s/Hz and 34.9 b/s/Hz while the developed PAP offers an average UL cell throughput of 43 b/s/Hz This shows that the performance improvement of the interfering users (cell edge) of the developed PAP schemes is better than that of the conventional and SPR schemes as the number of BS antennas increases. It can be seen that when the number of BS antennas was set at 256 the PAP scheme out performs SPR scheme which has a better performance than the conventional scheme and hence further proved that the performance improvement of the interfering users (cell users) of the PAP is better than of the SPR scheme as the number of BS antennas increases with MF detector. Figure 4.4: shows the Downlink (DL) Throughput against the Number of Base Station (BS) antennas for the developed PAP, SPR-MBD, SPR and conventional scheme all with MF precoder, with number of BS antennas ranging from 60 to 256 antennas and 50% of the bandwidth for data transmission allocated to DL data transmission.

Figure 4.4: shows theDownlink Rate against Number of BS Antennas for the four Schemes

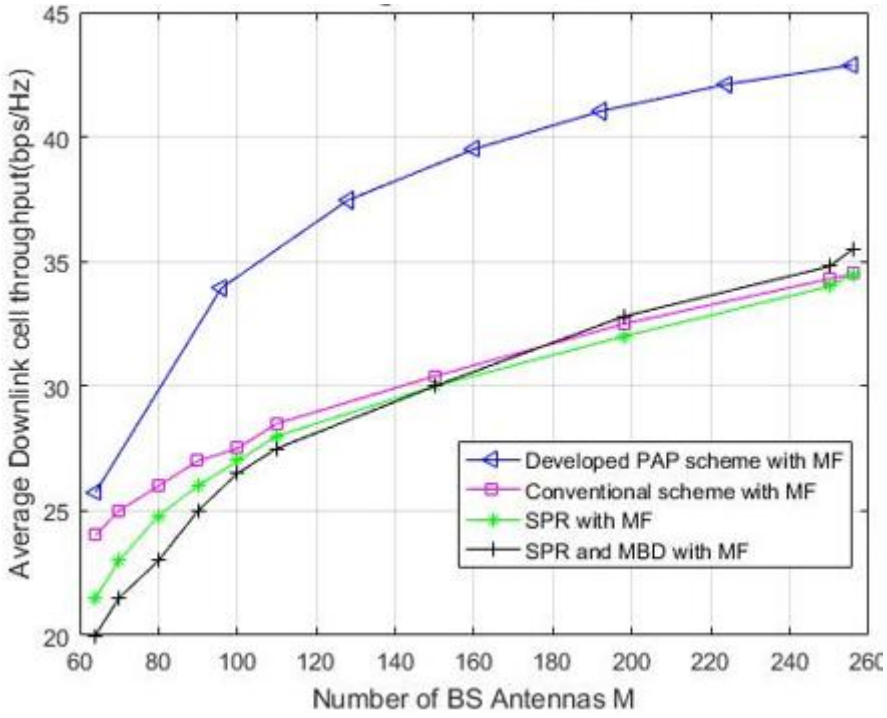


Figure 4.4: Downlink Rate against Number of BS Antennas for the four Schemes

Figure 4.4 shows the downlink rate against number of BS antennas for the four schemes the same analysis of UL holds for the DL, for the conventional, SPR and the developed PAP schemes when a MF precoder was used except for the SPR-MBD precoding scheme which offers an average DL cell throughput of 34.5 b/s/Hz and 35.5 b/s/Hz. When the number of BS antennas was set at 250 and 256 respectively.

Figure 4.5 shows the UL and DL Bit Error Rate performance of the developed PAP model when a ZF was used.

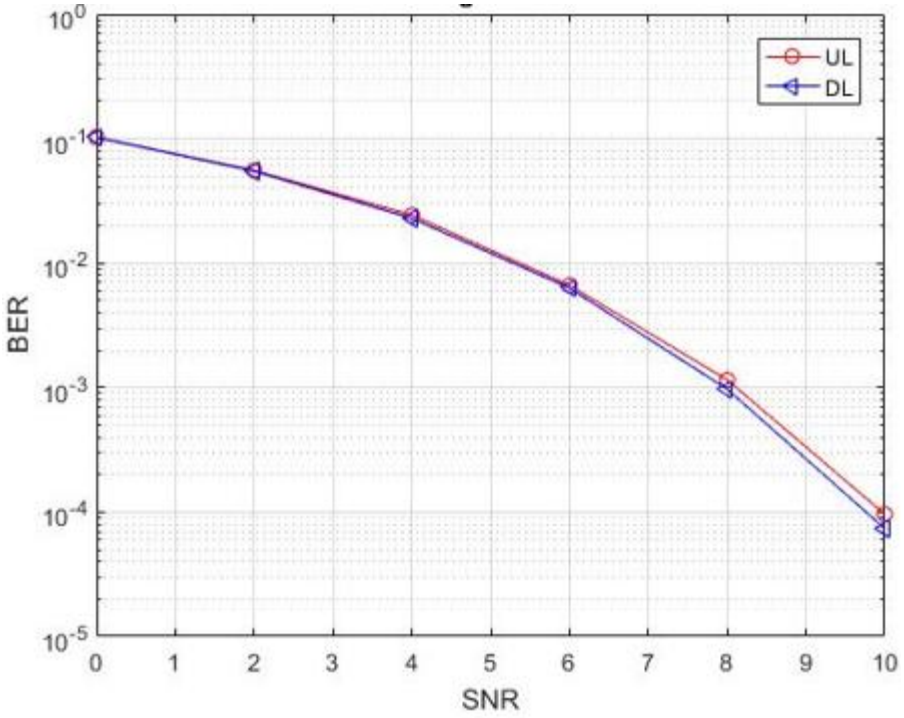


Figure 4.5: Plot of BER Performance for the PAP Scheme with ZF

It can be observed from Figure 4.5 that, as the SNR increases the BER decreases and the developed PAP when a ZF was used both UL and DL met the BER requirement for audio signal that is10^{-3} of BER in digital communications at SNR of 8 dB, which means in every 1000 bit you have 1 error.

Figure 4.6 shows the UL and DL Bit Error Rate performance of the developed PAP model using ZF.

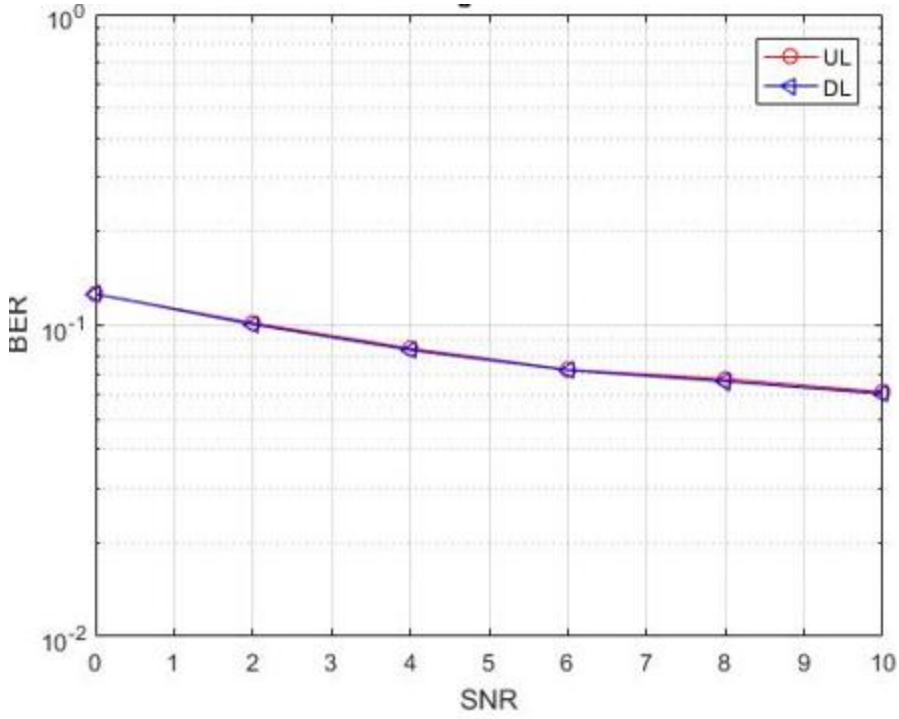


Figure 4.6: Plot of BER Performance for the PAP Scheme with MF

It can be observed from Figure 4.6 that, the developed PAP when a MF was used both UL and DL attained a BER of $10^{-1.25}$ = $1/10^{1.25}$=1/17.8 = 1/18, which means in every 18 bits of transmission you have 1 error, at SNR of 8 dB

4.4 SUMMARY OF RESULTS

From the simulation results obtained from the developed PAP scheme using the ZF/MF detection/precoding schemes evaluated at 64,250 and 256 BS antennas, the average cell throughput improvement of the developed PAP scheme outperforms that of the conventional, SPR and MBD schemes. The improvement occurred as a result of the pilot sequence allocation protocol adopted by the PAP technique and the way the interfering users (cell edge users) were efficiently separated after sharing of pilot sequence occurs between

users. The PAP scheme minimum distance pilot sequence reuse is doubled that of the SPR and MBD, which then creates intracell interference and suppressed the effect of Intercell Interference (ICI) to a large extent which is the major cause of Pilot Contamination (PC) during Uplink pilot transmission. Furthermore, it is important to have observed that, the average cell throughput improvement performance of the PAP technique is better than that of the conventional; PR and MBD schemes when both ZF and MF detection/precoding schemes were used throughout the range of BS antennas considered (64,250 and 256), this is due to the fact that in the PAP technique pilot sequence of users within and across the neighboring cells were made to be orthogonal to each other and when sharing occurs (when pilot sequence of users were made to be non-orthogonal) to each other, codes were used to separate the interfering users throughout the length of the coherence interval.

4.5 VALIDATION

The simulation results of the developed PAP technique, and that of conventional and SPR techniques obtained from Zhu *et., al* (2016) at 64, 250 and 256 range of BS antennas consideredwhen both ZF and MF were usedas shown in Table 4.1.

Table 4.1 Results obtained from the developed PAP, conventional and SPR-MBD schemes

SIMULATION PARAMETERS		**DETECTION/PRECODING SCHEMES**			
		WITH ZF (b/s/Hz)		**WITH MF(b/s/Hz)**	
Scheme	NBSA	UL	DL	UL	DL
CS	64	31	31	24	24
	250	37	37	34.4	34.4
	256	37.5	37.5	34.9	34.9
SPR-MBD	64	30	30	21.5	21.5
	250	37	37.2	34.5	34.5
	256	37.8	39	34.9	35.5
PAP	64	33	33	25.5	25.5
	250	57.5	57.5	42.5	42.5
	256	58	58	43	43

Comparing the results from Table 4.1, the developed PAP scheme had an average cell throughput improvement over conventional; and; SPR and MBD schemes for both uplink and downlink of 2 b/s/Hz, 3b/s/Hz at 64 BS antennas, 20.5 b/s/Hz for uplink, 20.3 b/s/Hz for downlink at 250 BS antennas, and 20.2 for uplink, 19 b/s/Hz at 256 BS antennas for

downlink with ZF detector/precoder while with MF detector/precoder the developed PAP technique had an average uplink and downlink cell throughput improvement of 1.5 b/s/Hz for both UL and DL at 64 BS antennas, 8.1 b/s/Hz for both UL and DL at 250 BS antennas, and 8.1 b/s/Hz BS antennas for both UL and DL. Therefore, this shows that, the developed PAP technique has a better average cell throughput improvement performance when compared with conventional and SPR-MBD schemes. This upholds the view that the developed PAP technique as proposed is an effective pilot decontamination scheme and will help in reaping the full benefits of Massive Multiple Input Multiple Output (M-MIMO) technology.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATION

5.1 INTRODUCTION

This chapter presents a conclusion of the work done, significant contributions achieved in this research. Recommendations for furtherresearch work are alsomade.

5.2 CONCLUSIONS

Pilot Contamination (PC) is considered as the major drawback of Time Division Duplexing (TDD) Massive Multiple-Input Multiple-Output (M-MIMO) systems because it limits their expected capacity. Several mitigation techniques such as Eigenvalue Decomposition, Cooperative Bayesian Channel Estimation, Blind Equalization Technique, Time Staggering Pilot, Smart Pilot Assignment, etc. have been proposed in literature to address the issue of PC. This research work focused on Pilot-based estimation approach, in the pilot-based approach, channels of users are estimated using orthogonal pilot sequences within the cell and non-orthogonal pilot (the same pilot) sequences across the cells. However, this technique is largely affected by Intercell Interference (ICI) which is the major cause of Pilot Contamination during UL pilot sequence transmission, therefore, we developed a Pilot Allocation Protocol (PAP) decontamination scheme for TDD mode M-MIMO system based on sectional pilot sequence initialization and sharing which allocates more than one user to share the same orthogonal pilot sequence within a cell which then creates Intra Cell Interference, suppresses Inter Cell Interference (ICI) and mitigate the effect of PC among the interfering User Terminals (UTs). The developed PAP scheme provides an average cell throughput improvement over conventional and SPR-MBD schemes of 2 b/s/Hz,

3b/s/Hz at 64 BS antennas, 20.5 b/s/Hz for uplink, 20.3 b/s/Hz for downlink at 250 BS antennas, and 20.2 b/s/Hz for uplink, 19 b/s/Hz for downlink at 256 BS antennas with ZF detector/precoder at 64, 250 and 256 BS while with MF precoder/detector the developed PAP technique had an average uplink and downlink cell throughputs improvement of 1.5 b/s/Hz for both UL and DL at 64 BS antennas, 8.1 b/s/Hz for both UL and DL at 250 BS antennas, and 8.1 b/s/Hz for both UL and DL at 256 BS antennas over conventional and SPR techniques, thereby improving Bit Error Rate (BER) performance degradation and mitigate the effect of PC and hence improve the performance of M-MIMO technology. The performance of the developed PAP technique was evaluated using average UL and DL cell throughputs, and BER as performance metrics and results showed that the developed technique was efficient with substantial improvement of average UL and DL cell throughputs.

5.3 SIGNIFICANT CONTRIBUTIONS

Although several research works have been carried out on mitigating the effect of PC in M-MIMO system, the contributions in this work which are different from other researchers are:

i. A Pilot Allocation Protocol (PAP)based on sectional pilot sequence initialization and pilot sequence sharing was developed

ii. The developedPAPwas able to increase the number of users that can use the available resources by 22 more users as against 10 users in SPR and MBD scheme without increasing the length of the pilot sequence by sharing orthogonal pilot sequence to users within the same cell and the same cell was used to separate them without corporation among neighboring cells.

iii. The developed PAP provides an average UL and DL cell throughputs improvement over conventional; and; SPR and MBD schemes of 2 b/s/Hz

and 3b/s/Hz at 64 BS station antennas, 20.5 b/s/Hz for uplink and 20.3 b/s/Hz for downlink at 250 BS antennas, and 20.2 for uplink and 19 b/s/Hz for downlink at 256 BS antennas with ZF detector/detector while with MF detector/detector the developed PAP technique had an average uplink and downlink cell throughputs improvement of 1.5 b/s/Hz for both UL and DL at 64 BS antennas, 8.1 b/s/Hz for both UL and DL at 250 BS antennas, and 8.1 b/s/Hz for both UL and DL at 256 BS antennas, thereby improving Bit Error Rate (BER) performance degradation and mitigate the effect of PC and hence improve the performance of M-MIMO technology.

5.4 RECOMENDATIONS

Though the aim of the research which is to develop a pilot allocation protocol decontamination scheme to mitigate the effect of pilot contamination (PC) in order to enhance the performance of cell edge users has been achieved, the following areas for further research are recommended for consideration:

i. More number of users can be considered for sharing the available resources, in order to increase the data rate achievement of the developed PAP technique.

ii. Other linear detection/precoding schemes such as Minimum Mean Square Error (MMSE) and Iterative Least Square (ILS) can also be considered for equalizing the data in place of ZF and MF in a quest to have a better data rate improvement.

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APPENDICES

APPENDIX A1

COMPLETE MATLAB CODE OF PILOT ALLOCATION PROTOCOL TECHNIQUE.

```
Function PAP Technique

% PILOT ALLOCATION PROTOCOL DECONTAMINATION SCHEME FOR TDD
MODE M-MIMO SYSTEM.

%WAZIRISaidu Muhammad P15EGCM8046.

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POST-GRADUATE DEPARTMENT OFCOMMUNICATIONENGINEERING,

AHMADU BELLOUNIVERSITY, ZARIA

% NIGERIA.

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% Channel State Estimation in OFDM nMIMO channels
% first started 24/11/2017. Last updated 10/02/2018
clc; clear; close all;

%Channel Model Development.
Initialise2

NoCy = 100; %Number of cycles;
NoCI = 16;  %Number of Connected Intervals
Samp = 8;
BErr = zeros(2, Samp);
RATE = zeros(2, Samp);

for kk = 2:Samp
   Snr = Chan.SNR;
BStn.NoAn=kk*32;
BEr = [0; 0]; Rate = [0; 0];
forjj = 1:NoCy
```

```
      Par = 0;
AcCSI=randn(UsEq.noUE, BStn.NoAn);      %Actual CSI of channel from each UE to each
antenna
PrULp=
AcCSI'*(UsEq.TrSy(:,(1+BStn.NoTS):(UsEq.noUE)))/sqrt(UsEq.noUE)....%Previous
Uplink Pilot Transmission
               + power(10,-Snr/20)*randn(BStn.NoAn, BStn.NoTS);
for ii = 1:NoCI
         Data1= randi([0 1],[UsEq.noUEBStn.CoIn-BStn.NoTS]);   %Downlink from BS and
Uplink from UEs

%Rayleigh based mMIMO channel
         [AcCSI,PrULp,Par, RxUL, RxDL]=mMIMOchan(2*Data1-
1,PrULp,AcCSI,Chan,BStn,UsEq,Snr,Par);
         [ErrUL, ErrDL, RtUL, RtDL] = ErRate(2*Data1-1, RxDL, RxUL,Chan,BStn,UsEq);
BEr = BEr + [ErrUL; ErrDL];
         Rate = Rate + [RtUL; RtDL];
end
end
BErr(:,kk) = BEr/(NoCy*NoCI);
   RATE(:,kk) = Rate/(NoCy*NoCI);
end
clear
PrULpErrULErrDLBErRtULRtDLRateRxDLRxULBlockData1iijjkkSnrNoCyNoCIAcCSIP
ar;

semilogy(32*(2:Samp), BErr(1,2:end), 'r-o'); hold on
semilogy(32*(2:Samp), BErr(2,2:end), 'b-<'); grid on
xlabel('Number of BS Antennas'); ylabel('BER'); title('BER against Number of BS
Antennas');
legend('UpLink','DownLink');% axis([-5 5 1e-6 1]);

figure
plot(32*(2:Samp), RATE(1,2:end), 'r-o'); grid on
xlabel('Number of BS Antennas'); ylabel('Average UL cell throughput(bps/Hz)');
title('Uplink Rate against Number of BS Antennas');
legend('Uplink');% axis([-5 5 1e-6 1]);

hold on;
NoAnt = [60,70,80,90, 100, 110, 150, 198  250, 256];
RateU = [24,25,26,27, 27.5,28.5 30.4,32.5,34.3, 34.5];
plot(NoAnt,RateU,'m-s');
hold on

NoAnt = [60,  70,80, 90, 100, 110, 150, 198, 250, 256];
RateU = [21.5,23,24.8,26, 27, 28,  30, 32,  34, 34.5];
plot(NoAnt,RateU,'g-*');
```

```
hold on
legend('Developed PAP scheme with MF','Conventional scheme with MF', 'SPR with MF');


figure
plot(32*(2:Samp), RATE(2,2:end), 'b-<'); grid on
xlabel('Number of BS Antennas M'); ylabel('Average Downlink cell throughput(bps/Hz)');
title('Downlink Rate against Number of BS Antennas');

hold on;

NoAnt = [60,70,80,90,100, 110, 150, 198 250, 256];
RateU = [24,25,26,27,27.5,28.5,30.4,32.5,34.3, 34.5];
plot(NoAnt,RateU,'m-s');
hold on

NoAnt = [60,  70, 80,  90,  100,110,150, 198,250,256];
RateU = [21.5,23, 24.8,26,  27, 28,  30,  32,34,34.5];
plot(NoAnt,RateU,'g-*');
hold on

NoAnt = [60,70,  80, 90, 100, 110, 150, 198, 250, 256];
RateU = [20,21.5,23, 25, 26.5,27.5, 30, 32.8,34.8, 35.5];
plot(NoAnt,RateU,'k-+');


legend('Developed PAP scheme with MF','Conventional scheme with MF', 'SPR with
MF','SPR and MBD with MF');% axis([-5 5 1e-6 1]);



%Channel parameters
Chan.vCSI = 0.1;          %RMS/Amplitude of Variation in CSI through one coherent
interval.
Chan.TyVa = 3;   %Type of CSI variation.  1==None, 2=Linear, 3=Half Cos.
Chan.Freq = 2.6e9;   %Channel Frequency
Chan.SyBW = 10.0e6;   %System Bandwith
Chan.SNR = 6;   %Signal to Noise Ratio in dB

MxVe = 625/9;%Maximum Velocity of UE in m/s =(250km/hr)
DySp = 5e-6; %Delay Spread in secs = 1.5km delay(for 1.0km diameter)
C = 3e8;   %Speed of light in m/s
CoIn = 3*C/(4*sqrt(pi)*Chan.Freq*DySp*MxVe);
clear MxVeDySpC;

%Base station parameters(Initialisations)
BStn.CoIn = power(2,floor(log2(CoIn))); %Coherent Interval
```

```
BStn.NoAn = 90;   %Number of Antennaes
BStn.NoTS = 12*(floor(BStn.CoIn/60));   %No of Training Symbols
BStn.bsDL = round(0.7*(BStn.CoIn-BStn.NoTS));%Downlink Symbols 80% of Data
Bandwidth
BStn.PrOp = 1;   %Precoding option. 1 = ZF, 2 = Matched filtering

%UE parameters(Initialisations)
UsEq.noUE = 2*BStn.NoTS;          %Number of User Equipment
UsEq.ueUL = BStn.CoIn-BStn.NoTS-BStn.bsDL;%Number of Uplink Symbols 20% of
Data Bandwidth
% UsEq.UPwr = ones(UsEq.noUE,1);    %Transmitted Power by UEs
UsEq.TrSy = hadamard(UsEq.noUE);    %Training Symbols from UEs

function
[AcCSI,ULPilot,MSEr,BER,Par]=mMIMOchan(Block,PrULp,AcCSI,Chan,BStn,UsEq,Snr,
Par)
%SYNTAX:
[AcCSI,ULPilot,MSEr,BER,Par]=mMIMOchan(Block,PrULp,AcCSI,Chan,BStn,UsEq,Snr,
Par)
%

%Preparation
   SNR   = power(10,-Snr/20);  %Linear Noise amplitude

%rms of variation of CSI from one symbol to another
if(Chan.TyVa == 1)   %No variation
      Var2=  zeros(1,BStn.CoIn);
elseif(Chan.TyVa == 2)%Linear variation
      Var2=  Chan.vCSI*ones(1,BStn.CoIn)/BStn.CoIn;
elseif(Chan.TyVa == 3)%Half Cosine variation
      Var2= 0.5*Chan.vCSI*pi*sin(pi*(1:BStn.CoIn)/BStn.CoIn)/BStn.CoIn;
else
error('Wrong option of CSI variation.');
end
   Var1 = randn(UsEq.noUE, BStn.NoAn);

%Uplink Pilot Transmission from UE to BS for Traning at BS
ULPilot = zeros(BStn.NoAn, BStn.NoTS);
for ii = 1:BStn.NoTS
ULPilot(:,ii) = AcCSI'*UsEq.TrSy(:,ii+Par*BStn.NoTS);
AcCSI = AcCSI + Var1*Var2(ii);
end
ULPilot = ULPilot/sqrt(UsEq.noUE) + SNR*randn(BStn.NoAn, BStn.NoTS);

%Combined Pilots
if(Par==0)
cPilot  = [ULPilot,PrULp];
```

```
else
cPilot  = [PrULp,ULPilot];
end

%CSI estimation at BS
EsCSI= UsEq.TrSy*cPilot'/sqrt(UsEq.noUE);
MSEr = sum(sum((AcCSI-EsCSI)).^2)/numel(AcCSI);%Mean square error in CSI estimate

%Downlink precoded transmission
%Precoding
if(BStn.PrOp == 1)
PreCoder = pinv(EsCSI);
elseif(BStn.PrOp == 2)
PreCoder = EsCSI';
else
error('Precoding Option not Supported.');
end
DLdata = PreCoder*Block(:,1:BStn.bsDL);%Beamforming

%Passing through channel
DLRxdata = zeros(UsEq.noUE, BStn.bsDL);
for ii = 1:BStn.bsDL
DLRxdata(:,ii) = AcCSI*DLdata(:,ii);
AcCSI = AcCSI  + Var1*Var2(ii+BStn.NoTS);
end

%Uplink transmission from UE to BS and reception/equalisation at BS
%Passing through channel
ULdata = zeros(BStn.NoAn,UsEq.ueUL);
for ii = 1:UsEq.ueUL
ULdata(:,ii) = AcCSI'*Block(:,ii+BStn.bsDL);
AcCSI    = AcCSI  + Var1*Var2(ii+BStn.NoTS+BStn.bsDL);
end

%Equalisation
ULRxdata = PreCoder'*ULdata;

if(Chan.TyVa ~= 1)
AcCSI = AcCSI/sqrt(1+Chan.vCSI.^2);
end

%Quantisation and bit error rate determination.
QauntDL = DLRxdata;
QauntDL(QauntDL<=0) = 0;
QauntDL(QauntDL> 0) = 1;

QauntUL = ULRxdata;
```

```
QauntUL(QauntUL<=0) = 0;
QauntUL(QauntUL> 0) = 1;

QuantData = (1+Block)/2;

   BER = [biterr(QuantData(:,1:BStn.bsDL),    QauntDL)/numel(QauntDL);...
biterr(QuantData(:,BStn.bsDL+1:end),QauntUL)/numel(QauntUL)];

   Par = 1-Par;
end
```

APPENDIX A2

COMPLETE EQUATIONS FOR DERIVATION OF LINEAR DETECTION/PRECODING SCHEMES FOR PILOT ALLOCATION PROTOCOL TECHNIQUE.

Uplink Transmission

All *K* users share the same frequency resource, the $M \times 1$ received signal vector at the BS is the combination of all signals transmitted from all *K* users.

$$y_{ul} = \sqrt{\rho_u} \sum_{k=1}^{K} h_k s_k + n \quad \text{(A2.1)}$$

$$= \sqrt{\rho_u H_s + n} \quad \text{(A2.2)}$$

Where, ρ_u is the average signal to noise ratio (SNR), $n \in \mathrm{C}^{M \times 1\ 1}$ is the additive noise vector, and $s \square \left[s_1 ... s_k \right]^T$.

Downlink Transmission

BS antenna array. Then, the received signal at the K_{th} useris given by:

$$y_{dl} = \sqrt{\rho_d} H^T x + z_k \qquad \text{(A2.3)}$$

Assuming Z_k is Gaussians with zero mean and unit variance. Then the received vector of the k users is given by:

$$ydl = \sqrt{\rho_d H^T x + z,} \quad \text{(A2.4)}$$

Linear Receivers (in the UPLINK)

With linear equalization schemes at the BS, the received signal y_{ul} is separated into K streams by multiplying it with an $M \times K$ linear equalization matrix, A:

$$y_{ul} = A^H y_{ul} = \sqrt{\rho}_u A^H H_s + A^H n \qquad \text{(A2.5)}$$

Each stream is then decoded independently. From the aforementioned equation the K_{th} stream (element) of $\tilde{y}_{ul}$, which is used to decode S_k is given by:

$$\tilde{y}_{ul,k} = \underbrace{\sqrt{\rho_u a_k^H} h_k s_k}_{desiredsignal} + \underbrace{\sqrt{\rho_u} \sum_{k^i \neq k}^{k} a_k^H h_{k^i} s_{k^i}}_{\text{int}eruser\,\text{int}erference} + \underbrace{a_k^H n}_{noise} \qquad \text{(A2.6)}$$

where: a_k denotes the K_{th} column of $\boldsymbol{A}$. The interference plus noise is treated as effective noise, and hence, the received signal to interference plus noise ratio (SINR) of the K_{th} stream is given by:

$$SINR_K = \frac{\rho_u \mid a^H h_k \mid^2}{\rho_u \sum_{K^i}^{K} \mid \mathrm{a}_k^H h_{k^i} \mid^2 + \| a_k \|^2} \qquad \text{(A2.7)}$$

Maximum Ratio Combining Receiver

With MRC, using equation (2.7), the K_{th} column of the MRC receiver matrix **A** is

$$a_{mrc,k} = \underset{a_k \in c^{M\times 1}}{\arg\max} \frac{power\left(desiredsignal\right)}{power\left(noise\right)} \qquad \text{(A2.8)}$$

$$= \underset{a_k \in c^{M\times 1}}{\arg\max} \frac{\rho_u \mid a_K^H \mathrm{h}_k \mid^2}{\| \mathrm{a}_K \|^2}$$

Since.

$$\frac{\rho_{u|}\,|\,a_K^H h_K\,|^2}{\|\,a_K\,\|^2} \le \frac{\rho_u\,\|\,a_K\,\|^2 \|\,\mathrm{h}_K\,\|^2}{\|\,a_K\,\|^2} = \rho_u\,\|\,h_k\,\|^2, \quad \text{(A2.9)}$$

Note that the equality holds when a_k = constant. h_k. The MRC receiver is: $a_{mrc,k}$ = constant. h_k. Putting $a_{mrc,k}$ into equation (2.13) into, the received SINR of the K_{th} stream for MRC is given by:

$$SINR_{mrc,k} = \frac{\rho_u\,\|\,h_K\,\|^4}{\rho_u \sum_{K^I=\neq K}^{K} |\,h_K^H\,\mathrm{h}_{K^I}\,|^2 + \|\,\mathrm{h}_K\,\|^2} \quad \text{(A2.10)}$$

$$\rightarrow \frac{\|\,h_K\,\|^4}{\sum_{K^i=K}^{K} |\,h_K^H h_{k^i}\,|^{2,}}$$

$$as \rho_u \rightarrow \infty$$

Zero Forcing

The k_{th} column of the ZF receiver matrix satisfies:

$$\begin{cases} a_{zf,k}^H h_k \neq 0 \\ a_{zf,k}^H h_{k^i} = 0, \forall \mathrm{k}^i \neq k. \end{cases} \quad \text{(A2.11)}$$

The ZF receiver matrix, which satisfies the above equation for all *K,* is the pseudo-inverse of the channel matrix **H.** With ZF, we have:

$$\tilde{y}_{ul} = \left(H^H H\right)^{-1} H^H y_{ul} = \sqrt{\rho_u s} + \left(H^H H\right)^{-1} H^H n \quad \text{(A2.12)}$$

This scheme requires that $M \geq K$ (so that the matrix $H^H H$ is invertible). It can be observed that each stream (element) of y_{ul} in the previous equation is free of multi-user interference. The k_{th} stream is of y_{ul} is used to detect s_k:

$$\tilde{y}_{ul,k} = \sqrt{\rho_u s_k} + \tilde{n}_k, \qquad \text{(A2.13)}$$

where: n_k denotes the k_{th} element $\left(H^H H\right)^{-1} H^H n$. Thus, the received SINR of the k_{th} stream is given by:

$$SINR_{zf,k} = \frac{\rho_u}{\left[\left(H^H H\right)^{-1}\right]_{kk}} \qquad \text{(A2.14)}$$

Minimum Mean Square Error

The minimum mean square error between the estimate $A^H y_{ul}$ and the transmitted signal **s is given by**:

$$A_{mmse} = \arg\min_{A \in \mathbb{C}^{M \times K}} \mathrm{E}\left\{\| A^H y_{ul} - s \|^2\right\} \qquad \text{(A2.15)}$$

$$= \arg\min_{A \in \mathbb{C}^{M \times K}} \sum_{K=1}^{K} \mathrm{E}\left\{| a_K^H y_{ul} - s_K |^2\right\}. \quad \text{(A2.16)}$$

where a_k is the k_{th} column of A. Therefore, the k_{th} column of the MMSE is:

$$a_{mmse,k} = \arg\min_{A \in C^{M \times K}} \left\{| a_K^H y_{ul} - s_k |^2\right\} \qquad \text{(A2.17)}$$

$$a_{mmse,k} = \sqrt{r_u} + \left(r_u H H^H + I_M\right)^{-1} h_{k,} \qquad \text{(A2.18)}$$

The received SINR for MMSE receiver is given by:

$$SINR_{mmse,k} = \rho_u h_k^H \left(\sum_{i \neq k}^{H} h_i h_i^H + I_M \right)^{-1} h_k \quad \text{(A2.19)}$$

Linear precoders (in the Downlink)

Then the linearly precoded signal vector **x** is given by:

$$x = \sqrt{\alpha W_{q.}} \quad \text{(A2.20)}$$

where $q \square \left[q_1 q_2 ... q_k \right]^T$, $W \in \mathbf{C}^{M \times K}$ is the precoding matrix, and α is a normalization constant chosen to satisfy the power constraint $\mathbf{E}\left\{ \| x \|^2 \right\} = 1$. Thus.

$$\alpha = \frac{1}{\mathbf{E}\left\{ (trWW^H) \right\}} \quad \text{(A2.21)}$$

Based on Figure. 2.33, using equations (2.4) into (2.22), we obtain

$$y_{dl,k} = \sqrt{ar_d h_k^T w_k q_k} + \sqrt{ar_d} \sum_{k^i}^{k} h_k^T w_{k^i} q_{k^i} + z_{k.} \quad \text{(A2.22)}$$

Therefore, the SINR of the transmission from BS to the k_{th} user is

$$SINR_k = \frac{\alpha \rho_d | h_k^T w_k |^2}{\alpha \rho_d \sum_{k^i \neq k}^{k} | h_k^T w_{k^i} |^2 + 1} \quad \text{(A2.23)}$$

Thus, the final formulas for these precoders are:

$$W = \begin{cases} H^*, \ for MRT \\ H^* \left(H^H H^* \right)^{-1}, \ for ZF \\ H^* \left(H^T H^* + \dfrac{K}{\rho_d} I_k \right)^{-1}, \ for MMSE \end{cases} \qquad \text{(A2.24)}$$