Performance Evaluation of Down Link Rate Splitting Multiple Access for MIMO System in Massive Machine Type Communication

Elias Tsegaw Tadesse

A Thesis Submitted to

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 (Communication Engineering)

Office of Graduate Studies

Adama Science and Technology University

June 2023

Adama, Ethiopia

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APPROVAL PAGE OF MSc. THESIS

We hereby confirm that the thesis review committee's recommendations and suggestions have been successfully incorporated into the final thesis entitled **"Performance Evaluation of Down Link Rate Splitting Multiple Access for MIMO System in Massive Machine Type Communication"** by Elias Tsegaw Tadesse.

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Major Advisor	Signature	Date
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Co-advisor	Signature	Date

We, the undersigned, members of the Board of Examiners of the thesis by Elias Tsegaw Tadesse have read and evaluated the thesis entitled **"Performance Evaluation of Down Link Rate Splitting Multiple Access for MIMO System in Massive Machine Type Communication"** 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.

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RECOMMENDATION OF ADVISORS

I, the major advisor of this research proposal, hereby certify that I have closely advised the student while developing this proposal and read the draft thesis proposal entitled **"Performance Evaluation of Down Link Rate Splitting Multiple Access for MIMO System in Massive Machine Type Communication"** prepared under my guidance by **Mr. Elias Tsegaw Tadesse**. Therefore, I recommend the submission of the proposal to the department for further review and evaluation.

We, the advisors of this thesis, hereby certify that we have read the revised version of the thesis entitled **"Performance Evaluation of Down Link Rate Splitting Multiple Access for MIMO System in Massive Machine Type Communication"** prepared under our guidance by **Elias Tsegaw Tadesse** submitted in partial fulfillment of the requirements for the degree of Masters of Science in Electronics and Communication Engineering (Communication Engineering). Therefore, we recommend the submission of the revised version of the thesis to the department following the applicable procedures.

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Major Advisor/Supervisor	Signature	Date
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Co-advisor/Co-supervisor	Signature	Date

DECLARATION

I hereby declare that this Master Thesis entitled **"Performance Evaluation of Down Link Rate Splitting Multiple Access for MIMO System in Massive Machine Type Communication"** is my original work. That is, it has not been submitted for the award of any academic degree, diploma, or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

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Name of student	Signature	Date

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LIST OF ACRONYMS

mMTC	massive Machine Type Communication
MTCd	Machine Type Communication device
SDMA	Space Division Multiple Access
OMA	Orthogonal Multiple Access
NOMA	Non-Orthogonal Multiple Access
RSMA	Rate Splitting Multiple Access
MIMO	Multiple Input Multiple Output
PP-RSMA	Power Partitioning RSMA
DoF	Degree of Freedom
CSIT	Chanel State Information at the Transmitter
QoS	Quality of Service
MCS	Monte Carlo Simulation
LLS	Link Level Simulation
SC	Superposition Coding
SIC	Successive Interference Cancellation
IoT	Internet of Things
URLLC	Ultra Reliable Low Latency Communication
MA	Multiple Access

ABSTRACT

The advent of advanced cellular technologies, such as 5G and beyond, has enabled the realization of a converged network supporting various use cases. Among these, massive Machine Type Communication (mMTC) has emerged as a prominent application, facilitating communication between a massive number of devices within a single network. To address the challenges posed by mMTC, recent advancements have introduced Non-Orthogonal Multiple Access (NOMA) and Rate Splitting Multiple Access (RSMA) techniques. Recently RSMA has shown a promising improvement in rate and Degree of Freedom (DoF) analysis. However its application and performance in the context of downlink mMTC, particularly in a Multiple-Input Multiple-Output (MIMO) setting remain unexplored. Motivated by the need to enhance mMTC support while maintaining low power usage this thesis project focuses on the performance evaluation of RSMA and its extension Power Partitioning Rate Splitting Multiple Access (PP-RSMA) in a MIMO system for mMTC services. The analysis primarily revolves around two key aspects: rate and DoF analysis. The study investigates the performance characteristics of the Broadcast Channel (BC) RSMA system in terms of DoF and compares RSMA with NOMA and other related multiple access (MA) techniques in terms of DoF and achievable sum rate. Using MATLAB software, extensive simulations were conducted to assess the performance of the proposed PP-RSMA technique. The results demonstrated that RSMA outperformed other MA techniques in terms of rate, exhibiting a significant increase of 22.9% to 11.64% compared to Space Division Multiple Access (SDMA) and 20.2% to 15% compared to NOMA across different MTC deployments, particularly under low Channel State Information at the Transmitter (CSIT) quality. Additionally, RSMA enhanced the DoF performance of the system by 20.2% to 22.1% compared to SDMA and 22.94% to 11.64% compared to NOMA when low CSIT quality is available for MTC devices. Moreover, in scenarios where MTC devices have low or no CSIT information, PP-RSMA effectively handled the heterogeneity in demand and CSIT requirements of MTC devices, exhibiting superior performance. Link Level Simulations (LLS) demonstrated that the throughput achieved by the system aligned closely with the rate capacity, reinforcing the efficacy of PP-RSMA in mMTC MIMO systems.

Key Words: mMTC, RSMA, MIMO, PP-RSMA, DoF, LLS, Throughput.

CHAPTER ONE

1. INTRODUCTION

1.1 Background of the Study

One of the excitement surrounding fifth generation (5G) and beyond communication systems is the seamless integration of Massive Machine Type Communication (mMTC) which will transform and touch many industries in automating processes and allowing for Internet of Things (IoT) deployment. Our country Ethiopia will also benefit from this technology, especially in modernizing different industries like Agriculture and Manufacturing. Although the deployment of 5G networks is in its infancy, let alone beyond 5G communication, in our country, looking at how far we have come, it is evident that this technology will take the market by storm within a few years.

The key performance indicators for 5G show that for mMTC communications the coverage can have a maximum coupling loss of 164dB and user equipment battery life should be beyond 10 years and connection density is 1 Million devices per square kilometer and the maximum latency should be 10 seconds (Payam, 2018). This restrictive constraint will be even more tightened in 6G so an efficient communication system is mandatory to satisfy all these requirements. (Mao, et al., 2022)

The advantages of RSMA include its Universality in summing different MA techniques like OMA, NOMA, Multicasting, and SDMA making RSMA a superset of all those MA techniques. Its flexibility in different network loads and deployments is evident since RSMA employs a flexible interference management strategy by partially decoding the interference and partially treating the interference as noise, which generalizes the design principle of fully treating interference as noise (as in SDMA), fully decoding interference (as in NOMA), and single-user transmission to avoid interference (as in OMA). It’s Robustness against CSIT uncertainties resulting from different sources of impairment. It’s High spectral efficiency in both perfect and imperfect CSIT. Its High energy efficiency exceeds all MA schemes listed above. It gives Enhanced Quality of Service (QoS) and user fairness since it has better sum-DoF and MMF-DoF. Lower complexity in the receiver and transmitter design compared to NOMA and other MA schemes. Also, RSMA has been shown to improve Throughput over SDMA and NOMA with finite length polar codes and to attain the same transmission rate as

SDMA and NOMA but with shorter block length and therefore lower latency. (Mao, et al., 2022)

With all the advantages listed above the disadvantages of RSMA are stated here. Disadvantages of RSMA include the SIC requirement at the receivers increasing exponentially with the number of user K for generalized RS and M-DPCRS. Higher encoding complexity than that of other MA schemes since RSMA requires more data streams to be encoded due to the message splitting (and recombining). Higher signaling burden and higher optimization burden. (Mao, et al., 2022)

RSMA can generalize different MA techniques such as OMA, NOMA, SDMA, and multicasting. This capability makes RSMA attractive for serving different types of user equipment. As per the rate and energy efficiency requirements of the specified use cases it can adapt for each user type. For example, if we need a higher data rate RSMA can be used with small disadvantages like signaling burden and optimization burden. Again for low data rate requirements, we can easily use RSMA as OMA and serve the user equipment with less signaling burden. With this attractive solution, Power Partitioning and Time Partitioning RSMA based multiple access techniques have been introduced highlighting the best performance of PP-RSMA for Iot solutions with heterogeneous operation requirements. (Mao, Piovano, & Clerckx, 2020) .

A Two User RSMA is shown in Figure 1.1. The two users have messages $W1$ and $W2$ and these messages are scheduled and a massage splitter will split them into two pairs of messages, hence the name rate splitting, a private part, and a common part of the message is generated for each user. A massage combiner will combine the common parts of the two messages into a single common part. The two private parts and the common part ate then encoded into the three streams Sc, $Sp1$, and $Sp2$. Finally, the three steams will be linearly precoded into the final message signal $x1$ and $x2$. (Mao, et al., 2022)

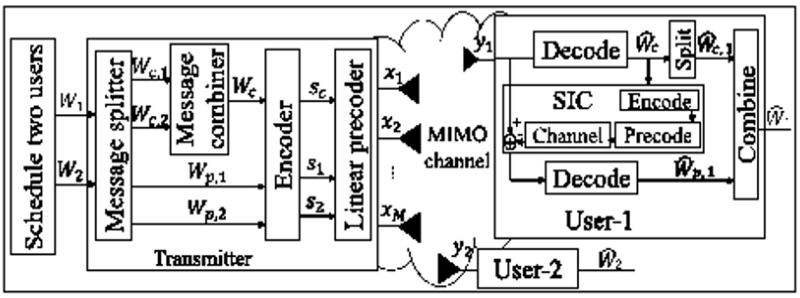

Figure 1.1 Two User RSMA (Mao, et al., 2022)

Equation 1 gives the transmitted signal for RSMA Transmitter with Nt transmit antennas serving K single antenna users. S_n denotes a stream of the signal encoded from the common and private parts of the user messages. p_k gives the linear precoder elements for each stream. Equation 2 gives a power constraint that must be satisfied in which the total summed power from each user must not exceed the total allocated system power Pt.

$$\boldsymbol{x} = \boldsymbol{p}_c S_c \ \sum_{k=1}^{K} \boldsymbol{p}_k S_k \tag{1}$$

$$\|\mathbf{p_c}\|^2 + \sum_{\mathrm{k=1}}^{\mathrm{K}} \|\mathbf{p_k}\|^2 \leq Pt \tag{2}$$

$$y_k = \boldsymbol{h}_k^H x + n_k \tag{3}$$

On the receiver side, only the common message will be subjected to Successive Interference Cancellation (SIC) and the result is subtracted from the input and the private part is decoded. As the number of users increases the complexity of the receiver will increase since the number of SIC needed is increased but at least it is better than NOMA in which case the complexity will increase exponentially. Equation 3 gives the received signal at the RSMA receiver. $\boldsymbol{h}_k$ denotes the channel matrix where H shows the complex conjugate transpose of the channel matrix. nk is an additive white Gaussian noise with zero mean and standard deviation $\sigma_{n,k}^2$. (Mao, Clerckx, & Li, 2018)

1.2 Statement of the problem

The promising advancement in wireless communication technology made massive connectivity available for different industries. Allowing the application of massive Machine Type Communication (mMTC) services to improve the quality of products and services given by each industry. The demanding nature of mMTC services, based on the KPI of 5G and beyond, calls for an improvement in multiplexing gain and the rate of the MA techniques employed to be improved. In recent years Rate Splitting Multiple Access (RSMA) has gained attention over Power Domain Non-Orthogonal Multiple Access (PD-NOMA) due to its superior performance in terms of Degree of Freedom (DoF) and robustness against interference in multi-antenna systems. For mMTC services, MISO PP-RSMA has shown better performance in terms of DoF (which dictates the number of user equipment we can multiplex in a single resource element) and rate (total system sum data rate in bits/s/Hz) analysis. The study of PP-RSMA is yet to be given under MIMO configuration so in this thesis work a performance analysis of Power Partitioning RSMA (PP-RSMA) technique is given under MIMO Configuration.

1.3 Objective of the Study

1.3.1 General Objectives

The general objective of this thesis work is to carry out a performance Evaluation of Down Link Rate Splitting Multiple Access (RSMA) for Multiple Input Multiple Output (MIMO) System in massive Machine Type Communication (mMTC).

1.3.2 Specific Objectives

- To investigate and analyze performance characteristics of BC RSMA system in terms of DoF.
- To compare the performance of RSMA with NOMA and related MA techniques in terms of DoF and achievable sum rate.
- To investigate and analyze the performance characteristic of PP-RSMA in an overloaded mMTC system in terms of DoF and achievable sum rate.
- To investigate and analyze the performance characteristic of PP-RSMA in a MIMO mMTC system in terms of DoF and achievable sum rate.
- To analyze the Throughput of the system with Link Level simulation.

1.4 Significance of the Study

In recent years the demand to integrate massive Machine Type Communication Systems in the industry is increasing. Providing this system in a cellular system will make it easily accessible. But to provide the service in a cellular system a highly efficient Multiple Access system in terms of energy and rate must be employed. In this thesis, the performance of an efficient MA scheme (RSMA) in MIMO system is studied.

1.5 Contributions of the Thesis Work

The expected outcome for this thesis is a detailed performance analysis for PP-RSMA multiple access techniques for massive Machine Type Communication with multiple antenna at both transmitter and receiver. Rate and degree of freedom analysis is given, and the improvement the system gives over related Multiple Access techniques is analyzed. This will help future research works that might be done on this type of multiple access techniques.

1.6 Scope and Limitations of the Study

This thesis focuses on the performance analysis of PP-RSMA for the mMTC communication system under MIMO setup. A comparison of the NOMA technique with the proposed method was carried out in terms of DoF and Rate analysis. Analytical methods was employed to compare the proposed system with benchmark NOMA and SDMA techniques. MATLAB Communication software is used to simulate all the proposed techniques.

The limitations of this thesis are it is limited to simulation based analysis and although not critical for this other performance analysis like energy efficiency is not studied.

1.8 Thesis Organization

The remaining part of the thesis is organized as follows. In Chapter Two the literature review and the related papers relevant to the study are presented. In Chapter Three materials and methods followed in this thesis research are described and in Chapter Four the results and discussions are briefly provided. In Chapter Five Conclusions and future recommendations are given. Finally, references are listed.

CHAPTER TWO

2. LITERATURE REVIEW

2.1 Multiple Access Techniques

2.1.1 Multiple Access Techniques from 1G to 5G

In the 1G cellular system, FDMA is used where the frequency band is divided into frequency channels where users are assigned channels. In 2G TDMA was employed, here a new dimension of resource which is time was used for a resource element. The problem with TDMA is its receiver complexity increases exponentially with the increase in data rate, number of antennas, and order of modulation. In 3G CDMA was used which uses larger bandwidth with PN code as a resource element. The challenge of CDMA technology is its complexity increase with an increase in data rate. 4G of cellular systems employed OFDMA and utilized a shared channel concept from 3G. The physical resources elements being frequency subcarriers and time slots gave flexibility for resources and bandwidth. Receiver complexity is kept relatively low by using a cyclic prefix with frequency domain processing. 5G also has continued to use OFDMA due to the reasons given above. (Boccuzzi, 2019)

2.1.2 What is Non-Orthogonal Multiple Access?

For Orthogonal Multiple Access (OMA) systems listed above inter-user interference is handled using orthogonal resource allocation which makes the number of users to be limited to the number of orthogonal resources. In Non-orthogonal multiple access (NOMA) inter-user interference is utilized in the resource allocation of users. Superposition coding (SC) on the transmitter side and Successive Interference Cancelation (SIC) in the receiver is used in Power Domain NOMA. (Boccuzzi, 2019)

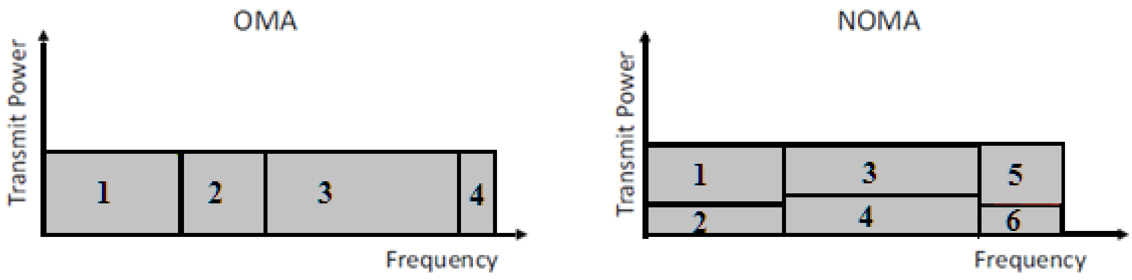

Figure 2.1 Orthogonal multiple access vs Non Orthogonal multiple access (Boccuzzi, 2019)

2.2 MIMO

Under multi-antenna communication, MIMO is a system where there is multiple input at the transmitter and multiple output at the receiver. Under the umbrella of the MIMO system, three types of systems are included the first one is a single-user MIMO system with multiple antennae at the transmitter and receiver as shown in Figure 2.2 a. The second one is a multi-user MISO system which consists of a multi-antenna transmitter and multiple single-antenna users it is given in Figure 2.2 b. The final type of MIMO system is multi-user MIMO where the system is similar to the previous one but each user receiver is equipped with multiple antennas. It is given in Figure 2.2 c. (Godara, 2004) (Goldsmith, 2005)

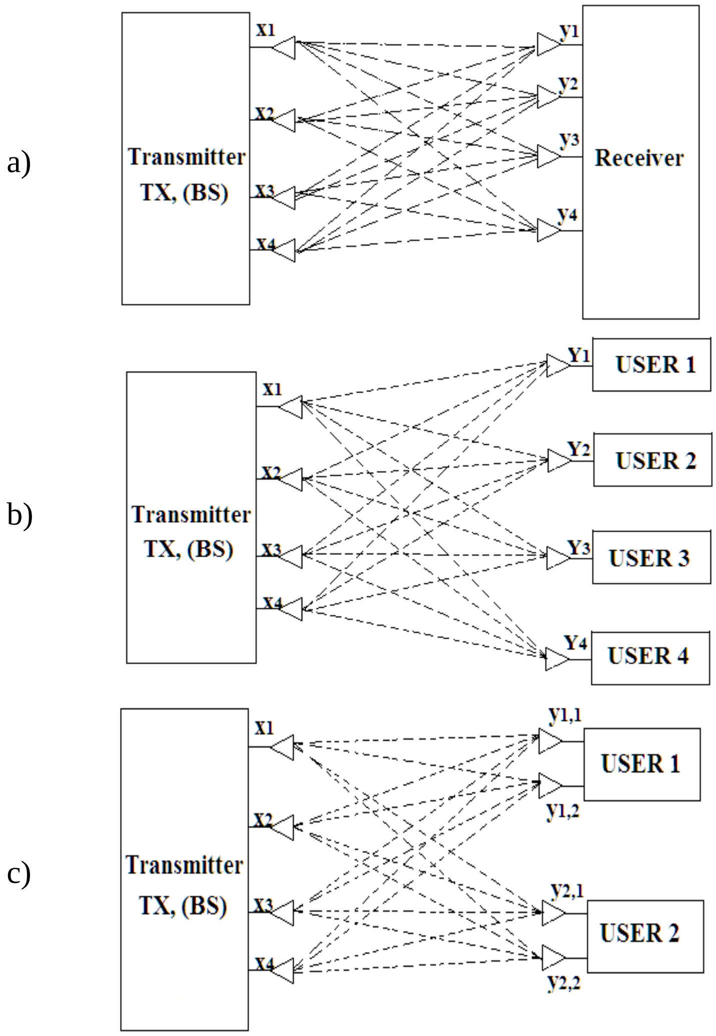

Figure 2.2 MIMO system types. a) Single user MIMO b) multi-user MISO and c) multi-user MIMO

The first system will not benefit from Multiplexing Gain so our focus is the rest two systems that are MU-MISO and MU-MIMO. Multiple antennae at the receiver could allow for multiple stream transmission or be used as a diversity gain. For a downlink transmission, the channel state information (CSI) of the system must be known at either the receiver (CSIR) or at the transmitter (CSIT). At the receiver side, the channel state could easily be known with fair accuracy which is why it is normally assumed a perfect CSIR knowledge. (Bruno & Claude, 2013)

Once the receiver receives a message it can perform equalization to estimate the received signal. But this is not a desirable method since it will burden the receiver with complex computation that will not be possible for low-capability receivers and also in some cases, it will enhance the noise at the receiver. Another way is to use precoding where the transmitter is informed about the channel state (CSIT) from each user by TDD or FDD feedback and the transmitter will adjust its transmission to the specific user by nulling or reducing multi-stream interference. (Goldsmith, 2005)

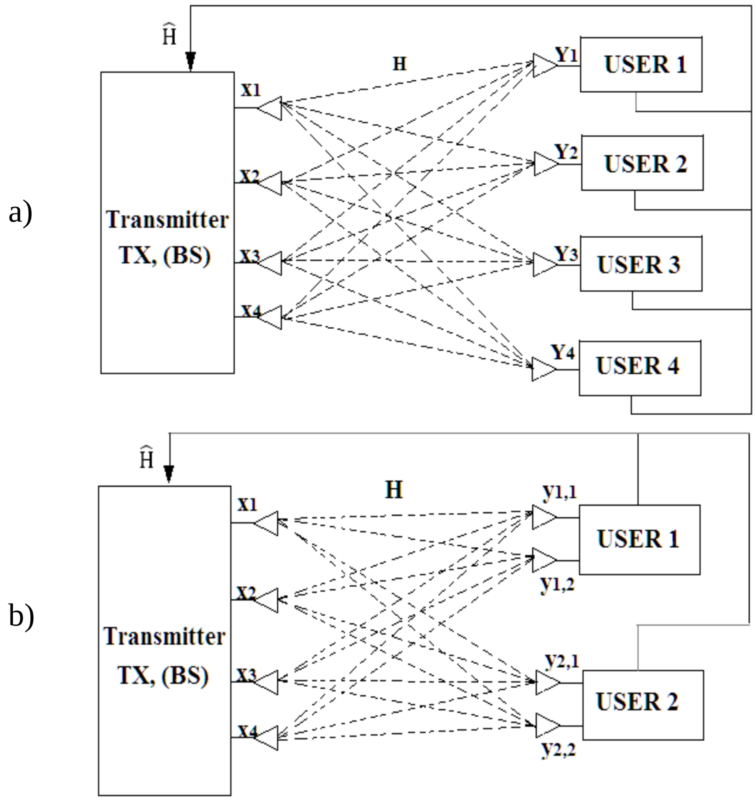

Figure 2.3 CSI Feedback for Downlink transmission in MIMO a) multi-user MISO and b) multi-user MIMO

2.3 Linear Precoder

2.3.1 Matched Beamforming

It aims at maximizing the received power of each user and ignores interference. As the number of transmit antennas Nt increases, assuming perfect CSIT, the matched beam former of user q becomes orthogonal to co-scheduled users (s = q) channels (Bruno & Claude, 2013). The precoder is given by

$$P = \sqrt{\frac{Pt}{Nt}} \frac{H^H}{\|H^H\|} \tag{2.1}$$

2.3.2 Zero-Forcing Beamforming

Zero-forcing transmit precoder forces the inter-user interference to zero. The precoder P of user k is chosen to make $H_j P_k = 0 \ \forall j \neq k$. Such precoder is given by.

$$P = \sqrt{\frac{Pt}{Nt}} \frac{H^H(HH^H)^{-1}}{\|H^H(HH^H)^{-1}\|} \tag{2.2}$$

The problem with this kind of precoding is that the normalization constant $\|H^H(HH^H)^{-1}\|$ is often very large because of the large singular values in the inverse of the channel matrix H and is getting larger as the MIMO paths get closer to each other leading to poor performance at low SNR region. (Goldsmith, 2005) (Godara, 2004)

2.3.3 Regularized Zero Forcing

Regularization of the channel matrix with scaled identity matrix αI_{Nt} is employed before channel inversion to control the amount of multi-user interference.

$$P = \sqrt{\frac{Pt}{Nt}} \frac{H^H(HH^H + \alpha I_{Nt})^{-1}}{\|H^H(HH^H + \alpha I_{Nt})^{-1}\|} \tag{2.3}$$

The regularization factor α determines the amount of multiuser interference. If α = 0, Regularized ZFBF is similar to ZFBF which means there is no multiuser interference. For α > 0, α can be selected large enough to make the inverse behave as intended. The amount of interference increases with α, so one feasible criterion for selecting α is to maximize the SINR (Bruno & Claude, 2013) (Godara, 2004).

2.3.4 Weighted Sum Rate Beam Forming (WSRBF-WMMSE)

In a MIMO precoding, given a Weighted Sum Rate (WSR) optimization problem $\mathcal{P}_1$ to find the precoder that would maximize the WSR of the system, WSRBF-WMMSE algorithm can be used to find the optimum precoding for each user. Let us define the optimization problem as

$$\begin{aligned} &\max_{\boldsymbol{p}} \textstyle\sum_{k=1}^{K} \mu_k R_k \\ &s.t.\ \textstyle\sum_{k=1}^{K} tr(p_k p_k^H) \leq P \end{aligned} \quad (2.4)$$

The problem is non-convex and WMMSE algorithm works well with non-convexity arising from rate expressions. The WSR problem can be solved as a WMMSE problem with optimized MSE weights. An iterative algorithm for WSR optimization in the MIMO-BC can be employed. The algorithm iterates between WMMSE transmit filter design, MMSE receive filter computation using well-known closed-form expressions, and weighting matrix update. Each of the three steps is solved by evaluating closed-form expressions (Søren Skovgaard, Rajiv, Elisabeth, & John, 2008).

Algorithm 1 Alternating Optimization

$set\ n = 0.\ P_k^n = P_k^{init}, \forall k$

$iterate$

$update\ n = n + 1$

1. $compute\ G_k^n |\ P_k^{n-1} \forall i\ for\ all\ k\ using$ (2.5)
2. $compute\ W_k^n |\ P_k^{n-1} \forall i\ for\ all\ k\ using$ (2.7)
3. $compute\ P_k^n |\ G_k^n,\ W_k^n\ using$ (2.11)

$until\ convergence$

First the MMSE-receive filters (G_k^{MMSE}) are updated using the transmit filters (P_k) of the previous iteration. Here R_{vkvk} is the noise and interference covariance matrix.

$$G_k^{MMSE} = P_k^H H_k^H (H_k P_k P_k^H H_k^H + R_{vkvk})^{-1} \quad (2.5)$$

$$R_{vkvk} = I_k + \textstyle\sum_{i=1, i\neq k}^{K} H_k P_i P_i^H H_k^H \quad (2.6)$$

Next updating the MSE weight (W_k) using the transmit filters as a function of the MSE matrix (E_k) will follow. Here we note that the rate of user k is a function of the inverse of the MSE matrix.

$$W_k = \mu_k E_k^{-1} \quad (2.7)$$

$$E_k = (I_k + P_k^H H_k^H R_{vkvk}{}^{-1} H_k^H P_k^H) \quad (2.8)$$

$$R_k = log_2\, det(E_k)^{-1} \quad (2.9)$$

Finally, the WMMSE transmit filters (P^{WMMSE}) are computed given the receive filters(G) and MSE-weights(W).$W = diag\{w_1, \dots, w_K\}\ and\ G = diag\{g_1, \dots, g_K\}$ are block-diagonal matrices and b is a normalization factor.

$$\bar{P} = (H^H G^H W G H + \frac{Tr(WGG^H)}{Pt} I_p)^{-1} H^H G^H W \quad (2.10)$$

$$P^{WMMSE} = b\bar{P},\ b = \sqrt{\frac{Pt}{Tr(\bar{P}\bar{P}^H)}} \quad (2.11)$$

2.4 Interference Management

In a multi-user communication system, the effect of interference can be handled either by treating it as noise or canceling its effect. The two common methods are Decoding Interference as noise and Successive Interference cancellation (SIC).

2.4.1 Decoding Interference as Noise

If the Interference level is comparable to the noise level it can be treated as noise at higher SNR regions. That is just decoding the intended message directly by treating interference from other streams as noise. The problem with this is if the interference from any of the transmitted streams is significantly higher the performance will degrade severely. If there is any stream with high interference it is better to use SIC to cancel out its effect rather than decoding it as noise (Bruno & Claude, 2013).

2.4.2 Successive Interference Cancellation (SIC)

In this method symbols from interfering users are successively decoded and canceled (subtracted) from the received signal to remove the interference. The decoding order is important and is based on the SINR of each symbol. The symbol with the Highest SINR is decoded first at each SIC layer. Given an initial signal y and MMSE filter G_{MMSE} It follows three steps as given below. First based on the SINR the q_i^{th} transmitted symbol $\tilde{s}_{q_i}$ is extracted then it is sliced to get the estimated symbol $\hat{s}_{q_i}$. With the assumption that the estimated symbol is the same as the original symbol s_{q_i} it is subtracted (canceled) from the received signal which contains the rest of the symbols to be canceled in the same fashion until there are none left (Bruno & Claude, 2013).

$$Initialize: i \leftarrow 1, y^{(1)} = y, G^{(1)} = G_{MMSE}(H)\ , q_1 = \underset{j}{argmin}\|G^1(j)\|^2$$

$Recursion$:

$Step$ 1: $extract\ the\ q_i^{th} transmitted\ symbol\ from\ the\ received\ signal\ y^{(i)}$

$$\tilde{s}_{q_i} = G^{(i)}(q_i)y^{(i)}$$

$Step$ 2: $slice\ \tilde{s}_{q_i}\ to\ obtain\ the\ estimated\ transmitted\ symbol\ \hat{s}_{q_i}$

$Step$ 3: $assume\ that\ \hat{s}_{q_i} = s_{q_i}\ and\ construct\ the\ received\ signal$

$$y^{(i+1)} = y^{(i)} - \sqrt{\frac{Pt}{Nt}} H(q_i)\ \hat{s}_{q_i}$$

$$G^{(i+1)} = G_{MMSE}(H_{q_i})$$

$$i \leftarrow i + 1$$

$$k_{i+1} = \underset{j \notin \{k_1,\dots,k_i\}}{argmin}\left\|G^{i+1}(j)\right\|^2$$

The major challenge with SIC decoding is error propagation. The weakest stream will contribute more to the error. Without user ordering the performance will be lower than the ordered one given above.

2.5 Performance

2.5.1 Degree of Freedom

Considering K user MIMO system where each user is indexed with $k\ \epsilon\ \{1, \dots, K\}$ the degree of freedom or the multiplexing gain of user k is the first-order approximation of the rate of the user k at high SNR which is the pre-log factor of $R_k(P)$ and is given by

$$d_k = \lim_{P\to\infty} \frac{R_k(P)}{log_2 P} \tag{2.12}$$

And it can be interpreted as the number or fraction of interference-free streams that can be simultaneously transmitted from transmitter to user k (Clerckx, et al., 2021) (Mao, et al., 2022).

2.5.2 Weighted Sum Rate

The weighted sum rate of the system is the sum of all rates achieved by each user and is given by

$$WSR = \sum_{k=1}^{K} \mu_k (R_k) \tag{2.13}$$

The benefit of the Weighted Sum Rate is it allows for giving priority to each user based on the weight specified by μ_k. For example, the weights might be adjusted based on the status of packet queues leading to a maximum stability service or by giving equal weights for maximizing the system sum rate which in turn gives the best effort service. (Søren Skovgaard, Rajiv, Elisabeth, & John, 2008).

2.5.3 Throughput

The Throughput of the system gives how much the system successfully recovered the data bits for all users for each channel use. Let us denote the number of channel uses for the l_{th} Monte Carlo realization as $S^{(l)}$ and let $D_{s,k}^{(l)}$ denote the number of data bits recovered successfully by each user then the throughput is calculated as. (Onur, Yijie, Wei, & Bruno, 2020) (Mao, et al., 2022)

$$Throughput(bps/Hz) = \sum_l \frac{\sum_k D_{s,k}^{(l)}}{S^{(l)}} \tag{2.14}$$

2.6 Adaptive Modulation and Coding (AMC)

In digital communication Adaptive modulation and coding is used to fully take advantage of the channel conditions. Based on the channel condition an AMC will choose the modulation type and coding rate to use so that the system is properly utilizing the channel capacity. The modulation scheme will be chosen from a set of modulation types based on the channel quality which allows for a certain symbol rate. Based on this rate that could be achieved the modulation scheme is varied and this intern will vary the code rate of the channel coding technique used. (Goldsmith, 2005)

2.7 mMTC

mMTC services play an important role in Factory Automation, Process Automation, Process, and asset monitoring, Electric-power distribution, smart grid control, and Intelligent transport systems. In uplink communication, this kind of service provides measurement data from a massive number of sensor devices distributed in a wider area. In the downlink setting a massive number of actuator devices are used to control specific action that is not as critical as the URLLC counterpart. mMTC devices are required to have 10 years of battery limiting the receiver complexity that can be employed for these devices. The connection density is different for each type of application but is significantly lower than eMBBC ranging from $50x10^4$ to 10^5 (3GPP, 2017) (Bana & Carvalho, 2019).

2.8 SDMA, NOMA and RSMA

For wireless communication systems it is desirable to transmit multiple streams of data multiplexed in the same frequency-time resource element. This is only possible if all the streams could be separated Spatially or in Code and Power Domain. This project focuses on spatial multiplexing and Power Domain Non-Orthogonal Multiplexing. Space Division Multiplexing (SDMA) uses multiple antenna technology to separate in space the multiplexed streams of different users. While NOMA takes advantage of the difference in the required power for each multiplexed user (Mao, et al., 2022).

2.8.1 SDMA

For SDMA when the number of antennas at the transmitter is sufficiently large we can multiplex different users in the same frequency-time resource as long as the channel state is known at the transmitter (CSIT). But in practice, it is not possible for the transmitter to know the channel state accurately. So there will naturally be multi-user interference at each user. For perfect CSIT we can find a precoding technique that could null out the interference of each user for a specific direction as in Zero forcing beam forming (ZF) which has the disadvantage of increasing the noise. MRT and MMSE precoding could also be used (Mao, et al., 2022). For imperfect CSIT the performance of SDMA will rapidly degrade with the quality of CSI. Also as the angle between users reduces (i.e. they are more aligned) the performance of SDMA will degrade. (Mao, Clerckx, & Li, 2018)

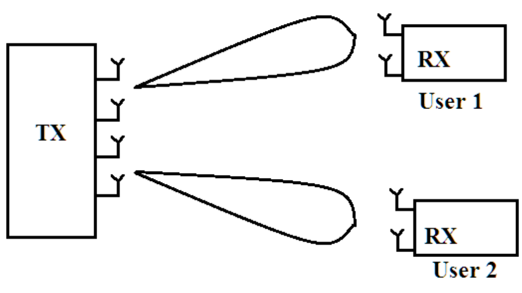

Figure 2.4 SDMA MIMO

2.8.2 NOMA

For NOMA we use Superposition Coding(SC) for the transmitter side where the total power P is divided between users that is the near user will have small power and the far user will have large power i.e. P = P1 + P2 where P2> P1. The receiver of User 2, which has the larger power and is the farthest, will directly decode its message. User 1 will first decode User 2 signal considering its signal as noise and it will subtract this signal from the received signal to get its signal this is called Successive Interference Cancellation (SIC). The problem with NOMA is as the power difference between the users decreases the performance is quickly degraded. The second major problem with NOMA is it is not suited for multi-antenna MIMO transmission and even faces a Degree of Freedom loss in this setting. (Mao, Clerckx, & Li, 2018) (Mao, et al., 2022) (Clerckx, Joudeh, Hao, Dai, & Rassouli, 2016)

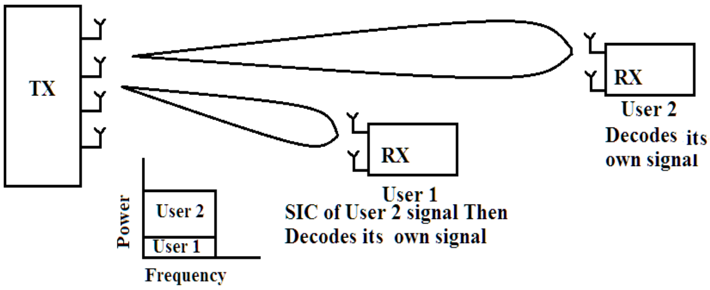

Figure 2.5 NOMA MIMO (Boccuzzi, 2019)

2.8.3 RSMA

RSMA gives a balance between the two and shows a good performance in different scenarios. It is robust against CSIT inaccuracy and has better DoF gain. Instead of fully treating MUI as noise as in SDMA or decoding the full message of the other user for SIC as in NOMA it partially decodes interference and partially treats interference as noise (Mao, Clerckx, & Li, 2018). The basic operation is it splits the messages of each user into two namely the common message and the private message. Each common message from each user is combined to give one common message which will be decoded by each user. The transmitter will precode all the private messages and this one common message gives N +1 transmission streams (Clerckx, Joudeh, Hao, Dai, & Rassouli, 2016). On the receiver side once each user decodes the common message it is subtracted (SIC) from the received signal and only the private messages will be left. Each private stream will be decoded treating other user's private message as noise. The common message is split to get the specific user's common message and this message is combined to get the full message of each user.

The power of RSMA is it can utilize CSIT inaccuracy to its advantage. Whatever the multi-antenna setting can do to reduce MUI will do with the private messages and the MUI that can't be reduced due to CSIT inaccuracy will be reduced by decoding and performing SIC on the common messages. This gives RSMA an advantage over all transmission multiple access strategies.

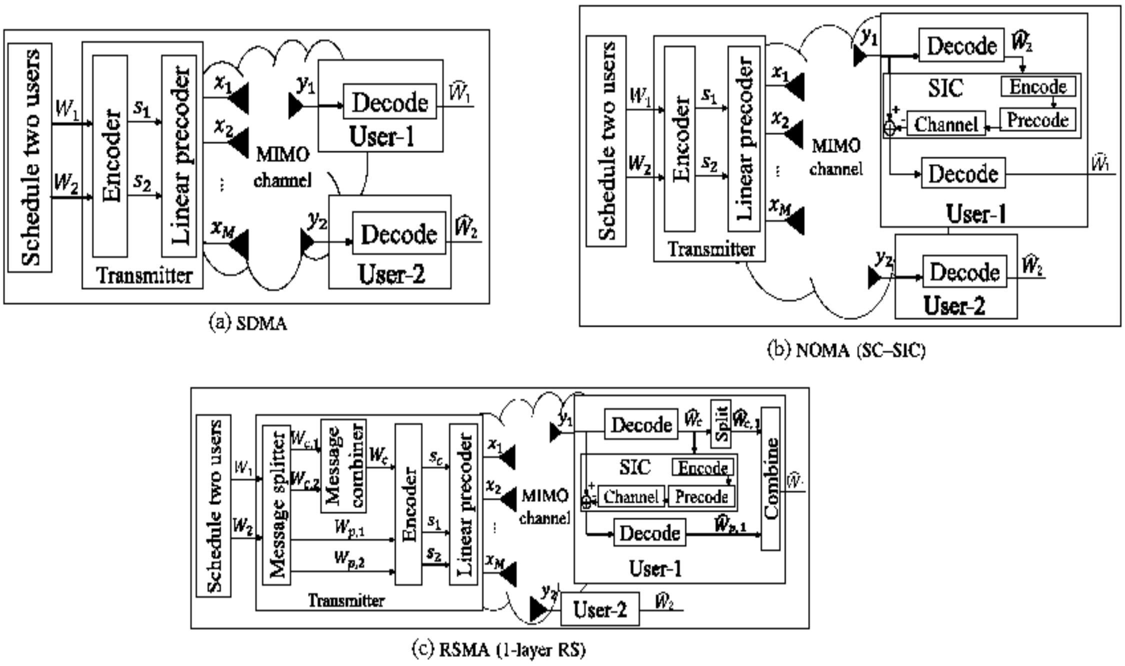

Figure 2.6 Working of the MA techniques described above (a) SDMA (MULP) (b) NOMA (c) RSMA (Mao, et al., 2022)

2.8.4 Power Partitioning (PP-RSMA)

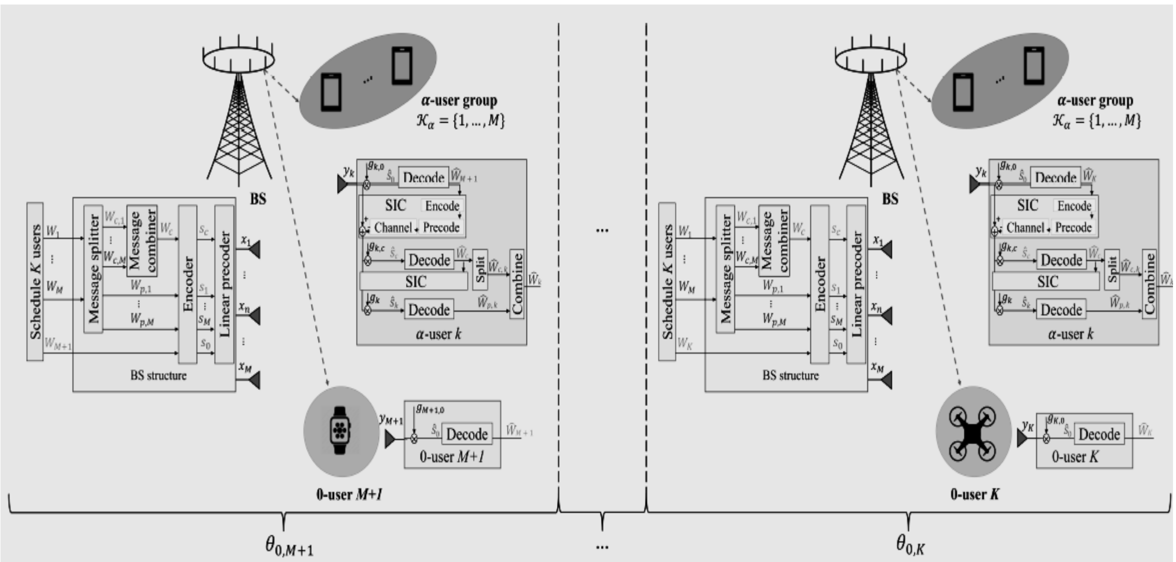

Figure 2.7 Power Partitioning RSMA (PP-RSMA) (Mao, Piovano, & Clerckx, 2020)

Figure 2.7 shows a PP-RSMA system in a MISO setting which is an extension of the RSMA system. PP-RSMA aims at serving two user groups simultaneously while achieving a sum rate and DoF performance improvement. The two user groups are identified as 0 user groups which are not able to update their CSIT and α user groups which in this case are higher-end devices that can update their CSIT. The α users are served using RSMA and the 0 users share the transmission time with the α users incorporating their message as an additional private message on top of the α users. Figure 2.8 shows how the Time-Power resource is shared among the 0 users and α users in PP-RSMA. We are using a single time frame and we have two α users utilizing RSMA so a portion of the Power resource Pt(α) is given to the private part of α users. The remaining Pt($1-\alpha$) is utilized by the common part of α users and the stream of o user.

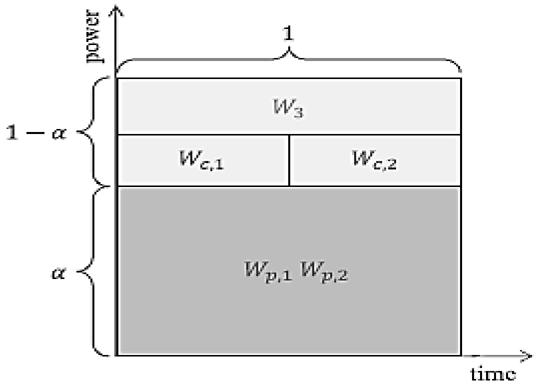

Figure 2.8 Time-Power resource sharing in PP-RSMA (Mao, Piovano, & Clerckx, 2020)

2.9 Related Works

In (Mao, Clerckx, & Li, 2018) the researchers argued that to efficiently cope with the high throughput, heterogeneity of quality of service (QoS), and massive connectivity requirements of future multi-antenna wireless networks multiple access designs need to depart from techniques that fully treat interference as noise (as in SDMA) and fully decode interference (as in NOMA). For this, they proposed a novel multiple-access framework, called rate-splitting multiple access (RSMA). They argue that it is more general and more powerful multiple access for downlink multi-antenna systems that contain SDMA and NOMA as special cases. Relying on linearly precoded rate-splitting with SIC to decode part of the interference and treat the remaining part of the interference as noise RSMA. It provides room for rate and QoS enhancements and complexity reduction.

In (Mao, et al., 2022) the researchers asked if NOMA is efficient in a multi-antenna scenario. Arguing the advantages of NOMA over OMA has been highlighted and shown in past research but the benchmark for the research was miss understood. In this research, they took a new look at the literature on downlink Multiple Access. They compared NOMA with two additional multiple-access baselines rather than comparing it to OMA. The first is Multi-User Linear Precoding (MU-LP) which is commonly known as Space Division Multiple Access (SDMA). The second one is Rate Splitting Multiple Access (RSMA) which is based on Rate Splitting (RS) in a multi-antenna setting. It was created in recent years concurrently with and independently of NOMA. Additionally, categorized as non-orthogonal transmission approach, it relies on SIC. They showed that compared to other MA techniques NOMA didn't meet the expectation in improving the multiplexing gain surprisingly showing a loss in DoF and even increasing receiver complexity. They showed that NOMA must not be used blindly for multi-antenna settings.

In (Clerckx, Joudeh, Hao, Dai, & Rassouli, 2016) the researchers demonstrated that RSMA might enhance MIMO. RSMA has substantial energy and spectrum efficiency gains by offering significant advantages in reliability and CSI feedback overhead reduction compared to other MA techniques. The fundamental challenge toward a multiuser MIMO system lies in the significant requirement for accurate CSIT. This has become more difficult to achieve due to an increase in the number of antennas and access points in future wireless networks that rely on dense heterogeneous networks and transmitters with a large number of antennae. Inaccurate CSIT leads to multi-user interference which is the major drawback with MIMO wireless networks. The researchers showed that RSMA has a promising performance gain in MIMO with imperfect CSIT.

In (Mishra, Mao, Dizdar, & Clerckx, 2021) the researchers proposed and extend the RSMA framework for multi-antenna receivers (Multiple Input Multiple Output MIMO) and formulated the precoder optimization problem to maximize the Weighted Ergodic Sum-Rate (WESR). Precoder optimization is solved using Sample Average Approximation (SAA) together with the proposed vectorization and Weighted Minimum Mean Square Error (WMMSE) based approach. The achievable sum- Degree of Freedom (DoF) of RSMA is derived for the proposed framework as an increasing function of the number of transmitted common and private streams, which is further validated by the Ergodic Sum Rate (ESR) performance using Monte Carlo simulations. Conventional MU-MIMO based on linear precoders and Non-Orthogonal Multiple Access (NOMA) schemes are considered baselines.

Numerical results show that with imperfect CSIT, the sum- DoF and ESR performance of RSMA is superior to that of the two baselines, and is increasing with the number of transmitted common streams. Moreover, by better managing the interference, RSMA not only has significant ESR gains over baseline schemes but is more robust to CSIT inaccuracies, network loads, and user deployments.

In (Bana & Carvalho, 2019) the researchers investigated the applicability of massive MIMO to IoT connectivity. Considering the two types of IoT connections in 5G: massive machine-type communication (mMTC) and ultra-reliable low-latency communication (URLLC). They showed the trade-offs that emerge when massive MIMO is applied to mMTC or URLLC and present several suitable communication schemes. They also showed the use of massive MIMO to simultaneously support IoT connections with very heterogeneous requirements. The main conclusion they draw is that massive MIMO can bring benefits to the scenarios with IoT connectivity, but it requires tight integration of the physical-layer techniques with the protocol design.

In (Mao, Piovano, & Clerckx, 2020) motivated by the requirement for cellular IoT to simultaneously serve a huge number of devices having heterogeneous requirements and qualities of Channel State Information at the Transmitter (CSIT), the researchers proposed two techniques. They introduced Time Partitioning RSMA (TP-RSMA) and Power Partitioning RSMA (PP-RSMA). So they demonstrated a novel method for two sets of CSIT characteristics on an overloaded MISO Broadcast Channel (BC). For the first set of users, the transmitter just has statistical information of the CSIT whereas for the second set of users, the transmitter has partial knowledge of the CSIT. The rate and DoF analysis helped to conclude that PP RSMA is an effective framework for cellular IoT serving a huge number of devices.

In (Reddy, Chopra, Dubey, Kumar, & Panigrahi, 2021) the researchers introduced a novel method based on RSMA called Rate Splitting Random Access (RSRA) which raises the success rates of Random Access Channel (RACH). The suggested approach improves decoding performance by separating the message into private messages and a common message.

In (Rahmati, Rupasinghe, Dai, Bhuyan, & Falls, 2019) the researchers showed that RSMA is superior to NOMA in a realistic transmission scheme in a cellular-connected UAV network. It showed superiority in energy efficiency over its counterpart NOMA.

In (Sena, et al., 2022) (Gamal, Rihan, Member, & Hussin, 2021) (Wang, Li, Deng, & Li, 2021) many researchers showed the benefit of RSMA in cell-free MIMO, massive MIMO, and Cognitive Radio.

Table 2.1 Analysis of Literature

Author	Year	Title	Contribution	Gap
(Mao, et al., 2022)	2022	Rate-Splitting Multiple Access: Fundamentals, Survey, and Future Research Trends.	A detailed tutorial and introduction to Rate Splitting Multiple Access.	Only gave a highlight on the application of RSMA for MIMO and mMTC applications.
(Clerckx, et al., 2021)	2021	Is NOMA Efficient in Multi-Antenna Networks? A Critical Look at Next Generation Multiple Access Techniques.	Showed that for multiple antenna setups, RSMA outperforms NOMA and other MA techniques in terms of rate and DoF.	Focused on the comparison of RSMA with NOMA and OMA didn’t consider the performance of each in MIMO and mMTC applications.
(Mishra, Mao, Dizdar, & Clerckx, 2021)	2021	Rate-Splitting Multiple Access for Downlink Multiuser MIMO: Precoder Optimization and PHY-Layer Design.	Extended the RSMA framework for multi-antenna receivers MIMO and formulate the precoder optimization problem to maximize the Weighted Ergodic Sum-Rate (WESR).	It uses generalized RSMA with multiple users in a single resource element so both transmitter and receiver complexity is high.

(Mao, Piovano, & Clerckx, 2020)	2020	Rate-Splitting Multiple Access for Overloaded Cellular Internet of Things.	Proposed two MA techniques which are TP-RSMA and PP-RSMA for MISO IOT system. Showed PP-RSMA has better performance.	MIMO system with multiple antennae at both transmitter and receiver not considered.

CHAPTER THREE

3. MATERIALS AND METHODS

3.1 Introduction

For the successful completion of the thesis work, relevant secondary data sources such as different books in multiple access and non-orthogonal transmission researchers, previous studies, different IEEE and Elsevier journals, articles, development in 5G and beyond technology in general, and RSMA basics were revised.

3.2 Materials

In this research work, software such as MATLAB/R2017b is used. MATLAB is computing software that runs on a computer and consists of technical toolboxes and Simulink.

CVX optimization tool is used to solve all optimization problems that are convex in nature. It is a software package that works with mat lab and is free to use. The default solver (SDPT3) is used in all cases.

3.3 System Model

3.3.1 SDMA

Let us consider a simple SDMA system first, which is multi-user (MTCd) with linear precoding. We have Nt transmit antennas and K single antenna MTC devices, that is Nr = K. The set of MTC devices $\kappa = \{1, .., K\}$ is indexed with k. We assume the receivers have perfect CSIR and the transmitter has partial knowledge of the CSIT. The block diagram is given in Figure 3.1. We are assuming FDD feedback and for simplicity, it is not drawn on the diagram.

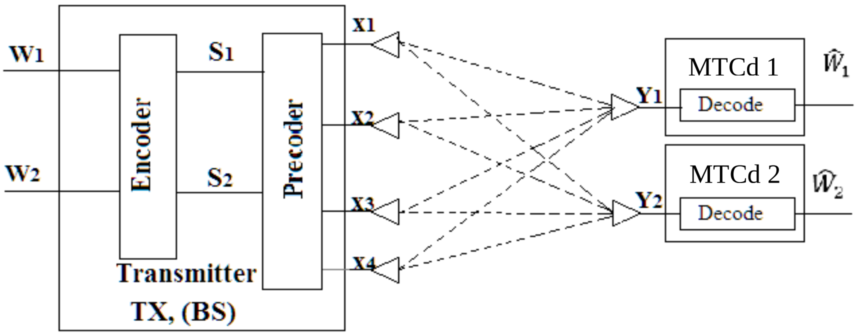

Figure 3.1 Multi User (MTCd) Linear Precoding (SDMA)

The transmitted signal $\boldsymbol{x} \in \mathbb{C}^{Nt}$ is given as the multiplication of the stream $\boldsymbol{S} = [S_1, S_2, \ldots, S_k\ ]^T \in \mathbb{C}^{K\times 1}$ and the precoder $\boldsymbol{P} = [\boldsymbol{p}_1, \boldsymbol{p}_2, \ldots, \boldsymbol{p}_K], \in \mathbb{C}^{Nt\times Nr}$.

$$\boldsymbol{x} = \sum_{k=1}^{K} \boldsymbol{p}_k S_k = \boldsymbol{PS} \tag{3.1}$$

The received signal y_k at each MTC device k is given by the multiplication of channel matrix transpose $\boldsymbol{h}_k^H$ of the MTCd with the transmitted signal $\boldsymbol{x}$. At the receiver an Additive White Gaussian noise (AWGN) $n_k \sim CN(0, \sigma_{n,k})$ is added. We can safely assume equal noise variance σ_n at each MTCd and drop the device indexing k and just use n for the AWGN noise.

$$y_k = \boldsymbol{h}_k^H \boldsymbol{x} + n\ ,\ \forall k \in K \tag{3.2}$$

Using the matrix notation of the system the received signal is given by

$$\boldsymbol{Y} = \boldsymbol{H}^{\boldsymbol{H}} \boldsymbol{x} + \boldsymbol{n} \tag{3.3}$$

Where $\boldsymbol{Y} = \begin{bmatrix} y_1 \\ \vdots \\ y_K \end{bmatrix}$, $\boldsymbol{x} = \begin{bmatrix} x_1 \\ \vdots \\ x_{Nt} \end{bmatrix}$, $\boldsymbol{H} = \begin{pmatrix} h_{1,1} & \cdots & h_{K,1} \\ \vdots & \ddots & \vdots \\ h_{1,Nt} & \cdots & h_{K,Nt} \end{pmatrix}$ and $\boldsymbol{n} = \begin{bmatrix} n_1 \\ \vdots \\ n_K \end{bmatrix}$

The Signal to Interference and noise ratio (SINR) γ at each MTCd k is given by

$$\gamma_k = \frac{\left|\boldsymbol{h}_k^H \boldsymbol{P}_k\right|^2}{\sum_{i\neq k}\left|\boldsymbol{h}_k^H \boldsymbol{P}_i\right|^2 + \sigma_n{}^2} \tag{3.4}$$

From the SINR we can find the rate R_k of each MTCd k as

$$R_k = \log_2(1 + \gamma_k) \tag{3.5}$$

3.3.2 NOMA

For the NOMA system, we take a similar multi-antenna system where the transmitter is equipped with Nt antennas serving K single antenna NOMA MTCds. We have therefore $Nr = K\ x\ 1$ receive antennas. The messages $\boldsymbol{W} = [W_1, \ldots, W_K]^T$ intended for each MTCds are encoded into stream $\boldsymbol{S} = \begin{bmatrix} S_1 \\ \vdots \\ S_K \end{bmatrix}$. The streams are then linearly precoded by $Nt \times 1$

precoder $\boldsymbol{P} = [\boldsymbol{p}_1 \dots \boldsymbol{p}_K]$ and superposed at the transmitter so that the transmit signal is given by

$$\boldsymbol{x} = \boldsymbol{p}_1 S_1 + \dots + \boldsymbol{p}_K S_K. \tag{3.6}$$

The average transmit (sum) power constraint is written as $P_1 + \dots + P_K \leq P$ where $P_k = ||\boldsymbol{p}_k||^2$,with $k = 1, 2, \dots, K$. The NOMA system for two MTCds is shown in Figure 3.2 below.

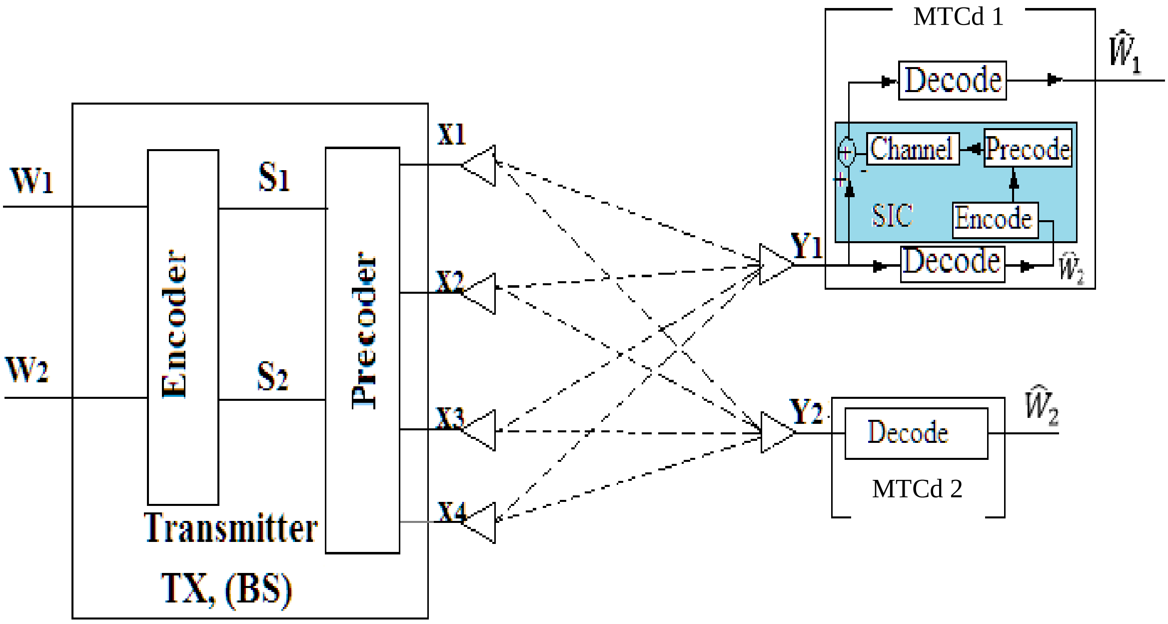

Figure 3.2 Multi User (MTCd) NOMA

All the assumptions are the same as in the SDMA case and the received signal y_k at each NOMA MTCd k is given by

$$y_k = \boldsymbol{h}_k^H \boldsymbol{x} + n\,, \ \forall k \in K \tag{3.7}$$

On the receiver side, at both MTCds, stream S_2 is decoded first into $\widehat{W}_2$ by treating the interference from S_2 as noise. Using SIC at MTCd 1, $\widehat{W}_2$ is re-encoded, precoded, and subtracted from the received signal, such that MTCd 1 can decode its stream S_1 into $\widehat{W}_1$. The MTCd ordering will affect the achievable rate in this case and for this two-MTCd example the ordering is $user_2 \rightarrow user_1$.

The achievable sum rate for two MTCd NOMA is given by $R_s = R_1 + R_2$ where $R_k$is the achievable rate for MTCd k.

$$R_1 = \log_2(1+\gamma_1) \quad (3.8)$$

$$R_2 = \min(\log_2(1+\gamma_{1,2}), \log_2(1+\gamma_2)) \quad (3.9)$$

Where $\gamma_1 = |\boldsymbol{h}_1^H \boldsymbol{p}_1|^2$ is the SINR of MTCd 1, $\gamma_{1,2} = \frac{|\boldsymbol{h}_1^H \boldsymbol{p}_2|^2}{1+|\boldsymbol{h}_1^H p_1|^2}$ is the SINR of MTCd 1 when decoding the stream S_2 and $\gamma_2 = \frac{|\boldsymbol{h}_2^H \boldsymbol{p}_2|^2}{1+|\boldsymbol{h}_2^H \boldsymbol{p}_1|^2}$ is the SINR of MTCd 2. Since MTCd 1 must decode the message of the second MTCd the rate of MTCd 2 must be set to ensure MTCd 2 message is decodable at MTCd 1.

3.3.3 RSMA

The system model for RSMA can be extended from the above two systems. Instead of fully treating Interference as noise like in SDMA and fully decoding and canceling Interference like in NOMA in RSMA Interference is partially treated as noise and partially decoded for cancellation with SIC.

For the two MTCd system we have two messages $\boldsymbol{W} = [W_1, W_2]^T$ the messages are split in two namely private part and common part $\boldsymbol{W} = [W_{1,c}, W_{2,c}\ W_{1,p}, W_{2,p}]^T$. Then by a message combiner, the common parts are combined to form one common message that is $\boldsymbol{W} = [W_c, W_{1,p}, W_{2,p}]^T$. With the encoder, which includes the channel coding and modulation system, these messages are then encoded into a stream of the common and private parts $\boldsymbol{S} = [S_c, S_{1,p}, S_{2,p}]^H$. By the linear precoder $\boldsymbol{P} = \begin{bmatrix} p_{c,1} & p_{p1,1} & p_{p2,1} \\ p_{c,2} & p_{p1,2} & p_{p2,2} \\ p_{c,3} & p_{p1,3} & p_{p2,3} \\ p_{c,4} & p_{p1,4} & p_{p2,4} \end{bmatrix}$, where any of the linear precoders discussed in Chapter Two can be used, the streams are precoded by using the precoding matrix **P** to give a transmitted signal $\boldsymbol{x}$ which is given by

$$\boldsymbol{x} = \boldsymbol{PS} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix}, \in \mathbb{C}^{\boldsymbol{Nt}} \quad (3.10)$$

The received signal $\boldsymbol{y_k}$ at each MTCd is given by

$$y_k = \boldsymbol{h}_k^H x_k + n = \boldsymbol{h}_k^H \boldsymbol{p}_c S_c + \boldsymbol{h}_k^H \boldsymbol{p}_k S_k + \sum_{i=1, i\neq k}^{K} \boldsymbol{h}_k^H \boldsymbol{p}_i S_i + n \quad (3.11)$$

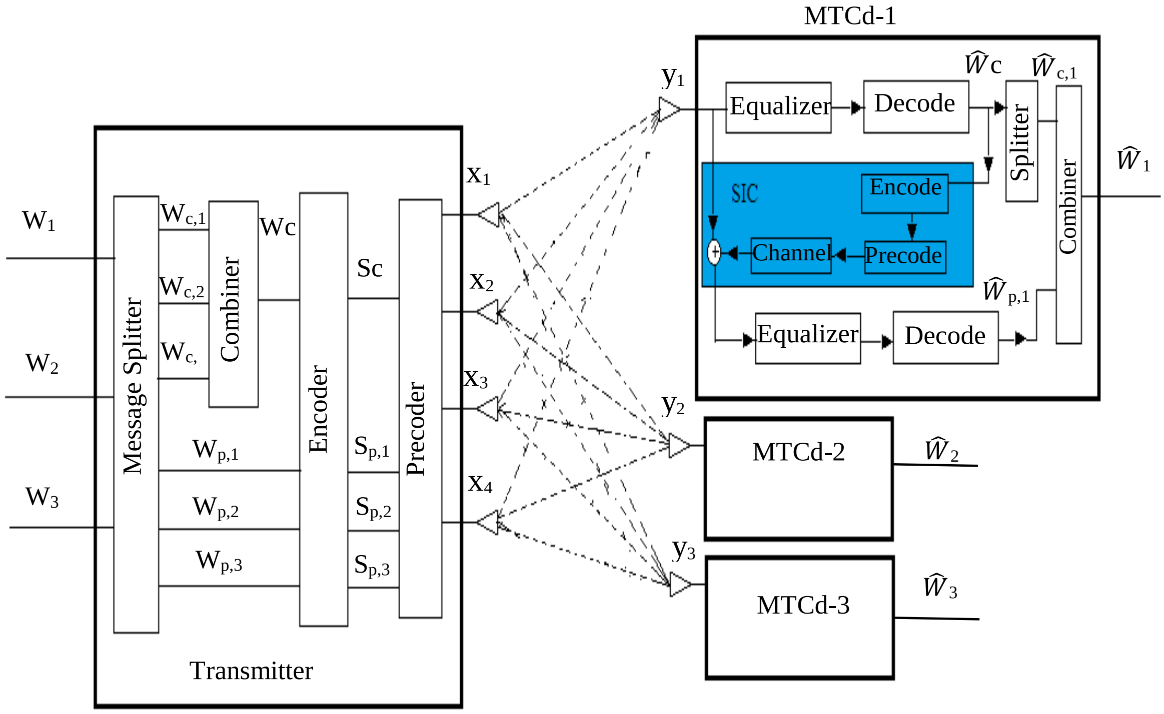

Figure 3.3 Three MTCd RSMA

Each MTCd first decodes the common part treating Interference from other streams as noise. The decoded common part, $\widehat{W}_c$, will be used for SIC and a splitter will separate the common part of that specific MTCd, $\widehat{W}_{c,k}$, to be combined with the private part, $\widehat{W}_{p,k}$, of that specific MTCd to get $\widehat{W}_k$. The SIC is done by first reconstructing $\widehat{W}_c$ by encoding, precoding, and passing it through the channel matrix as in $\hat{y}_c = \boldsymbol{h}_k^H \hat{x}_c = \boldsymbol{h}_k^H \boldsymbol{p}_c \hat{S}_c$. This is subtracted from the received signal to get the private part only $y_{k,p} = y_k - \hat{y}_c$. Now $y_{k,p}$is decoded treating interference from other streams as noise to get $\widehat{W}_{p,k}$.

The rate achieved by each MTCd is the sum of the common rate with the private rate of that MTCd, that is $R_k = R_{c,k} + R_{p,k}$. Each rate is given by equation 3.12 and $\gamma_{c,k}$ and $\gamma_{p,k}$ are SINR of the common and private each device.

$$R_{c,k} = \log_2(1 + \gamma_{c,k}) \text{ ,} where\ \gamma_{c,k} = \frac{|\boldsymbol{h}_k^H \boldsymbol{p}_{p,k}|^2}{1+\sum_{j=1,j\neq k}^{K} |\boldsymbol{h}_k^H \boldsymbol{p}_{p,j}|^2}$$
$$R_{p,k} = \log_2(1 + \gamma_{p,k}) \text{ ,} where\ \gamma_{p,k} \frac{|\boldsymbol{h}_k^H \boldsymbol{p}_{c,k}|^2}{1+\sum_{j=1}^{K} |\boldsymbol{h}_k^H \boldsymbol{p}_{p,j}|^2} \qquad (3.12)$$

The WSR optimization problem will be adjusted to accommodate the rate constraint for the common part since all MTCds must decode it the rate must be set to ensure the decodability of the common part at all MTCds. The WSR problem is then given by

$$
\begin{gathered}
\max_{\boldsymbol{p},\boldsymbol{c}} \sum_{k=1}^{K} \mu_k \left(c_k + R_{k,p}\right) \\
s.t.\ \sum_{k=1}^{K} c_k \le R_c \\
\sum_{k=1}^{K} tr(\boldsymbol{p}_k \boldsymbol{p}_k^H) \le Pt \\
R_k \ge R_k^{th} \forall k \in \{1,..,K\} \\
c > 0
\end{gathered} \tag{3.13}
$$

The sum rate maximization problem in Equation 3.13 aims at finding a precoding matrix $\boldsymbol{p}$ and a common rate $\boldsymbol{c}$ that maximizes the sum rate of the system, $\sum_{k=1}^{K} \mu_k\left(c_k + R_{k,p}\right)$ (Mao, et al., 2022). The four constraints set up the optimization problem where the first constraint,$\sum_{k=1}^{K} c_k \le R_c$, makes sure sum of the common rate c_k of each MTCd is less than or equal to the total common rate R_c. The second constraint, $\sum_{k=1}^{K} tr(\boldsymbol{p}_k \boldsymbol{p}_k^H) \le Pt$, ensures the total transmit power won't exceed the total allocated transmit power. The third constraint, $R_k \ge R_k^{th} \forall k \in \{1,..,K\}$, sets a minimum rate value for each MTCd. And the final constraint ensures the rate of the common part is greater than zero.

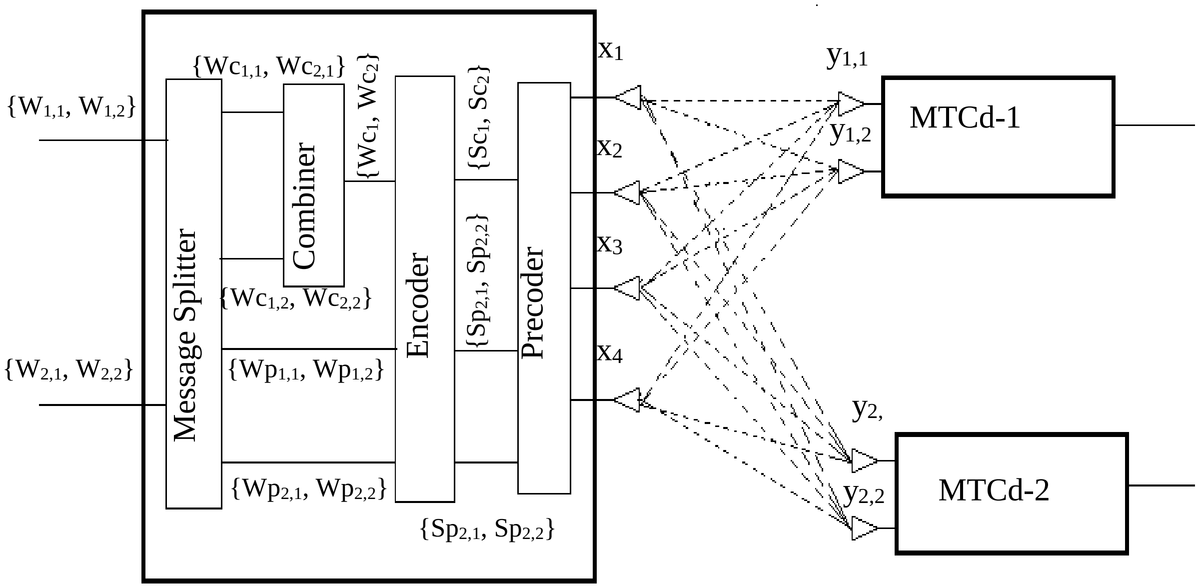

Figure 3.4 MU-MIMO RSMA for MTC

Figure 3.4 shows the multi-stream transmission for MIMO RSMA. Each MTCd is equipped with multiple antennas and the scheduled messages for each device contain multiple streams of data. The instantaneous rates for common and private parts of each MTCd given a channel estimate $\widehat{\boldsymbol{H}}$are given by.

$$R_{c,k}\left(\boldsymbol{H},\widehat{\boldsymbol{H}}\right) = \log_2 \det(\boldsymbol{I} + \boldsymbol{P}_c^H \boldsymbol{H}_k (\boldsymbol{R}_{c,vk})^{-1} \boldsymbol{H}_k^H \boldsymbol{P}_c) \tag{3.14}$$

$$R_{p,k}\left(\boldsymbol{H},\widehat{\boldsymbol{H}}\right) = \log_2 \det(\boldsymbol{I} + \boldsymbol{P}_k^H \boldsymbol{H}_k (\boldsymbol{R}_{p,vk})^{-1} \boldsymbol{H}_k^H \boldsymbol{P}_k) \tag{3.15}$$

Where $\boldsymbol{I}$is an identity matrix and, $\boldsymbol{P}_c$ and $\boldsymbol{P}_k$ gives the precoding matrix for the common and private part of each MTCd k. The channel matrix of MTCd $k$is given by $\boldsymbol{H}_k$.

The noise covariance matrix $\boldsymbol{R}_{c,vk}$for common and $\boldsymbol{R}_{p,vk}$private parts of k^{th}MTCd is also given as

$$\boldsymbol{R}_{c,vk}(\boldsymbol{H},\widehat{\boldsymbol{H}}) = \boldsymbol{I}_{Qc} + \sum_{i=1}^{K} \boldsymbol{H}_k^H \boldsymbol{P}_i \boldsymbol{P}_i^H \boldsymbol{H}_k\,,\ and\ \boldsymbol{R}_{p,vk}(\boldsymbol{H},\widehat{\boldsymbol{H}}) = \boldsymbol{I}_{Qp} + \sum_{i=1,i\neq k}^{K} \boldsymbol{H}_k^H \boldsymbol{P}_i \boldsymbol{P}_i^H \boldsymbol{H}_k \tag{3.16}$$

Where $\boldsymbol{I}_{Qc}$ and $\boldsymbol{I}_{Qp}$ are identity matrixes for the common and private part respectively. Q identifies the number of receive antenna at each MTCd.

We are using MMSE receive filter, from section 2.3.4 of chapter Two, so the receive filters for the common $G_{c,k}^{MMSE}(\boldsymbol{H},\widehat{\boldsymbol{H}})$ and private part $G_{p,k}^{MMSE}(\boldsymbol{H},\widehat{\boldsymbol{H}})$ of each MTCd is given by

$$G_{c,k}^{MMSE}(\boldsymbol{H},\widehat{\boldsymbol{H}}) = \boldsymbol{P}_c^H \boldsymbol{H}_k^H \left(\boldsymbol{H}_k \boldsymbol{P}_{c,k} \boldsymbol{P}_{c,k}^H \boldsymbol{H}_k^H + \boldsymbol{R}_{c,vk}\right)^{-1}\ and$$

$$G_{p,k}^{MMSE}(\boldsymbol{H},\widehat{\boldsymbol{H}}) = \boldsymbol{P}_p^H \boldsymbol{H}_k^H (\boldsymbol{H}_k \boldsymbol{P}_{p,k} \boldsymbol{P}_{p,k}^H \boldsymbol{H}_k^H + \boldsymbol{R}_{p,vk})^{-1} \tag{3.17}$$

The MSE-Matrix of the common part and the private part can be modified from section 2.3.4 of chapter Two and is given by

$$E_{c,k}^{MMSE}(\boldsymbol{H},\widehat{\boldsymbol{H}}) = (\boldsymbol{I} + \boldsymbol{P}_c^H \boldsymbol{H}_k (\boldsymbol{R}_{c,vk})^{-1} \boldsymbol{H}_k^H \boldsymbol{P}_c)^{-1}\ and$$

$$E_{p,k}^{MMSE}(\boldsymbol{H},\widehat{\boldsymbol{H}}) = (\boldsymbol{I} + \boldsymbol{P}_p^H \boldsymbol{H}_k (\boldsymbol{R}_{p,vk})^{-1} \boldsymbol{H}_k^H \boldsymbol{P}_p)^{-1} \tag{3.18}$$

3.3.4 Power Partition RSMA (PP-RSMA)

For devices that can't update their CSIT information OMA transmission is the only way. But since RSMA can handle this type of transmission by allowing for the integration of OMA devices on top of other devices which can update their CSIT information. Let us denote OMA devices with short transmission duration and no CSIT information feedback capabilities 0 MTCds. And those devices which can update their CSIT information and with relatively longer transmission duration as α MTCds.

In PP-RSMA with the transmission time duration T of α MTCds multiple 0 MTCds can be accommodated with a transmission time duration of $\theta_{0,K} = \frac{T}{N}$ where N is the number of 0 MTCds.

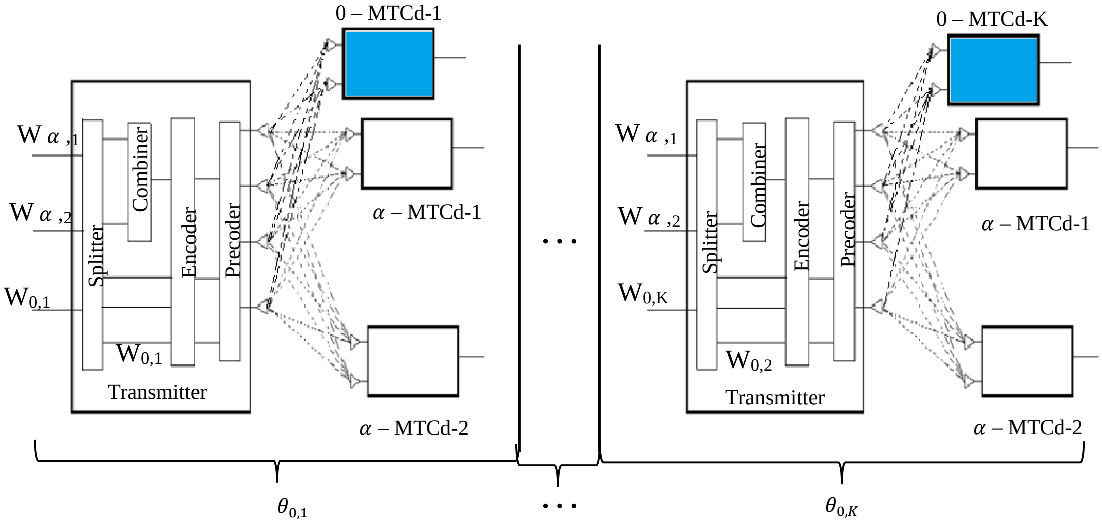

Figure 3.5 PP-RSMA Block Diagram

Figure 3.5 gives the Block Diagram of PP-RSMA system in a MIMO setting. At each α MTCd first, the message intended for 0 MTCd, $W_{0,k}$, will be decoded and canceled from the received signal. The rate of 0 MTCd must be set so that the decodability of 0 MTCd message with every α MTCd will be satisfied. The transmitted signal is given as (Mao, Piovano, & Clerckx, 2020)

$$\boldsymbol{x} = \boldsymbol{PS} = \boldsymbol{P}_0 S_0 + \boldsymbol{P}_c S_c + \sum_{k\in\alpha} \boldsymbol{P}_{k,p} S_{k,p} \tag{3.21}$$

Assuming an equal number of receive antennas per MTCd the precoder and transmit symbol are given by $\boldsymbol{P} = [\boldsymbol{P}_0, \boldsymbol{P}_\alpha] \in \mathbb{C}^{M\times Nk\times M+2}$ and $\boldsymbol{S} = [S_0, {S_\alpha}^T]^T \in \mathbb{C}^{M+2\times Nk}$ respectively where subscripts 0 and α represent 0 MTCd and α MTCd. At each 0 MTCd, the message is decoded treating other messages as noise. The ergodic rate achieved for this type of device in the system is given by

$$\bar{R}_{k,0} = \theta_{0,k} \min_i\{\bar{R}_{0,i}\}\ \forall k \in \{1,..,K_0\}, i \in \{1,..,K_0\} \cup\in \{1,..,K_\alpha\} \tag{3.22}$$

Where $\bar{R}_{0,i}$is the ergodic rate of 0 MTCd decoded in the i^{th} α MTCd and is given as

$$\bar{R}_{0,i} = \mathbb{E}_{(\boldsymbol{H},\widehat{\boldsymbol{H}})}\{\log_2(1+\gamma_{0,k})\} \tag{3.23}$$

And the SINR at each α MTCd while decoding S_0 is given by

$$\gamma_{0.k} = \frac{|\boldsymbol{h}_k^H \boldsymbol{p}_0|^2}{1+|\boldsymbol{h}_k^H \boldsymbol{p}_c|^2 + \sum_j |\boldsymbol{h}_k^H \boldsymbol{p}_j|^2} \forall k \in \{1,..,K_0\}, j \in \{1,..,K_\alpha\} \tag{3.24}$$

The sum rate maximization problem for the PP-RSMA system is given in Equation 3.25. Similar to the RSMA Problem this problem aims at finding a precoding matrix and common rate that maximizes the sum rate. The additional constraint, $\theta_{0,k}\min_{i}\left\{\hat{R}_{0,i}^{(N)}\right\} \geq R_k^{th} \forall k \in \{1,..,K_0\}, i \in \{1,..,K_0\} \cup \in \{1,..,K_\alpha\}$, is introduced that makes sure all 0 MTCds are decodable at all α MTCds. R_k^{th}correspond to the rate constraint that 0 MTCds must satisfy and it is analogous to the QoS requirement of that device.

$$\begin{gathered}\max_{\boldsymbol{p},\hat{C}_\alpha} \sum_{k=1}^{K} \mu_k(\hat{C}_{k,\alpha} + \hat{R}_{k,p,\alpha}^{(N)}) \\ s.t.\ \sum_{k=1}^{K} \hat{C}_{k,\alpha} \leq \hat{R}_{C_{k,\alpha}}^{(N)} \\ \theta_{0,k}\min_{i}\left\{\hat{R}_{0,i}^{(N)}\right\} \geq R_k^{th} \forall k \in \{1,..,K_0\}, i \in \{1,..,K_0\} \cup \in \{1,..,K_\alpha\} \\ \|\boldsymbol{P}_0\|^2 + \sum_{k=1}^{K} tr\left(\boldsymbol{p}_{k,\alpha}\boldsymbol{p}_{k,\alpha}^H\right) \leq Pt \\ \hat{C}_{k,\alpha} + \hat{R}_{k,p,\alpha}^{(N)} \geq R_k^{th} \forall k \in \{1,..,K_\alpha\} \\ \hat{C} > 0\end{gathered} \tag{3.25}$$

$\hat{C}_{k,\alpha}$ *and* $\hat{R}_{k,p,\alpha}^{(N)}$ are the rate of the common and private parts of k^{th} α MTCd. The rest of the constraints are similar to the MIMO RSMA system. In the same manner as the MIMO RSMA system, this problem is converted to its equivalent MMSE problem and is solved using the Alternating Optimization algorithm.

3.4 Sample Average Approximation (SAA)

For imperfect CSIT SAA is used to approximate the perfect channel from the estimated channel with CSIT error. Knowing the channel distribution density function $f_{H|\hat{H}}\{H|\hat{H}\}$ given an estimate of the channel, we can approximate the channel from N channel samples as $\mathbb{H}^{(N)} = \{H^{(n)} = \hat{H} + \tilde{H}^{(n)}|\hat{H}, n \in \{1, \dots, N\}\}$. The average rates can be approximated using the approximated channel as $\hat{R}_k^N = \frac{1}{N}\sum_{n=1}^{N} R_k^{(n)}$.

Now the approximated rates will be given by.

$$\begin{gathered}\hat{R}^{(N)}(Pt,\mu) = \max_{\boldsymbol{p},\hat{\boldsymbol{c}}} \sum_{k=1}^{K} \mu_k(\hat{c}_k + \hat{R}_{k,p}^{(N)}) \\ s.t.\ \sum_{k=1}^{K} \hat{c}_k \leq \hat{R}_c^{(N)} \\ \sum_{k=1}^{K} tr(p_k p_k^H) \leq Pt \\ R_k \geq R_k^{th} \forall k \in \{1,..,K\} \\ \hat{c} > 0\end{gathered} \tag{3.19}$$

The Weighted Average Sum Rate problem is solved using its equivalent Weighted Average Mean Squared Error (WAMMSE) form.

$$\begin{gathered}\hat{R}^{(N)}(Pt, \mu, U, G) = \max_{\boldsymbol{p},\hat{\boldsymbol{x}}} \sum_{k=1}^{K} \mu_k (\hat{x}_k + \hat{\xi}_{k,p}^{(N)}) \\ s.t.\ Q_c + \sum_{k=1}^{K} \hat{x}_k \leq \hat{\xi}_c^{(N)} \\ \sum_{k=1}^{K} tr(\boldsymbol{p}_k \boldsymbol{p}_k^H) \leq Pt \\ R_k \geq R_k^{th} \forall k \in \{1, .., K\} \\ \hat{x} > 0\end{gathered} \tag{3.20}$$

This can be solved using the Alternating Optimization algorithm stated in Chapter Two with small modifications to accommodate the common and private rates.

3.5 Degree of Freedom (DoF)

For a receive antenna of Q at each MTCd and Q_c and Q_p are the total number of common and private streams transmitted the multiplexing gain or DoF of the three MA techniques for an MU-MIMO system is given as

$$d_s RS = \begin{cases} Q_c(1-\alpha) + Q_p\alpha, M \in \{2Q, 3Q, \dots, KQ\} \\ \quad M, \quad\quad M \leq Q \end{cases} \tag{3.26}$$

$$d_s SDMA = \max(\min(M, Q), Q_p\alpha) \tag{3.27}$$

$$d_s NOMA = \min(M, Q) \tag{3.28}$$

Where $d_s RS$, $d_s SDMA$, and $d_s NOMA$ are the DoF for Rate splitting , SDMA and NOMA respectively as given in (Mishra, Mao, Dizdar, & Clerckx, 2021). M and K gives the number of transmit antennas and number of MTCds respectively.

3.6 Link-Level Simulation

The link level simulation employs an adaptive modulation and coding technique with polar coding and different QAM modulation schemes. The block diagram is shown in the Figure below and since we have a slow-fading Rayleigh channel it is ideally interleaved channel so to reduce the complexity the interleaving block is removed. Based on the Rates given in the previous sections the AMC will select which modulation scheme and coding rate must be used. Since the maximum rate calculated can't be attained an energy backoff is performed before calculating the Modulation order. (Onur, Yijie, Wei, & Bruno, 2020)

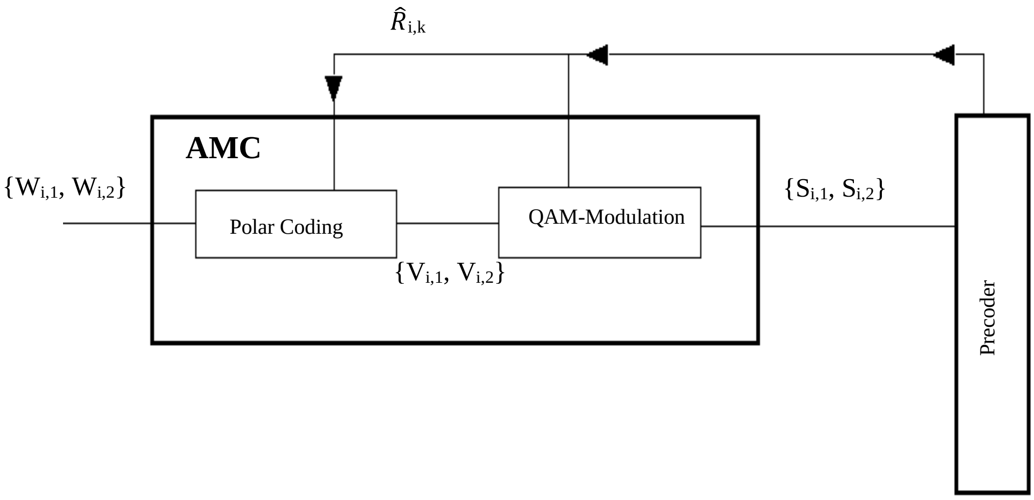

Figure 3.6 Adaptive Modulation and Coding

Given a rate $\hat{R}i, k$ calculated from the channel estimate, where $i \in \{c, k, 0, \alpha\}$, the modulation order is selected from a set of modulation schemes $Q = \{4QAM, 16QAM, 64QAM, 256QAM\}$ (Proakis, 2000) such that the set of all possible modulation schemes for a given rate is given by $Q(\hat{R}\mathrm{i}, \mathrm{k}) = \{\mathcal{M}: \log_2(|\mathcal{M}|) \geq \min(\frac{\hat{R}\mathrm{i}}{\beta}, M'), \mathcal{M} \in Q\}$. Here $\mathcal{M}$ is the order of modulation, $\beta$and M'gives maximum code rate and log of highest modulation order respectively. Finally, from the possible set of modulation orders, the best is selected with $\mathcal{M}\mathrm{i} = arg \min_{\mathcal{M} \in Q(\hat{R}\mathrm{i},\mathrm{k})} (|\mathcal{M}|)$, $i \in \{c, k, 0, \alpha\}$ .The block length for the channel coding is calculated by $Ni = S \log_2 |\mathcal{M}\mathrm{i}|$, where $S$is the stream length. Now we can calculate the code rate as $ri = \lceil Ni \min \hat{R}i/|\mathcal{M}\mathrm{i}| , \beta \rceil / Ni$.

At the receiver side, each MTCd employs an MMSE filter equalizer and detects the symbols with a Log-likelihood Ratio receiver with LLR calculated as $\lambda_k = \gamma_k [\min_{a \in \theta_1^{(i)}} (\varphi(a)) - \min_{a \in \theta_0^{(i)}} (\varphi(a))]$. The decoder is a successive cancellation list(SCL) for the CRC-aided polar coding.

3.7 Flow Chart of the system

Figure 3.7 gives the flow chart of the system assuming the channel state information at the receiver is already known and the rate constraint of each MTCd is given this information is first transmitted to the Transmitter with FDD feedback. This feedback will create inaccuracy in the CSIT at the transmitter/ Base Station. From the partial knowledge of the CSIT the Rate of each stream is calculated using the alternating optimization algorithm as discussed in section 3.1-3.4. Energy Back off is then performed in order to account for a rate estimate inaccuracy. Finally the modulation order and code rate of the polar coding is decided by the adaptive modulation and coding system discussed in section 3.6. In the receiver side the detection and decoding of each stream is performed as discussed in section 3.1-3.4.

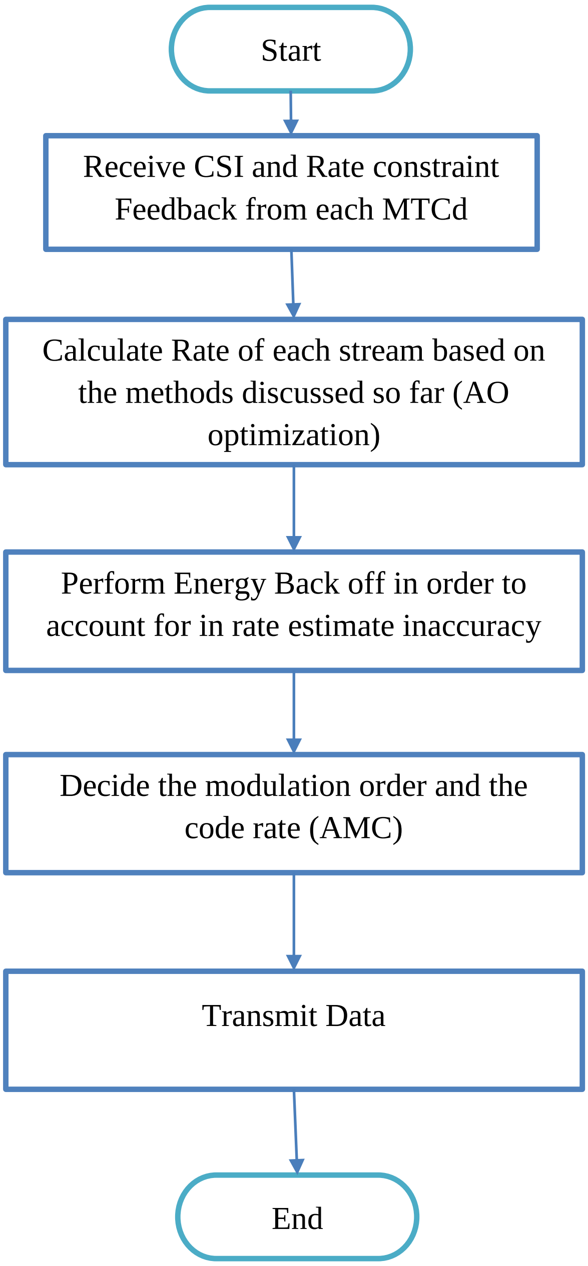

Figure 3.7 System Flow Chart

CHAPTER FOUR

4. RESULTS AND DISCUSSIONS

In this chapter simulation results are discussed for the rate and DoF analysis of RSMA, SDMA, and NOMA systems for mMTC system. MIMO system for all the MA techniques and PP-RSMA for a system having MTCd with and without CSIT feedback capability is simulated. Both overloaded and underloaded systems are simulated. Finally, the throughput of the systems is analyzed with LLS simulation.

4.1 Simulation Parameters

Table 4.1 Simulation Parameters

	Parameter	Value
1.	Number of Transmit Antennas	4,6
2.	Number of Receive Antennas	2
3.	Number of MTC Devices	2,3,4
4.	CSIT Quality($\propto$)	0 for 0-MTCds and 0.3 for α-MTCds
5.	Channel	Slow Fading Rayleigh fading with variance 1
6.	Precoder Initialization for Optimization	Random for 0-MTCds, MRT for $\propto$-MTCds private part, and SVD-MRT for $\propto$-MTCds common part.
7.	Modulation Order($\mathcal{M}$)	QAM(4,16,64,256)
8.	Modulated Block length(S)	256
9.	9. Maximum code rate	0.9
10	Rate Constraint for 0-MTCds	C1= [0.001, 0.04, 0.1, 0.2, 0.3, 0.5, 0.7] bit/s/Hz C2= [0.04, 0.1, 0.2, 0.4, 0.8, 1.4, 2] bit/s/Hz
11.	Rate Constraint for α-MTCds	0.1 bit/s/Hz
12	Noise	AWGN with 0 mean and 1 variance
13.	Number of MCS for LLS	100
14.	Number of Channel Realization	100

4.2 RSMA, SDMA, NOMA Sum Rate

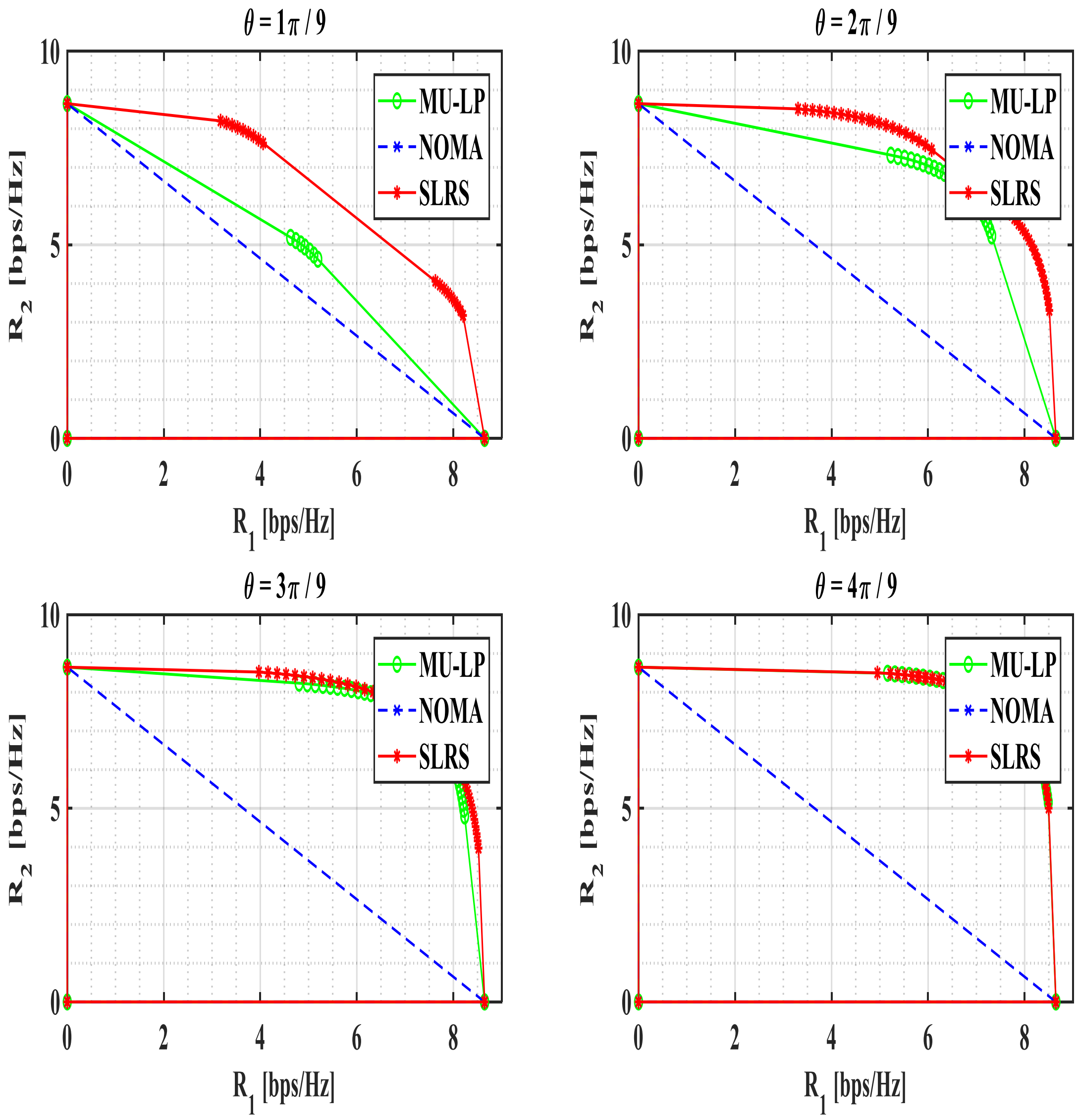

Figure 4.1 Rate region of different MA techniques for 2-MTCd with perfect CSIT, Nt=4, Nr=1, K=2.

In Figure 4.1 the rate region that can be achieved with different MA techniques for 2-MTCd with perfect CSIT is given. The system has 4 Transmit antennas and two single-antenna MTCds. The angle between the channels is varied from $\frac{\pi}{9}$ to $\frac{4\pi}{9}$ which represents that the two MTCds are close to parallel and perpendicular respectively. The instantaneous channels are given by $h1 = [1\ 1\ 1\ 1]\ ^{H} and\ h2 = \gamma[1\ e^{j\theta}\ e^{j2\theta}\ e^{j3\theta}]^{H}$. γ gives the power deference for the two devices and is set to 1. The SNR is set to 20dB. The weight μ_1 of MTCd-1 is set to 1 and the weight of MTCd-2 is varied with $[-3, -1, -0.95, \ldots, 0.95, 1, 3]$giving 43 weight combinations. Only the difference between the weights is necessary.

Since the power deference is 0 between the two MTCds NOMA performs worse than both SDMA and RSMA. When the angle between the channels decreases SDMA will lose its rate region this is due to interference will increase as the devices get closer to each other. As the devices are positioned close to the perpendicular SDMA will have an increased rate region and eventually match RSMA. As shown in the figure RSMA performs well in all situations this is due to that RSMA is not significantly affected by the position of the devices since it better manages interference.

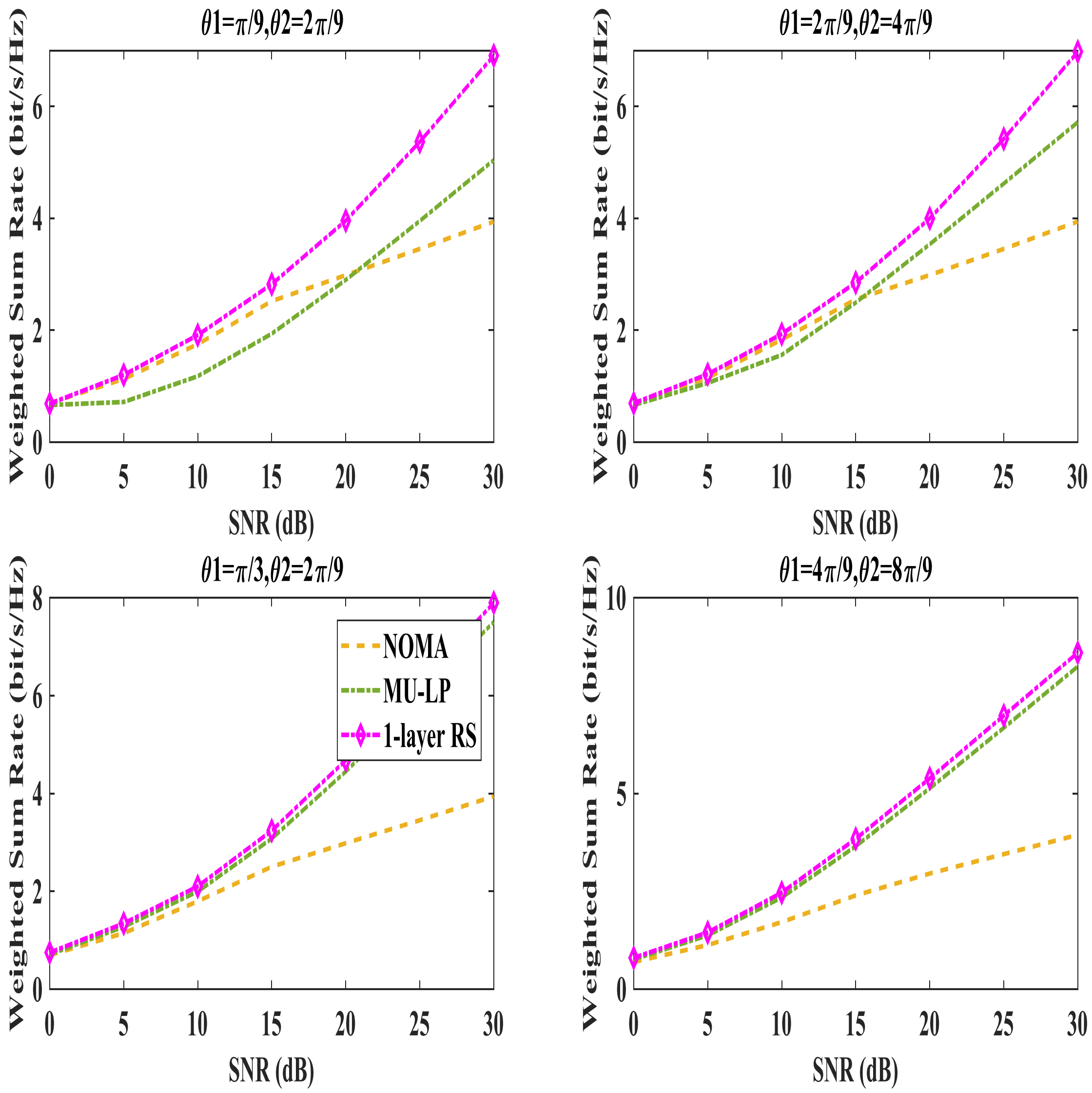

Figure 4.2 Weighted sum rate of different MA techniques for 3-MTCd with perfect CSIT Nt=4, Nr=1, K=3

For three MTCd in a perfect CSIT, the weighted sum rate is given in Figure 4.2. The channel strength is given as $\gamma 1 = 1$ and $\gamma 2 = 0.3$ which implies a 5dB difference between devices

1 and 2 and devices 2 and 3. Each device has weight $[\mu 1, \mu 2, \mu 3]$ =[0.,0.3,0.5] and their sum is equal to 1. The instantaneous channels are given by$h1 = [1\ 1\ 1\ 1]^H, h2 = \gamma 1[1\ e^{j\theta 1}\ e^{j2\theta 1}\ e^{j3\theta 1}]^H and\ h3 = \gamma 2[1\ e^{j\theta 2}\ e^{j2\theta 2}\ e^{j3\theta 2}]^H$. The angels are given as $\theta 1 = [\frac{\pi}{9}, \frac{2\pi}{9}, \frac{3\pi}{9}, \frac{4\pi}{9}]and\theta 2 = 2\theta 1$.

In all the cases NOMA performs the worst this is because NOMA is not suited to multi-antenna systems where the number of transmit antennas is greater than the number of receive antennas. SDMA performance gradually improves as the angle difference is increased. In all the cases RSMA performs well, outperforming both MA techniques.

4.3 MIMO RSMA, NOMA and SDMA Ergodic sum Rate and DoF

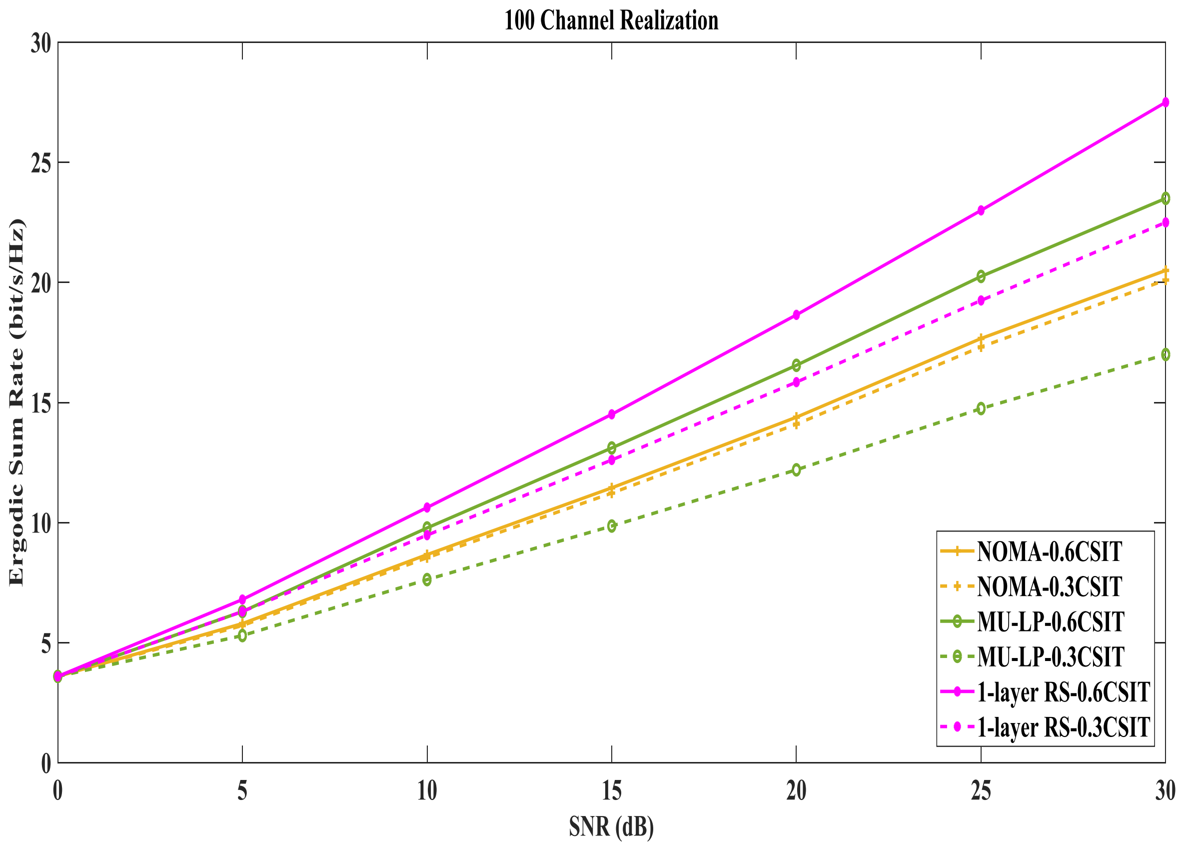

Figure 4.3 Ergodic Sum Rate of different MA techniques in three MTCd with perfect CSIT and 0.3 CSIT quality Nt = 4, Nr = 2, K = 3.

In Figure 4.3 the ergodic sum rate for three MTCd is given. In this simulation instead of focusing on a single channel the system's performance is given as an average of 100 random channel realizations. The CSIT quality is set to 0.6 which is moderate and 0.3 which is low quality. The result shows that even if NOMA performs worst overall it has a slight immunity from CSIT inaccuracy. SDMA is affected the most with CSIT quality and it performs worst in low CSIT quality. RSMA outperforms both in both moderate and low CSIT quality.

Table 4.2 DoF Performance for MU-MIMO RSMA and NOMA with 0.6 and 0.3 CSIT Quality

MA Technique	DoF Theoretical	DoF Calculated
RSMA	3.2 for α =0.3and 6 for $\alpha = 0.6$	2.257 for $\alpha = 0.3$and 2.759 for $\alpha = 0.6$
NOMA	2 for $\alpha = 0.3$ and 2 for $\alpha = 0.6$	2.006 for $\alpha = 0.3$and 2.05 for $\alpha = 0.6$
SDMA	2 for $\alpha = 0.3$ and 6 for $\alpha = 0.6$	1.806 for $\alpha = 0.3$ and 2.40 for $\alpha = 0.6$

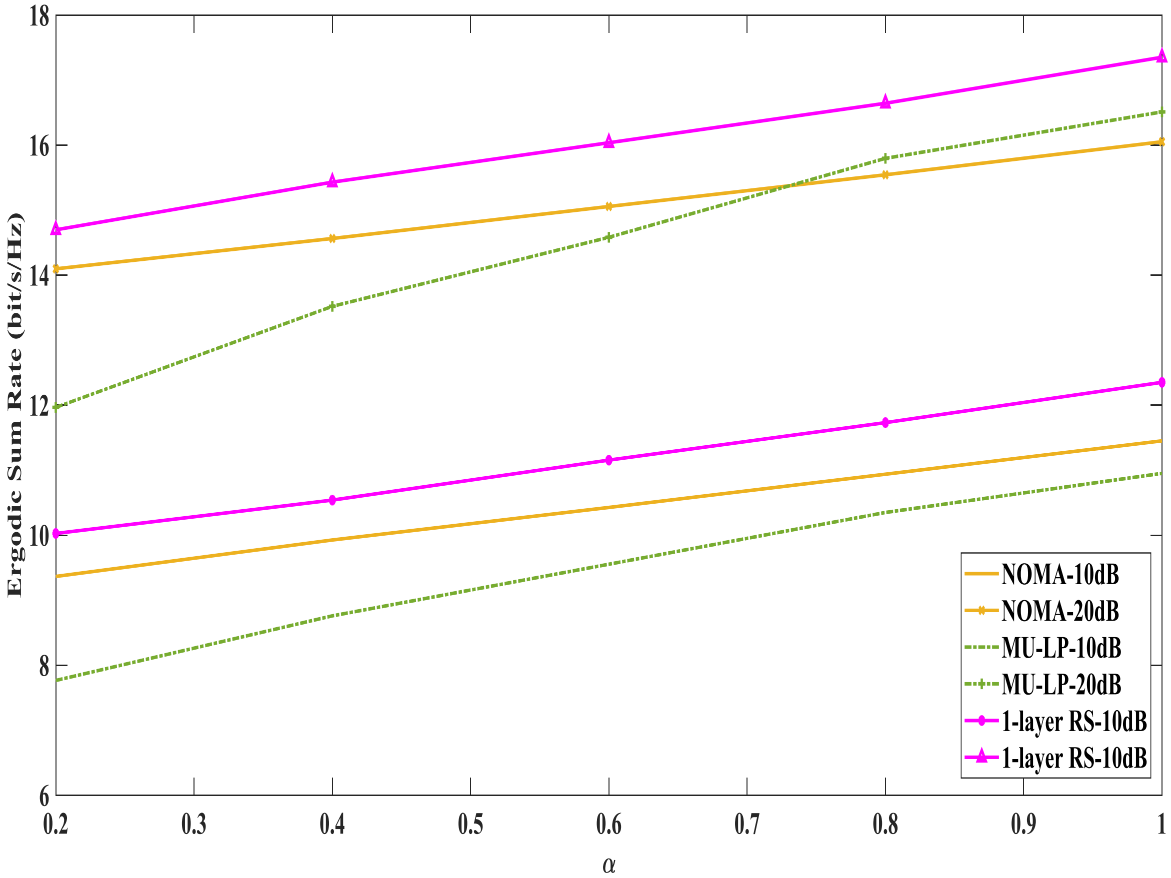

Figure 4.4 Ergodic Sum rate Vs CSIT quality factor at 10 and 20 dB

Figure 4.4 shows the Ergodic Sum Rate performance with an increase in CSIT quality value. It is evident that at any SNR value, the sum rate of SDMA is severely affected by low CSIT quality. NOMA and RSMA are relatively immune to low CSIT quality compared to SDMA. The MTCd devices will operate at relatively low CSIT quality. So SDMA is not suitable for this kind of application. RSMA shows better Ergodic rate performance at all CSIT qualities and SNR values. An increase in SNR will increase the Ergodic Sum Rate.

Table 4.3 Ergodic Sum rate Vs CSIT quality factor at 10 and 20 dB

ESR(b/s/Hz)		CSIT Quality(α)				
	[10,20 dB]	0.2	0.4	0.6	0.8	1
NOMA	10	9.37	9.95	10.46	10.90	11.45
	20	14.10	14.55	15.04	15.54	16.05
MULP	10	7.77	8.95	9.56	10.54	10.95
	20	11.97	13.55	15.04	15.84	16.51
RSMA	10	10.03	10.55	11.04	11.80	12.35
	20	14.70	15.55	16.04	16.54	17.35

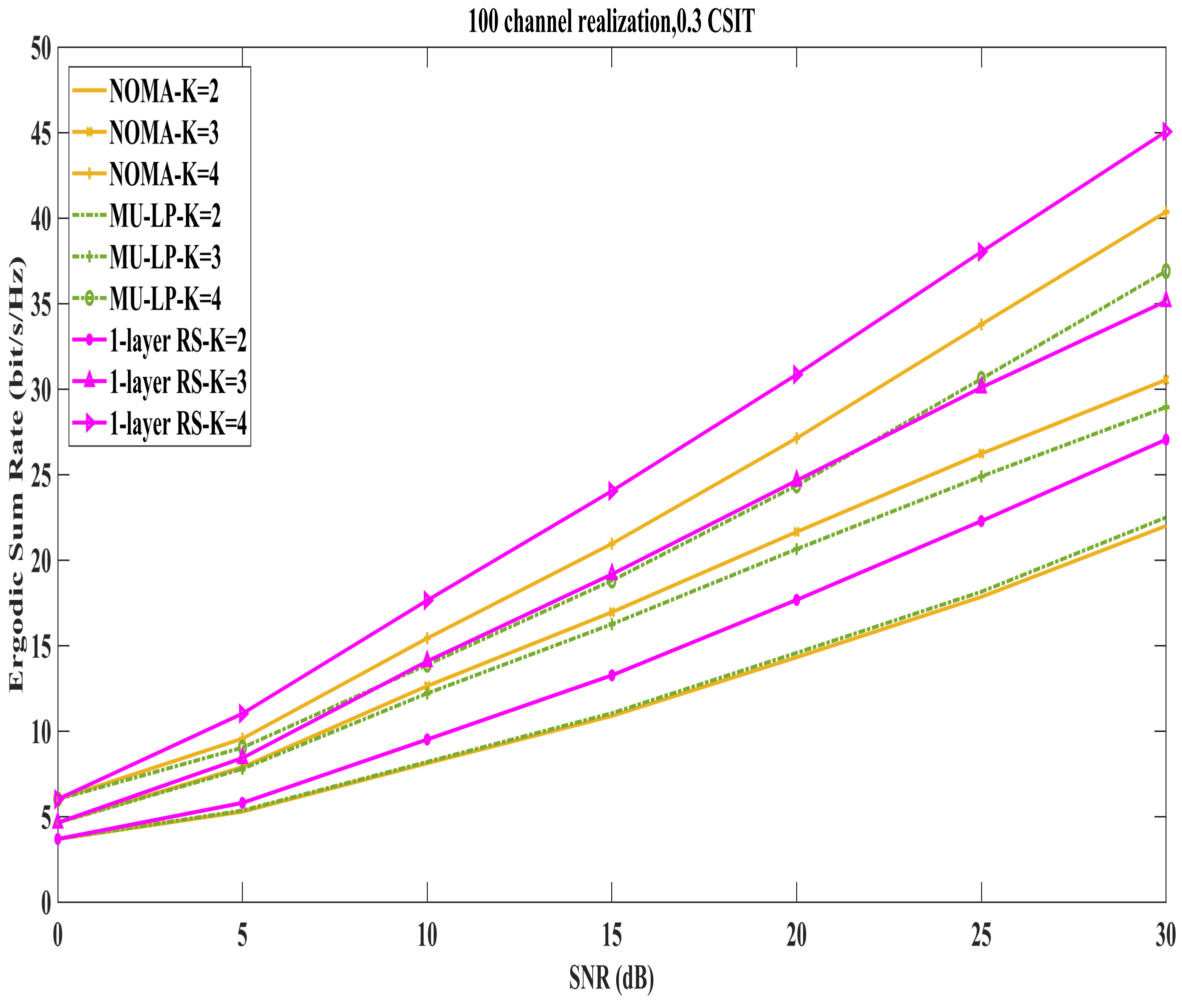

Figure 4.5 Ergodic Sum Rate for different MTCd deployment,$\alpha = 0.3$,Nt=6,Nr=2

Figure 4.5 summarizes the ESR performance of the system with different numbers of MTCd. The CSIT quality value is set to 0.3 and 6 transmit antennas are used with 2 receive antennas for each MTCd. Two streams for each MTCd are transmitted such that $Q_c = 2$ and $Q_p = 2 \times K$.

Since we are operating at low CSIT quality SDMA performs the worst in all scenarios. As the number of MTCds increases the ESR will increase this is obvious since the rate contribution of each MTCd will be summed. The interesting part is as the number of MTCds increases the difference or gap between the graphs will increase at high SNR region. This shows the DoF of each MA technique will increase with the number of MTCds.

RSMA shows the best performance for each number of MTCds. NOMA is favoring the overloaded scenario where the number of transmit antennas is less than the number of receive antennas. Table 4.4 gives the DoF result summary for the result in Figure 4.5 as the number of MTCds increase the deployment is overloaded and NOMA compared to SDMA showed a DoF gain. RSMA gave a better DoF gain with a significant increase in value event performing well in an overloaded scenario.

Table 4.4 DoF Performance for different numbers of MTCds

MA Technique	DoF Calculated [2 MTCds, 3 MTCds, 4 MTCds]		
RSMA	2.714875	3.527074	4.522454
NOMA	2.208114	3.065494	4.05066
SDMA	2.258285	2.904945	3.703672

4.4 PP-RSMA Ergodic sum Rate and DoF

So far devices that can update their CSIT with low accuracy have been studied. For MTCd devices that can't update their CSIT PP-RSMA was prosed. The result is given in Figure 4.6 showing the ergodic sum rate of α MTCds. The rate of 0 MTCds is fixed and given as a constraint to the optimization problem. As SNR increases the rate constraint of both types of devices will change. Four transmit antennas with two and three double antennae MTCd is considered.

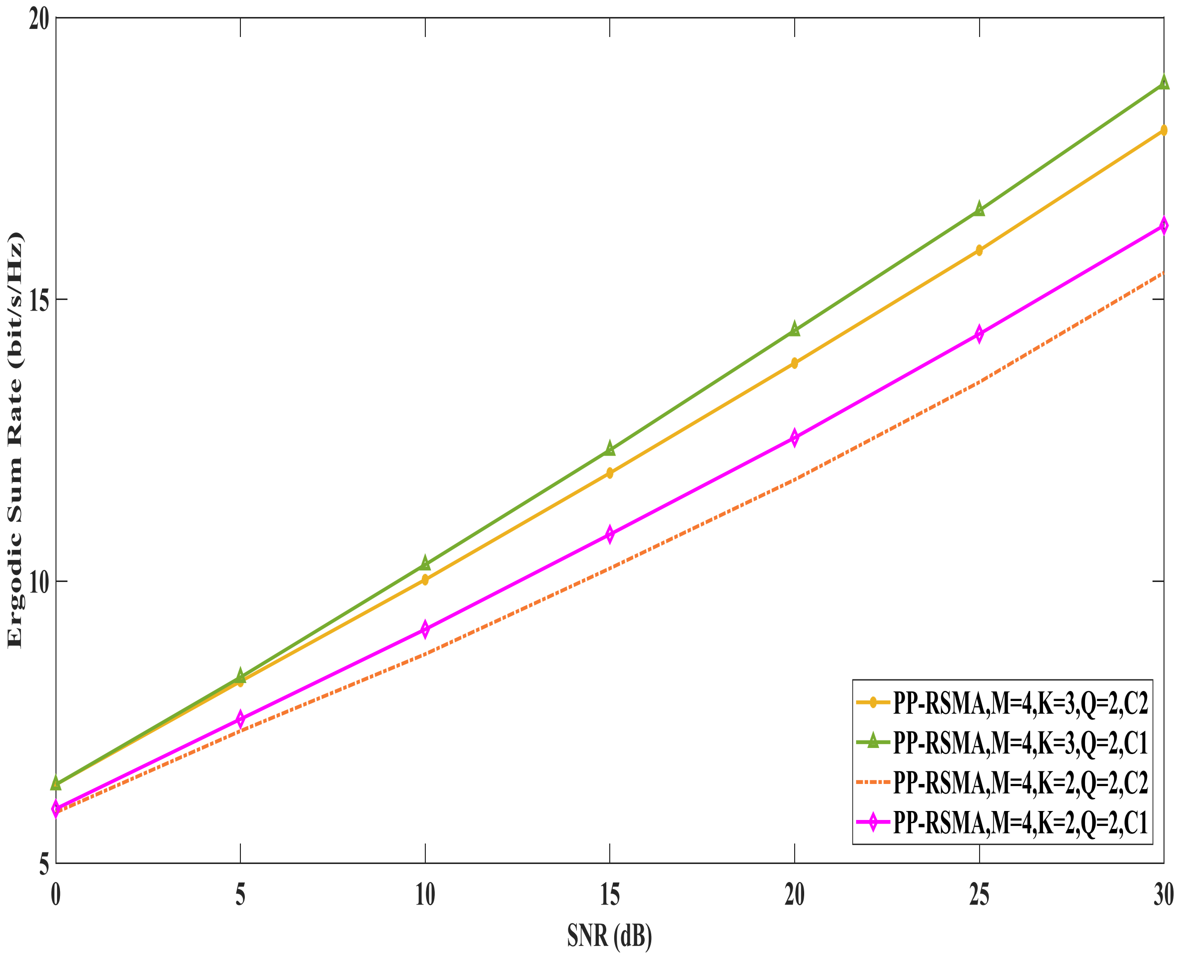

Figure 4.6 Ergodic Sum rate of PP-RSMA

The rate of 0 MTCds is varied with SNR according to constraint C1 and C2 given in the simulation parameters. To accommodate the higher rate constraint given in constraint C2 the system will allocate more power to the 0 MTCd effectively decreasing the achievable sum rate of α MTCd. Table 4.5 gives the DoF performance of PP-RSMA for the two constraints there will be a DoF loss for the second constraint as given in the table.

Table 4.5 DoF Performance of PP-RSMA with 2 0 MTCd and 2 and 3 α MTCd.

0-MTCd Rate Constraint	DoF PP-RSMA with 2 0 MTCD and [2 α MTCd , 3 α MTCd]	
C1	1.889089	1.636769
C2	1.806302	1.552823

4.5 PP-RSMA Link Level Simulation Throughut

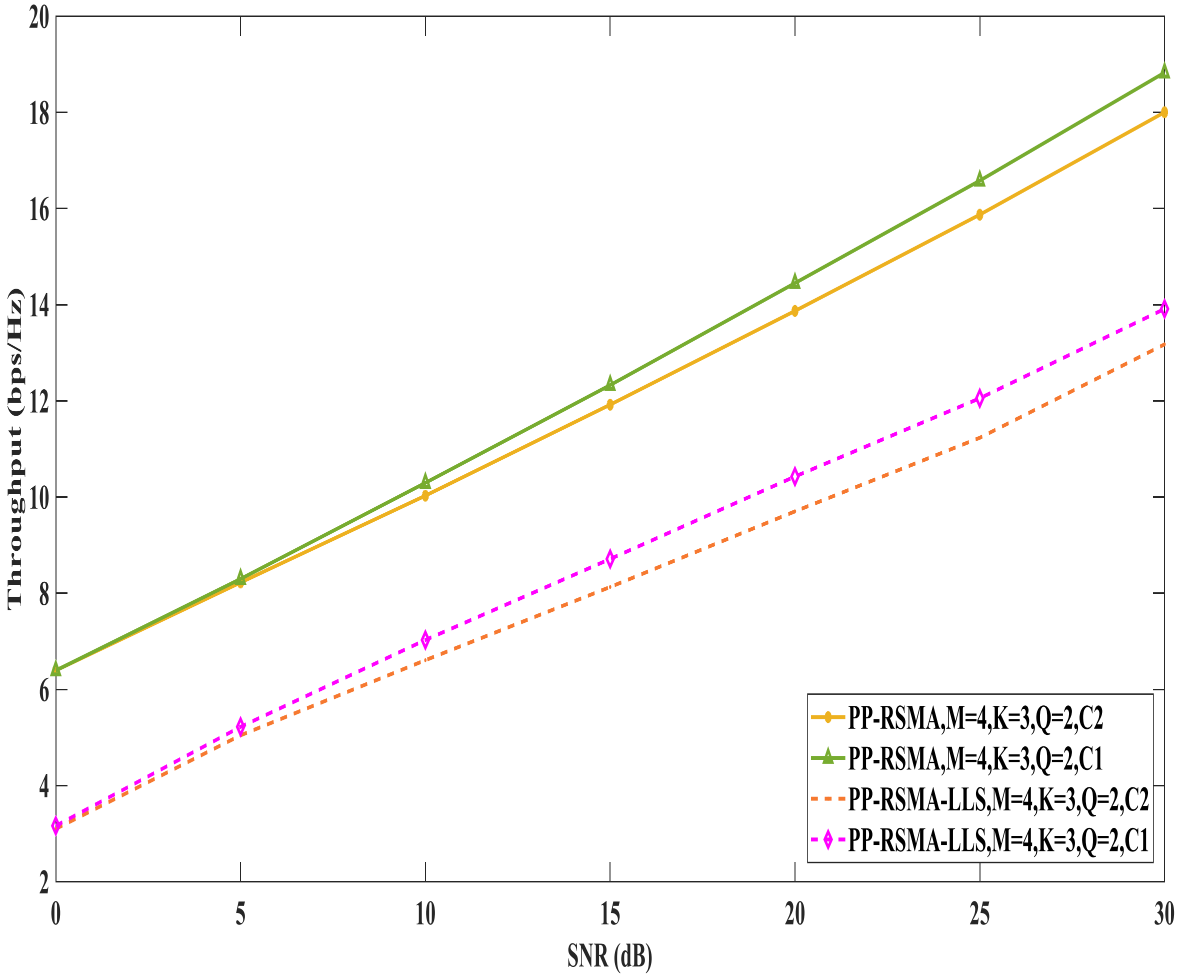

Figure 4.7 Throughput of PP-RSMA

The throughput of PP-RSMA is given in Figure 4.7 and it shows a good performance following the theoretical limit. These values are important because it shows how efficient the system will be in terms of spectral and Energy efficiency.

CHAPTER FIVE

5. CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The demanding nature of mMTC communication forces the communication system to adapt to new techniques. In a MIMO system, multi-MTCd interference is the main cause of performance loss. For a downlink communication, CSIT quality plays a vital role but it is hard to acquire a good CSIT feedback for MTCd. A good MA technique with better CSIT in accuracy immunity is necessary to improve the performance of this kind of system.

In this thesis, three performance matrices namely weighted sum rate, Degree of Freedom, and throughput have been used to study the performance of mMTC system. Three MA techniques have been studied and showed different performances for different setups.

RSMA outperformed other MA techniques in terms of rate, exhibiting a significant increase of 22.9% to 11.64% compared to Space Division Multiple Access (SDMA) and 20.2% to 15% compared to NOMA across different MTC deployments, particularly under low Channel State Information at the Transmitter (CSIT) quality. Additionally, RSMA enhanced the DoF performance of the system by 20.2% to 22.1% compared to SDMA and 22.94% to 11.64% compared to NOMA when low CSIT quality is available for MTC devices. Moreover, in scenarios where MTC devices have low or no CSIT information, PP-RSMA effectively handled the heterogeneity in demand and CSIT requirements of MTC devices, exhibiting superior performance. Link Level Simulations (LLS) demonstrated that the throughput achieved by the system aligned closely with the rate capacity, reinforcing the efficacy of PP-RSMA in mMTC MIMO systems. This method showed a potential for use in mMTC systems and PP-RSMA improved the throughput of the system while accommodating devices that can't update their CSIT.

5.2 Recommendation

The performance evaluation of RSMA for mMTC communication is considered. For this thesis, a precoder optimization is employed to measure the best performance possible to attain but a low complicity precoding can be used for practical purposes. A simple channel model is considered and Pathless and shadowing can be considered. Finally, this thesis could be expanded to multi-carrier and multi-cell communication.

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