Spectral Efficiency Enhancement in Uplink Cell-free Massive MIMO System over Fading Channel

Yenus Nurhisen Mehamedzen

A Thesis Submitted to

The Department of Electronics and Communication Engineering

School of Electrical Engineering and Computing

Presented in Partial Fulfillment of the Requirement for the Degree of Master's in Electronics and Communication Engineering

Office of Post Graduate Studies

Adama Science and Technology University

June, 2024

Adama, Ethiopia

Spectral Efficiency Enhancement in Uplink Cell-Free Massive MIMO System over Fading Channel

Yenus Nurhisen Mehamedzen

Major Advisor: - Dr. Demissie Jobir (PhD)

Co-Advisor: - Dr. Ram Sewak Singh (PhD)

A Thesis Submitted to

The Department of Electronics and Communication Engineering

School of Electrical Engineering and Computing

Presented in Partial Fulfillment of the Requirement for the Degree of Master's in Electronics and Communication Engineering

Office of Post Graduate Studies

Adama Science and Technology University

June, 2024

Adama, Ethiopia

APPROVAL PAGE OF M.SC. THESIS

We, the advisors of the thesis entitled "**Spectral Efficiency Enhancement in Uplink Cell-Free Massive MIMO System over Fading Channel**" and developed by **Yenus Nurhisen Mehamedzen**, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

Dr. Demissie Jobir	______________________	_______________
Major Advisor	Signature	Date
Dr. Ram Sewak Singh	______________________	_______________
Co-Advisor	Signature	Date

We, the undersigned members of the board of Examiners of the thesis by **Yenus Nurhisen Mehamedzen** have read and evaluated the thesis entitled "**Spectral Efficiency Enhancement in Uplink Cell-Free Massive MIMO System over Fading Channel**" and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Electronics and Communication engineering.

______________________	__________________	_____________
Chairperson	Signature	Date
______________________	__________________	_____________
Internal Examiner	Signature	Date
______________________	__________________	_____________
External Examiner	Signature	Date

Finally, approval and acceptance of the thesis is contingent upon submission of its final copy to the Office of Postgraduate Studies (OPGS) through the Department Graduate Council (DGC) and School Graduate Committee (SGC).

______________________	__________________	_____________
Department Head	Signature	Date
______________________	__________________	_____________
School Dean	Signature	Date
______________________	__________________	_____________
Office of Postgraduate Studies, Dean	Signature	Date

DECLARATION

I hereby declare that this Master Thesis entitled "**Spectral Efficiency Enhancement in Uplink Cell-Free Massive MIMO System over Fading Channel**" is my own work and has not been submitted to any University for a similar purpose. The references used in this thesis are duly recognized by proper citation.

Yenus Nurhisen Mehamedzen	________________	______________
Name of Student	Signature	Date

RECOMMENDATION

We, the advisors of this thesis, hereby certify that we have read the revised version of the thesis entitled "**Spectral Efficiency Enhancement in Uplink Cell-Free Massive MIMO System over Fading Channel**" prepared under our guidance by **Yenus Nurhisen Mehamedzen** submitted in partial fulfillment of the requirements for the degree of Mater's of Science in Electronics and Communication Engineering. Therefore, we recommend the submission of revised version of the thesis to the department following the applicable procedures.

Dr. Demissie Jobir	________________	__________________
Major Advisor	Signature	Date
Dr. Ram Sewak Singh	________________	__________________
Co-advisor	Signature	Date

ACKNOWLEDGEMENT

I begin by expressing my gratitude and thanks to the Almighty God for his blessings and mercy, which have enabled me to successfully complete this thesis. I would like to extend my heartfelt appreciation to my advisor **Dr. Demissie Jobir (PhD),** for his unwavering support, encouragement, and valuable time. His guidance and freedom allowed me to explore this thesis deeply and work in my own way. Without his assistance, it would not have been possible to achieve the ultimate goal of this thesis.

I also want to acknowledge my co-advisor **Dr. Ram Sewak Singh (PhD),** for his continuous support throughout my M.Sc. research. His patience, motivation, and enthusiasm were invaluable in guiding me through the research and writing of this thesis.

Additionally, I would like to express my gratitude to Adama Science and Technology University (ASTU) and the School of Electrical Engineering and Computing (SoEEC), particularly the program of electronics and communication engineering, for providing an excellent educational and research environment. I am thankful to all the students in the Communication Engineering division who shared their knowledge with me.

Lastly, I am grateful to my family for their unwavering support, allowing me to pursue my dreams and making me feel empowered to do whatever I wanted without feeling pressured.

TABLE OF CONTENTS

Contents

APPROVAL PAGE OF M.SC. THESIS ii

DECLARATION iii

RECOMMENDATION iv

ACKNOWLEDGEMENT v

TABLE OF CONTENTS vi

LIST OF TABLES ix

LIST OF FIGURES x

LIST OF ACRONYMS xiii

ABSTRACT xv

CHAPTER ONE 1

1. INTRODUCTION 1

1.1 Background of the Study 1

1.2 Motivation 4

1.3 Statement of the Problem 4

1.4 Objectives 5

1.4.1 General Objective 5

1.4.2 Specific Objectives 5

1.5 Scope of the Study 5

1.6 Significance of the Study 5

1.7 Thesis Contribution 6

1.8 Limitation of the Study 6

1.9 Thesis Outline 6

CHAPTER TWO 7

2. LITERATURE REVIEW 7
2.1 Introduction 7
2.2 Cellular Network 7
2.2.1 Some challenges and mitigation techniques in the cellular massive MIMO 8
2.3 Cell-free massive MIMO System 12
2.3.1 Advantages of cell-free massive MIMO system 14
2.3.2 Some limitations of cell-free massive MIMO system 14
2.3.3 The root components of cell-free massive MIMO system 15
2.3.4 Centralized operation 16
2.3.5 Distributed operation 17
2.4 Dynamic Cooperative Clustering 18
2.5 Review of Related Works 19
CHAPTER THREE 24
3. MATERIAL AND METHODOLOGY 24
3.1 Introduction 24
3.2 Materials 24
3.3 Methodology 24
3.3.1 System design 25
3.3.2 System model 25
3.4 Uplink Transmissions 31
3.4.1 Uplink training phase 31
3.4.2 Uplink data transmissions 31
3.5 Proposed Method 31
3.5.1 Successive interference cancellation (SIC) 32
3.6 Performance Metrics of Signal Detection Algorithms 35

3.6.1 Spectral efficiency (SE) 35

3.6.2 Sum spectral efficiency (sum SE).. 35

3.6.3 Bit error rate (BER) 36

3.6.4 Complex multiplications 36

CHAPTER FOUR.. 37

4. RESULT AND DISCUSSION 37

4.1 Chapter overview 37

4.2 Performance Comparison of Proposed Detector and Existing Detecting Techniques 38

4.2.1 Performance comparison between proposed and other existing decoding techniques based on sum spectral efficiency 38

4.2.2 Performance comparison between proposed and other existing decoding techniques based on spectral efficiency 47

4.2.3 Performance comparison between proposed and other existing decoding techniques based on number of complex multiplications 57

4.2.4 Summary of complex multiplications 63

4.2.5 Performance comparison between proposed and other existing decoding techniques based on bit error rate 64

5. CONCLUSION AND RECOMMENDATION 69

5.1 Conclusion 69

5.2 Recommendation 70

6. REFERENCES 71

LIST OF TABLES

Table 2.1 Summary of some related works 22
Table 3.1 Computational complexity of some centralized and distributed combining schemes.. 36
Table 4.1 Simulation parameters (Björnson & Sanguinetti, 2019).. 37
Table 4.2 Uplink sum SE comparison between proposed decoding technique and other decoding techniques for L = 100 and N = 2 39
Table 4.3 Uplink sum SE comparison between proposed decoding technique and other decoding techniques for L = 200 and N = 2 41
Table 4.4 Uplink sum SE comparison between proposed decoding technique and other decoding techniques for L = 100 and N = 4 44
Table 4.5 Uplink sum SE comparison between proposed decoding technique and other decoding techniques for L = 200 and N = 5 47
Table 4.6 CDF versus SE of the proposed decoding technique and other centralized techniques with L = 100, N = 2, and K = 50.. 48
Table 4.7 CDF versus SE of the proposed decoding technique and other centralized techniques with L = 100, N = 1, and K = 50.. 51
Table 4.8 CDF versus SE of the proposed decoding technique with both centralized and distributed techniques with L = 100, N = 1, and K = 50.. 56
Table 4.9 Performance comparison of different decoding techniques based on the number of complex multiplications of different decoding techniques for L = 10 and K = 10............... 58
Table 4.10 Performance comparison of different decoding techniques based on the number of complex multiplications of different decoding techniques for L = 20 and K = 20............... 62
Table 4.11 BER comparison between proposed and other existing decoding algorithms at K = 40, L = 200, and N = 4 65

LIST OF FIGURES

Figure 1.1 Current cellular massive MIMO system (Albreem et al., 2019b) 2
Figure 1.2 Cell-free massive MIMO system (Ozdogan et al., 2019).. 3
Figure 2.1 Representation of a standard cellular network (Interdonato et al., 2019)………………8
Figure 2.2 Challenges exist in deployment of massive MIMO system (Chataut & Akl, 2020)..... 8
Figure 2.3 Pilot contamination (Chataut & Akl, 2020) 9
Figure 2.4 Representation of both TDD and FDD operations (Chataut & Akl, 2020b)............... 10
Figure 2.5 Precoding in downlink massive MIMO system with M antennas at the base station (Chataut & Akl, 2020c).. 11
Figure 2.6 Structure of cell-free massive MIMO system (Zaher et al., 2021a)............................ 12
Figure 2.7 Representation of cell-free massive MIMO system with fronthaul link (Kassam et al., 2023) 13
Figure 2.8 Describing of cell-free massive MIMO system as a group of four technologies (Shaik, 2022) 15
Figure 2.9 Geographical representation of centralized operation system.................................... 17
Figure 2.10 Geographical representation of distributed operation system 18
Figure 2.11 Dynamic cooperative cluster (Björnson & Sanguinetti, 2019) 19
Figure 3.1 Methodology...…...….. 25
Figure 3.2 System model of cell-free *massive* MIMO system with one CPU, L AP and K UEs (Kassam et al., 2023) 26
Figure 3.3 Block diagram of the proposed detector P-MMSE with DCC and SIC...................... 33
Figure 3.4 Flowchart of the proposed decoding technique... 34
Figure 4.1 Sum SE comparison as function of UE for both the proposed and other existing techniques with L = 100 and N = 2……………………………………………………………..39
Figure 4.2 Sum SE comparison as function of UE for both the proposed and other existing techniques with L = 200 and N = 2... 41
Figure 4.3 Sum SE comparison as function of UE for both the proposed and other existing techniques with L = 200 and N = 3... 43
Figure 4.4 Sum SE comparison as function of UE for both the proposed and other existing techniques L = 100 and N = 4.. 44

Figure 4.5 Sum SE comparison as function of UE for both the proposed and other existing techniques with L = 100 and N = 5 45
Figure 4.6 Sum SE comparison as function of UE for both the proposed and other existing techniques with L = 200 and N = 5 46
Figure 4.7 CDF versus SE of the proposed decoding technique and other centralized techniques with L = 100, N = 2, and K = 50 48
Figure 4.8 CDF versus SE of the proposed decoding technique and other centralized techniques with L = 100, N = 2, and K = 40 49
Figure 4.9 CDF versus SE of the proposed decoding technique and other centralized techniques with L = 100, N = 1, and K = 50 50
Figure 4.10 CDF versus SE of the proposed decoding technique and other distributed techniques with L = 100, N = 1, and K = 50 52
Figure 4.11 CDF versus SE of the proposed decoding technique and other distributed techniques with L = 100, N = 2, and K = 50 53
Figure 4.12 CDF versus SE of the proposed decoding technique with centralized and distributed techniques by considering L = 100, N = 1, and K = 50 54
Figure 4.13 CDF versus SE of the proposed decoding technique with centralized and distributed techniques by considering L = 100, N = 2, and K = 50 55
Figure 4.14 CDF versus SE of the proposed decoding technique with centralized and distributed techniques by considering L = 100, N = 2, and K = 40 57
Figure 4.15 Performance comparison of proposed and existing decoding techniques based on complex multiplications with L = 10 and K = 10 58
Figure 4.16 Performance comparison of proposed and existing decoding techniques based on complex multiplications with L = 10 and K = 20 60
Figure 4.17 Performance comparison of proposed and existing decoding techniques based on complex multiplications with L = 20 and K = 10 61
Figure 4.18 Performance comparison of proposed and existing decoding techniques based on complex multiplications with L = 20 and K = 20 62
Figure 4.19 Performance comparison of proposed and existing decoding techniques based on complex multiplications with L = 30 and K = 30 63

Figure 4.20 BER comparison between proposed and other existing decoding techniques at K = 40, L = 200, and N = 4 65
Figure 4.21 BER comparison between proposed and other existing decoding techniques at K = 40, L = 300, and N = 4 66
Figure 4.22 BER comparison between proposed and other existing decoding techniques at K = 50, L = 200, and N = 4 67
Figure 4.23 BER comparison between proposed and other existing decoding techniques at K = 50, L = 100, and N = 4 68

LIST OF ACRONYMS

5G	Fifth Generation
ANN	Artificial Neural Network
APG	Accelerated Projected Gradient
APs	Access Points
B5G	Beyond Fifth Generation
BS	Base Station
CB	Conjugate Beamforming
CDF	Cumulative Distributed Function
CL	Cooperative Learning
COMP	Coordinated Multi-Point
CPU	Central Processing Unit
CRAN	Cloud Radio Access Point
CSI	Channel State Information
DAS	Distributed Antenna System
DCC	Dynamic Cooperative Clustering
DL	Downlink
DNN	Deep Neural Network
ECF	Expanded Compute-and-Forward
EE	Energy Efficiency
FCP	Fully Centralized Processing
FDD	Frequency Division Duplex
ICI	Inter-cell Interference
IDD	Iterative Detection and Decoding
IUI	Inter-User Interference
JAPSIC	Joint Access Point Successive Interference Cancellation

JMRZF	Joint Maximum Ratio Zero Force
L-MMSE	Local Minimum Mean Square Error
LSFD	Large Scale Fading Decoding
MF	Matched Filter
MIMO	Multiple Input Multiple Output
MMSE	Minimum Mean Square Error
MMSE-SIC	MMSE-Successive Interference Cancellation
MR	Maximum Ratio
MRT	Maximum Ratio Transmission
PC	Power Control
P-MMSE	Partial Minimum Mean Square Error
PWPFZF	Protective Weak Fully Pilot Zero Forcing
P-RZF	Partial Regularized Zero Forcing
QoS	Quality of Services
RAN	Radio Access Network
RF	Radio Frequency
SCA	Successive Convex Approximation
SE	Spectral Efficiency
SIC	Successive Interference Cancellation
TDD	Time Division Duplex
UCC	User Centric Clustering
UE	User Equipment
UL	Uplink
ZF	Zero Forcing

ABSTRACT

The advancement of technology has produced huge changes in modern wireless communication systems. This rapid growth of technology has brought high data rates, low costs, and reliable transmission across active users. The current cellular massive multiple-input multiple-output (MIMO) system is better at connecting user equipment (UE), offering substantial capacity, and delivering high data rates within specific cells. However, these systems grapple with signal interference issues, particularly at cell edges, which can be problematic for mobile users. To address the interference challenges inherent in cellular massive MIMO, a cell-free massive MIMO system has emerged. Unlike current cellular massive MIMO systems, it does not rely on predefined cell boundaries; instead, it utilizes an array of distributed antennas to concurrently serve multiple users. This innovative technology has substantial promise for the evolution of wireless communication networks, including the development of beyond fifth-generation (B5G) wireless communication. In the uplink of a cell-free massive MIMO system, multiple UEs generate interference across various combining schemes. To mitigate this interference and enhance system performance, this thesis has proposed a hybrid decoding technique using partial minimum mean square error (P-MMSE) combining and dynamic cooperative cluster (DCC) with successive interference cancellation (SIC) technique, to reduce interference and increase the spectral efficiency (SE) of the cell-free massive MIMO systems over the Rayleigh fading channel. The proposed decoding uses the received signal at the central processing unit (CPU) to maximize the desired signal by minimizing the interference for a given UE. The proposed method improved the sum SE by 6.347% for 200 APs, 5 antennas per access point (AP), and 60 UEs compared to the P-MMSE. Additionally, the SE, bit error rate (BER), and number of complex multiplications also improved compared to existing techniques in the presence of interferences.

Keywords*: Access point, bit error rate, cell-free massive MIMO system, successive interference cancellation, user equipment, and spectral efficiency.*

CHAPTER ONE

1. INTRODUCTION

1.1 Background of the Study

Wireless communication is one of the fastest-growing segments of the communication industry. The reason for this growth of wireless communication is the increasing number of users with the need for pure quality of services, high SE, high energy efficiency (EE), and throughput of wireless communication. For many years, wireless communication was used only for voice communications, but now we can use it for high-quality data transmission (Mumtaz et al., 2016). The massive MIMO system is one of the enabling technologies of 5G communication system for achieving substantial improvements in high data rates, high EE, better throughput, and great SE (Nguyen et al., 2023).

Current MIMO networks would provide a solution for bandwidth-demanding applications with large user traffic. Performance, quick connectivity, increased robustness, and substantially greater data rates are the main goals of 5G technologies. In today's massive MIMO system, multiple users can communicate simultaneously if the base station (BS) has a large number of antennas. Higher energy and spectrum efficiency can be achieved by this technology (Benzaghta & Rabie, 2021). The representation of cellular networks is that every piece of user equipment (UE) is allocated to a particular cell and served solely by its corresponding BS. The network functions in the time division duplex (TDD) model, where both downlink and uplink transmission occur within the same frequency band but are temporally segregated. Consequently, the BS can concurrently estimate the downlink and uplink channels by transmitting recognizable pilot signals from the UEs. This approach enables each BS to acquire local channel state information (CSI) about the connections between itself and the various UEs.

The massive MIMO serves as an essential technology for addressing the demand of the user in both performance and quality of services within wireless communication networks. Consequently, extensive research has focused on developing an optimal massive MIMO detection algorithm that balances performance and complexity. As shown in Figure 1.1, massive MIMO has been widely implemented in 5G systems. It has the ability to enhance throughput and SE in present wireless communication systems. The MIMO system has increased significantly and is utilizing efficiently the given spectral bandwidth by using the abundance of antenna elements (Albreem et al., 2019).

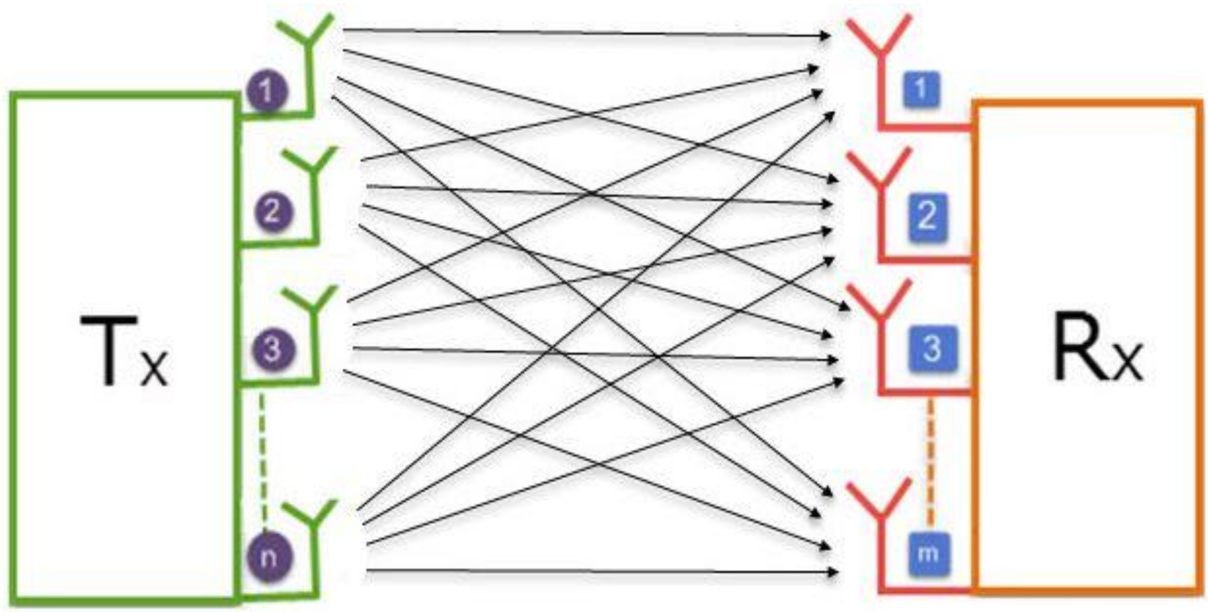

Figure 1.1 Current cellular massive MIMO system (Albreem et al., 2019b)

Cell-free is a situation in which the current cellular edge border during uplink and downlink is replaced by deploying distributed APs. In the wireless communication system, every AP has an impact on each UE that participates in the connection (Mobini et al., 2023). For example, if the APs receive an uplink signal from the UEs, they will work to decode the received signal. The APs used to provide service to all the currently active user devices within their coverage area. Figure 1.2 illustrates a cell-free massive MIMO system with one CPU and randomly distributed APs and UEs. In cellular massive MIMO systems, there are advantages like channel hardening systems, but at the cell edge, the UE may experience poor channel conditions. However, cell-free massive MIMO systems gain advantages from this, although the effectiveness of interference suppression relies on the specific operational approach. To ensure a fair comparison, our focus is on the uplink scenario with fixed UE transmit power (Demir et al., 2021).

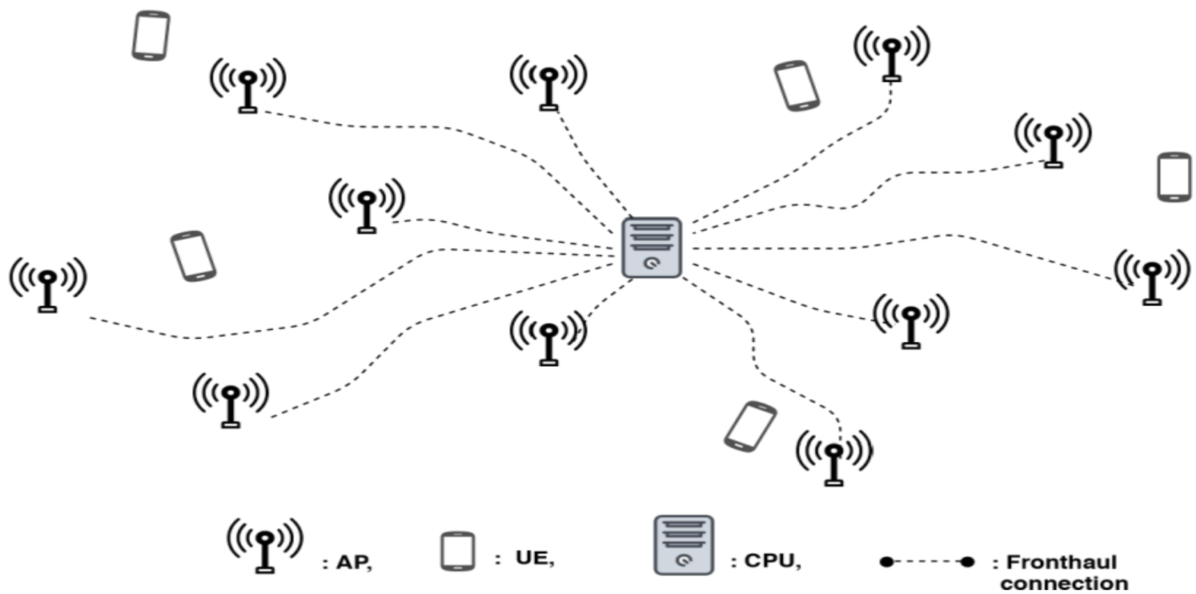

Figure 1.2 Cell-free massive MIMO system (Ozdogan et al., 2019)

The APs collaborate through a backhaul network system to transmit signals to all users using conjugate beamforming (CB) techniques from the CPU with the same time-frequency resources. Its investigation considers various factors, such as perfect channel estimation, power control systems, non-orthogonal pilot sequences, and both fronthaul and backhaul power consumptions, to assess the overall EE of the systems. A perfect AP selection scheme is used to reduce the power consumed in the backhaul link by using only a portion of APs actively providing service to each user, ensuring efficient utilization of system resources. The cell-free massive MIMO achieves high EE while maintaining a uniform level of service quality for all users. Specifically, when targeting a uniform level of spectral distribution, cell-free massive MIMO achieves good performance (Akyildiz et al., 2020; Zhang et al., 2019a).

Based on precisely measured channel parameters, a cell-free massive MIMO network comprises numerous distributed APs that simultaneously serve a significantly smaller UE while utilizing the same time and frequency resources. By deploying TDD operations and receiving uplink pilot signals transmitted by the users, the APs acquire CSI. Power control is significantly more crucial in reducing the impacts of pilot contamination than the pilot assignment method. Using a backhaul network, all APs work together phase-coherently to serve every user with the same given time-frequency resource using a TDD operation mode. When the number of UEs is coherent with the number of APs, then cell-free Massive MIMO can provide a high likelihood of coverage area (Ngo et al., 2017).

In a centralized, the APs play a critical role in enabling the system's operation. They responsible for receiving the CSI by aggregating pilot signals from all UEs within their coverage area. This information is then forwarded to the CPU, which performs joint channel estimation, decoding, and power control across the entire network of APs. This architecture allows for more efficient resource allocation and coordination, leading to improved system performance compared to fully distributed approaches.

1.2 Motivation

Current cellular massive MIMO systems have some interference on the edges of the cells because of the restricted geographical area of each cell boundary and the inter-cell interference problem. Deploying a cell-free large MIMO system with numerous geographically distributed AP and UE solves the problem of the existing cellular massive MIMO system. But to improve the performance of cell-free massive MIMO systems through consistency, some interference in the uplink combining has to be minimized. This indicates there is a need for further research in SE analysis of cell-free massive MIMO to develop efficient algorithms and techniques that can address these challenges.

1.3 Statement of the Problem

Even though the current cellular massive MIMO system has high data rates in the center of the cellular wireless networks, as we go from the center to the edge of the cell, there is variation in signal strength degradation due to the considerable difference in distances to the UEs being served. These fluctuations in data rates create challenges for the effectiveness of the received signal by the BS in the system. Reducing the coverage area of individual cells and increasing the number of BSs per given area gives some improvement in performance, but an increase in BS leads to a rise in inter-cell interference. In a cell-free massive MIMO system where a large number of distributed APs jointly serve multiple UEs, effective interference management is crucial to achieving high uplink SE by the CPU. One approach to addressing this challenge is to employ a P-MMSE combining and DCC with SIC technique at the CPU to achieve high data rates and consistent data transmission speeds across a given coverage area by minimizing the interference existing at the APs for all users.

1.4 Objectives

1.4.1 General Objective

The main objective of the thesis is to enhance the SE of uplink cell-free massive MIMO by reducing the interference in Rayleigh fading channel.

1.4.2 Specific Objectives

- To develop a hybrid decoding method based on P-MMSE and DCC with SIC to minimize the interference in the uplink signal detection.
- To investigate the performance parameter such as sum SE and SE of uplink signal through proposed decoding technique and existing techniques.
- To analyze the performance of proposed technique and existing techniques based on number of complex multiplications.
- To evaluate the performance of proposed technique and existing techniques based on BER.

1.5 Scope of the Study

The thesis's primary goal is to study and examine a cell-free massive MIMO wireless communication network by replacing the existing cellular massive MIMO network. It focuses on improving the SE by minimizing interference, reducing energy consumption, and reducing the BER of the cell-free massive MIMO systems in uplink data signal transmission using hybrid decoding techniques with available bandwidth. The simulation includes information about the SE, computational complexity, BER, and sum SE by comparing the proposed technique with existing techniques.

1.6 Significance of the Study

The advantages of this thesis are to enhance performance and reduce interference through the utilization of hybrid decoding techniques. The research also conducted related to this work was to offer insignificant observations on the merits and drawbacks of various decoding methods with the purpose of optimizing their SE and determining their overall effectiveness. Furthermore, this thesis study provides guidance and direction to researchers, encouraging further investigations that can make easy the deployment of cell-free technologies.

1.7 Thesis Contribution

Although cell-free massive MIMO systems have higher SE than the existing cellular systems, for large numbers of users, there is interference in the decoding area. This interference signal is part of the uplink cell-free massive MIMO network problem that is solved by using different decoding techniques. This thesis work has proposed a hybrid algorithm that is used in the uplink detection technique called P-MMSE and DCC with the SIC technique to reduce interference and improve the performance of cell-free massive MIMO systems over the Rayleigh fading channel. Performance is compared between proposed and existing techniques based on sum SE, SE, BER, and number of complex multiplications.

1.8 Limitation of the Study

The limitations of this work include the increased computational complexity of an increase in the number of APs and the higher cost of hardware implementation in the real world.

1.9 Thesis Outline

The remaining part of the thesis are arranged as follows: **Chapter two** presents basic introduction, clarification, the working principles, advantage and disadvantages of current cellular massive MIMO systems and cell-free massive MIMO systems. **Chapter three** focuses on system model, mathematical model, and block diagram of the thesis for different decoding techniques used in both centralized and distributed operations. **Chapter four** encompasses on simulation results and comprehensive discussion of the results for different decoding techniques. Finally, conclusion and recommendation for the future works are presented in this section of the thesis work.

CHAPTER TWO

2. LITERATURE REVIEW

2.1 Introduction

A cell-free massive MIMO system is a wireless communication system that has possibly answered the rising questions on the need for high-capacity data rates and high-performance wireless communication networks (Huo et al., 2023). In conventional cellular massive MIMO networks, a BS serves a predetermined, specific geographic area, which is a cell. In contrast, cell-free networks use a lot of scattered AP antennas to create a virtual cell with no set of geographical boundaries (Björnson & Sanguinetti, 2019). This emerging technology, envisioned for beyond 5G wireless communication, offers promising advantages over conventional MIMO technology, including higher SE and enhanced spatial diversity. The fundamental idea behind cell-free massive MIMO is to simultaneously serve numerous user devices using numerous scattered AP antennas. By employing advanced signal-processing techniques and efficient resource-allocation methods, it can achieve significant spectral efficiency, low latency, and reduced interference by utilizing the best signal-processing methods and efficient resource allocation approaches (Shaik et al., 2020).

2.2 Cellular Network

The cellular network is part of wireless communication, which uses electromagnetic waves, particularly radio waves, to transmit data and speech signals. It is designed to cover a large geographical area by dividing it into smaller units called cells. Each cell has a BS that acts as the central processor for communication within that cell. The components of a BS are the transmitter, receiver, antennas, and other hardware that facilitates communication between the devices (Y. Wu et al., 2019). The use of cells in cellular networks allows for efficient utilization of available radio frequencies. To prevent interference between neighboring cells, each cell operates on its own set of frequencies. This frequency reuse technique enables cellular networks to accommodate a large number of simultaneous users and provide high-quality voice and data services.

Figure 2.1 illustrates the typical structure of a cellular network, in which the users are linked to a single BS that can have either one or multiple antennas. Each BS is responsible for serving the users located within its respective cell. Mobile devices such as smartphones and tablets establish a connection with the cellular network by exchanging radio signals with a nearby BS. As individuals move within the network, their mobile devices seamlessly transition to the BS that offers the strongest signal. This allows for uninterrupted communication, even when it is ongoing. The handoff process is an essential component of cellular networks as it guarantees continuous connectivity for users (Interdonato et al., 2019).

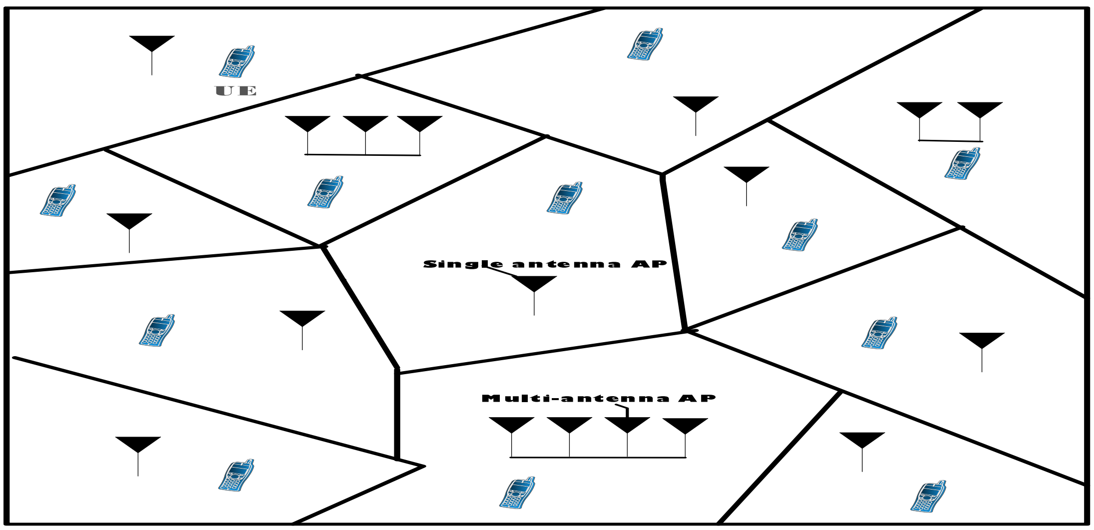

Figure 2.1 Representation of a standard cellular network (Interdonato et al., 2019)

2.2.1 Some challenges and mitigation techniques in the cellular massive MIMO

In order to bring the concept of massive MIMO technology into practical use, there are numerous problems and obstacles that must be overcome (Chataut & Akl, 2020). There are a number of fundamental issues within massive MIMO systems; Figure 2.2 shows some of the significant ones.

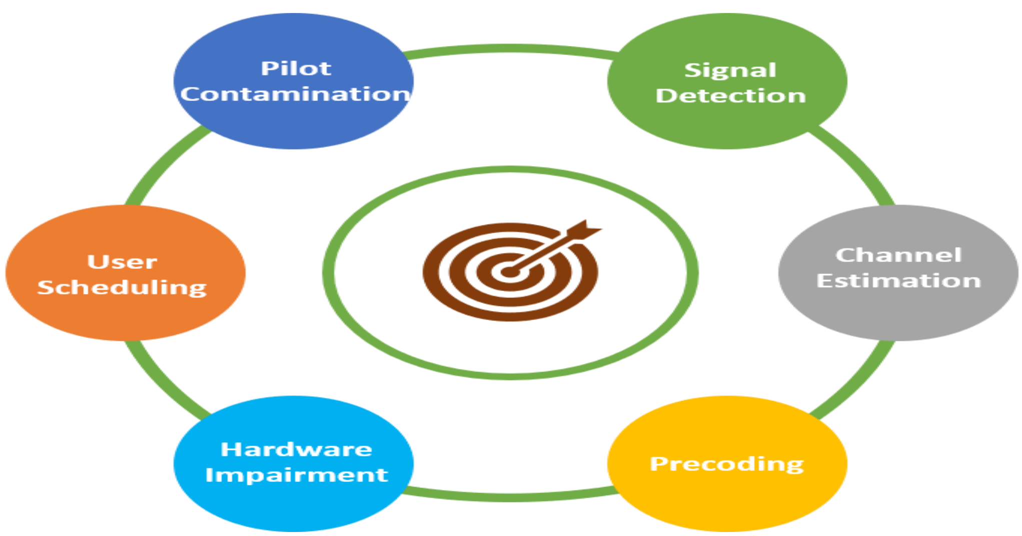

Figure 2.2 Challenges exist in deployment of massive MIMO system (Chataut & Akl, 2020)

2.2.1.1 Pilot contamination

Pilot contamination can be described as interference that results from reusing pilot signals from many users when they send them to the BS. The users should send orthogonal pilot signals to the BS in order to estimate the channel at the BS. The uplink channel estimation is performed when the users send pilot signals to the BS to estimate the channel (Marzetta, 2010). Furthermore, the BS predicts the downlink channel in the direction of the users by leveraging the massive MIMO channel reciprocity property. When the pilot signals in the target cell and surrounding cells are orthogonal to one another, accurate channel estimation can be accomplished (Lu et al., 2014). However, there is a limitation on the number of orthogonal pilot signals that can be utilized within a given bandwidth. Consequently, the same set of orthogonal pilots is reused in neighboring cells. This leads to the BS receiving a combined signal from both the targeted cell and neighboring cells. Figure 2.3 illustrates the geographical representation of pilot contamination (Al Ayidh et al., 2022).

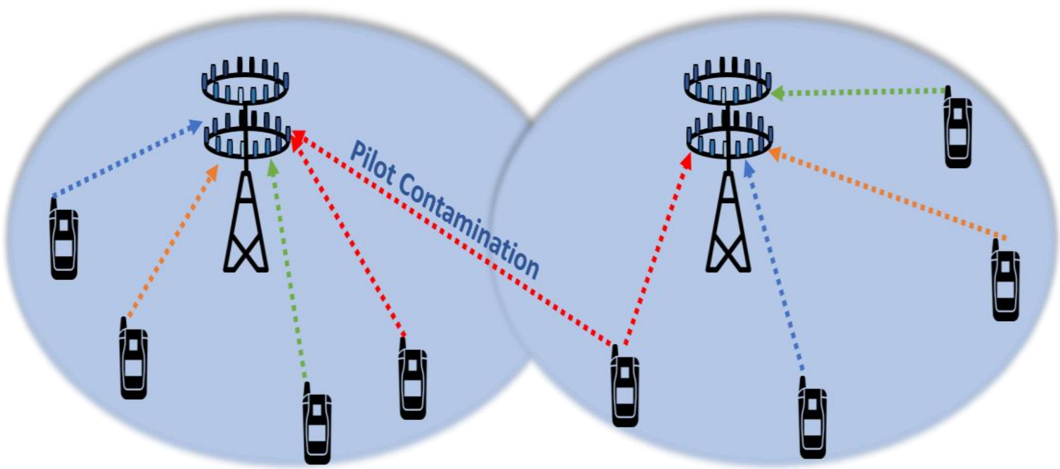

Figure 2.3 Pilot contamination (Chataut & Akl, 2020)

2.2.1.2 Channel estimation

Massive MIMO systems rely on CSI to detect and decode signals by providing essential information about the wireless communication connection between the sender and receiver, including factors like fading and scattering (Chataut & Akl, 2020b). In frequency division duplex (FDD) systems, a pair of frequencies are allocated for communication, one for uplink and the other for downlink transmissions. The BS uses orthogonal pilot signals sent by the UE to estimate the channel during the uplink. The user reacts to pilot signals sent by the BS in the downlink by providing estimated channel information for the downlink broadcast. However, the downlink channel estimate procedure in FDD becomes overly complicated and unfeasible for practical use in massive MIMO systems with multiple antennas (X. Wu et al., 2016).

To overcome this challenge, TDD mode is employed in wireless communication systems. It takes advantage of channel reciprocity, allowing the BS to estimate the downlink channel by utilizing uplink channel information. During the uplink, orthogonal pilot signals are sent by the user to enable the estimation of the CSI by the BS terminal. Subsequently, the BS employs the estimated CSI to direct the downlink data towards the users through beamforming (Choi & Jeong, 2012). Therefore, there is a strong demand for perfect channel estimation algorithms in massive MIMO systems that are low in complexity and overhead. Figure 2.4 shows the geographical representation of TDD and FDD in a massive MIMO system.

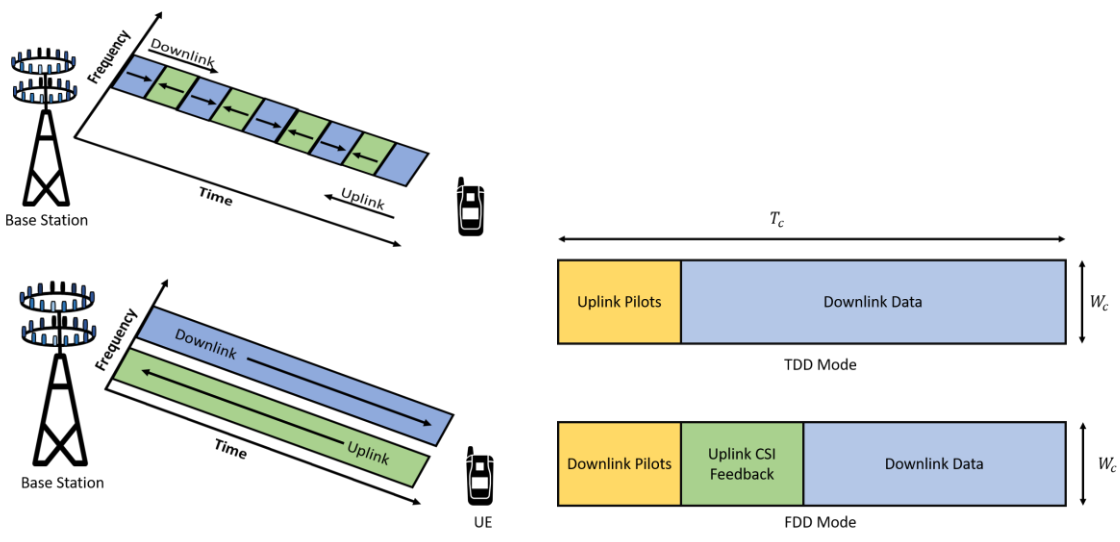

Figure 2.4 Representation of both TDD and FDD operations (Chataut & Akl, 2020b)

2.2.1.3 Precoding

Precoding is a fundamental aspect of beamforming that enables the transmission of multiple data streams in multi-antenna systems. In the context of massive MIMO systems, precoding plays a vital role by mitigating the impact of path loss and interference, thereby maximizing the system's throughput (Fatema et al., 2018). In a cellular massive MIMO system, the BS estimates the CSI using either uplink pilot signals or downlink transmitted signals. Despite the imperfect nature of the received CSI, the performance of the BS in the downlink heavily relies on the accuracy of the

CSI. Figure 2.5 illustrates the precoding techniques used in the downlink of a massive MIMO system with N-user and M-antennas in the BS (Dai et al., 2024). Even though it is significant in the massive MIMO system, as the number of antennas increase in the BS, additional complexity also increases. This can be reduced by applying different decoding techniques.

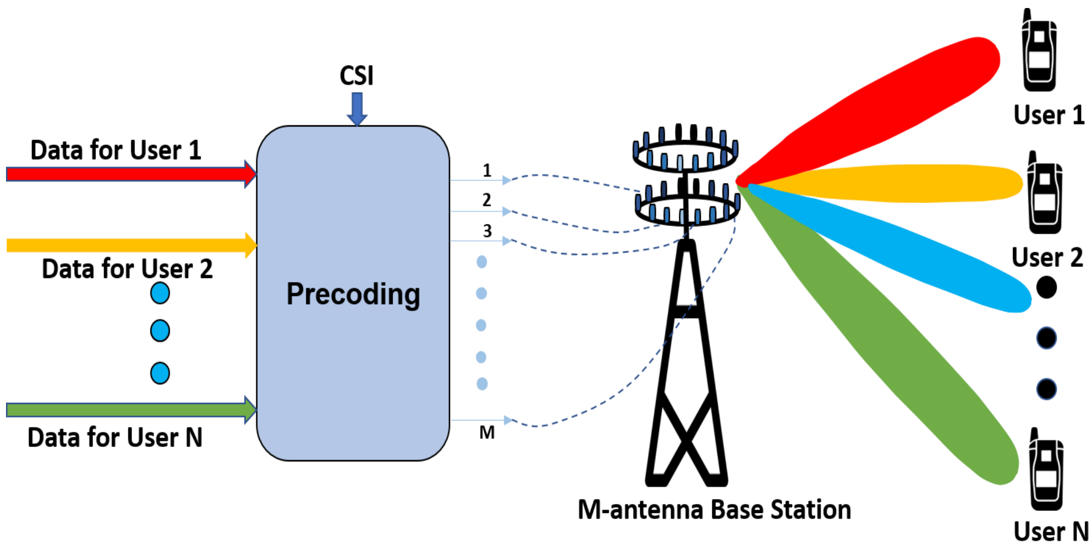

Figure 2.5 Precoding in downlink massive MIMO system with M antennas at the base station (Chataut & Akl, 2020c)

2.2.1.4 Energy efficiency

The relationship between SE and transmitted power is known as the EE. By achieving higher SE at lower power consumption, massive MIMO systems can dramatically boost EE. It measures how much energy is effectively used in the system to transfer data while minimizing energy consumption. Nevertheless, when more antennas and users are added, power consumption also rises, which means that an increase in antennas always results in an increase in SE. To lower the power consumption at the massive MIMO BS, numerous simple and inexpensive techniques such as channel estimation, decoding, and user scheduling have been presented (Choi & Jeong, 2012).

$$\text{Energy Efficiency} = B*SE*P \quad \text{(bits/Joule)} \tag{2.1}$$

where B represents the bandwidth of the given system and P indicates the power required to transmit the signal in watts.

2.3 Cell-free massive MIMO System

A cell-free massive MIMO refers to a network characterized by a large number of APs compared to UEs. The APs work together to provide the UE through a coordinated approach involving joint coherent transmission and reception (Ngo et al., 2017). The network comprises L APs, each containing N antennas, that are placed geographically across the given area. The total number of AP's antennas in the system is denoted by M, where M = N * L. The APs collaborate to serve K UEs, with each UE establishing communication with a specific subset of APs selected based on the given requirements of the UE. To facilitate AP coordination, the fronthaul links are used to link the APs to the CPUs in the cell-free architecture, which is capable of accommodating UEs with multiple antennas (Ssettumba et al., 2024). The following Figure 2.6 illustrates how the connection between APs and CPUs is undertaken with a fronthaul link in the system.

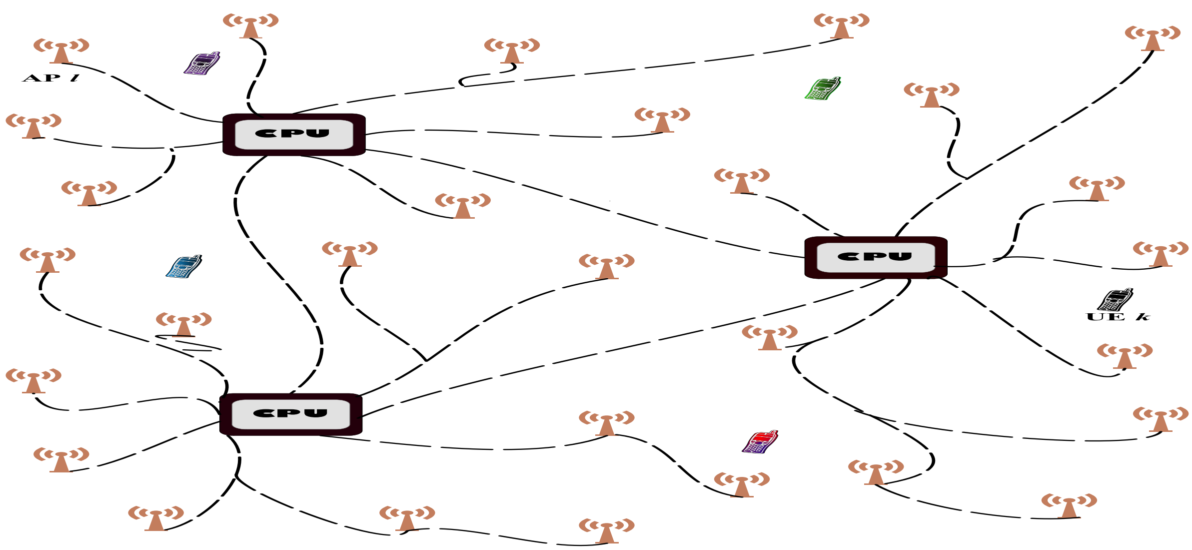

Figure 2.6 Structure of cell-free massive MIMO system (Zaher et al., 2021a)

A cell-free massive MIMO system is a promising physical layer technology that holds potential for future wireless communication networks. It combined the merits of distributed antenna systems (DASs) and network MIMO systems. DAS is a network of antennas that are strategically placed throughout a given area to improve wireless communication. It is commonly used in large buildings, stadiums, campuses, and other areas where a high density of users is present (Imoize et al., 2022). In network configurations, multiple distributed APs work in conjunction with decoding techniques to serve a large number of users while utilizing the same time-frequency resources.

Each AP has multiple antennas, enabling the provision of consistently satisfactory service to all users within the networks (Kassam et al., 2023).

The concept of cell-free massive MIMO network infrastructure is an advantageous implementation of the broader distributed massive MIMO system concept. The TDD operation is used in this method. where a CPU and fronthaul network support a large number of geographically distributed antennas, collectively providing a smaller set of UE within the same time-frequency resources (Ngo et al., 2017). In a cell-free wireless communication system, the same time-frequency resources mean that multiple APs within the system share and use the available radio resources, such as time slots and frequency bands. This is different from traditional cellular systems, where each cell operates on its own separate time-frequency resources (Björnson & Sanguinetti, 2019a). Figure 2.7 shows the distribution of UE and AP within less fronthaul signaling. The cell-free massive MIMO solution is particularly well-suited for various generations, like 5G and beyond, within indoor and hotspot coverage scenarios, like train stations, small villages, factories, stadiums, shopping malls, hospitals, community centers, subways, and college campuses (Zhang et al., 2019b).

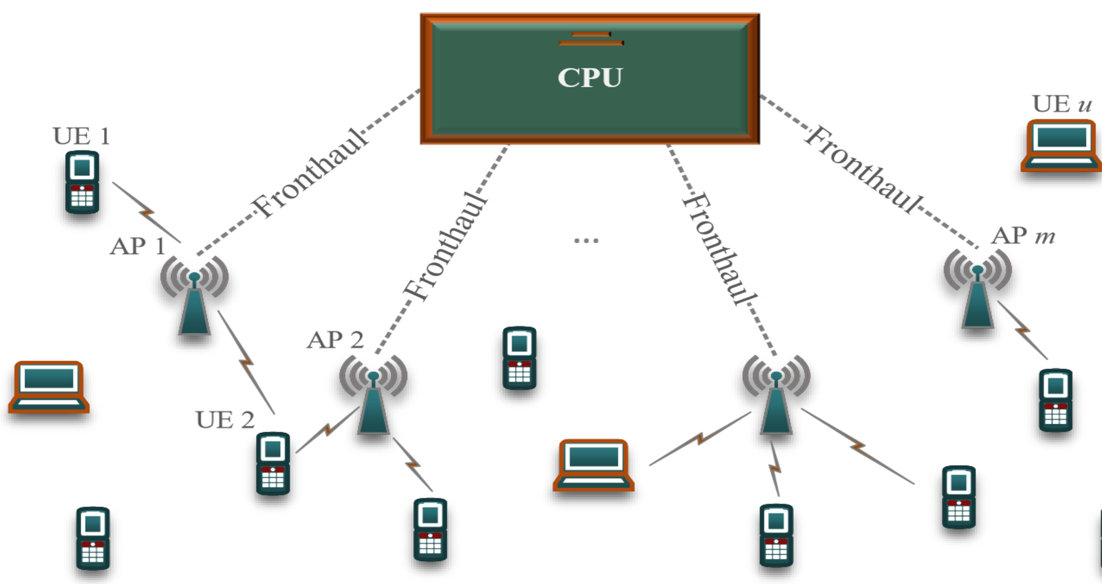

Figure 2.7 Representation of cell-free massive MIMO system with fronthaul link (Kassam et al., 2023)

2.3.1 Advantages of cell-free massive MIMO system

Cell-free massive MIMO system networks offer several advantages in today's wireless communication system (Zhang et al., 2019b). Some of the main elements of it are as follows:

I, High capacity: Multiple users can be accommodated concurrently by cell-free massive MIMO system networks because of their many antennas and distributed APs. The network can handle massive volumes of data traffic and provide high capacity.

II, Improve\d spectral efficiency: The cell-free system employs cooperative signal processing and beamforming techniques to enhance SE, thereby allowing for the transmission of a greater amount of data within a given bandwidth.

III, Better coverage and connectivity: In systems, the use of randomly distributed APs enhances coverage, connectivity, and increasing the likelihood that users will be in close proximity to at least one access point.

IV, Lower latency: The user-centric strategy reduces latency in cell-free large MIMO systems by guarantying optimal user experience and minimizing data transmission delay.

V, Enhanced reliability: The combination of distributed APs and cooperative signal processing techniques enhances network reliability, ensuring that users experience minimal interruptions in their connections.

VI, Lower power consumption: Cell-free massive MIMO systems networks utilize strategies for managing interference, such as power regulation, resource allocation, and scheduling, in order to minimize power consumption and costs.

VII, Flexible: In cell-free massive MIMO system, the network is operating with adaptable to satisfy the requirements of both the user and networks.

2.3.2 Some limitations of cell-free massive MIMO system

Even though cell-free massive MIMO systems offer significant advantages, they also have inherent drawbacks. Some key disadvantages of the system include:

I, Implementation complexity: The deployment of cell-free massive MIMO networks without cells requires considerable coordination and processing resources to manage signals from multiple scattered antennas. This complexity and resource requirement can lead to challenges in implementing the system, making it potentially expensive.

II, Power usage: Cell-free massive MIMO systems without cellular infrastructure require an abundance of antennas and advanced signal processing, which can consume significant power.

III, Limited coverage area: Cell-free massive MIMO systems without cellular infrastructure are commonly deployed in densely populated urban areas, where it is feasible to distribute antennas across the coverage area. However, in rural or remote regions where dispersing antennas is more challenging, the coverage area of the system may be limited.

2.3.3 The root components of cell-free massive MIMO system

The term cell-free massive MIMO system is a network that has distributed APs without a specific cell boundary. As shown in Figure 2.8, a cell-free massive MIMO can be described by four components that operate in TDD mode and have a huge number of APs effectively used for each UE present in the system (Shaik, 2022).

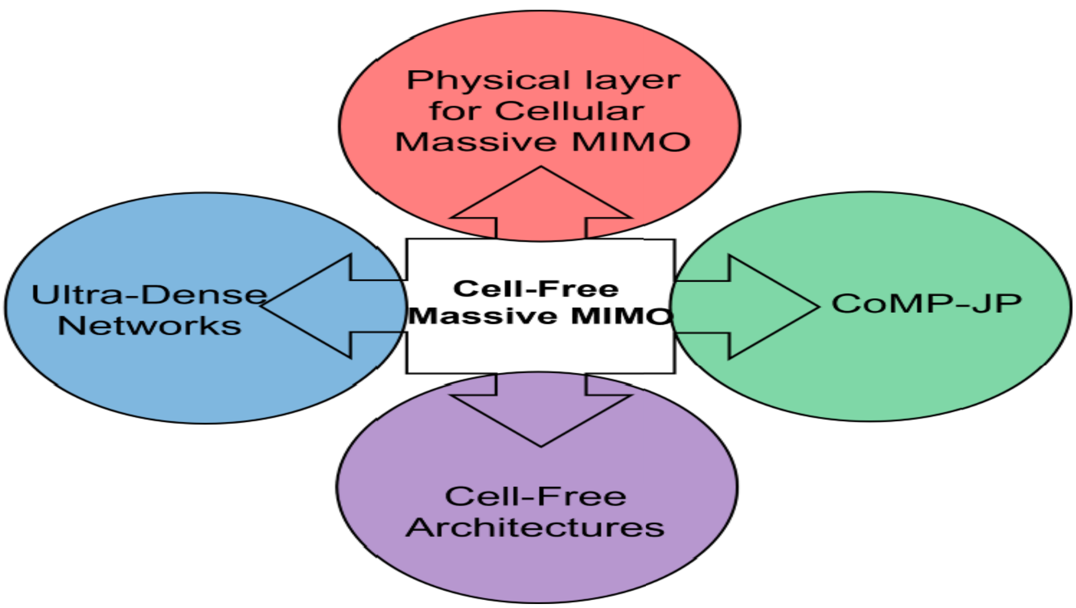

Figure 2.8 Describing of cell-free massive MIMO system as a group of four technologies (Shaik, 2022)

1. Physical layer aspect of cellular massive MIMO: For a given geographical area, a massive number of antennas are serving UEs, with a much greater number of antennas. This technology is used in cellular networks for wireless communication systems. It considers antenna arrays, beamforming, channel estimation, and interference management. The TDD operation is used to use the channel knowledge learned during the uplink training phase in the downlink without having to re-estimate again. enable the network to know the CSI during downlink training in the uplink without re-estimating.

2. Coordinated multipoint joint processing (CoMP-JP): This is a method used in cellular networks to improve the performance by cooperating signal processing of the APs with partial or no CSI exchange among the APs during the uplink and downlink transmitting systems.

3. Ultra-dense networks (UDNs): This refers to a wireless communication system characterized by a large number of distributed antennas and a dense network system to guarantee the UEs provided by many APs. This forms the robustness against the signal blockage as the UEs close the AP antennas.

4. Cell-free architecture: In the context of cell-free massive MIMO systems, it is an architecture used in the wireless communication system to improve the SE by envisioning new cell-free networks from the beginning rather than deploying distributed signal processing on existing cellular networks.

2.3.4 Centralized operation

The centralized cell-free massive MIMO system is the most sophisticated uplink implementation, in which an AP is used to transmit the received signals to the CPU for the signal decoding process. Every AP transmits the received uplink data signal to the CPU. In the CPU, data detection, receive combining, and channel estimation of the transmitted signal are performed (Demir et al., 2021).

$$y^{ul} = \sum_{i=1}^{k} h_i \, s_i + \text{n} \tag{2.2}$$

Where y^{ul} represents the uplink data signal received by the AP, h_i indicates the channel of the system, s_i reveals the transmitted signal, and n implies noise of the system.

The following, Figure 2.9, demonstrates the geographical representation of centralized operations in the cell-free massive MIMO systems, where the two APs are sending the received signal from UEs to the CPU. The CPU's operation could be split across the numerous edge cloud processors located throughout different regions. In centralized operations, every UE is linked to a nearby processor, which is called the CPU, and all APs forward their individual signals to the CPU. The

CPU uses the uplink data signals that are received from the APs to estimate the signal that is delivered by UE k.

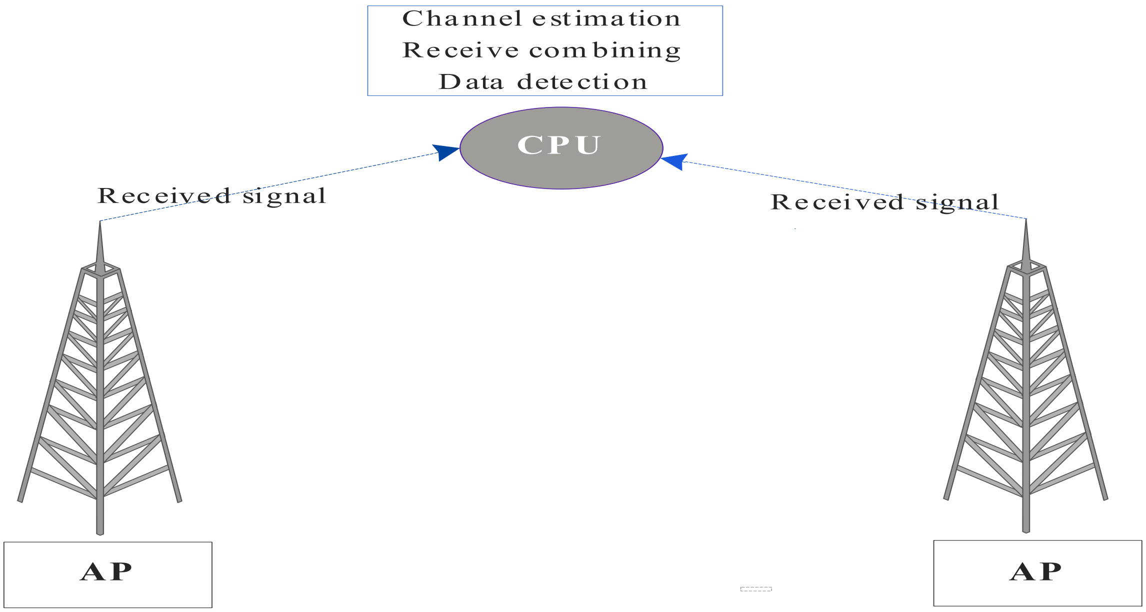

Figure 2.9 Geographical representation of centralized operation system

2.3.5 Distributed operation

Distribution operations are the same as centralized operations, with the only difference being that channel estimation and receiving combining take place across multiple APs, whereas data detection takes place on the CPU. This method is motivated by the fact that each AP has a powerful baseband processor that can be effectively utilized by the APs using their processing capabilities. The goal is to enable the development of a dense network where the number of APs is greater than the number of UEs. The capability of the CPU is determined based on the UEs and is not significantly affected by the deployment of new APs that are added to the network without requiring CPU upgrades (Van Rompaey & Moonen, 2024).

Another reason for deploying distribution operations is to minimize the amount of fronthaul signaling needed and avoid quantization distortion that can occur compared to centralized operations. Figure 2.10 provides an interpretation of distribution operations in cell-free massive MIMO systems, where the two APs are sending the estimated signal to the CPU.

Since, in the cell-free network, multiple APs are involved in handling the UEs, the final detection is executed at the CPU by combining multiple inputs from the APs.

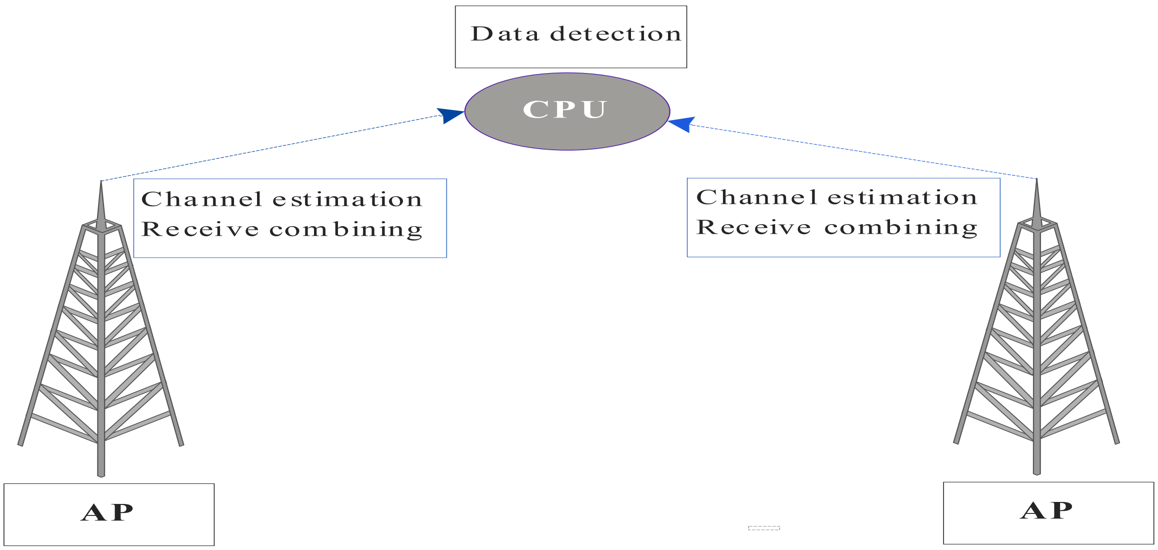

Figure 2.10 Geographical representation of distributed operation system

2.4 Dynamic Cooperative Clustering

Dynamic refers to the ability of a group of APs to adjust to variables that change over time, such as UE locations, interference levels, and service requirements. It refers to the construction of temporary groupings of APs that work together to receive and process uplink signals sent by user devices. These clusters are dynamically created based on the current channel circumstances, user locations, and system requirements (Göttsch et al., 2023).

Figure 2.11 shows a demonstration of the DCC architecture with three UEs and a huge number of APs. The figure-colored zones show which clusters of APs are providing to UEs. Neighboring APs are included in the selection of APs inside a colored zone, denoted by the set $\acute{m}_k$. The user-centric character of this cell-free network, where it is impossible to segregate the APs into various groups that only service different subsets of UEs, is highlighted by the overlapping clusters among UEs. More broadly, when there are many UEs dispersed over the coverage area, each AP serves UEs concurrently with a group of other APs. This co-serving keeps going until all APs are taken into account (Demir et al., 2021b). In the analysis of data transmission performance, we assume that the sets $\acute{m}_k$, where k ranges from 1 to K, are pre-established and familiar in all relevant locations.

We do this assumption because significant changes happen over longer time intervals compared to the changes caused by channel fading.

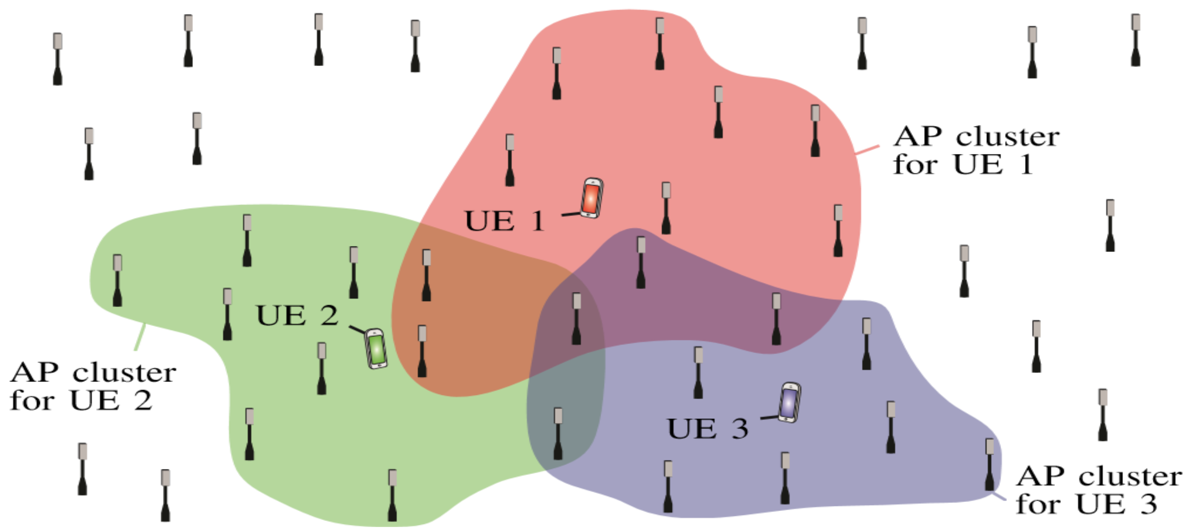

Figure 2.11 Dynamic cooperative cluster (Björnson & Sanguinetti, 2019)

2.5 Review of Related Works

In this section, some works related to performance and interference in cell-free massive MIMO systems were reviewed. Some of them are the following:

In the study (Wang et al., 2021a), a two-layer decoding approach is proposed, where the first layer used an arbitrary combining scheme and the second layer employed optimal large-scale fading decoding (LSFD). They provided closed-form SE expressions for this two-layer decoding with maximum ratio (MR) combining. They also explored four different uplink implementation systems, both distributed and centralized, for deriving SE expressions using minimum mean-squared error successive interference cancellation (MMSE-SIC) decoding. Additionally, they introduced local and global MMSE combining schemes that utilize full and local CSI obtained through pilot contamination, designed to maximize achievable SE for both centralized and distributed implementations. While the channel estimation in this work used MMSE, which has high computational complexity, the authors did not account for variations in the number of UEs.

In (Shi et al., 2022), the authors suggest an uplink partial channel estimator in cell-free massive MIMO under the Rician fading channel, and a set of APs with the best channel condition was evaluated. In addition, the author showed the comparison of phase-aware MMSE with P-MMSE in terms of normalized minimum mean square. The author demonstrated that when the number of UE increased, the quality of the channel estimation decreased. Moreover, when the number of antennae per AP increases, the channel estimation is more beneficial. In this paper, the analysis is limited to channel estimations; only the SE of the paper is addressed. The author did not show the channel estimation when the number of antennas per UE is more than one.

In (Wang et al., 2023), they present two processing algorithms: the fully centralized processing (FCP) scheme and the LSFD scheme. Additionally, they investigate uplink decoding schemes based on iteratively weighted minimum mean square error (iteratively WMMSE) algorithms to improve the weighted sum SE for both processing schemes. Notably, the authors claim to derive closed-form expressions for achievable SE and optimal precoding schemes for the LSFD scheme with MR combining. While it provides improved performance, it lacks specific details about uplink precoding schemes for pilot transmission, fronthaul networks, and only single-antenna UE considered.

The work (Almeida et al., 2024) presents decentralized power optimization methods for cell-free massive MIMO networks. They proposed a cooperative learning structure that utilizes deep neural network (DNN) modules to manage coordination and computation strategies between CPU and APs via fronthaul coordination and enable the CPU and APs to learn and adapt their strategies based on network conditions. For a large number of APs, this introduces computational and communication overhead, which impacts the scalability and complexity of the system, particularly in the context of large-scale systems.

The proposed method in the study (Shakya & Ali, 2021) suggested a lower complexity adaptive method for cell-free massive MIMO networks, aiming to improve network capacity. The authors argue that existing techniques, such as the MMSE receiver, have shown notable capacity gains, but they have high computational complexity and multi-user interference (MUI). The author proposed an approach that involves the CPU iteratively removing MUI without increasing the residual term to improve signal to interference plus noise ratio (SINR) without introducing additional complexity. Even though the proposed method focused on MUI by combining the strongest AP technique selected, it did not assume the effect of the change in AP and UE in the system.

In (Hao et al., 2024), the authors presented two distinct strategies for small-scale and large-scale cell-free massive MIMO systems for simultaneously designing UE connections and power control (PC) in the downlink cell-free massive MIMO network, and they provided numerical outcomes to compare their approaches with other schemes. Successive convex approximation (SCA) and learning-based methods for joint cell-free networks for small-scale systems, as well as the low-complexity algorithm using accelerated projected gradient (APG) algorithms for large-scale systems, are valuable contributions to this work. These techniques offer efficient approaches to tackling the optimization problem. Although the proposed schemes, the SCA method and the APG algorithm, aim to address this challenge, they did not consider techniques like SIC and DCC for minimizing interference.

In the work (et al., 2023), they proposed two precoding techniques in distributed implementation: local partial zero-forcing and local protective partial zero-forcing, which enhanced SE by balancing interference cancellation and desired signal boosting. These schemes require only a few antennas for AP and do not entail additional fronthauling overhead. The study derives the achievable SE for both schemes in the Rayleigh fading channels with the help of minimizing channel estimation errors and pilot contamination. According to the work, the proposed method has better performance than MRT and zero-forcing. They are also able to achieve similar results to regularized zero force, which is considered a benchmark in the downlink. However, the author did not consider techniques of SIC for minimizing interference, and the number of antennas on the system was not clearly defined. Additionally, they did not compare the method with existing techniques used in centralized precoding.

According to (Du et al., 2021), a joint maximum-ratio and zero-forcing (JMRZF) precoding technique was proposed in the cell-free massive MIMO system, which involves certain APs cooperating to perform ZF while other APs employ the straightforward maximum-ratio transmission (MRT) method. Additionally, the authors presented a similar method for choosing an AP based on a large-scale fading coefficient with a mathematical representation that provides a closed-form solution for determining the achievable SE of the proposed technique. The simulations conducted in the study indicate that the JMRZF technique outperforms local precoding techniques, even when only a small subset of APs is combined to perform. In the cell-free setup, estimating the channels among the distributed APs and the users becomes a challenging task. The author didn't provide detailed insights into how channel estimation is performed, and the proposed precoding technique is used only for comparison with the local precoders; there is no interaction with centralized precoding schemes.

The work (Settumba et al., 2024) improved the performance of cell-free massive MIMO systems by using the proposed iterative interference cancellation algorithms. An iterative detection and decoding (IDD) method are implemented with log-likelihood ratio refinement strategies that incorporate AP selection. They also drove closed-form expressions for centralized and decentralized linear minimum mean square error (MMSE) received under imperfect CSI, providing solutions for MMSE-SIC and MMSE filters. Additionally, a new Gaussian approximation of the likelihood function was formulated to minimize the error propagation in the MMSE-SIC receiver by using a list-based detector that uses interference cancellation. Although comparing the proposed centralized and decentralized IDD schemes with existing systems gives a lower bit error rate and complexity under both perfect and imperfect CSI, they did not address the impact of varying numbers of UE and AP on the performance of the system.

Table 2.1 Summary of some related works

Author/year	Title	Contribution	Gap
(Wang et al., 2021a)	Uplink Performance of cell-free massive MIMO system over Rayleigh fading channel	They derived SE expressions, utilizing MMSE-SIC detectors, and introduced global and local MMSE combining schemes for centralized and distribution operations, respectively.	This technique has a high computational complexity and the variation of number of users is not considered.
(Wang et al., 2023)	Uplink precoding design for cell-free massive MIMO with iteratively weighted MMSE	The authors proposed the use of fully centralized and large-scale fading decoding schemes. They investigated uplink precoding techniques based on iteratively weighted MMSE algorithms to	Lacks specific details in uplink precoding schemes for pilot transmission, fronthaul networks, and only single-antenna UE considered.

		improve the weighted sum SE for both processing techniques.	
(Shakya & Ali, 2021)	Joint access point selection and interference cancellation for cell-free massive MIMO system	JAPSIC is proposed to combine signals from the APs that have the strongest signal, cancel interference and the CPU used to lower the complexity.	The proposed method focused only on MUI by combining the selected strongest AP technique, it did not assume the effect of the change in AP and UE in the system.
(Hao et al., 2024)	Joint user association and power control for cell-free massive MIMO	SCA and learning-based methods for small-scale systems and low-complexity suboptimal algorithm using the APG for large-scale systems were proposed.	They did not consider techniques like SIC and DCC for minimizing interference.
(Du et al., 2021)	Joint Maximum-Ratio and Zero-Forcing Precoder with Power Control	JMRZF precoding techniques, which have higher performance than local precoding techniques with some AP's antennas.	The proposed precoding technique is restricted to comparing with local precoders only.

CHAPTER THREE

3. MATERIAL AND METHODOLOGY

3.1 Introduction

In this study, some sources of information related to the SE in the uplink signal detection of cell-free massive MIMO systems with multi-antennas UE over fading channels are included. The methodology of the thesis is demonstrated based on some reviewed literature and various articles from the Institute of Electrical and Electronics Engineers (IEEE), journals, and books that applied their own proposed techniques to emerge with enhanced performance and minimum interference decoding methods.

3.2 Materials

This thesis utilizes two software programs, which are MATLAB and ConceptDraw DIAGRAM. MATLAB is a popular programming tool that scientists and engineers use for research, design, simulations, and the development of new technologies. It was used to simulate the results presented in Chapter 4. ConceptDraw DIAGRAM, on the other hand, is a versatile drawing software that gives professionals a tool to draw figures. It allows for the easy creation and customization of diagrams. Apart from these simulation results in chapter four, all other diagrams in the thesis, such as basic shapes, flowcharts, block diagrams, technical drawings, computer networking, and telecommunication network diagrams, were created using ConceptDraw DIAGRAM.

3.3 Methodology

In order to perform the objectives that we have discussed in chapter one, thesis work is expressed by the following steps.

Literature Review: this thesis work is intimately linked to previous research on the subject by experts or scholars.

Problem Identification: based on the paper reviewed from different journals, articles and conferences the problem (research gaps) is identified for research study.

System Designing: after the identification of research gap the systems are designed for proposed work. After modeling of the proposed system, the simulation is done using MATLAB tools.

Result and Discussion: depending up on the results from simulation, discussions are performed on the results and performance evaluation are also done on proposed techniques. Finally, after analyzing the results of the designed system, the whole work of the research study is concluded by suggesting an implied recommendation and further work to be done on the areas.

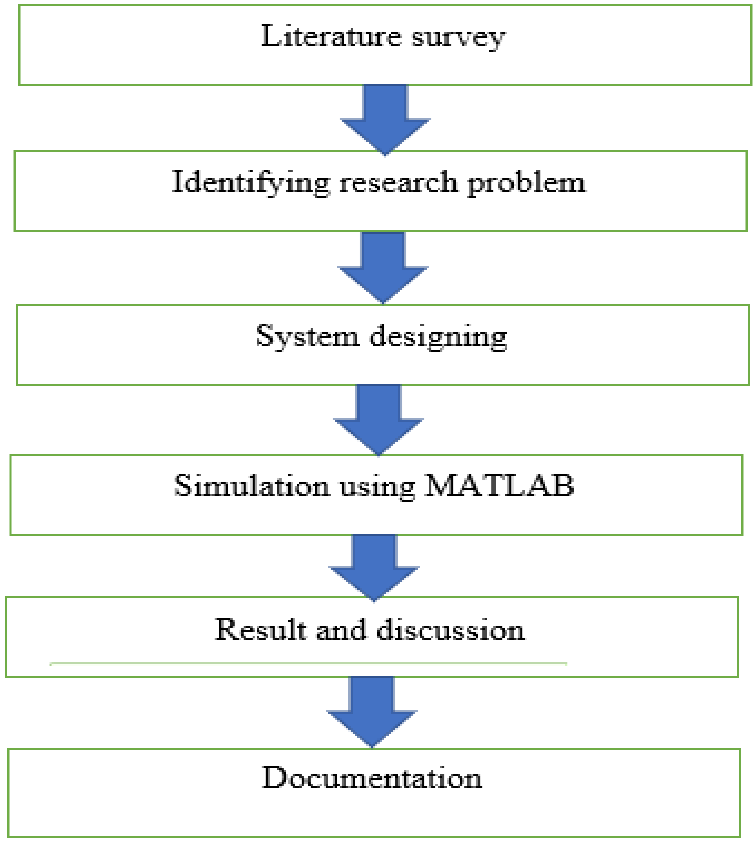

Figure 3.1 Methodology

3.3.1 System design

- Examine and analyze the mathematical model of the proposed technique and existing decoding techniques to find the improved SE of the system.
- Developing hybrid signal decoding techniques based on P-MMSE and DCC with SIC for the uplink cell-free massive MIMO network.

3.3.2 System model

We consider a cell-free massive MIMO network with L APs, each AP having an N antenna, where the APs are geographically randomly distributed over a given specific area. The number of antennas in the system is denoted by M = N * L. The UEs are served by the APs, which are represented by K (Gao et al., 2023). The system operates in TDD mode, where the coherent time in each block is represented by $\tau_c = \tau_p + \tau_d + \tau_u$ samples, with τ_p samples set for pilot signal transmitting, τ_u for uplink data transmitting, and τ_d for downlink data transmitting. The number of active APs needed in the system depends on the number of UEs operating in the system. The fronthaul signaling used to link the APs to the CPU is shown in Figure 3.1.

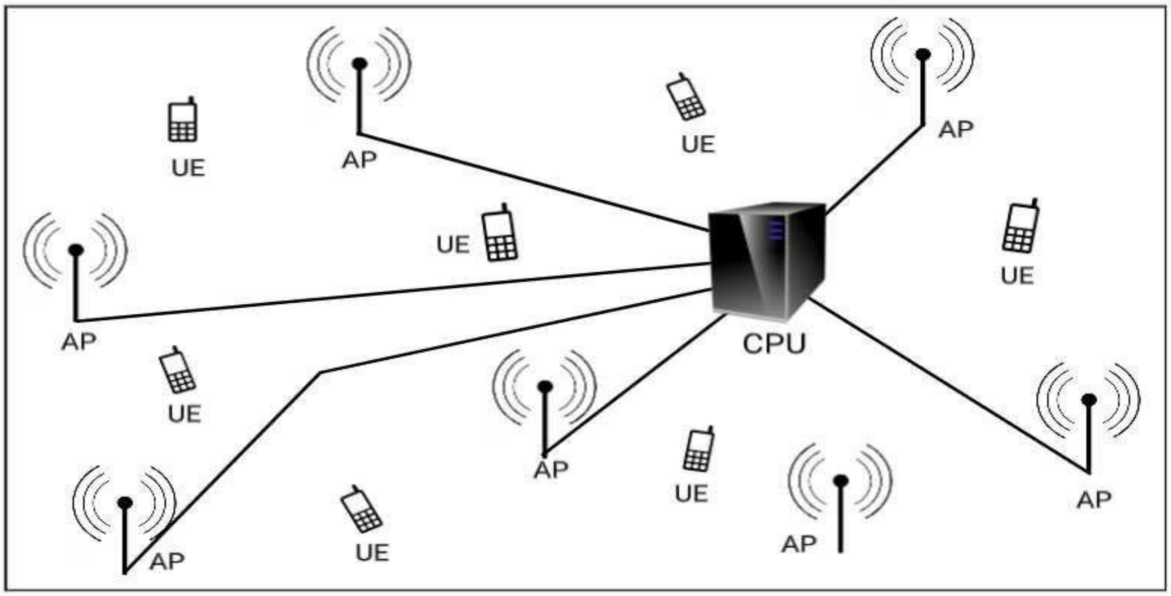

Figure 3.2 System model of cell-free massive MIMO system with one CPU, L AP and K UEs (Kassam et al., 2023)

There is a coherence block that divides into three distinct phases: uplink pilot transmitting, uplink data, and downlink data transmissions. When the uplink training phase is underway, the pilot sequences are transmitted by the UE to the APs, allowing each AP to estimate the channel for all UEs. This estimated channel is used for precoding the received signals in the downlink and detecting the received signals in the uplink. The following expression is used for the uplink desired signal receiving at AP (Shakya & Ali, 2021).

$$y^{ul} = \begin{bmatrix} y_l^{ul} \\ \vdots \\ y_L^{ul} \end{bmatrix} = \sum_{i=1}^{K} h_i \, s_i + \text{n} \quad (3.1)$$

where $y^{ul} \in \mathbb{C}^{LN}$ reveals the collective uplink data signal received by AP, n = $[n_1^T \cdots n_L^T]^T \in \mathbb{C}^{LN}$ represents the collective noise vector and the APs receive the signal from all UE's, s_i represents the signal transmitted from the UE in the uplink transmission system, and the channel vector is written as $\{h_i : i = 1, \ldots, K\}$. The CPU uses the signal received by APs in coherent to compute an estimate $\hat{S}_k$ of the signal s_k which transmitted by UE k is described by (Demir et al., 2021).

$$\hat{S}_k=\sum_{l=1}^{L} V_{kl}^{H} D_{kl} y_l^{ul} = V_k^H D_k y^{ul} \tag{3.2}$$

where $V_k = [V_{k1}^T \cdots V_{kL}^T]^T \in \mathbb{C}^{LN}$ represents the centralized combining vector, V_{kl}^H implies the Hermitian transpose of V_{kl} and V_{kl}^T is transpose of V_{kl}, and D_k indicates block diagonal matrix with the following expression:

$$D_{kl} = \begin{cases} I_N & , \quad l \in M_k \\ 0_{NxN} & , \text{otherwise} \end{cases} \tag{3.3}$$

where k and l represent UE and AP respectively. Since the CPU apply a receiving combining using the received signals by APs, then the block-diagonal matrix should $D_{kl} \neq 0_{NXN}$. Meaning that, the above equation (3.2) can write as:

$$\hat{S}_k= \sum_{l\in M_k} V_{kl}^{H}\, y_l^{ul} \tag{3.4}$$

3.3.2.1 Spectral efficiency with centralized operation

We can perform possible expression for SE that works with any decoding method. The received signal from UE K can be breakdown into the following parts (Demir et al., 2021):

$$\hat{S}_k = \underbrace{v_k^H D_k \check{h}_k s_k}_{\text{desired signal}} + \underbrace{\sum_{\substack{i=1 \\ i\neq k}}^{K} v_k^H D_i h_i s_i}_{\text{interference}} + \underbrace{v_k^H D_k n}_{\text{noise}} \tag{3.5}$$

From the above equation (3.5), the first one is the desired signal, which was received over the known, partially estimated channel of k^{th} UE. The next second and third are interference and noise, respectively. By (Sheikh, 2023) the uplink SE of UE with centralized operation is given by the following expression:

$$SE_k^{(ul,c)} = \frac{\tau_u}{\tau_c} \log_2\left(1 + SINR_k^{(ul,c)}\right) \qquad \text{(bit/s/Hz)} \tag{3.6}$$

where the coefficient $\frac{\tau_u}{\tau_c}$ is the fraction of uplink to coherent block, which is applied in the data transmission systems and SINR is the ratio of signal to interference and noise ratio in the uplink cell free massive MIMO systems. SINR is expressed by the following equation:

$$\mathrm{SINR}_k^{(\mathrm{ul,c})} = \frac{\mathbf{p}_k \left|\mathbf{V}_k^{\mathrm{H}} \mathbf{D}_k \hat{\mathbf{h}}_k\right|^2}{\sum_{\substack{i=1 \\ i \neq k}}^{K} \mathbf{p}_i \left|\mathbf{V}_k^{\mathrm{H}} \mathbf{D}_k \hat{\mathbf{h}}_i\right|^2 + \mathbf{V}_k^{\mathrm{H}} \mathbf{Z}_k \mathbf{V}_k + \sigma_{\mathrm{ul}}^2 \|\mathbf{D}_k \mathbf{V}_k\|^2} \quad (3.7)$$

with $\hat{\mathbf{h}}_k$ is the estimated channel matrix and $\mathbf{Z}_k = \sum_{i=1}^{K} \mathbf{p}_i \mathbf{D}_k \mathbf{C}_i \mathbf{D}_k$ is the spatial correlation matrix of received signals via the undefined portion of the channel. $\mathbf{C}_i$ is the matrix of error correlation in the collective channel $\mathbf{h}_i$ with a transmitted power of $\mathbf{p}_i$. The last term of the denominator of equation (3.7) is the noise power of the received combining.

3.3.2.2 Minimum mean square error (MMSE) combining

The MMSE combining technique is used to minimize the mean squared error between the desired and estimated signals while adhering to certain constraints related to the channel model and noise signals. By mitigating the impact of interference and noise signals, MMSE can enhance system efficiency. However, it has a higher complexity than other combining techniques due to the necessity of direct matrix inversion during its implementation (Miretti et al., 2024). The SINR of UE K is the same as equation (3.7), which is enhanced by the MMSE combining vector and given as below (Björnson & Sanguinetti, 2019; Mai et al., 2020):

$$\mathrm{SINR}_k^{(\mathrm{ul,c})} = \frac{\mathbf{p}_k \left|\mathbf{V}_k^{\mathrm{H}} \mathbf{D}_k \hat{\mathbf{h}}_k\right|^2}{\sum_{\substack{i=1 \\ i \neq k}}^{K} \mathbf{p}_i \left|\mathbf{V}_k^{\mathrm{H}} \mathbf{D}_k \hat{\mathbf{h}}_i\right|^2 + \mathbf{V}_k^{\mathrm{H}} \mathbf{Z}_k \mathbf{V}_k + \sigma_{\mathrm{ul}}^2 \|\mathbf{D}_k \mathbf{V}_k\|^2}$$

where the combining vector is given by:

$$V_k^{\mathrm{MMSE}} = p_k \left(\sum_{i=1}^{K} p_i \mathbf{D}_k \left(\hat{\mathbf{h}}_i \hat{\mathbf{h}}_i^{\mathrm{H}} + \mathbf{C}_i \right) \mathbf{D}_k + \sigma_{\mathrm{dl}}^2 \mathbf{I}_{LN} \right)^{-1} \mathbf{D}_k \hat{\mathbf{h}}_k \quad (3.8)$$

3.3.2.3 Partial MMSE (P-MMSE) combining

The P-MMSE combining technique is a modified version of MMSE combining that is used in uplink cell-free massive MIMO networks. It offers a balance between the performance and computational complexity of the systems by considering only a subset of the interference produced during the process. In this way, the distributed APs work coherently to serve numerous users. The computational complexity of P-MMSE decoding is lower than that of MMSE due to the selection of a subset of the existing user’s signal. It is reasonable to assume that, in a large cell-free network with scattered UEs, the majority of the interference affecting UE K is generated by a small fraction of the other nearby UE k. Using this fact, we hope to arrive at a scalable alternative by lowering the computational complexity of the optimal MMSE combination (Lancho et al., 2022). The SE has the same formula as equation (3.6); the only difference is in combining vectors, and it is given by:

$$V_k^{\mathrm{P-MMSE}} = p_k\left(\sum_{i\epsilon s_k}^{K} \ p_i \mathbf{D}_k \hat{\mathbf{h}}_i \hat{\mathbf{h}}_i^{\mathrm{H}} \mathbf{D}_k + Z_{S_k} + \sigma_{\mathrm{ul}}^2 \mathbf{I}_{LN}\right)^{-1} \mathbf{D}_k \hat{\mathbf{h}}_k \tag{3.9}$$

where

$$Z_{S_k} = \sum_{i\epsilon s_k} p_i \mathbf{D}_k \mathbf{C}_k \mathbf{D}_k \tag{3.10}$$

$$S_k = \{i: \ \mathbf{D}_k \mathbf{D}_i \ \neq \ 0_{LNxLN}\} \tag{3.11}$$

3.3.2.4 Partial regularized zero force (P-RZF) combining

The P-RZF combining technique is a modified version of ZF that is used at the receiver section in an uplink cell-free massive MIMO system to suppress the interference of the users. Although there may be numerous antennas near UE K, the complexity of the P-RZF combining vector is scaled assuming that each AP has a small number of antennas in the network. But because the combining vector is processed by the CPU, there may be higher computational complexity. However, it is important to further reduce the computational complexity without affecting performance. The combining vector can be written as follows (Sheikh, 2023):

$$V_k^{\mathrm{P-RZF}} = p_k\left(\sum_{i\epsilon s_k} p_i \mathbf{D}_k \hat{\mathbf{h}}_i \hat{\mathbf{h}}_i^{\mathrm{H}} \mathbf{D}_k + \sigma_{\mathrm{ul}}^2 \mathbf{I}_{LN}\right)^{-1} \mathbf{D}_k \hat{\mathbf{h}}_k \tag{3.12}$$

3.3.2.5 Maximum ratio (MR) combining

MR combining is the simplest technique used in both centralized and distributed operations. When we compare it with other methods, in the presence of interference, it has poor performance because the high level of propagation cannot be warranted between all UEs. In the context of computational complexity per user, it has lower computational complexity, and independent of UE, it is a scalable method with lower complexity. The combining vector is given by:

$$V_k^{\mathrm{MR}} = \mathbf{D}_k \hat{\mathbf{h}}_k \tag{3.13}$$

3.3.2.6 Spectral efficiency with distributed operation

Instead of having both data detection and channel estimation take place on the CPU, the cell-free massive MIMO system offers a distribution approach where the estimation of the channel is done on the APs and data detection is done on the CPU. The approach is motivated by the fact that each AP has a baseband processor as powerful as those in the UEs. The CPU's capacity is primarily decided by the number of UE, which means it doesn't affect the deployment of new APs, which can be added to the system without the need to upgrade the CPUs since each AP has its own local processor (Shaik, 2022).

In addition, the distributed operation minimizes the fronthaul quantization in practical terms and has another significant advantage over the centralized operation in terms of lowering fronthaul signaling levels. Since each UE in a cell-free massive network is served by many APs, data detection takes place at the place where the inputs from all of the APs are aggregated.

$$\mathrm{SE}_k^{(\mathrm{ul,c})} = \frac{\tau_u}{\tau_c} \log_2 \left(1 + \mathrm{SINR}_k^{(\mathrm{ul,c})}\right) \text{ bit/s/Hz} \tag{3.14}$$

where

$$\mathrm{SINR}_k^{(\mathrm{ul,c})} = \frac{\mathbf{p}_k \left|\mathbf{a}_k^{\mathrm{H}} \mathbf{E}\{\mathbf{g}_{kk}\}\right|^2}{\mathbf{a}_k^{\mathrm{H}} (\sum_{\mathrm{i}=1}^{K} \mathbf{p}_i \mathbf{E}\{\mathbf{g}_{ki} \mathbf{g}_{ki}^{\mathrm{H}}\} - \mathbf{p}_k \mathbf{E}\{\mathbf{g}_{k}\} \mathbf{E}\{\mathbf{g}_{kk}^{\mathrm{H}}\} + \mathbf{F}_k) a_k} \tag{3.15}$$

$$\mathbf{F}_k = \sigma_{ul}^2 \mathrm{diag}(E\{\|D_{k1} v_{k1}\|^2\}, \cdots, E\{\|D_{kL} v_{kL}\|^2\}) \in R^{LxL} \tag{3.16}$$

3.3.2.7 Local Partial MMSE (LP-MMSE) combining

$$V_{kl}^{\mathrm{LP-MMSE}} = p_k \left(\sum_{i \epsilon \dot{\mathrm{D}}_L}^{K} p_i (\hat{\mathbf{h}}_{il} \hat{\mathbf{h}}_{il}^{\mathrm{H}} + c_{il}) + \sigma_{\mathrm{ul}}^2 \mathbf{I}_N\right)^{-1} \mathbf{D}_{kl} \hat{\mathbf{h}}_{kl} \tag{3.17}$$

LP-MMSE combining is a technique used in the cell-free massive MIMO system where the AP locally combines the received signal. As UEs k → ∞, the number of complex multiplications required by LP-MMSE has not increased since it is scalable. The complexity per UE of LP-MMSE has a matrix inverse of N x N, which is lower than the complexity of P-MMSE with a matrix inverse of $N|M_k|\ x\ N|M_k|$.

3.3.2.8 Local MMSE (L-MMSE) combining

The L-MMSE combining technique is one method of the decoding algorithm used in distributed operations, which can minimize the signaling overhead and computational complexity. It improves the system's scalability; the combining vector used for this is expressed in the following equation:

$$V_{kl}^{\mathrm{L-MMSE}} = p_k \left(\sum_{i=1}^{K} p_i (\hat{\mathbf{h}}_{il} \hat{\mathbf{h}}_{il}^{\mathrm{H}} + c_{il}) + \sigma_{\mathrm{ul}}^2 \mathbf{I}_N\right)^{-1} \mathbf{D}_{kl} \hat{\mathbf{h}}_{kl} \tag{3.18}$$

3.4 Uplink Transmissions

3.4.1 Uplink training phase

During this stage, the APs receive the pilot signals simultaneously from each antenna of the users. The received pilot signals by the APs will be used to estimate the channels present between the transmitter and receiver. Let represent the coherence block, which is the product of coherence block time and coherence block bandwidth and represents the duration of the training phase per coherent interval. Assuming that every user's antenna uses coherent orthogonal pilot sequences, $\tau \geq K * N$ (Wang et al., 2021b).

3.4.2 Uplink data transmissions

The data transmitted from the UE to the APs in the network is referred to as uplink data transmission. Multiple APs receive the data signals from the UE at the same time, and they work together to process the signal that is received, and the CPU estimates the CSI of the UEs. The enormous number of dispersed antennas enables the CPU to efficiently cancel out the interference coming from other UEs and jointly decode the received signal (Chataut & Akl, 2020).

3.5 Proposed Method

The main issues in an uplink cell-free massive MIMO system are detecting the original signal by removing the interference signal that exists in the channel. We consider a cell-free massive MIMO system in which the APs and UEs are uniformly randomly distributed over a given geographical area, with different antenna sizes given a specific area. The proposed detection technique follows a novel algorithm termed P-MMSE and DCC with the SIC detection algorithm by modifying P-MMSE detection methods through the formation of a group matrix. The UEs in the cell-free massive MIMO systems transmit their data signals to the APs. UE's signal may experience multiple paths due to the presence of multiple APs. The received signals from UEs are combined at each AP using a P-MMSE combining technique to improve the signal quality by minimizing the mean square error between the combined signal and the desired signal. On the other hand, SIC enhances interference cancellation by progressively eliminating the strongest interference signals, and a DCC is utilized to create a group of distributed APs that collaborate with each other to serve a set of UE. This clustering mitigates interference within clusters, allowing the cancellation of interference from neighboring clusters. The interference cancellation technique is performed at the APs for distributed uplink operations and at the CPU for proposed centralized uplink operations.

$$y^{ul} = \begin{bmatrix} y_l^{ul} \\ \vdots \\ y_L^{ul} \end{bmatrix} = \sum_{i=1}^{K} h_i \, s_i + \text{e} \tag{3.19}$$

From the above equation (3.19), the first part is the desired signal, whereas the second part is the unwanted signal which can be expressed in the following:

$$\text{e} = \text{n} + \sum_{i=1}^{K} \tilde{h}_i \, s_i \tag{3.20}$$

where n = $[n_1^T \ \cdots \ n_L^T]^T \in \mathrm{C}^{LN}$ represents the noise and $\sum_{i=1}^{k} \tilde{h}_i \, s_i$ indicates the interference comes signal from the unwanted channel respectively.

$$\text{SE}_k^{proposed} = \frac{\tau_u}{\tau_c} \log_2 \mathrm{E}\left\{\log_2 \det\left(\mathbf{I}_k + P\hat{h}^H f^{-1}\hat{h}\right)\right\} \tag{3.21}$$

$$f = \sum_{i=1}^{K} p_i \mathbf{C}_i + \sigma_{\text{dl}}^2 \mathbf{I}_{LN} \tag{3.22}$$

where $\mathbf{I}_k$ is the identity matrix with the vector matrix of k

P = diag($\text{p}_1, \dots, \text{p}_K$), is the diagonal matrix of the transmitted power in each UE

$\hat{h} = [\hat{h}_1, \dots, \hat{h}_K] \in C^{LNxK}$ is the estimated channel

in this work, all the channel estimation and data detections are takes place at the CPU. All APs are served for receiving the signal from the UEs and send to CPU to detect the data signal (Wang et al., 2021a).

3.5.1 Successive interference cancellation (SIC)

In the centralized operation of an uplink cell-free massive MIMO network, the CPU is responsible for coordinating the operation of multiple distributed APs in the system. The SIC technique is applied to mitigate interference and improve the system's performance. Each AP receives the uplink signals transmitted by the UE in the coverage area, where the received signals contain both the desired signal and unwanted interference from the other UEs due to the presence of multiple UEs transmitting simultaneously. After the initial detection and decoding, SIC is applied at the CPU to cancel the interference caused by the signals of other UEs. The CPU uses the estimated interference from the successfully detected UEs to remove it from the combined signal. The interference cancellation process is performed iteratively. After canceling the interference of one UE, the central unit repeats the process to detect and decode the signals of the remaining UEs. The interference estimation and cancellation are updated at each iteration until all UEs are successfully detected.

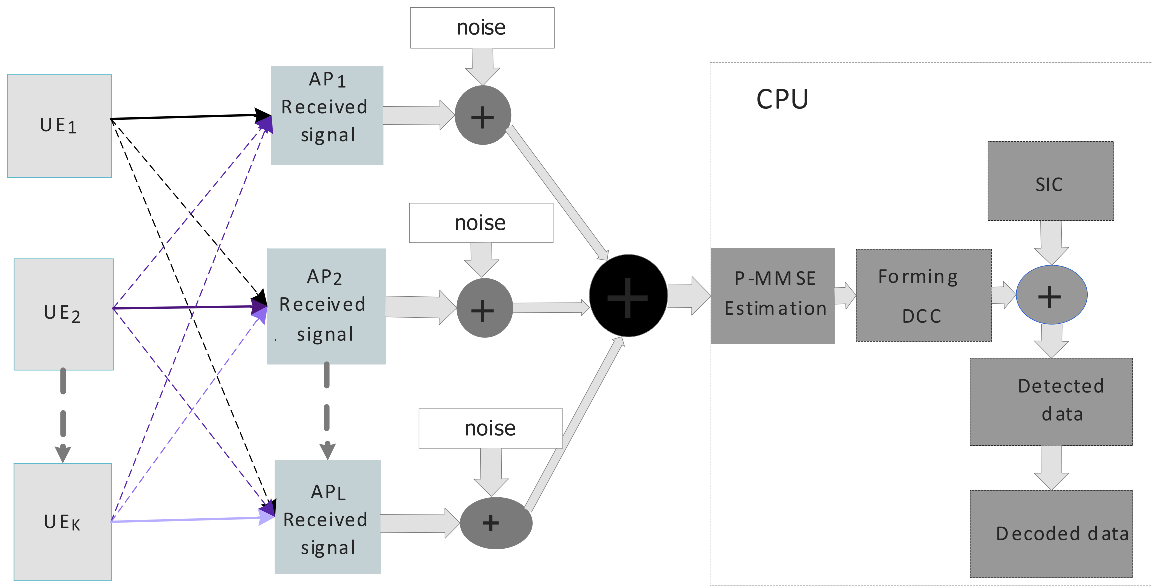

Figure 3.3 Block diagram of the proposed detector P-MMSE with DCC and SIC

The flow chart shows the combination of P-MMSE and DCC with SIC in uplink cell-free massive MIMO systems. Channel realization is generated to receive the signal at AP. The P-MMSE equalization matrix is used to reduce the interference coming from other users, followed by DCC, and each cluster undergoes SIC to eliminate the interference from each user. The SINR is calculated for each user, and data detection is used to estimate the transmitted signals. Finally, the received data is decoded using the estimated signals, enabling reliable communication in the uplink cell-free communication systems.

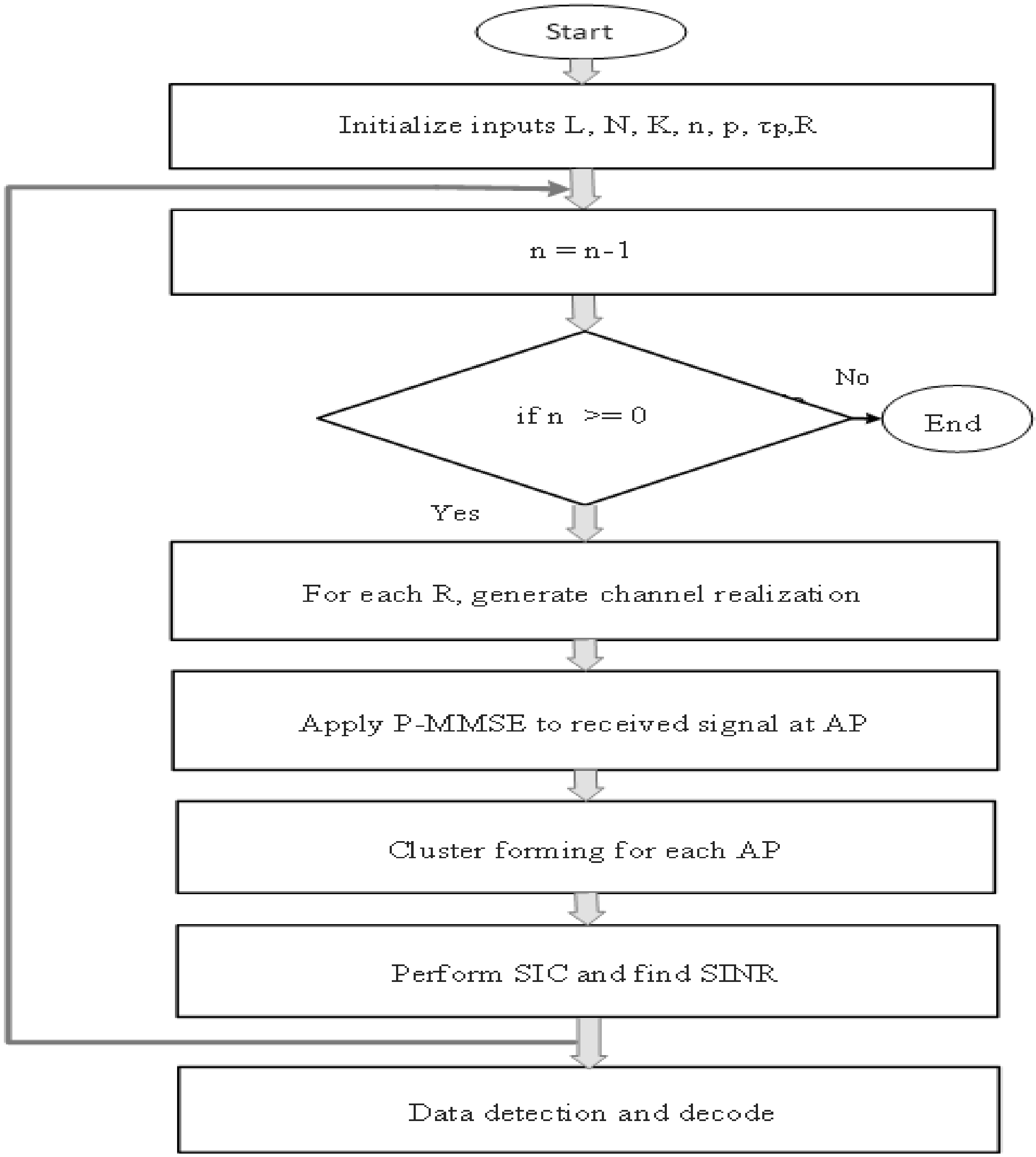

Figure 3. 4 Flowchart of the proposed decoding technique

Algorithm 1: Pseudo-code for the proposed decoding technique based on P-MMSE and DCC with SIC is given by the following

---

Start
Inputs: L, N, n, K, R, p, τ_c

while n ≥ 0

Iteration:

for i = 1: R

generate channel realization

cluster forming in the APs

performing SIC

find SINR

data detection

data decoding

end

end while

3.6 Performance Metrics of Signal Detection Algorithms

The performance of the signal decoding used in uplink cell-free massive MIMO systems is measured using measurements such as SE, sum SE, and number complex complications.

3.6.1 Spectral efficiency (SE)

SE is the amount of data that can be transmitted via a communication channel per bandwidth. It is commonly expressed in bit/s/Hz. With more signal power, the system's SE will rise. However, when signal power increases, so does the system's power consumption, which significantly lowers the system's energy efficiency (Jayaweera et al., 2024).

$$\text{Spectral Efficiency} = \frac{\text{transmited data rate}}{\text{given bandwidth}} \quad \text{(bit/s/Hz)} \tag{3.23}$$

3.6.2 Sum spectral efficiency (sum SE)

In a cell-free massive MIMO system, the sum SE refers to the total amount of SE that could be reliably transmitted by the UEs over the wireless communication channel. It has the same measurement as the SE, with a unit of bit/s/Hz. It can be influenced by several factors, like the number of APs, UE, channel conditions, the amount of transmitted power, and the beamforming algorithms.

3.6.3 Bit error rate (BER)

BER is one of the most methods to examine the performance of cell-free massive MIMO systems. It is the ratio of total error bit to the total transmitted bits in the wireless communication. It can be written as:

$$\text{BER} = \frac{\text{tatal bits in error}}{\text{tatal number of transmitted bits}} \tag{3.24}$$

The BER is the percentage of received bits that have errors with respect to the transmitted bits in a communication. It is a critical parameter for assessing the performance of signal detection algorithms.

3.6.4 Complex multiplications

Considering the complex multiplication in the decoding technique, it is an important key in the uplink cell-free massive MIMO system. The network makes extensive use of the distributed APs inside the designated area to improve the performance of the system. Many parameters, including the number of UEs and transmit and receiving antennas, influence the computational complexity of the decoding method.

Table 3.1 Computational complexity of some centralized and distributed combining schemes

Technique	Precoding vector computational complexity
MMSE	$\frac{(N\|\mathcal{M}_k\|)^2 + N\|\mathcal{M}_k\|}{2}K + (N\|\mathcal{M}_k\|)^2 + \frac{(N\|\mathcal{M}_k\|)^3 - N\|\mathcal{M}_k\|}{3}$
P-MMSE	$\frac{(N\|\mathcal{M}_k\|)^2 + N\|\mathcal{M}_k\|}{2}\|\mathcal{P}_k\| + (N\|\mathcal{M}_k\|)^2 + \frac{(N\|\mathcal{M}_k\|)^3 - N\|\mathcal{M}_k\|}{3}$
P-RZF	$\frac{\|\mathcal{S}_k\|^2 + \|\mathcal{S}_k\|}{2}N\|\mathcal{M}_k\| + \|\mathcal{S}_k\|^2 + \|\mathcal{S}_k\|N\|\mathcal{M}_k\| + \frac{\|\mathcal{S}_k\|^3 - \|\mathcal{S}_k\|}{3}$

CHAPTER FOUR

4. RESULT AND DISCUSSION

4.1 Chapter overview

The simulation results to validate the proposed technique were performed, and the results are presented in this chapter. The simulation results and discussion on the performance of the proposed decoding and other existing decoding techniques for uplink cell-free massive MIMO systems over the Rayleigh fading channel based on SE, sum SE, and BER are provided. In addition, the number of complex multiplications for both proposed and existing decoding techniques is also presented. The simulation parameters used in this thesis work to analyze the performance of the proposed and existing decoding techniques are listed in Table 4.1.

Table 4.1 Simulation parameters (Björnson & Sanguinetti, 2019)

No.	Parameters	Value or type
1	Area of the system	1 km × 1 km
2	Network deployment	Random deployment
3	Number of antennas (N)	1,2,3,4,5, and 10 to 100 for complex multiplications
4	Number of APs (L)	100, 200,300,400, 500
5	Total Number of antennas in APs (M = L * N)	100, 200, 300, 400, 600, 800, 1000
6	Bandwidth (B)	20 MHz
7	Noise power of receiver (σu_l^2)	-94 dBm
8	Maximum transmit power (p)	100 mw
9	Number of samples in each coherence block (τc)	200
10	Pilot sequences length (τp)	1000
11	Number of realizations (R)	1000
12	Number of setups (n)	100
13	Signal to noise ratio (SNR)	-10 to 20 dB

4.2 Performance Comparison of Proposed Detector and Existing Detecting Techniques

To evaluate and discuss the performance between the proposed and other existing detector methods, different techniques are taken, such as sum SE, SE, cumulative distribution function (CDF), and BER with changing the parameters like number of UE, number of antennas per AP, and number of APs on the system. These parameters give important ideas in the performance comparison between proposed and other different decoding techniques.

4.2.1 Performance comparison between proposed and other existing decoding techniques based on sum spectral efficiency

In a cell-free massive MIMO system, sum SE refers to the total SE achieved by all the users in the network when the users send the signal at the same time to the APs. It also measures how efficiently the available spectrum bandwidth is utilized by all the users in the system. Within this section, our focus is to compare the performance of both proposed and existing decoding techniques in the uplink cell-free massive MIMO system for both centralized and distribution operations. The simulation results presented here evaluate the performance for both proposed and other existing methods based on the sum SE systems with varying the number of antennas of the APs, number of APs, and UE. For the proposed technique, the CPU is responsible for coherently processing and evaluating the sum SE based on the received signals from multiple APs.

Figure 4.1 shows the sum SE for both proposed and existing methods in the uplink cell-free massive MIMO networks with respect to the change in UE. The total number of APs is L = 100, with each AP having an antenna value of N = 2. The total antennas in the system are M = L * N = 200, and the range of the UE is taken from K = 10 to K = 60. For the minimum value of UE K = 10, the proposed decoding technique achieved a sum SE of 77.84 bit/s/Hz. The centralized decoding techniques P-MMSE and P-RZF have the same sum SE of 73.25 bit/s/Hz, whereas the distributed decoding techniques L-MMSE, LP-MMSE, and MR achieved a sum SE of 60.26 bit/s/Hz, 56.79 bit/s/Hz, and 24.42 bit/s/Hz, respectively. When the number of UE increased from K = 10 to K = 20, the proposed decoding technique achieved a sum SE of 154.1 bit/s/Hz, while the other techniques, P-MMSE, P-RZF, L-MMSE, LP-MMSE, and MR decoding techniques, achieved a sum SE of 145.3 bit/s/Hz, 144.3 bit/s/Hz, 110.4 bit/s/Hz, 104.5 bit/s/Hz, and 37.7 bit/s/Hz, respectively. As we can see from the results, the proposed technique outperforms all the existing decoding techniques P-MMSE, P-RZF, L-MMSE, LP-MMSE, and MR in all UE's values. For a small value of UE, the decoding techniques achieved a comparatively low value of sum SE, but for an increase in the number of UEs, it achieved a large value of sum SE.

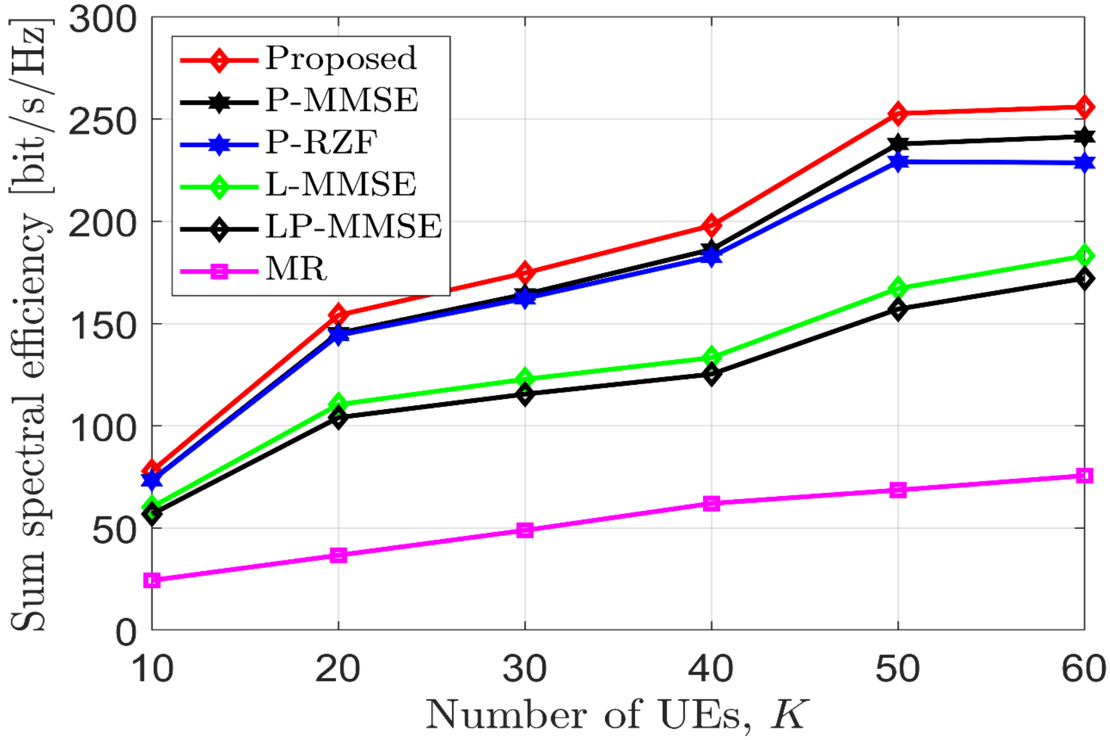

Figure 4.1 Sum SE comparison as function of UE for both the proposed and other existing techniques with L = 100 and N =2

Table 4.2 illustrates the performance comparison between the proposed and other existing decoding techniques for different values of UE ranging from K = 10 to K = 60, and the number of AP L = 100, with each having an antenna value of N = 2. As we can see from the numerical results of the table, the proposed technique outperforms the other techniques for all values of UEs. The table illustrates the tabular form of Figure 4.1.

Table 4.2 Uplink sum SE comparison between proposed decoding technique and other decoding techniques for L = 100 and N = 2

No. UEs	Sum SE					
	Proposed	P-MMSE	P-RZF	L-MMSE	LP-MMSE	MR

10	77.84	73.25	73.25	60.26	56.79	24.42
20	154.1	145.3	144.3	110.4	104.5	36.7
30	174.7	164.6	162.3	122.8	115.5	48.89
40	197.9	186.2	182.6	133.5	125.3	62.05
50	252.7	237.8	228.5	167.1	157.1	68.57
60	256	241.5	229.2	183.1	172.1	75.63

Figure 4.2 shows the sum SE of both the proposed and existing decoding techniques used in the uplink cell-free massive MIMO system with respect to UE. The total APs for the simulation are taken as L = 200, with each AP having an antenna value of N = 2, and the range of the UE is taken from K = 10 to K = 60. At K = 10, the proposed decoding technique achieved a sum SE of 93.05 bit/s/Hz. The centralized decoding techniques P-MMSE and P-RZF achieved a sum SE of 87.94 bit/s/Hz and 87.94 bit/s/Hz, whereas the distributed techniques L-MMSE, LP-MMSE, and MR decoding algorithms achieved a sum SE of 70.77 bit/s/Hz, 66.7 bit/s/Hz, and 32.09 bit/s/Hz, respectively. When the number of UE in the system is increased to K = 60, the proposed decoding technique achieved a sum SE of 390.8 bit/s/Hz, while the other techniques, P-MMSE, P-RZF, L-MMSE, LP-MMSE, and MR decoding techniques, achieved a sum SE of 367.7 bit/s/Hz, 358.7 bit/s/Hz, 239.5 bit/s/Hz, 224.9 bit/s/Hz, and 110.6 bit/s/Hz, respectively. For all values of UE, the proposed technique outperforms all the existing techniques, and for the minimum value of UE, the proposed technique outperforms Figure 4.1 by 16.34%. This is due to a doubling of the antenna size in the system by considering all other parameters the same, and for all techniques, the sum SE increased with the number of UEs. This increase in SE is directly related to the transmitting signals from the UEs.

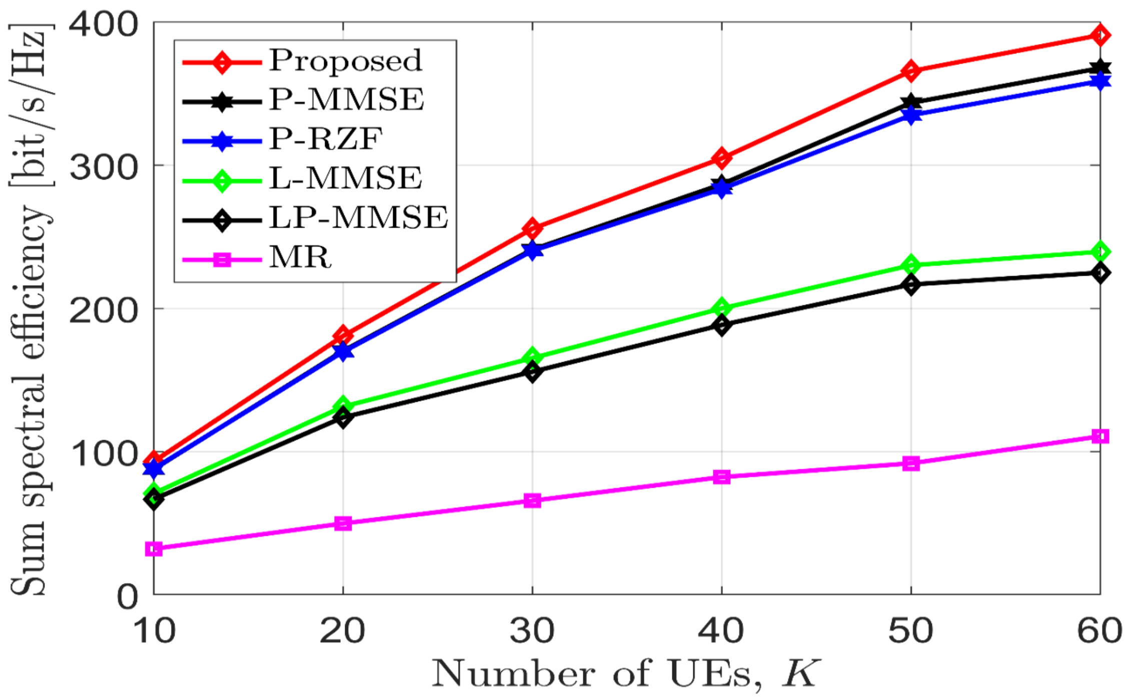

Figure 4.2 Sum SE comparison as function of UE for both the proposed and other existing techniques with L = 200 and N = 2

Table 4.3 provides a tabular representation of the result in Figure 4.2 by allowing a simple comparison among the decoding techniques, which is the numerical values of the sum SE across different values of the UE range from K = 10 to K = 60 and the number of AP L = 200, with each having an antenna value of N = 2. As we can see from the table, the proposed technique outperforms the other decoding techniques in the uplink cell-free massive MIMO systems. Since the number of antennas increased, the decoding techniques gave better performance compared to Table 4.2.

Table 4.3 Uplink sum SE comparison between proposed decoding technique and other decoding techniques for L = 200 and N = 2

No. UEs	Sum SE					
	Proposed	P-MMSE	P-RZF	L-MMSE	LP-MMSE	MR
10	93.05	87.94	87.94	70.77	66.7	32.09
20	180.2	169.7	169.7	131.1	123.9	49.78

30	255.6	240.2	240.0	165.2	155.7	65.68
40	304.7	286.6	283.3	200	188.4	82.19
50	365.6	343.4	334.8	230.1	216.4	91.77
60	390.8	367.7	358.7	239.5	224.9	110.6

Figure 4.3 illustrates the sum SE for both the proposed and existing decoding techniques for both centralized and distributed operations in the uplink cell-free massive MIMO systems, where the number of APs is L = 200 and the antenna per AP is L = 3, with a total AP antenna of M = 600. For the given value of UE K = 10, the proposed algorithm has a sum SE of 104.5 bit/s/Hz, whereas the centralized decoding techniques P-MMSE and P-RZF achieved the same SE of 98.34 bit/s/Hz, while the distributed decoding techniques L-MMSE, LP-MMSE, and MR achieved a sum SE of 86.32 bit/s/Hz, 81.36 bit/s/Hz, and 31.03 bit/s/Hz, respectively. From this, we can conclude that the centralized decoding techniques outperform the distributed techniques. For the same value of UE, the proposed decoding technique outperforms P-MMSE by a percentage of 5.8947% and L-MMSE by a percentage of 17.397%. For K = 60, the proposed method achieved a high sum SE of 446.8 bit/s/Hz. P-MMSE and P-RZF achieved sum SE of 419.7 bit/s/Hz and 409.5 bit/s/Hz, respectively, while L-MMSE, LP-MMSE, and MR achieved sum SE of 299.4 bit/s/Hz, 280.1 bit/s/Hz, and 125 bit/s/Hz, respectively.

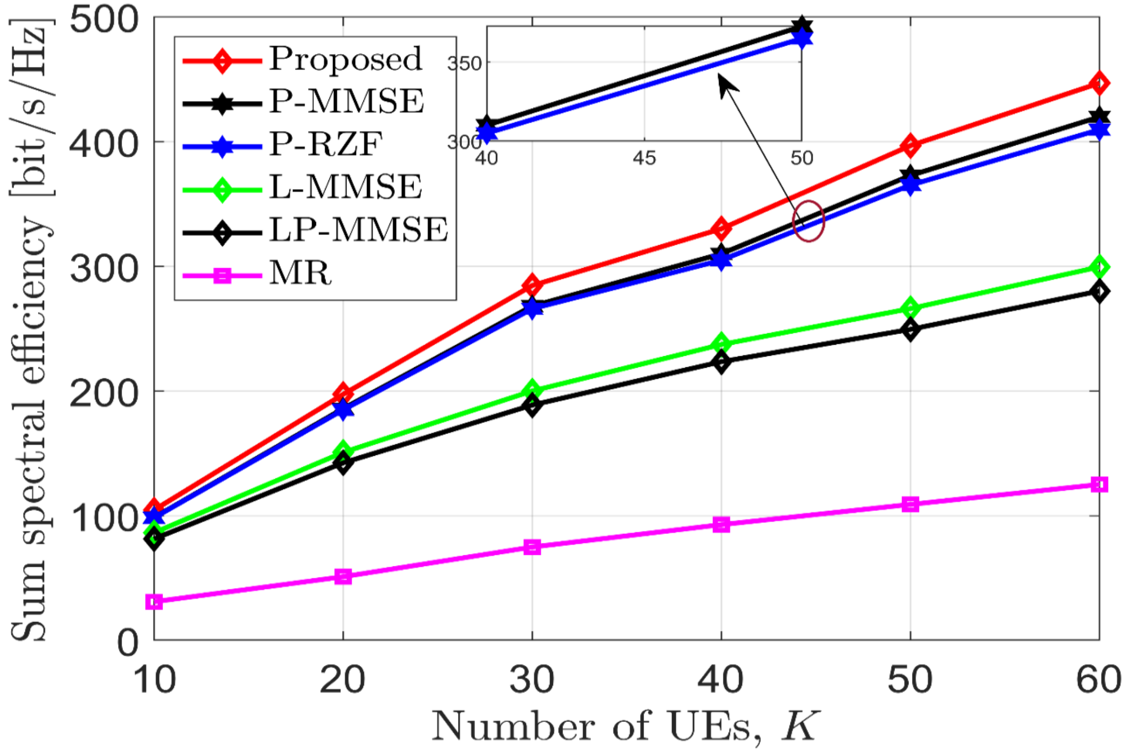

Figure 4.3 Sum SE comparison as function of UE for both the proposed and other existing techniques with L = 200 and N = 3

Figure 4.4 shows the relationship between sum SE and UE for both the proposed and other centralized and distributed decoding techniques used in uplink cell-free massive MIMO systems at L = 100 and L = 4. As observed from the graph, the sum SE of the decoding techniques increased with respect to the UE. At K = 10, the proposed decoding technique has a sum SE of 86.36 bit/s/Hz, whereas the centralized decoding techniques P-MMSE and P-RZF achieved the same sum SE of 81.38 bit/s/Hz, while the distributed decoding techniques L-MMSE, LP-MMSE, and MR achieved a sum SE of 80.82 bit/s/Hz, 76.17 bit/s/Hz, and 29.76 bit/s/Hz, respectively. When the UE is increased from K = 10 to K = 20, the proposed technique achieves a high sum SE of 167.9 bit/s/Hz, which outperforms the other techniques. P-MMSE and P-RZF achieved a sum SE of 158.0 bit/s/Hz and 157.1 bit/s/Hz, respectively. While L-MMSE, LP-MMSE, and MR have a sum SE of 140.1 bit/s/Hz, 132.0 bit/s/Hz, and 49.27 bit/s/Hz, respectively, at this UEs value, the proposed technique outperforms the existing centralized technique P-MMSE by 5.896%.

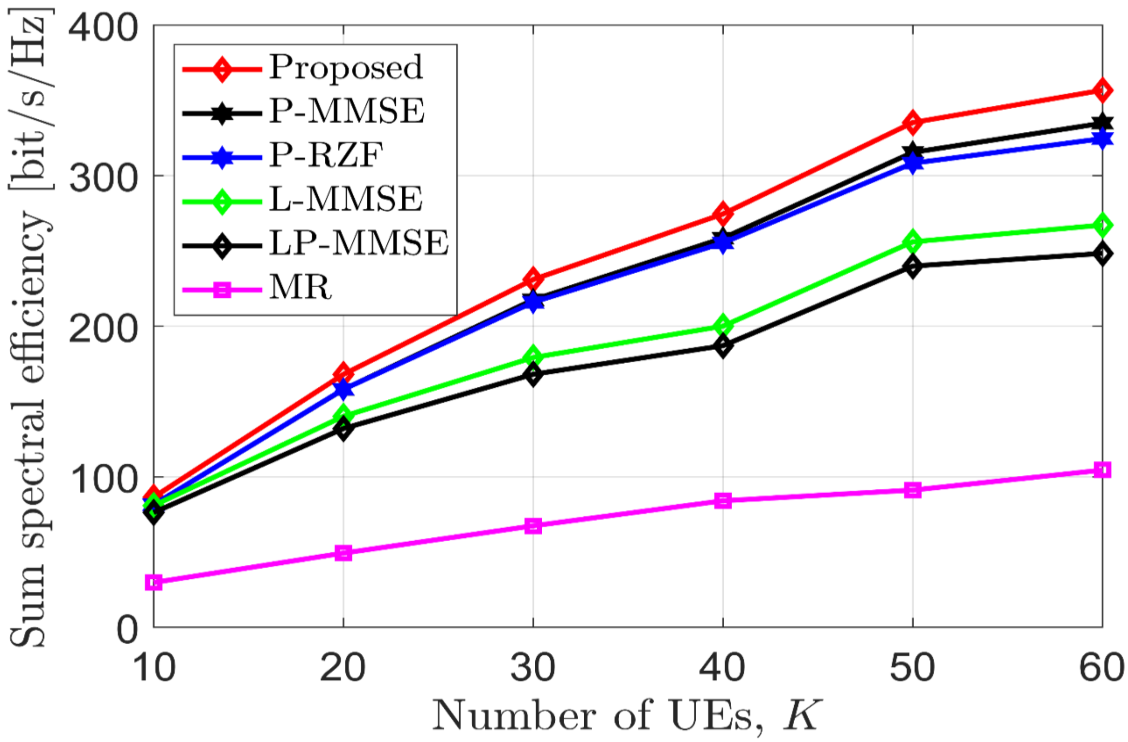

Figure 4.4 Sum SE comparison as function of UE for both the proposed and other existing techniques L = 100 and N = 4

Table 4.4 depicts the comparison in performance between the proposed and existing decoding techniques used in both centralized and distributed methods with respect to the UE at AP L = 100, with each having an antenna value of N = 4. As we can see from the table, the proposed technique has good performance. The table shows the tabular form of the above Figure 4.4.

Table 4.4 Uplink sum SE comparison between proposed decoding technique and other decoding techniques for L = 100 and N = 4

No. UEs	Sum SE					
	Proposed	P-MMSE	P-RZF	L-MMSE	LP-MMSE	MR
10	86.36	81.38	81.38	80.82	76.17	29.76
20	167.9	158.0	157.1	140.1	132.0	49.27
30	230.9	217.4	215.8	179.1	168.0	67.39

40	274.4	258.4	255.3	200	187	84.02
50	335.2	315.3	308.2	256	239.9	91.13
60	356.6	334.7	324.5	267.1	248.3	104.4

Figure 4.5 demonstrates the sum SE of both the proposed and existing decoding techniques for both centralized and distributed decoding techniques for L = 100 and the antenna per AP is N = 5. For K = 10, the proposed technique has a sum SE of 92.77 bit/s/Hz, and P-MMSE, P-RZF, L-MMSE, LP-MMSE, and MR achieved a sum SE of 80.65 bit/s/Hz, 80.65 bit/s/Hz, 78.25 bit/s/Hz, 73.75 bit/s/Hz, and 32.79 bit/s/Hz, respectively. At K = 20, the proposed method achieved a high value of sum SE of 172.7 bit/s/Hz, and P-MMSE, P-RZF, L-MMSE, LP-MMSE, and MR achieved sum SE of 163.4 bit/s/Hz, 162.3 bit/s/Hz, 150.5 bit/s/Hz, 141.3 bit/s/Hz, and 54.08 bit/s/Hz, respectively.

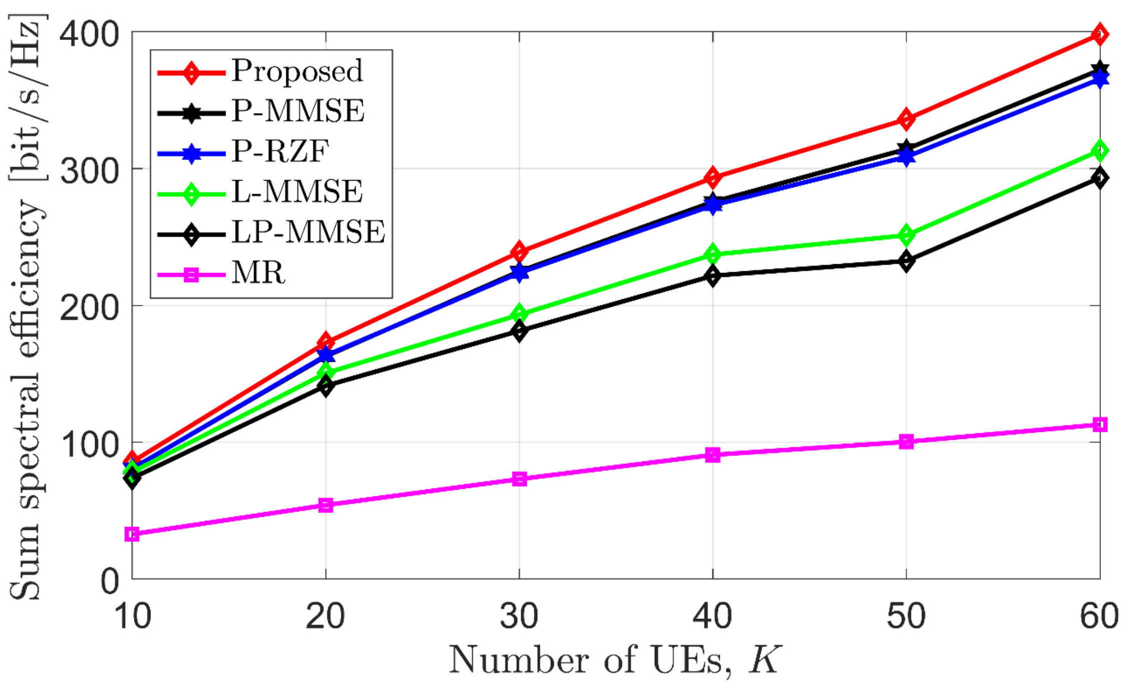

Figure 4.5 Sum SE comparison as function of UE for both the proposed and other existing techniques with L = 100 and N = 5

Figure 4.6 demonstrates the sum SE of both the proposed and other decoding techniques for L = 200, and the antenna per AP is N = 5. At K = 10, the proposed technique achieved a sum SE of 109.5 bit/s/Hz, and P-MMSE and P-RZF achieved a sum SE of 103.4 bit/s/Hz, while the distributed techniques L-MMSE, LP-MMSE, and MR achieved 98.1 bit/s/Hz, 92.46 bit/s/Hz, and 37.78 bit/s/Hz, respectively. At K = 60, the proposed technique achieved a high value of sum SE of 509.3 bit/s/Hz, and P-MMSE, P-RZF, L-MMSE, LP-MMSE, and MR achieved sum SE of 478.5 bit/s/Hz, 469.5 bit/s/Hz, 387.5 bit/s/Hz, 360.2 bit/s/Hz, and 146.1 bit/s/Hz, respectively. At UE K = 10, when we compare this with the previous Figure 4.5, the performance of the system increased by a percentage of 11.45%. Since the total number of antennas in the system increased from 500 to 1000, we can say that for an increase in the number of antennas in the system, the decoding techniques gave better performance compared to a lower antenna.

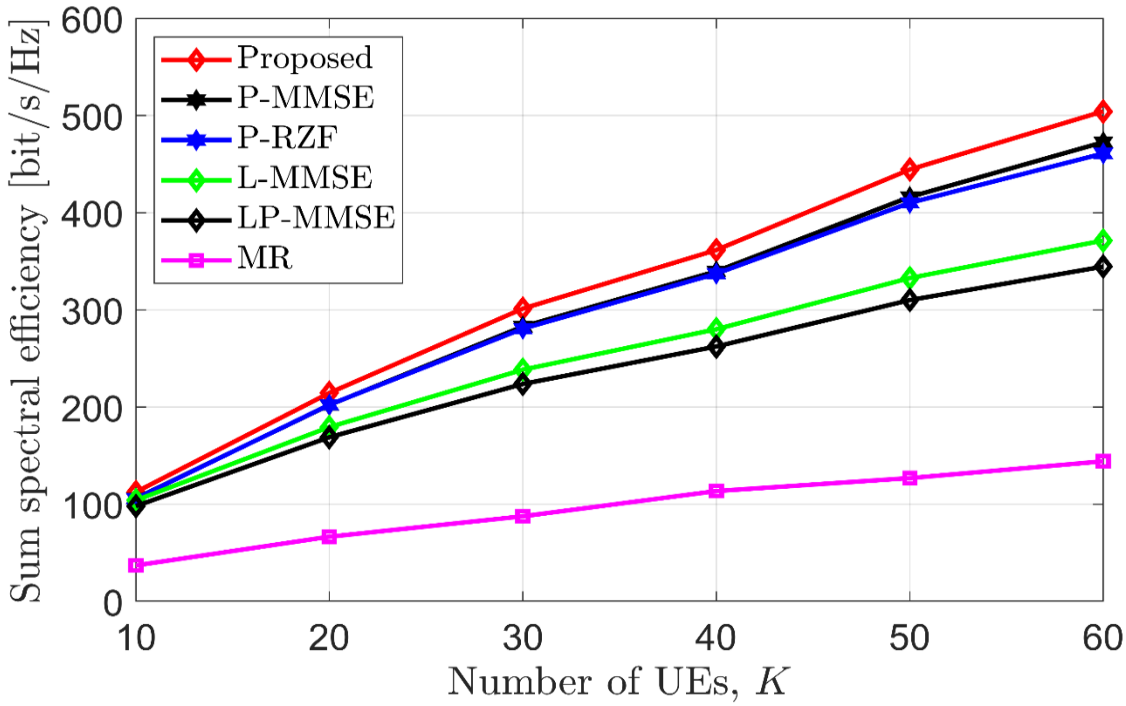

Figure 4.6 Sum SE comparison as function of UE for both the proposed and other existing techniques with L = 200 and N = 5

Table 4.5 illustrates the comparison in performance between the proposed and other existing decoding techniques used in both centralized and distributed methods for different values of UE, L = 200, and N = 5. As we observed from the table, the proposed algorithm has good performance compared to the other existing techniques. The following table shows the tabular form of the above Figure 4.6.

Table 4.5 Uplink sum SE comparison between proposed decoding technique and other decoding techniques for L = 200 and N = 5

No. UEs	Sum SE					
	Proposed	P-MMSE	P-RZF	L-MMSE	LP-MMSE	MR
10	109.5	103.4	103.4	98.1	92.46	37.78
20	217.2	203.5	202.1	171	161.1	62.21
30	281.6	264.4	261.7	214.5	200.5	91.67
40	378	355.1	349.2	283.8	265.7	105
50	473.1	444.6	439.8	362.7	339.1	123.6
60	509.3	478.5	469.5	387.5	360.2	146.1

4.2.2 Performance comparison between proposed and other existing decoding techniques based on spectral efficiency

In wireless communication, SE is the main key performance measurement that is used in cell-free massive MIMO systems to show how much data is transmitted per given bandwidth or measure how efficiently the available spectrum is utilized to transmit the data, measured in the unit of a bit/s/Hz. On the other hand, CDF is a statistical function that demonstrates the probability distribution of a random variable. It is often used to characterize the system's performance metrics, which are the SE.

Figure 4.7 shows the SE comparison for both proposed and existing centralized decoding techniques with L = 100, N = 2, and K = 50. For CDF = 0.2, the proposed decoding technique achieved a higher performance than the others, which have a SE of 5.385 bit/s/Hz, and the existing techniques MMSE and P-MMSE achieved the same SE of 4.202 bit/s/Hz, whereas P-RZF and MR achieved a SE of 4.061 bit/s/Hz and 0.915 bit/s/Hz. At CDF = 0.4, the proposed technique achieved a SE of 7.012 bit/s/Hz, which is better than the existing techniques. MMSE and P-MMSE achieved a SE of 5.301 bit/s/Hz and 5.301 bit/s/Hz, while P-RZF and MR achieved a SE of 5.152 bit/s/Hz and 1.635 bit/s/Hz, respectively.

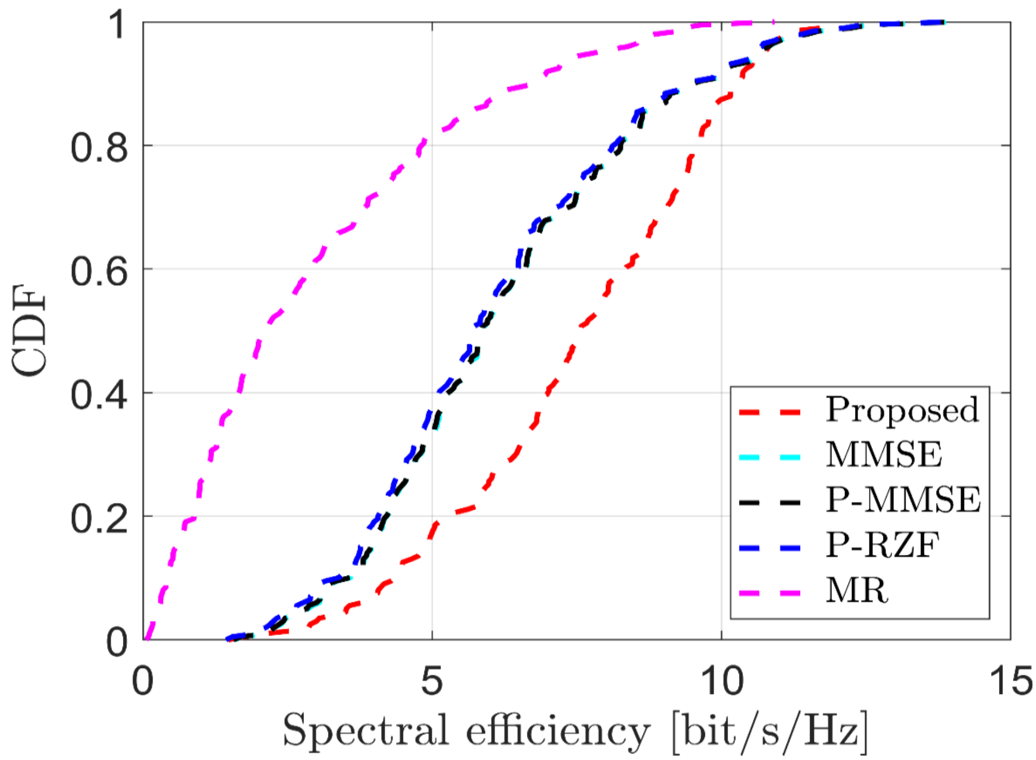

Figure 4.7 CDF versus SE of the proposed decoding technique and other centralized techniques with L = 100, N = 2, and K = 50

Table 4.6 illustrates the performance comparison between proposed and existing techniques in the centralized operation for Figure 4.7. The APs are taken as L = 100, N = 2, and the UEs on the system are K = 50. The numerical value of the table shows that the proposed technique has a good SE compared with the existing techniques.

Table 4.6 CDF versus SE of the proposed decoding technique and other centralized techniques with L = 100, N = 2, and K = 50

CDF	SE				
	Proposed	MMSE	P-MMSE	P-RZF	MR
0.2	5.385	4.202	4.202	4.061	0.915
0.4	7.012	5.301	5.301	5.152	1.635
0.6	8.329	6.503	6.503	6.428	2.924

0.8	9.561	8.219	8.219	8.118	4.774
1	13.95	13.2	13.2	12.9	10.920

Figure 4.8 shows the SE of both the proposed and existing centralized decoding techniques in the uplink cell-free massive MIMO systems, and L = 100, N = 2, and K = 40 are given. At CDF = 0.2, the proposed technique outperforms the others, and it has a SE value of 5.671 bit/s/Hz. The existing techniques, MMSE and P-MMSE, achieved the same SE value of 3.788 bit/s/Hz, whereas P-RZF and MR achieved SE values of 3.624 bit/s/Hz and 0.851 bit/s/Hz, respectively. At CDF = 0.4, the proposed method achieved a SE of 7.425 bit/s/Hz, and the existing techniques, MMSE and P-MMSE, achieved the same SE of 5.162 bit/s/Hz. P-RZF and MR achieved a SE of 5.036 bit/s/Hz and 1.672 bit/s/Hz, respectively. For the same value of CDF = 0.2, the proposed technique outperforms Figure 4.7 by a percentage of 5.034%. This is due to a decrease in the number of UE from 50 to 40 for the same total AP antennas.

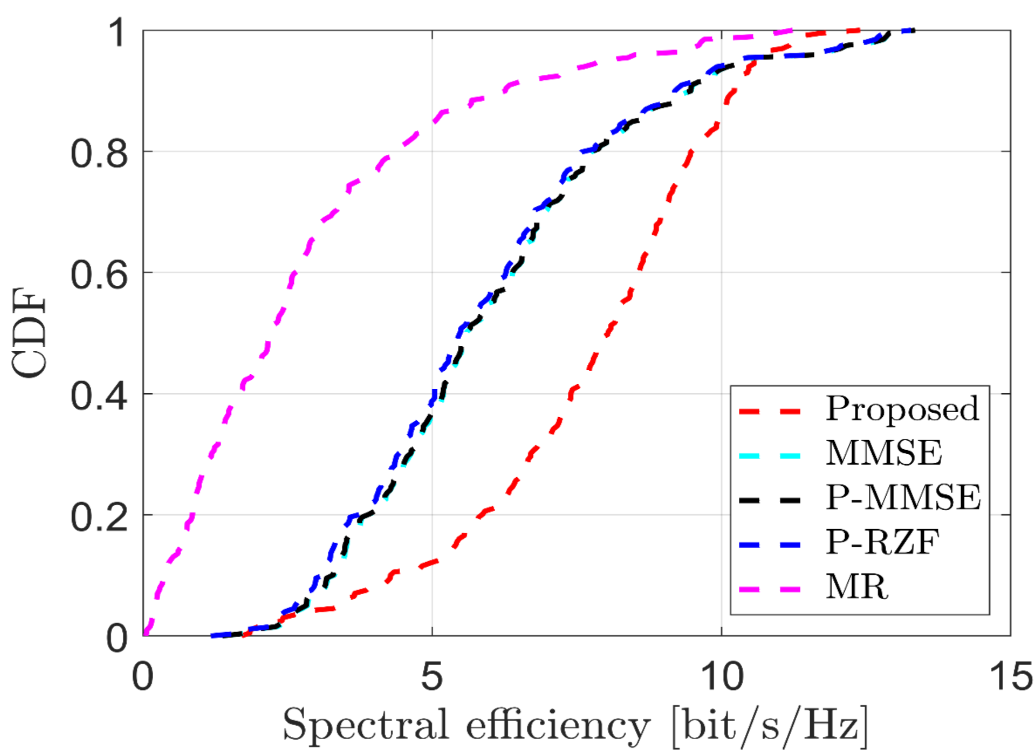

Figure 4.8 CDF versus SE of the proposed decoding technique and other centralized techniques with L = 100, N = 2, and K = 40

Figure 4.9 depicts the SE of both the proposed and existing centralized decoding techniques in the uplink cell-free massive MIMO systems. The number of APs is taken as L = 100; each has a single antenna, and the value of UEs in the system is K = 50. At CDF = 0.2, as shown from the graph, the proposed technique achieved a better output with a SE of 5.385 bit/s/Hz, and the existing techniques MMSE and P-MMSE achieved the same SE of 4.202 bit/s/Hz, whereas P-RZF and MR achieved a SE of 4.061 bit/s/Hz and 0.915 bit/s/Hz, respectively. When the CDF value changed from 0.2 to 0.4, the performance also improved, with a SE of 7.012 bit/s/Hz for the proposed technique, and the existing techniques MMSE and P-MMSE achieved the same SE of 5.301 bit/s/Hz. Whereas P-RZF and MR achieved a lower SE of 5.152 bit/s/Hz and 1.635 bit/s/Hz, respectively. For the same UE at CDF = 0.2, this result achieved a lower percentage of 4.840% in SE than Figure 4.8. This lowering in SE is because of the decreasing size of antennas in the cover area.

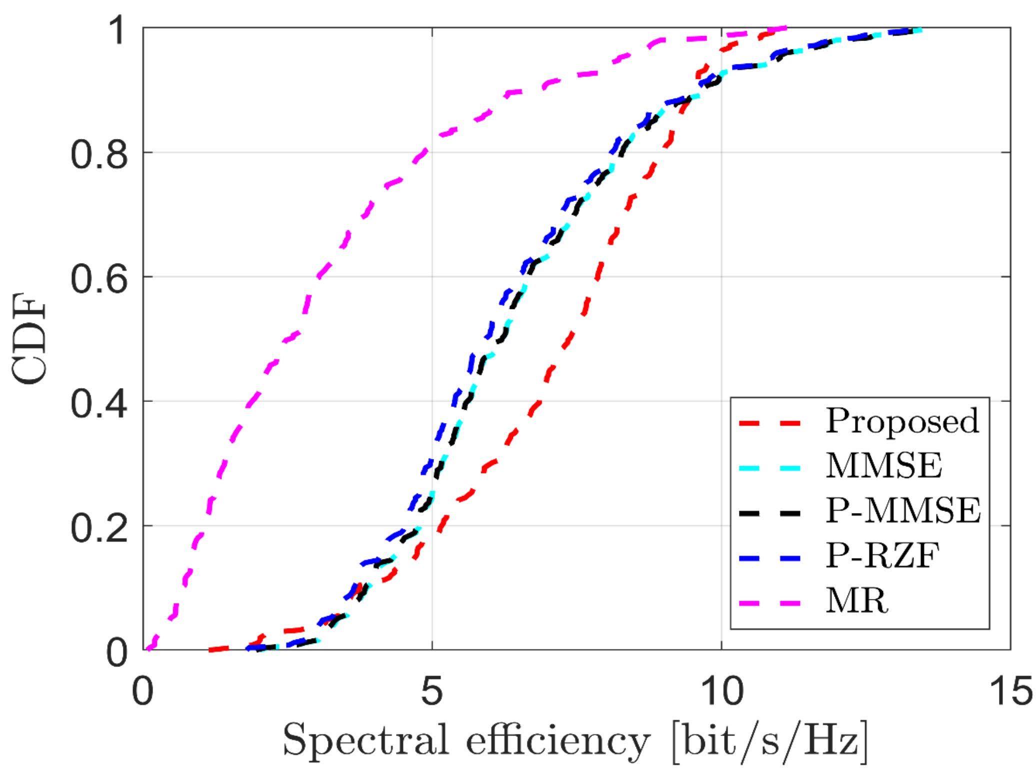

Figure 4.9 CDF versus SE of the proposed decoding technique and other centralized techniques with L = 100, N = 1, and K = 50

Table 4.7 illustrates the performance comparison between proposed and existing techniques in the centralized operation. The APs are given as L = 100 and a single antenna per AP, with a total number of UEs on the system being K = 50. The table demonstrates the tabular form of Figure 4.9.

Table 4.7 CDF versus SE of the proposed decoding technique and other centralized techniques with L = 100, N = 1, and K = 50

CDF	SE				
	Proposed	MMSE	P-MMSE	P-RZF	MR
0.2	5.165	4.771	4.771	4.552	1.102
0.4	6.821	5.652	5.652	5.394	1.928
0.6	7.858	6.647	6.647	6.443	2.981
0.8	9.032	8.332	8.332	8.124	4.920
1	11.131	13.430	13.430	13.434	11.131

Figure 4.10 shows the SE for both proposed and existing distributed decoding techniques in the uplink cell-free massive MIMO systems. The simulation parameters are taken as L = 100 with a single antenna AP and K = 50. For CDF = 0.2, the proposed technique achieved a SE of 4.865 bit/s/Hz, and the existing techniques L-MMSE, LP-MMSE, and MR achieved a SE of 4.285 bit/s/Hz, 4.125 bit/s/Hz, and 4.087 bit/s/Hz, respectively.

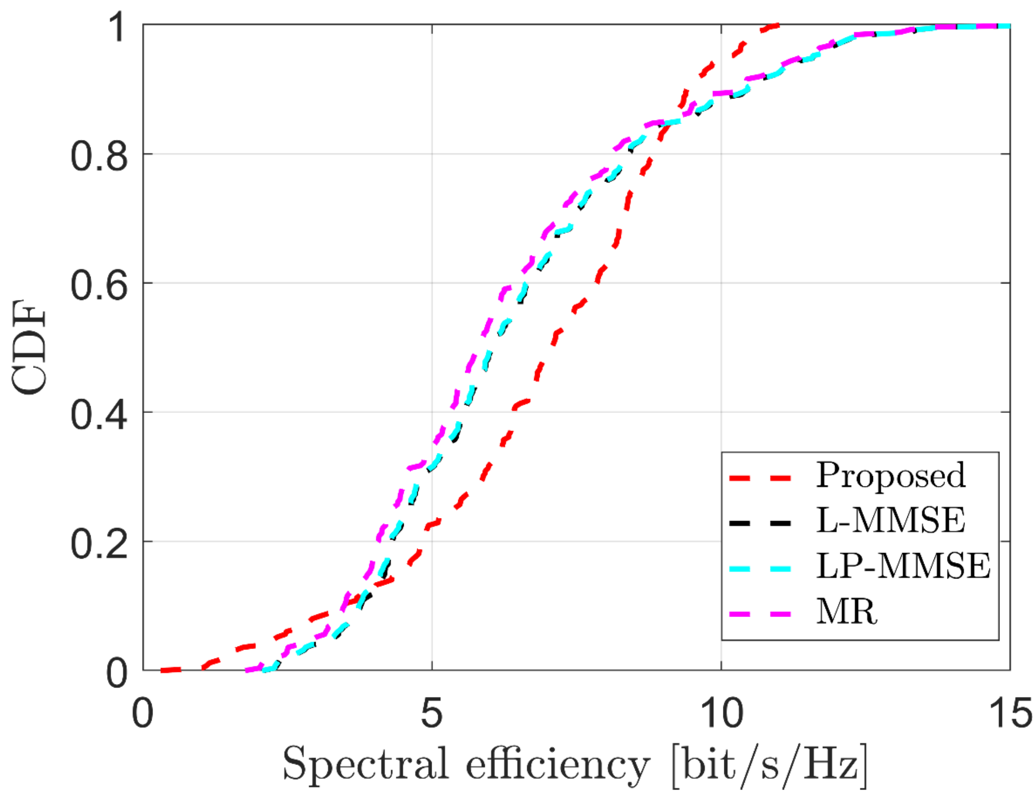

Figure 4.10 CDF versus SE of the proposed decoding technique and other distributed techniques with L = 100, N = 1, and K = 50

Figure 4.11 illustrates the SE of both the proposed and existing distributed decoding techniques in uplink cell-free systems. Where L = 100, N = 2, and K = 50 are taken for the simulation. For CDF = 0.2, the proposed technique achieved a SE of 5.852 bit/s/Hz, which outperforms the other existing techniques. L-MMSE, LP-MMSE, and MR achieved a SE of 3.817 bit/s/Hz, 3.623 bit/s/Hz, and 0.7412 bit/s/Hz, respectively. At CDF = 1, the proposed technique achieved a SE of 11.830 bit/s/Hz, and the existing techniques L-MMSE, LP-MMSE, and MR achieved a SE of 11.695 bit/s/Hz, 11.265 bit/s/Hz, and 8.552 bit/s/Hz, respectively.

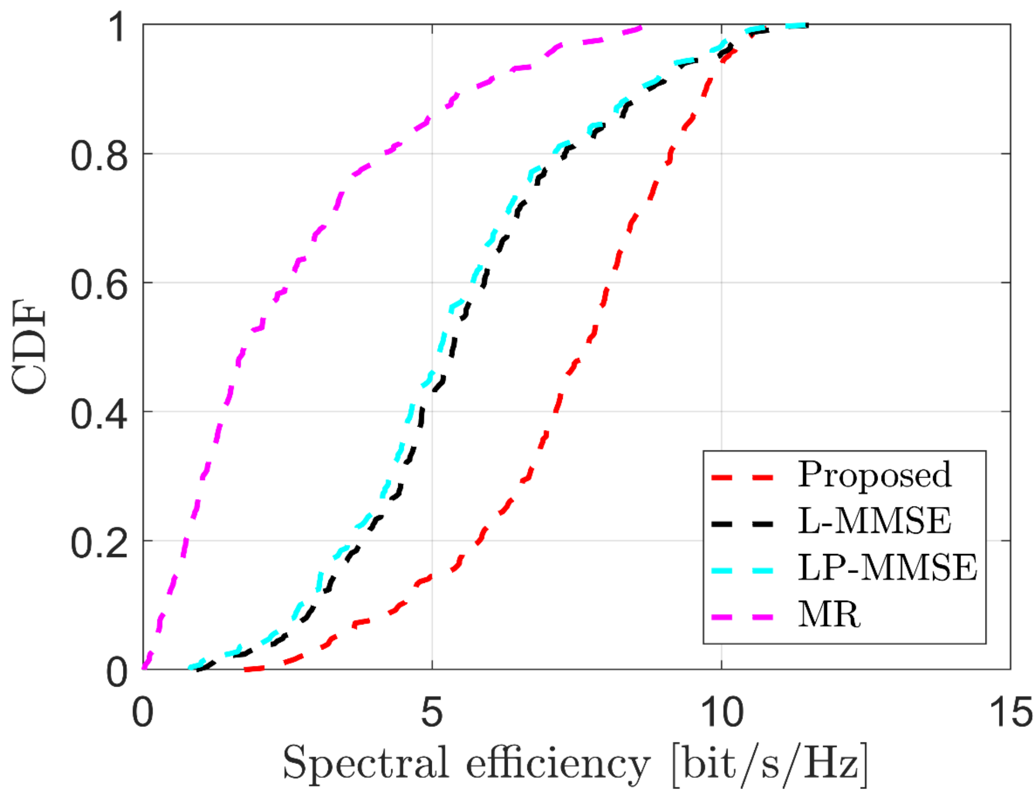

Figure 4.11 CDF versus SE of the proposed decoding technique and other distributed techniques with L = 100, N = 2, and K = 50

Figure 4.12 depicts the SE of the proposed decoding technique with both centralized and distributed decoding techniques in the uplink ell-free massive MIMO systems. The number of APs is L = 100 with a single antenna per AP, N = 1, and K = 50 UEs. At CDF = 0.2, the proposed technique achieved a SE of 5.221 bit/s/Hz, and the centralized operation techniques, MMSE, P-MMSE, and P-RZF, achieved a SE of 4.685 bit/s/Hz, 4.685 bit/s/Hz, and 4.487 bit/s/Hz, respectively. Whereas the distribution decoding techniques L-MMSE, LP-MMSE, and MR achieved a SE of 2.870 bit/s/Hz, 2.824 bit/s/Hz, and 0.965 bit/s/Hz, respectively. At CDF = 0.4, the proposed technique outperforms the others with a SE value of 6.825 bit/s/Hz, and the existing techniques used in the centralized techniques, MMSE, P-MMSE, and P-RZF, achieved SE of 5.462 bit/s/Hz, 5.462 bit/s/Hz, and 5.261 bit/s/Hz, respectively. And the distribution decoding techniques L-MMSE, LP-MMSE, and MR achieved a SE of 3.621 bit/s/Hz, 3.561 bit/s/Hz, and 1.705 bit/s/Hz, respectively.

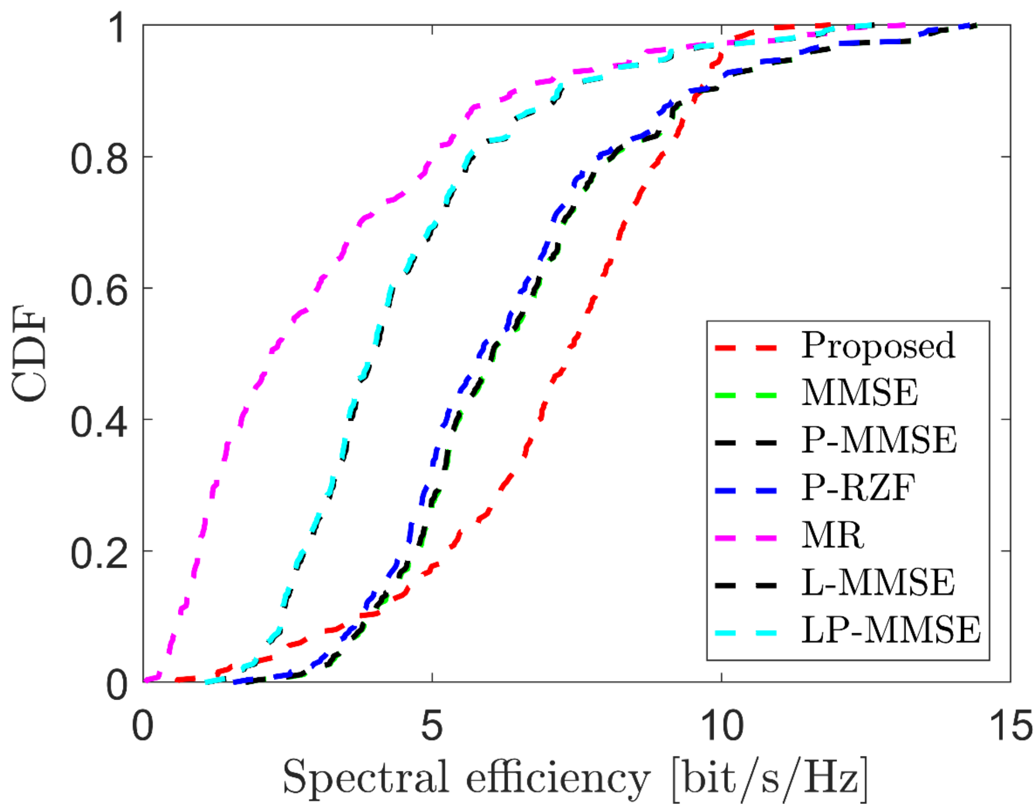

Figure 4.12 CDF versus SE of the proposed decoding technique with centralized and distributed techniques by considering L = 100, N = 1, and K = 50

Figure 4.13 illustrates the SE of the proposed decoding technique with both centralized and distributed decoding techniques in the uplink cell-free massive MIMO systems. The number of APs for the simulation is taken as L = 100, and the number of antennas per AP is N = 2, with a total number of UEs on the system being K = 50. The proposed technique achieved a SE value of 5.665 bit/s/Hz, and the centralized techniques, MMSE, P-MMSE, and P-RZF, achieved a SE of 3.615 bit/s/Hz, 3.615 bit/s/Hz, and 3.337 bit/s/Hz at CDF = 0.2, respectively. And for the same value, the distribution decoding techniques L-MMSE, LP-MMSE, and MR achieved a SE of 2.007 bit/s/Hz, 1.999 bit/s/Hz, and 0.752 bit/s/Hz, respectively. When the CDF changed from 0.2 to 0.4, the proposed technique outperformed the others with a SE value of 7.108 bit/s/Hz, and the existing techniques used in the centralized operation MMSE, P-MMSE, and P-RZF achieved SE values of 4.702 bit/s/Hz, 4.702 bit/s/Hz, and 4.482 bit/s/Hz, respectively. And the distributed decoding techniques L-MMSE, LP-MMSE, and MR achieved a SE of 2.742 bit/s/Hz, 2.712 bit/s/Hz, and

1.520 bit/s/Hz, respectively. At CDF = 1, the proposed technique outperforms the others with a SE value of 13.69 bit/s/Hz, and the existing techniques used in the centralized operation MMSE, P-MMSE, and P-RZF achieve SE of 11.85 bit/s/Hz, 11.67 bit/s/Hz, and 11.27 bit/s/Hz, respectively. And the distribution decoding techniques L-MMSE, LP-MMSE, and MR achieved spectral efficiencies of 11.85 bit/s/Hz, 11.67 bit/s/Hz, and 11.27 bit/s/Hz, respectively. Due to the increased antenna per AP from one to two, both the proposed and existing decoding techniques increased the SE of the system.

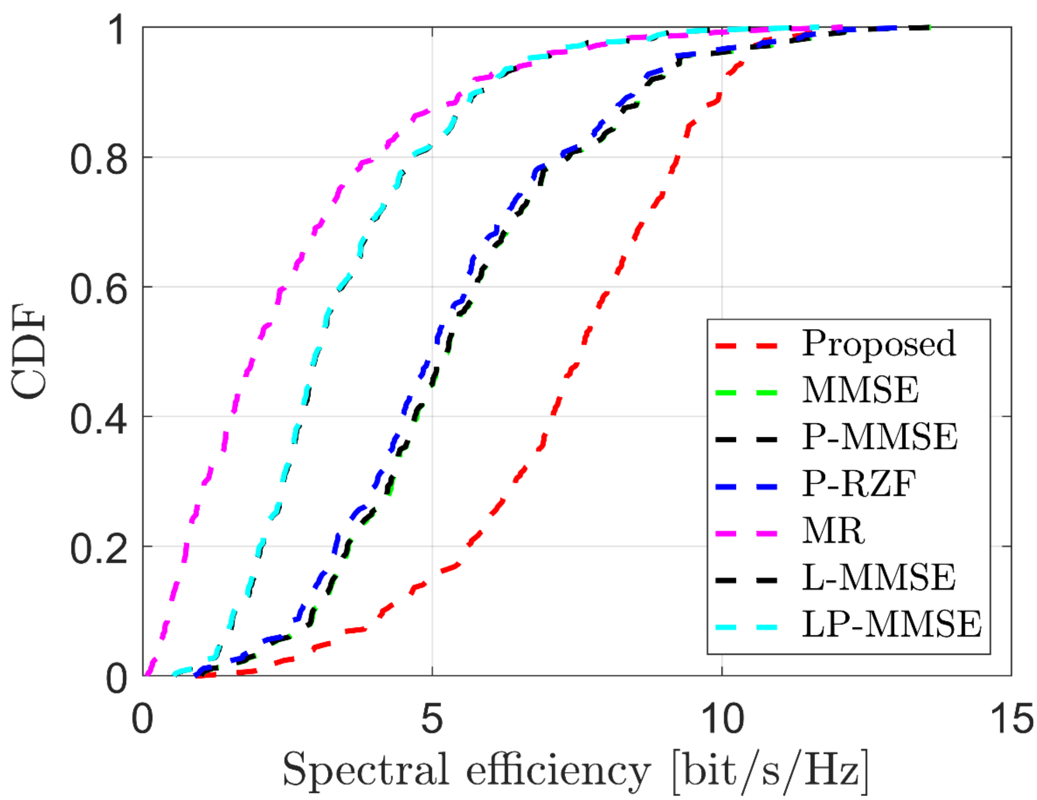

Figure 4.13 CDF versus SE of the proposed decoding technique with centralized and distributed techniques by considering L = 100, N = 2, and K = 50

Table 4.8 illustrates the tabular form of Figure 4.13 by comparing the performance between proposed and existing decoding techniques in both centralized and distribution operations. For the simulation, the following parameters are taken: L = 100, N = 2, and K = 50. As we can see from the table, the proposed technique outperforms the other technique.

Table 4.8 CDF versus SE of the proposed decoding technique with both centralized and distributed techniques with L = 100, N = 1, and K = 50

CDF	SE						
	Proposed	MMSE	P- MMSE	P-RZF	L-MMSE	LP-MMSE	MR
0.2	5.665	3.615	3.615	3.337	2.007	1.999	0.752
0.4	7.108	4.702	4.702	4.482	2.742	2.712	1.520
0.6	8.012	5.710	5.710	5.582	3.424	3.359	2.364
0.8	9.324	7.314	7.314	7.148	4.739	4.589	3.985
1	13.69	13.25	13.25	12.09	11.85	11.67	11.27

Figure 4.14 shows the SE of the proposed decoding technique with both centralized and distributed decoding techniques with L = 100, N = 2, and K = 40. At CDF = 0.2, the proposed technique has a SE of 6.026 bit/s/Hz, and the existing techniques used in the centralized technique, MMSE, P-MMSE, and P-RZF, achieved a SE of 3.985 bit/s/Hz, 3.985 bit/s/Hz, and 3.871 bit/s/Hz, respectively. And the distribution decoding techniques L-MMSE, LP-MMSE, and MR achieved a SE of 2.470 bit/s/Hz, 2.324 bit/s/Hz, and 0.885 bit/s/Hz, respectively. At CDF = 0.4, the proposed technique achieved a SE value of 7.382 bit/s/Hz, and the existing techniques used in the centralized technique MMSE, P-MMSE, and P-RZF have achieved a SE of 5.242 bit/s/Hz, 5.242 bit/s/Hz, and 5.104 bit/s/Hz, respectively. And the distribution decoding techniques L-MMSE, LP-MMSE, and MR achieved a SE of 3.210 bit/s/Hz, 3.145 bit/s/Hz, and 1.705 bit/s/Hz, respectively. When we compare with Figure 4.13, since the number of UE decreased from 50 to 40, the performance of the proposed technique improved by 3.854%.

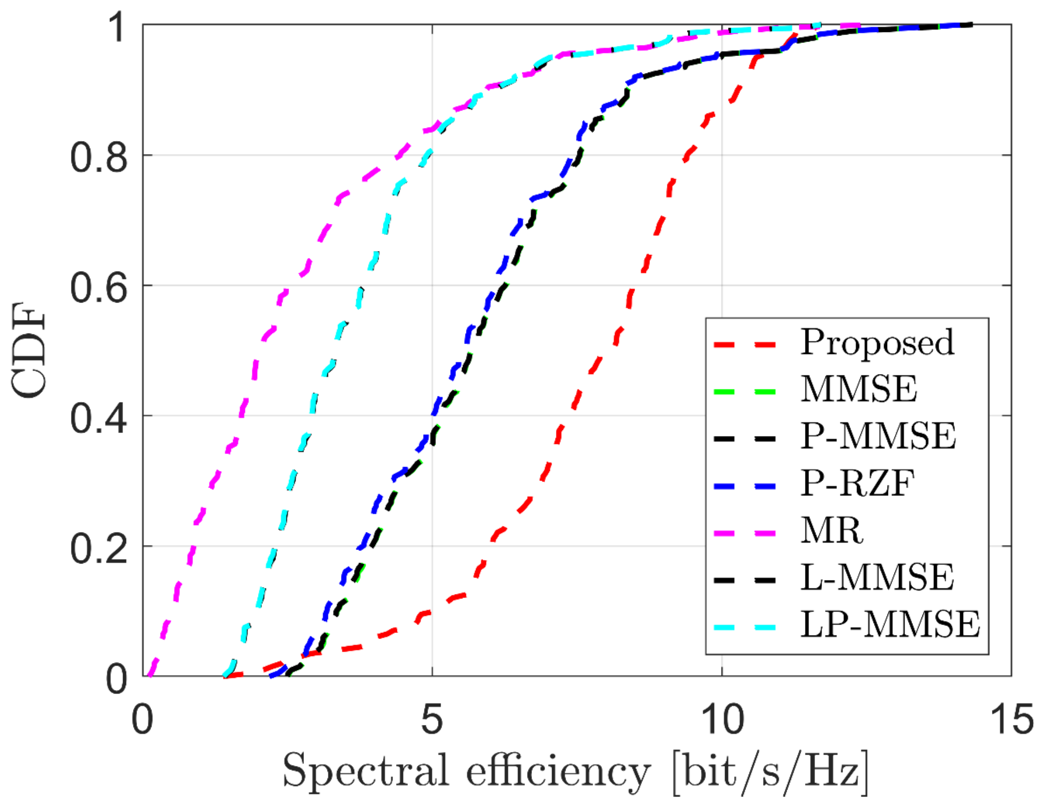

Figure 4.14 CDF versus SE of the proposed decoding technique with centralized and distributed techniques by considering L = 100, N = 2, and K = 40

4.2.3 Performance comparison between proposed and other existing decoding techniques based on number of complex multiplications

In massive MIMO systems, a large number of antennas are designed on a given network area to simultaneously facilitate multiple users. The number of complex multiplications in an uplink cell-free massive MIMO system is influenced by various parameters, like the number of APs, the number of UEs, the types of decoding techniques, and other specific signal processing algorithms. Figure 4.15 demonstrates the number of complex multiplications needed to decode the received signal by the AP at the CPU. Where L = 10, K = 10, and N ranging from 10 to 100 are given. At N = 10, the proposed technique has a number of complex multiplications of 20,300, which is less than MMSE's number of complex multiplications of 25,830, whereas P-RZF and MR have a number of complex multiplications of 20,980 and 19,000, respectively. When the number of antennas per AP increased from 10 to 100, the proposed technique had 673,800 complex multiplications, whereas MMSE, P-RZF, and MR had a number of complex multiplications of

1,128,000, 206,800, and 190,000, respectively. As we observed from these numerical values, with an increase in the antenna size of the system, the complexity of all decoding techniques also increased. The complexity of the existing technique, MMSE decoding, increased more as compared with the proposed one. P-RZF and MR have a smaller number of complex multiplications.

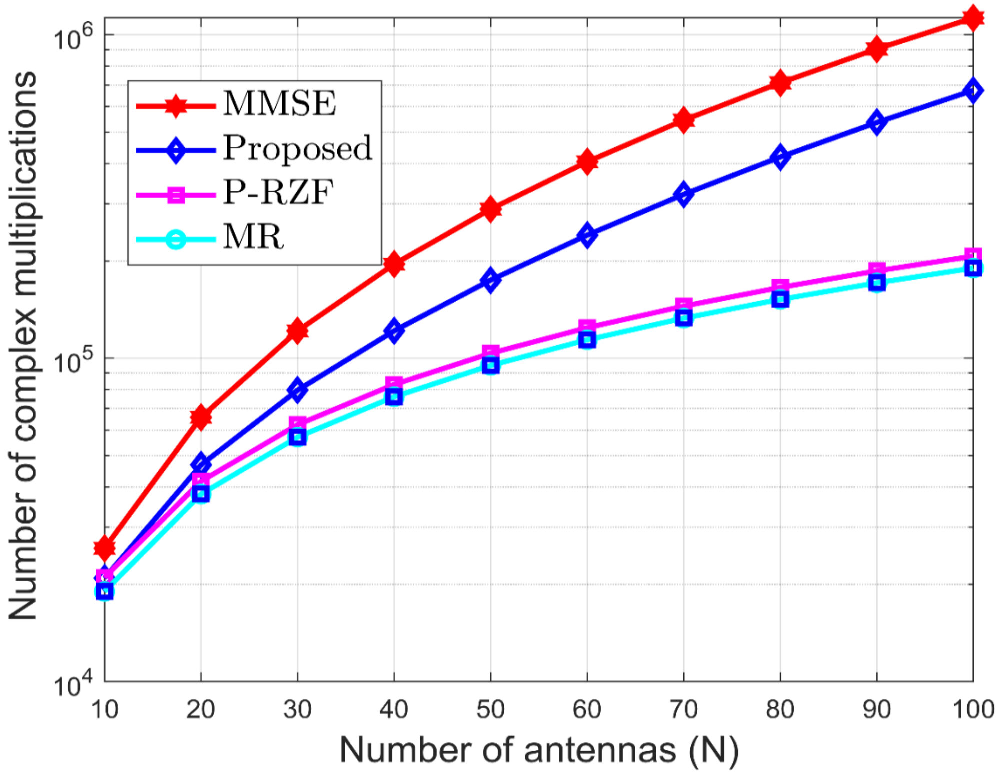

Figure 4.15 Performance comparison of proposed and existing decoding techniques based on complex multiplications with L = 10 and K = 10

Table 4.9 Performance comparison of different decoding techniques based on the number of complex multiplications of different decoding techniques for L = 10 and K = 10

Number of antennas per AP	Number of complex multiplications			
	MMSE	Proposed	RZF	MR
10	25,830	21,300	20,980	19,000
20	65,660	46,760	41,630	38,000

30	121,500	79,640	62,280	57,000
40	195,300	121,500	82,930	76,000
50	289,200	174,400	103,600	95,000
60	405,000	240,300	124,200	114,000
70	544,800	321,200	144,900	133,000
80	710,600	419,000	165,500	152,000
90	904,500	535,900	186,200	171,000
100	1,128,000	673,800	206,800	190,000

Figure 4.16 shows the number of complex multiplications required to decode the received signal at the CPU. The parameters are taken as L = 10 and K = 20. The proposed technique has 39,430 complex multiplications, whereas MMSE, P-RZF, and MR have a number of complex multiplications of 49,330, 44,960, and 36,000 at N = 10. For the same value of antenna per AP, there is an increase in the number of complex multiplications when we compare with Figure 4.15. This is because of the increase in UE in the system. For N = 100, the proposed technique has 994,300 complex multiplications, while MMSE has 1,903,000, whereas P-RZF and MR have 425,700 and 360,000, respectively. As we observed from the simulation results, there is an increase in the number of complex multiplications of the proposed technique by 32.23% compared to Figure 4.15 due to the doubling of the number of UEs.

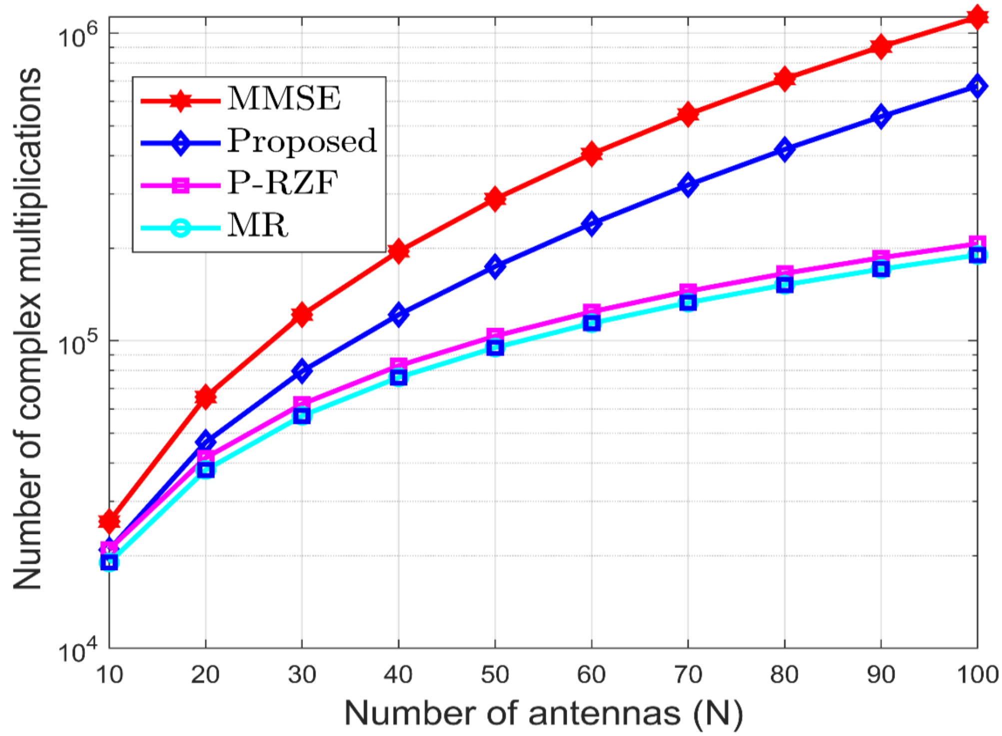

Figure 4.16 Performance comparison of proposed and existing decoding techniques based on complex multiplications with L = 10 and K = 20

Figure 4.17 this simulation result shows the relationship between the number of complex multiplications needed to decode the received signal with respect to the number of antennas at L = 20 and K = 10. At N = 10, the proposed technique has a number of complex multiplications of 20,980, while the MMSE has a number of complex multiplications of 31,330, whereas the P-RZF and MR have a number of complex multiplications of 20,980 and 19,000, respectively. Even though the latter two decoding techniques have a lower complex, they have a lower SE, so our target is to compensate for both SE and the number of complex multiplications needed. When N increased from 10 to 100, the proposed technique has 673,800 number of complex multiplications, and MMSE, P-RZF, and MR have a number of complexes of 163,3000, 206,800, and 190,000, respectively. This shows that with an increase in antenna sizes, the number of complex multiplications also increases.

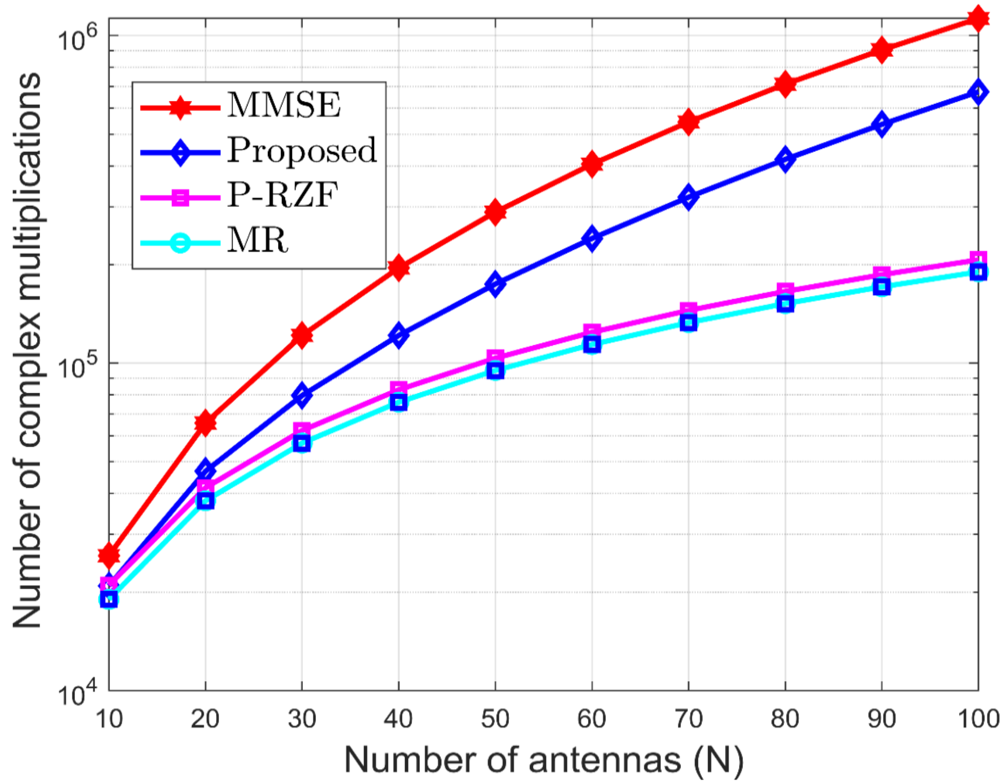

Figure 4.17 Performance comparison of proposed and existing decoding techniques based on complex multiplications with L = 20 and K = 10

Figure 4.18 demonstrates the number of complex multiplications needed to decode the received signal with parameters L = 20 and K = 20. At N = 10, the proposed and MMSE techniques have 39,430 and 60,330 complex multiplications, respectively. Whereas P-RZF and MR have a number of complex multiplications of 44,960 and 36,000, respectively. At N = 20, the proposed technique has an 86,860 number of complex multiplications, and MMSE, P-RZF, and MR have a number of complex multiplications of 166,700, 87,260, and 72,000, respectively. For N = 100, the proposed technique has 144,300 complex multiplications, and MMSE, P-RZF, and MR have a number of complex multiplications of 321,000, 129,600, and 108,000, respectively. This result shows that with an increase in the antenna size, the complexity of the proposed technique increases, but the number of complex multiplications of the existing technique of MMSE decoding increases more.

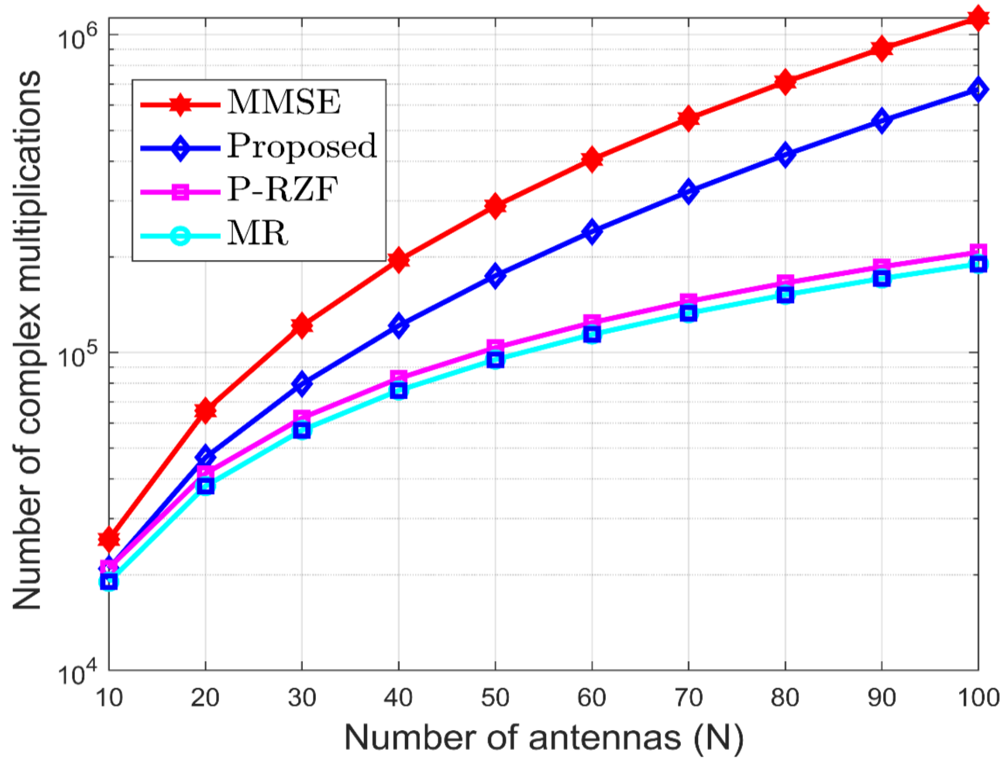

Figure 4.18 Performance comparison of proposed and existing decoding techniques based on complex multiplications with L = 20 and K = 20

Table 4.10 Performance comparison of different decoding techniques based on the number of complex multiplications of different decoding techniques for L = 20 and K = 20

Number of antennas	Number of complex multiplications			
	MMSE	Proposed	P-RZF	MR
10	60,330	39,430	44,960	36,000
20	166,700	86,860	87,260	72,000
30	321,000	144,300	129,600	108,000
40	525,300	213,700	171,900	144,000
50	781,700	297,200	214,200	180,000
60	1,092,000	396,600	256,500	216,000
70	1,458,000	514,000	298,800	252,000

80	1,883,000	651,400	341,100	288,000
90	2,367,000	810,900	383,400	324,000
100	2,913,000	994,300	425,700	360,000

Figure 4.19 illustrates the effect of the number of AP antennas on the complexity needed to decode the received signal at the CPU in the uplink system with L = 30 and N = 30. For N = 10, the proposed technique has a complexity of 55,980, whereas the existing techniques MMSE, P-RZF, and MR have complex multiplications of 103,800, 73,940, and 51,000, respectively.

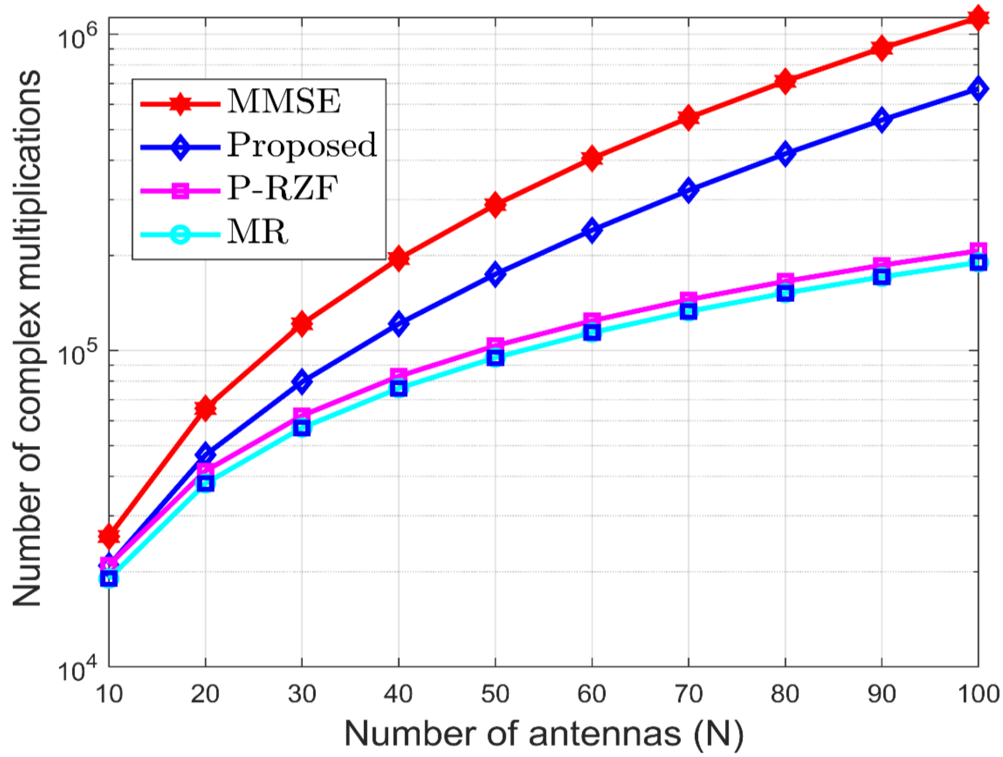

Figure 4.19 Performance comparison of proposed and existing decoding techniques based on complex multiplications with L = 30 and K = 30

4.2.4 Summary of complex multiplications

The proposed decoding technique in the simulation results has a lower computational complexity than the existing MMSE decoding technique. While the P-RZF and MR decoding techniques have even lower complexity than the proposed technique, they exhibit lower performance in comparison. This trade-off between complexity and performance is a key consideration in the design of cell-free massive MIMO systems. The proposed technique, though more computationally complex, achieved better performance compared to all existing decoding techniques. The proposed technique plays an important role in balancing complexity and performance to optimize the overall system design and efficiency.

4.2.5 Performance comparison between proposed and other existing decoding techniques based on bit error rate

Evaluating the performance of uplink cell-free massive MIMO systems using bit error rate (BER) versus signal-to-noise ratio (SNR) is a fundamental relationship that characterizes the performance of wireless communication. This relationship describes how the BER of the wireless communication system varies with the SNR, SNR measures the ratio of the power of the desired signal to the power of the noise signal, expressed in decibels (dB). BER, on the other hand, measures the ratio of missed bits received at the CUP to the total bits transmitted by the UE, providing a crucial metric for assessing the reliability and quality of the wireless link. Understanding the relationship is essential for designing the uplink cell-free massive MIMO systems.

Figure 4.20 shows the comparison between the proposed decoding technique and other decoding techniques. For the simulation, L = 200, each equipped with N = 4 antennas, K = 40, and the SNR ranges from -10 to 20 dB are taken. At SNR = -10 dB, the proposed technique has a BER of 4.224×10^{-1}, MMSE has 5.280×10^{-1}, whereas P-RZF, and MR have the same value of BER 5.938×10^{-1}. When the SNR value changed from -10 dB to 5 dB, the proposed technique has a BER of 7.467×10^{-4}, whereas MMSE, P-RZF, and MR have 9.333×10^{-4}, 4.917×10^{-2} and 9.727×10^{-2}, respectively.

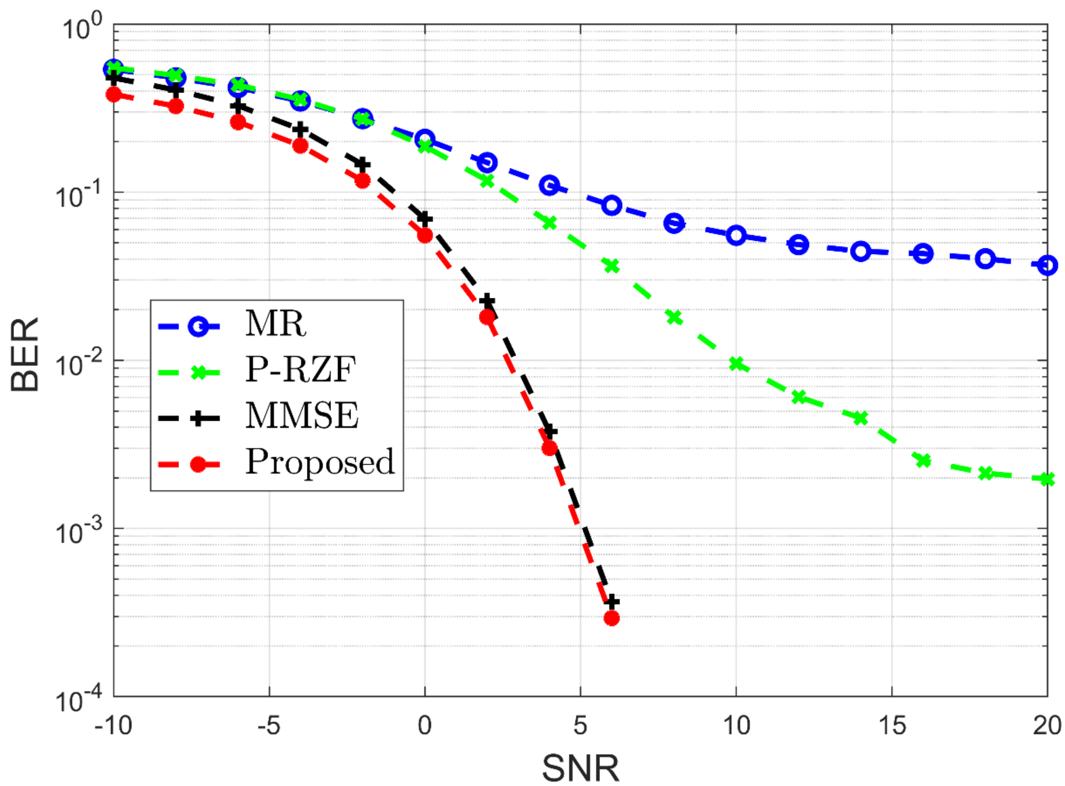

Figure 4.20 BER comparison between proposed and other existing decoding techniques at K = 40, L = 200, and N = 4

Table 4.11 illustrates a performance comparison between the proposed and other existing detecting techniques at K = 40, L = 200, and N = 4 in the uplink decoding system. As we can see from the table, the proposed technique has a lower BER for all values of SNR. It is the tabular form of Figure 4.20 within the given value of SNR.

Table 4.11 BER comparison between proposed and other existing decoding algorithms at K = 40, L = 200, and N = 4

SNR (dB)	BER			
	Proposed	MMSE	P-RZF	MR
-10	4.224×10^{-1}	5.280×10^{-1}	5.938×10^{-1}	5.938×10^{-1}
-5	2.250×10^{-1}	2.812×10^{-1}	3.935×10^{-1}	3.935×10^{-1}

0	$5.5528{\times}10^{-2}$	$6.910{\times}10^{-2}$	$1.875{\times}10^{-1}$	$2.062{\times}10^{-1}$
5	$7.467{\times}10^{-4}$	$9.333{\times}10^{-4}$	$4.917{\times}10^{-2}$	$9.727{\times}10^{-2}$

Figure 4.21 shows the comparison between the proposed decoding technique and other detection techniques. For the simulation, L = 300, each equipped with an antenna of N = 4, and UE of K = 40. At SNR = 5 dB, the proposed technique has a BER of $2.6667{\times}10^{-5}$, whereas MMSE, P-RZF, and MR have $3.333{\times}10^{-5}$, $1.01{\times}10^{-2}$ and $3.887{\times}10^{-2}$, respectively.

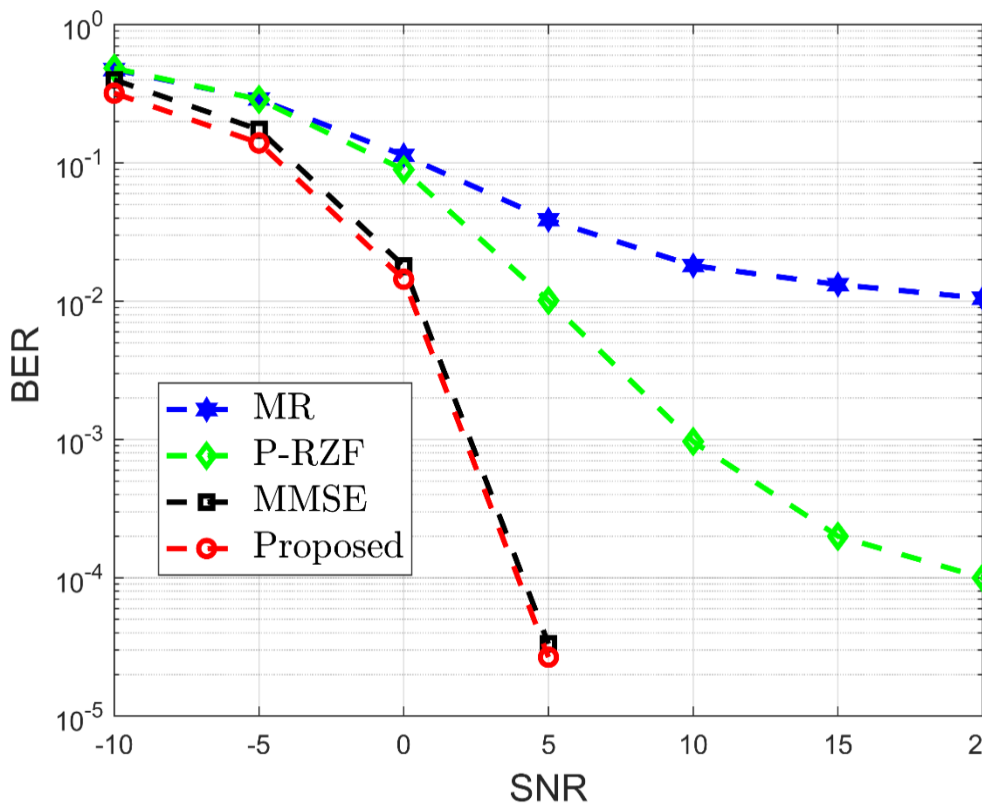

Figure 4.21 BER comparison between proposed and other existing decoding techniques at K = 40, L = 300, and N = 4

Figure 4.22 shows the comparison between the proposed and other existing decoding techniques in the uplink decoding systems at L = 200, N = 4, and K = 50. At SNR = -5 dB, the proposed technique has a BER of $2.878{\times}10^{-1}$ whereas the existing techniques MMSE, P-RZF, and MR have $3.598{\times}10^{-1}$, $4.469{\times}10^{-1}$, and $4.676{\times}10^{-1}$, respectively. When the SNR increased to 5 dB, the proposed technique had a BER of 8.340×10^{-3} whereas the existing techniques MMSE, P-RZF, and MR had 1.043×10^{-2}, 1.058×10^{-1}, and 1.563×10^{-1}, respectively.

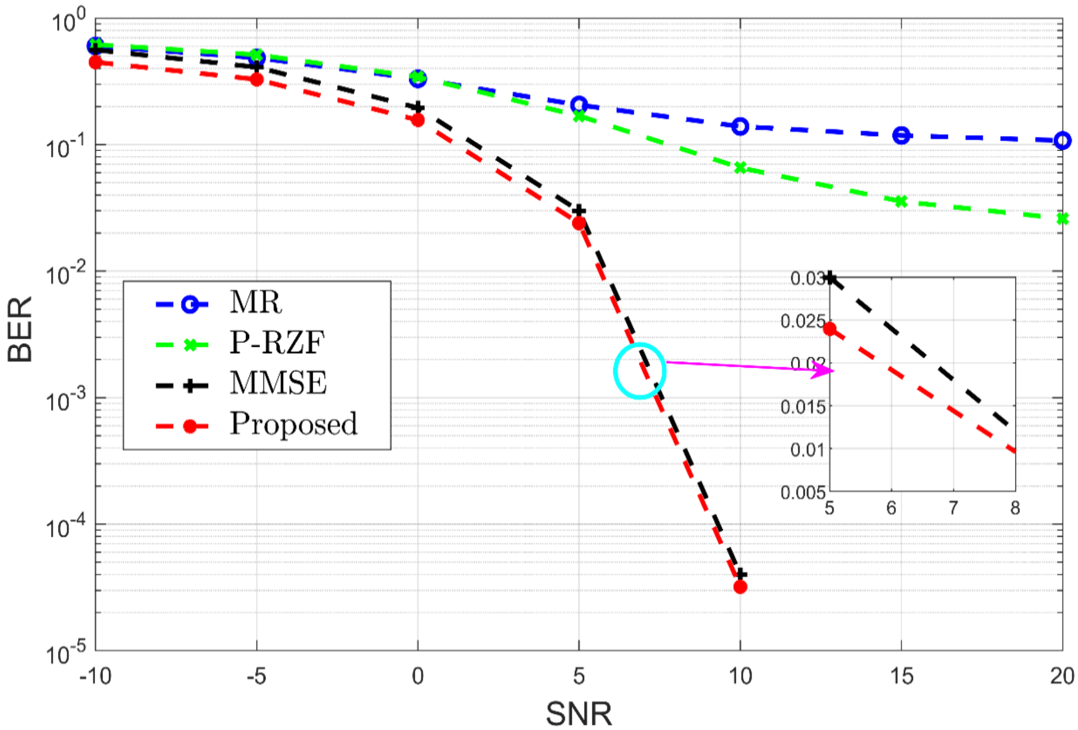

Figure 4.22 BER comparison between proposed and other existing decoding techniques at K = 50, L = 200, and N = 4

Figure 4.23 shows the comparison between the proposed decoding technique and other existing decoding techniques in uplink decoding systems. Where L = 100, each having N = 4 antennas, and UE of K = 50. At SNR = -5 dB, the proposed technique has a BER of 4.337×10^{-1} whereas the existing decoding techniques MMSE, P-RZF, and MR had 5.421×10^{-1}, 5.887×10^{-1}, and 6.328×10^{-1}, respectively. At SNR = 0 dB, the proposed technique has a BER of 3.14×10^{-1} whereas the existing techniques MMSE, P-RZF, and MR had 3.925×10^{-1}, 4.791×10^{-1}, and 5.422×10^{-1}, respectively. When the SNR value changed from SNR 0 dB to 5 dB, the proposed technique has an improved lower BER of 3.14×10^{-1} whereas the existing techniques MMSE, P-RZF, and MR have 3.925×10^{-1}, 5.422×10^{-1}, and 4.791×10^{-1}, respectively. As we observed from the simulation result, for a small value of SNR, the BER of all decoding techniques is almost the same, but the BER of the proposed technique decreased with an increase in the SNR value. In addition, all decoding techniques have a large BER compared to Figure 4.22; this is due to a decrease in the number of APs in the system.

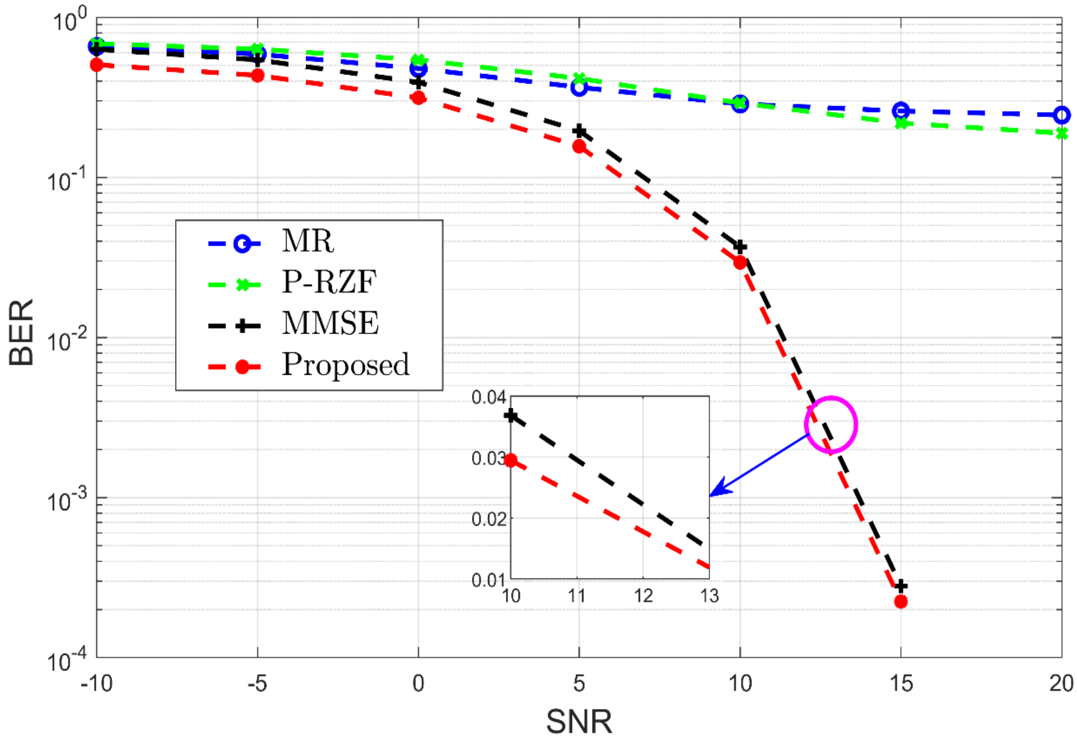

Figure 4.23 BER comparison between proposed and other existing decoding techniques at K = 50, L = 100, and N = 4

As shown from the above results, the proposed decoding technique has a lower BER compared to the MMSE, P-RZF, and MR existing decoding techniques. In this, the relationship between the SNR and BER performance in an uplink cell-free massive MIMO system is considered, with a varying number of UEs and APs. The BER of the proposed technique decreased as the SNR values increased. Additionally, the BER improved for decreasing the UEs because of increasing multi-user interference for an increase in UEs. Conversely, increasing the number of APs improved the system by decreasing the BER for a given SNR level, providing more diversity, enhancing the received signal quality, and mitigating the effects of interference.

5. CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The uplink cell-free massive MIMO system is a key enabling technology in the wireless communication area for 5G and beyond due to its high SE, high data rate, and minimizing interferences. In uplink received signal detection, interference is a major challenge because of the simultaneous transmission of signals from the UE to the AP. To mitigate this interference, this thesis developed a new hybrid decoding technique based on the P-MMSE combining scheme and the DCC with SIC technique to enhance the performance of cell-free massive MIMO systems by eliminating the interference that exists in the combing process.

According to the simulation results, the performance of the proposed decoding technique has been evaluated using sum SE, SE, BER, and the number of complex multiplications by comparing it with centralized decoding techniques such as MMSE, P-MMSE, P-RZF, and MR and distributed decoding techniques like L-MMSE and LP-MMSE decoding techniques. Based on the SE, the centralized decoding techniques outperformed the distributed decoding techniques. For both proposed and existing decoding techniques, the performance has improved with an increase in the number of antennas per AP, SNR, and number of AP. Whereas, the increase in the number of UEs has been decreased the performance of the decoding techniques because of increasing the IUI exist in the system, but for the sum SE the performance was increased with respect to the number of UEs. This is because the sum SE is calculated by adding the SE for each individual UE. In addition, as we have seen from the simulation results, the BER of the proposed decoding technique decreased with an increase in the SNR value. This shows that for large values of the desired received signal and low values of the unwanted signal, the performance of the uplink cell-free massive MIMO system became good as compared to low values of the desired received signal. The proposed technique has improved the sum SE by 6.347% for 200 APs, 5 antennas per AP, and 60 UEs compared to the P-MMSE decoding technique.

In summary, we conclude that the proposed centralized decoding technique outperformed the existing decoding techniques. This is due to coordinating with SIC for interference cancellation and adding the concept of DCC to the P-MMSE combining schemes to enhance cooperation among the distributed APs.

5.2 Recommendation

In this thesis work, the proposed decoding technique has only been evaluated at the simulation level using MATLAB software tool, so it needs more research and works to facilitate the real-world implementation of the proposed detecting technique. In the future, this thesis performance can be further improved by using machine learning and deep learning-based, scalable signal detection algorithms in the uplink cell-free massive MIMO system in order to improve the performance by minimizing the number of complex multiplications, power allocation, and perfect channel estimations.

6. REFERENCES

Akyildiz, I. F., Kak, A., & Nie, S. (2020). 6G and Beyond: The Future of Wireless Communications Systems. *IEEE Access*, *8*, 133995–134030. https://doi.org/10.1109/ACCESS.2020.3010896

Al Ayidh, A., Sambo, Y., & Imran, M. A. (2022). Mitigation pilot contamination based on matching technique for uplink cell-free massive MIMO systems. *Scientific Reports*, *12*(1), 1–14. https://doi.org/10.1038/s41598-022-21241-0

Albreem, M. A., Juntti, M., & Shahabuddin, S. (2019a). Massive MIMO Detection Techniques: A Survey. In *IEEE Communications Surveys and Tutorials* (Vol. 21, Issue 4, pp. 3109–3132). Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/COMST.2019.2935810

Albreem, M. A., Juntti, M., & Shahabuddin, S. (2019b). Massive MIMO Detection Techniques: A Survey. In *IEEE Communications Surveys and Tutorials* (Vol. 21, Issue 4, pp. 3109–3132). Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/COMST.2019.2935810

Almeida, D. B. T., Alencar, M. S., Duarte, R. M., Silva, H. S., Madeiro, F., Lopes, W. T. A., & Queiroz, W. J. L. (2024). On the Adaptive Modulation for User-Centric Cell-Free Massive MIMO Systems. *IEEE Access*, *12*(March), 35325–35336. https://doi.org/10.1109/ACCESS.2024.3370944

Benzaghta, M., & Rabie, K. M. (2021). Massive MIMO systems for 5G: A systematic mapping study on antenna design challenges and channel estimation open issues. *IET Communications*, *15*(13), 1677–1690. https://doi.org/10.1049/cmu2.12180

Björnson, E., & Sanguinetti, L. (2019). *Scalable Cell-Free Massive MIMO Systems*. https://doi.org/10.1109/TCOMM.2020.2987311

Chataut, R., & Akl, R. (2020a). Massive MIMO systems for 5G and beyond networks—overview, recent trends, challenges, and future research direction. In *Sensors (Switzerland)* (Vol. 20, Issue 10). MDPI AG. https://doi.org/10.3390/s20102753

Chataut, R., & Akl, R. (2020b). Massive MIMO systems for 5G and beyond networks—overview, recent trends, challenges, and future research direction. In *Sensors (Switzerland)* (Vol. 20, Issue 10). MDPI AG. https://doi.org/10.3390/s20102753

Choi, S., & Jeong, E. R. (2012). Digital predistortion based on combined feedback in MIMO transmitters. *IEEE Communications Letters*, *16*(10), 1572–1575. https://doi.org/10.1109/LCOMM.2012.080312.120224

Dai, J., Ge, J., Zhi, K., Pan, C., & Wang, Y. (2024). *RIS-assisted Cell-Free Massive MIMO Systems With Two-Timescale Design and Hardware Impairments*. 1–51.

Demir, Ö. T., Björnson, E., & Sanguinetti, L. (2021). Foundations of user-centric cell-free massive MIMO. *Foundations and Trends in Signal Processing*, *14*(3–4), 162–472. https://doi.org/10.1561/2000000109

Du, L., Li, L., Ngo, H. Q., Mai, T. C., & Matthaiou, M. (2021). Cell-Free Massive MIMO: Joint Maximum-Ratio and Zero-Forcing Precoder with Power Control. *IEEE Transactions on Communications*, *69*(6), 3741–3756. https://doi.org/10.1109/TCOMM.2021.3059300

Fatema, N., Hua, G., Xiang, Y., Peng, D., & Natgunanathan, I. (2018). Massive MIMO Linear Precoding: A Survey. *IEEE Systems Journal*, *12*(4), 3920–3931. https://doi.org/10.1109/JSYST.2017.2776401

Gao, W., Zhang, Y., Liu, L., Fang, R., Sun, J., Zhu, L., & Zhang, Z. (2023). Robust Energy-Efficient Transmission for Cell-Free Massive MIMO Systems with Imperfect CSI. *Electronics (Switzerland)*, *12*(16), 1–15. https://doi.org/10.3390/electronics12163384

Göttsch, F., Osawa, N., Ohseki, T., Amano, Y., Kanno, I., Yamazaki, K., & Caire, G. (2023). User-Centric Clustering Under Fairness Scheduling in Cell-Free Massive MIMO. *IEEE International Symposium on Information Theory - Proceedings*, *2023-June*, 292–297. https://doi.org/10.1109/ISIT54713.2023.10206527

Guenach, M., Gorji, A. A., & Bourdoux, A. (2021). Joint Power Control and Access Point Scheduling in Fronthaul-Constrained Uplink Cell-Free Massive MIMO Systems. *IEEE Transactions on Communications*, *69*(4), 2709–2722. https://doi.org/10.1109/TCOMM.2020.3047801

Hao, C., Vu, T. T., Ngo, H. Q., Dao, M. N., Dang, X., Wang, C., & Matthaiou, M. (2024). Joint User Association and Power Control for Cell-Free Massive MIMO. *IEEE Internet of Things Journal*, 1–18. https://doi.org/10.1109/JIOT.2024.3351633

Huo, Y., Lin, X., Di, B., Zhang, H., Hernando, F. J. L., Tan, A. S., Mumtaz, S., Demir, Ö. T., & Chen-Hu, K. (2023). Technology Trends for Massive MIMO towards 6G. *Sensors*, *23*(13). https://doi.org/10.3390/s23136062

Imoize, A. L., Obakhena, H. I., Anyasi, F. I., & Sur, S. N. (2022). A Review of Energy Efficiency and Power Control Schemes in Ultra-Dense Cell-Free Massive MIMO Systems for Sustainable 6G Wireless Communication. *Sustainability (Switzerland)*, *14*(17). https://doi.org/10.3390/su141711100

Interdonato, G., Björnson, E., Quoc Ngo, H., Frenger, P., & Larsson, E. G. (2019). Ubiquitous cell-free Massive MIMO communications. In *Eurasip Journal on Wireless Communications and Networking* (Vol. 2019, Issue 1). Springer International Publishing. https://doi.org/10.1186/s13638-019-1507-0

Jayaweera, N., Manosha, K. B. S., Rajatheva, N., & Latva-aho, M. (2024). Minimizing Energy Consumption in Cell-free Massive MIMO Networks. *IEEE Transactions on Vehicular Technology*, *PP*, 1–15. https://doi.org/10.1109/TVT.2024.3392790

Jit Singh, M. S., Wan Saleh, W. S., T. Abed, A., & Fauzi, M. A. (2023). A Review on Massive MIMO Antennas for 5G Communication Systems on Challenges and Limitations. *Jurnal Kejuruteraan*, *35*(1), 95–103. https://doi.org/10.17576/jkukm-2023-35(1)-09

Kassam, J., Castanheira, D., Silva, A., Dinis, R., & Gameiro, A. (2023). A Review on Cell-Free Massive MIMO Systems. In *Electronics (Switzerland)* (Vol. 12, Issue 4). MDPI. https://doi.org/10.3390/electronics12041001

Lancho, A., Durisi, G., & Sanguinetti, L. (2022). *Cell-Free Massive MIMO for URLLC: A Finite-Blocklength Analysis*. 1–13. https://doi.org/10.1109/TWC.2023.3265303

Lu, L., Li, G. Y., Swindlehurst, A. L., Ashikhmin, A., & Zhang, R. (2014). An overview of massive MIMO: Benefits and challenges. *IEEE Journal on Selected Topics in Signal Processing*, *8*(5), 742–758. https://doi.org/10.1109/JSTSP.2014.2317671

Mai, T. C., Ngo, H. Q., & Duong, T. Q. (2020). Downlink Spectral Efficiency of Cell-Free Massive MIMO Systems with Multi-Antenna Users. *IEEE Transactions on Communications*, *68*(8), 4803–4815. https://doi.org/10.1109/TCOMM.2020.2990951

Marzetta, T. L. (2010). Noncooperative cellular wireless with unlimited numbers of base station antennas. *IEEE Transactions on Wireless Communications*, *9*(11), 3590–3600. https://doi.org/10.1109/TWC.2010.092810.091092

Miretti, L., Cavalcante, R. L. G., Bjornson, E., & Stanczak, S. (2024). UL-DL Duality for Cell-free Massive MIMO with Per-AP Power and Information Constraints. *IEEE Transactions on Signal Processing*. https://doi.org/10.1109/TSP.2024.3376809

Mobini, Z., Ngo, H. Q., Matthaiou, M., & Hanzo, L. (2023). *Cell-Free Massive MIMO Surveillance Systems*. http://arxiv.org/abs/2310.09769

Ngo, H. Q., Ashikhmin, A., Yang, H., Larsson, E. G., & Marzetta, T. L. (2017). Cell-Free Massive MIMO Versus Small Cells. *IEEE Transactions on Wireless Communications*, *16*(3), 1834–1850. https://doi.org/10.1109/TWC.2017.2655515

Nguyen, N. T., Ma, M., Lavi, O., Shlezinger, N., Eldar, Y. C., Swindlehurst, A. L., & Juntti, M. (2023). Deep Unfolding Hybrid Beamforming Designs for THz Massive MIMO Systems. *IEEE Transactions on Signal Processing*, *71*, 3788–3804. https://doi.org/10.1109/TSP.2023.3322852

Shaik, Z. H. (2022). *Cell-Free Massive MIMO: Distributed Signal Processing and Energy Efficiency* (Vol. 1924).

Shaik, Z. H., Björnson, E., & Larsson, E. G. (2020). *MMSE-Optimal Sequential Processing for Cell-Free Massive MIMO With Radio Stripes*. http://arxiv.org/abs/2012.13928

Shakya, I. L., & Ali, F. H. (2021). Joint Access Point Selection and Interference Cancellation for Cell-Free Massive MIMO. *IEEE Communications Letters*, *25*(4), 1313–1317. https://doi.org/10.1109/LCOMM.2020.3041640

Sheikh, J. A. (2023). *DCC : CF-MIMO- A new Dynamic Cooperation Cluster Driven Cell-Free Massive MIMO Architecture Network for Future Networks*.

Ssettumba, T., Shao, Z., Landau, L. T. N., Facina, M. S. P., Da Silva, P. B., & De Lamare, R. C. (2024). Centralized and Decentralized IDD Schemes for Cell-Free Massive MIMO Systems: AP Selection and LLR Refinement. *IEEE Access*, *12*(May), 62392–62406. https://doi.org/10.1109/ACCESS.2024.3395585

Van Rompaey, R., & Moonen, M. (2024). Distributed Combined Channel Estimation and Optimal Uplink Receive Combining for User-Centric Cell-free Massive MIMO Systems. *IEEE Open Journal of Signal Processing*, *5*(March), 559–576. https://doi.org/10.1109/OJSP.2024.3377098

Wang, Z., Zhang, J., Ai, B., Yuen, C., & Debbah, M. (2021a). *Uplink Performance of Cell-Free Massive MIMO with Multi-Antenna Users Over Jointly-Correlated Rayleigh Fading Channels*.

Wang, Z., Zhang, J., Ai, B., Yuen, C., & Debbah, M. (2021b). *Uplink Performance of Cell-Free Massive MIMO with Multi-Antenna Users Over Jointly-Correlated Rayleigh Fading Channels*.

Wang, Z., Zhang, J., Ngo, H. Q., Ai, B., & Debbah, M. (2023). Uplink Precoding Design for Cell-Free Massive MIMO With Iteratively Weighted MMSE. *IEEE Transactions on Communications*, *71*(3), 1646–1664. https://doi.org/10.1109/TCOMM.2023.3235919

Wu, X., Gu, L., Wang, W., & Gao, X. (2016). Pilot design and AMP-based channel estimation for massive MIMO-OFDM uplink transmission. *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, PIMRC*. https://doi.org/10.1109/PIMRC.2016.7794663

Wu, Y., Gao, X., Zhou, S., Yang, W., Polyanskiy, Y., & Caire, G. (2019). *Massive Access for Future Wireless Communication Systems*. http://arxiv.org/abs/1910.12678

Yu, D., Lee, H., Hong, S. E., & Park, S. H. (2023). Learning Decentralized Power Control in Cell-Free Massive MIMO Networks. *IEEE Transactions on Vehicular Technology*, *72*(7), 9653–9658. https://doi.org/10.1109/TVT.2023.3251415

Zhang, J., Chen, S., Lin, Y., Zheng, J., Ai, B., & Hanzo, L. (2019a). Cell-free massive MIMO: A new next-generation paradigm. *IEEE Access*, *7*, 99878–99888. https://doi.org/10.1109/ACCESS.2019.2930208

Zhang, J., Chen, S., Lin, Y., Zheng, J., Ai, B., & Hanzo, L. (2019b). Cell-free massive MIMO: A new next-generation paradigm. *IEEE Access*, *7*, 99878–99888. https://doi.org/10.1109/ACCESS.2019.2930208

Zhang, J., Chen, S., Lin, Y., Zheng, J., Ai, B., & Hanzo, L. (2019c). Cell-free massive MIMO: A new next-generation paradigm. *IEEE Access*, *7*, 99878–99888. https://doi.org/10.1109/ACCESS.2019.2930208