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GROUP REPORT

Multiple Access Techniques (MAT); Classification of Candidate Multiple Access Techniques for 6G and their comparison with specified 3GPP features

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ETSI

650 Route des Lucioles
F-06921 Sophia Antipolis Cedex - FRANCE

Tel.: +33 4 92 94 42 00 Fax: +33 4 93 65 47 16

Siret N° 348 623 562 00017 - APE 7112B
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Foreword

This Group Report (GR) has been produced by ETSI Industry Specification Group (ISG) Multiple Access Techniques (MAT).

Modal verbs terminology

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Executive summary

Multiple Access Techniques (MAT) are considered as a key technology to enhance the radio interface for IMT-2030. The present document studies candidate MAT for 6G in the downlink that improve spectral efficiency in the presence of inter-user interference.

The candidate MAT are compared against MAT specified in the 3GPP technical specifications, i.e. Orthogonal Multiple Access (OMA), Multi-User MIMO (MU-MIMO) and Multi-User Superposition Transmission (MUST). Candidate MAT considered in the present document are power-domain Non-Orthogonal Multiple Access (power-domain NOMA), Rate-Splitting Multiple Access (RSMA) and Cache-Aided MU-MIMO (CA MU-MIMO). The studies focus on the physical layer of the 3GPP radio interface.

Candidate MAT and specified MAT are compared in terms of:

- transmit processing architectures;

- receiver types such as Treating Interference as Noise (TIN), Reduced complexity Maximum Likelihood (R-ML) and Successive Interference Cancellation (SIC);
- requirements on assistance information from the base-station to the UEs to supress/cancel inter-user interference;
- requirements on DM-RS; and
- spectral efficiency performance evaluation under the considered simple scenario.

The performance evaluation shows that candidate MAT can provide spectral efficiency gains against specified MAT in certain channel conditions such as when the channels between the scheduled UEs are highly correlated (e.g. UEs with small angular separation) or when there is power imbalance between scheduled UEs.

Comparing with 3GPP specified MU-MIMO, requirements on additional processing, number of DM-RS, and details on assistance information from network to UEs for the candidate MAT is presented. The limitations of the evaluation methodology are highlighted and potential next steps for evaluation are also identified.

Introduction

At the end of 2023, the 3GPP Organizational Partners: ARIB, ATIS, CCSA, ETSI, TSDSI, TTA and TTC announced that 3GPP will develop the 6th generation of global communications specifications (6G). Starting from August 2025, technical studies for 6G in 3GPP Release 20 include fundamental technologies for the physical layer of the 6G radio interface. 3GPP Release 21 will be the start of the normative work. The present document studies candidate Multiple Access Techniques (MAT) in downlink for the physical layer of the 3GPP radio interface.

1 Scope

The present document studies candidate downlink MAT for 6G that improve spectral efficiency in the presence of inter-user interference. The scope of the study is on the physical layer of the 3GPP radio interface and candidate techniques are compared against techniques specified in 3GPP technical specifications.

2 References

2.1 Normative references

Normative references are not applicable in the present document.

2.2 Informative references

References are either specific (identified by date of publication and/or edition number or version number) or non-specific. For specific references, only the cited version applies. For non-specific references, the latest version of the referenced document (including any amendments) applies.

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The following referenced documents may be useful in implementing an ETSI deliverable or add to the reader's understanding, but are not required for conformance to the present document.

[i.1] Recommendation ITU-R M.2160-0 (11-2023): "Framework and overall objectives of the future development of IMT for 2030 and beyond".

[i.2] Report Recommendation ITU-R M.2516-0 (11-2022): "Future technology trends of terrestrial International Mobile Telecommunications systems towards 2030 and beyond".

[i.3] Recommendation ITU-R M.2083-0 (09-2015): "IMT Vision - Framework and overall objectives of the future development of IMT for 2020 and beyond".

[i.4] 6GWS-250238: "Chair's summary of the 3GPP workshop on 6G", 3GPP RAN 6G Workshop, Incheon - South Korea, March 10-11, 2025.

[i.5] 6GWS-250061: "Lenovo views on 6G RAN Vision and Priorities", 3GPP RAN 6G Workshop, Incheon - South Korea, March 10-11, 2025.

[i.6] 6GWS-250102: "Intel views on 6G RAN and Radio Interface", 3GPP RAN 6G Workshop, Incheon - South Korea, March 10-11, 2025.

[i.7] 6GWS-250104: "A BBC View on Multiple Access Techniques for 6G", 3GPP RAN 6G Workshop, Incheon - South Korea, March 10-11, 2025.

[i.8] 6GWS-250132: "VIAVI's Vision & Priorities for 6G Radio Technologies", 3GPP RAN 6G Workshop, Incheon - South Korea, March 10-11, 2025.

[i.9] RP-251881: "New SID: Study on 6G Radio", 3GPP RAN#108 Plenary Meeting, Prague - Czech Republic, June 9-13, 2025.

[i.10] ETSI TS 138 211: "5G; NR; Physical channels and modulation (3GPP TS 38.211)".

[i.11] ETSI TS 138 214: "5G; NR; Physical layer procedures for data (3GPP TS 38.214)".

[i.12] Erik Dahlman, Stefan Parkvall, and Johan Skold: "5G NR: The Next Generation Wireless Access Technology", Academic Press, 1st edition, August 2018.

[i.13] ETSI TS 138 212: "5G; NR; Multiplexing and channel coding (3GPP TS 38.212)".

[i.14] ETSI TS 138 101-4: "5G; NR; User Equipment (UE) radio transmission and reception; Part 4: Performance requirements (3GPP TS 38.101-4)".

[i.15] 3GPP TR 38.878: "NR demodulation performance evolution".

[i.16] Eleftherios Lampiris and Petros Elia: "Adding Transmitters Dramatically Boosts Coded-Caching Gains for Finite File Sizes", IEEE™ Journal on Selected Areas in Communications, vol. 36, no. 6, pp. 1176-1188, June 2018.

[i.17] 3GPP TR 36.859: "Study on Downlink Multiuser Superposition Transmission (MUST) for LTE".

[i.18] 3GPP RP-162265: "Status Report to TSG for Downlink Multiuser Superposition Transmission for LTE".

[i.19] 3GPP RP-162504: "Summary of LTE R14 MUST".

[i.20] ETSI TS 136 213: "LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer procedures; (3GPP TS 36.213 Release 14)".

[i.21] ETSI TS 136 211: "LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical channels and modulation; (3GPP TS 36.211 Release 14)".

[i.22] 3GPP RP-161019: "Revised work item proposal: Downlink Multiuser Superposition Transmission for LTE".

[i.23] E. A. Jorswieck: "Next-Generation Multiple Access: From Basic Principles to Modern Architectures", in Proceedings of the IEEE™, vol. 112, no. 9, pp. 1149-1178, September 2024.

[i.24] A. F. M. S. Shah, A. N. Qasim, M. A. Karabulut, H. Ilhan, and M. B. Islam: "Survey and performance evaluation of multiple access schemes for next-generation wireless communication systems", IEEE™ Access, vol. 9, pp. 113428–113442, 2021.

[i.25] B. Clerckx et al.: "Is NOMA Efficient in Multi-Antenna Networks? A Critical Look at Next Generation Multiple Access Techniques", in IEEE™ Open Journal of the Communications Society, vol. 2, pp. 1310-1343, 2021.

[i.26] Z. Ding, F. Adachi and H. V. Poor: "The Application of MIMO to Non-Orthogonal Multiple Access", in IEEE™ Transactions on Wireless Communications, vol. 15, no. 1, pp. 537-552, January 2016.

[i.27] Y. Mao, O. Dizdar, B. Clerckx, R. Schober, P. Popovski and H. V. Poor: "Rate-Splitting Multiple Access: Fundamentals, Survey, and Future Research Trends", in IEEE™ Communications Surveys & Tutorials, vol. 24, no. 4, pp. 2073-2126, Fourth quarter 2022.

[i.28] B. Clerckx, H. Joudeh, C. Hao, M. Dai and B. Rassouli: "Rate splitting for MIMO wireless networks: a promising PHY-layer strategy for LTE evolution", in IEEE™ Communications Magazine, vol. 54, no. 5, pp. 98-105, May 2016.

[i.29] H. Joudeh and B. Clerckx: "Sum-Rate Maximization for Linearly Precoded Downlink Multiuser MISO Systems with Partial CSIT: A Rate-Splitting Approach", in IEEE™ Transactions on Communications, vol. 64, no. 11, pp. 4847-4861, November 2016.

[i.30] A. Mishra, Y. Mao, O. Dizdar and B. Clerckx: "Rate-Splitting Multiple Access for Downlink Multiuser MIMO: Precoder Optimization and PHY-Layer Design", in IEEE™ Transactions on Communications, vol. 70, no. 2, pp. 874-890, February 2022.

[i.31] B. Clerckx, Y. Mao, R. Schober and H. V. Poor: "Rate-Splitting Unifying SDMA, OMA, NOMA, and Multicasting in MISO Broadcast Channel: A Simple Two-User Rate Analysis", in IEEE™ Wireless Communications Letters, vol. 9, no. 3, pp. 349-353, March 2020.

[i.32] S. Zhang, B. Clerckx, D. Vargas, O. Haffenden and A. Murphy: "Rate-Splitting Multiple Access: Finite Constellations, Receiver Design, and SIC-Free Implementation", in IEEE™ Transactions on Communications, vol. 72, no. 9, pp. 5319-5333, September 2024.

[i.33] Mao, Y., Clerckx, B. & Li, V.O.: "Rate-splitting multiple access for downlink communication systems: bridging, generalizing, and outperforming SDMA and NOMA", EURASIP Journal on Wireless Communications and Networking Network, vol. 2018, p. 133 (2018).

[i.34] 3GPP TR 36.866: "Study on network-assisted interference cancellation and suppression (NAIC) for LTE (Release 12)".

[i.35] E. Björnson et al.: "Optimal Multiuser Transmit Beamforming: A Difficult Problem with a Simple Solution Structure [Lecture Notes] ", IEEE™ Signal Processing Magazine, vol. 31, no. 4, pp. 142-148, July 2014.

3 Definition of terms, symbols and abbreviations

3.1 Terms

Void.

3.2 Symbols

Void.

3.3 Abbreviations

For the purposes of the present document, the following abbreviations apply:

3GPP	3rd Generation Partnership Project
5G	5th Generation
6G	6th Generation
AI	Artificial Intelligence
ARIB	Association of Radio Industries and Businesses
ATIS	Alliance for Telecommunications Industry Solutions
AWGN	Additive White Gaussian Noise
CA MU-MIMO	Cache-Aided Multi-User Multiple-Input Multiple-Output
CA	Cache-Aided
CCSA	China Communications Standards Association
CSI	Channel State Information
CWIC	CodeWord Interference Cancellation
DM-RS	Demodulation Reference Signals
eMBB	enhanced Mobile BroadBand
FSTD	Frequency Switched Transmit Diversity
GHz	Gigahertz
GR	Group Report
IMT	International Mobile Telecommunications
LDPC	Low-Density Parity Check
LOS	Line-Of-Sight
LTE	Long-Term Evolution
MAT	Multiple Access Techniques
MIMO	Multiple-Input Multiple-Output
MMF	Max-Min Fairness
MMSE	Minimum Mean Square Error
MMSE-IRC	Minimum Mean Squared Error - Interference Rejection Combining
mMTC	massive Machine-Type Communications
MRT	Maximum Ratio Transmission
MU-MIMO	Multi-User Multiple-Input Multiple-Output
MUST	Multi-User Superposition Transmission
NOMA	Non-Orthogonal Multiple Access
OFDM	Orthogonal Frequency Division Multiplexing

OMA	Orthogonal Multiple Access
PDSCH	Physical Downlink Shared Channel
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RAN	Radio Access Network
RB	Resource Block
RE	Resource Element
RF	Radio Frequency
R-ML	Reduced complexity Maximum Likelihood
RSMA	Rate-Splitting Multiple Access
SC	Superposition Coding
SFBC	Space-Frequency Block Codes
SIC	Successive Interference Cancellation
SNR	Signal to Noise Ratio
SU-MIMO	Single-User Multiple-Input Multiple-Output
TBS	Transport Block Size
TIN	Treating Interference as Noise
TM	Transmission Mode
TR	Technical Report
TS	Technical Specification
TSDSI	Telecommunications Standards Development Society India
TTA	Telecommunications Technology Association
TTC	Telecommunication Technology Committee
UE	User Equipment
URLLC	Ultra-Reliable and Low-Latency Communications
XR	eXtended Reality
ZF	Zero Forcing

4 Motivation

4.1 Development of IMT-2030

The objective for the development of IMT-2030 is to address the needs of users, applications and services using mobile services in the years 2030 and beyond. IMT-2030 is expected to be a pervasive general-purpose communication system connecting humans and machines and supporting a wide range of use cases with potentially very different requirements [i.1], [i.2]. The IMT-2030 framework categorizes different use cases with similar characteristics and requirements into usage scenarios, such as Immersive Communication, Hyper Reliable & Low-Latency Communication, and Massive Communication, that expand the IMT 2020 [i.3] usage scenarios (eMBB, URLLC and mMTC, respectively) with evolved and new capabilities. However, IMT-2030 also adds new usage scenarios: Ubiquitous Connectivity, AI & Communication and Integrated Sensing and Communication.

A key capability of IMT-2030 is improved spectrum efficiency, i.e. the average data throughput per unit of spectrum and per cell. The goal is to surpass the spectrum efficiency levels of IMT-2020 [i.3], potentially reaching 1,5 to 3 times higher, although even greater improvements may also be explored. Enhancing spectrum efficiency, ensuring reliable service quality and effectively balancing high data rates with mobility across diverse environments are crucial objectives [i.1]. To achieve high data throughput within limited bandwidth, smart use of multiple frequency bands and the application of advanced technologies to boost spectrum efficiency are essential [i.2].

IMT-2030 considers various candidate key technologies to satisfy the targeted capabilities. MAT are considered among these candidate key technologies to enhance the radio interface [i.1], [i.2].

4.2 Discussions in 3GPP

3GPP held a 6G workshop in March 2025 to get a high-level view from different organizations including vendors, operators, chip manufacturers, researchers and regulators. Companies provided their inputs on promising applications and potential enhancements over 5G to get the maximum benefit from 6G. The first 6G study item on use cases and requirements for 6G has subsequently been approved, led by several operators.

With new device types, such as those to support XR, the number of devices connected to the network is expected to grow significantly.

Although new bands (such as 7 - 24 GHz) are likely to be standardized for 6G, the available spectrum will be limited due to the existence of other non-3GPP systems (satellite, radar, etc.). Meanwhile, sub-6 GHz spectrum (3GPP FR1) will continue to be used to provide sufficient coverage. With the growing concentration of mobile devices, including in dense urban areas, very high spectral efficiency is crucial, especially in this FR1 band.

As outlined in the 3GPP 6G workshop summary, and emphasized in many individual company proposals, spectral efficiency is therefore crucial to support a high number of devices with limited spectrum [i.4].

There are several new technologies that can contribute to the spectral efficiency enhancement, and new multiple access techniques are good candidates for potential enhancements. Several companies provided their interest on new multiple access techniques to unlock the full benefits of 6G [i.5], [i.6], [i.7] and [i.8]. Finally, the first 6G RAN study item that was approved in RAN#108 Plenary Meeting defined a clear target on spectral efficiency enhancement [i.9], highlighting the necessity of studying new MAT as enablers.

5 System model

This clause provides the system model considered and general assumptions. The scope of the present document is on downlink communication.

A single cell transmitter communicating with K users (UEs) is considered as illustrated in Figure 5-1.

OFDM is assumed as the waveform for the physical layer. Each pair of OFDM subcarrier in the frequency domain and OFDM symbol in the time domain is called an RE [i.10]. An RB consists of a group of 12 consecutive OFDM subcarriers in the frequency domain [i.10].

The following delivery mode is considered:

- Unicast delivery mode where the transmitter sends a different message to each UE.

The transmitter is equipped with N_T physically collocated antennas each connected to a dedicated Radio Frequency (RF) chain (e.g. digital-to-analogue conversion, up-conversion, filtering, power amplification, etc.) to convert the baseband digital signal to an analogue radio frequency signal. The UEs each have N_R physical receive antennas each connected to a dedicated RF chain.

The transmitter can acquire CSI by feedback from the UEs or uplink reference signals [i.10], [i.11] so the transmitter can efficiently multiplex the UE's messages onto the physical resources (e.g. time, frequency, space). For the present document, it is assumed that the transmitter has perfect knowledge of the CSI.

In the downlink, DM-RS are embedded within the data transmission layers and are used at the receiver to estimate the channel for coherent demodulation. Each DM-RS measures the channel from the associated data transmission layer [i.10], [i.12]. DM-RS are processed with the same multi-antenna precoder as the associated data transmission layer. More details on multi-antenna precoders and transmission layers is provided in clause 6 of the present document.

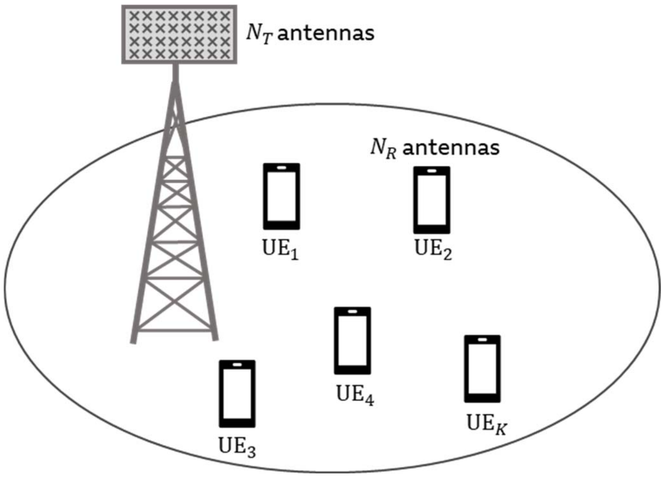


Figure 5-1: Single cell transmitter with N_T antennas communicating with K UEs each with N_R antennas

6 MAT baseline architectures specified in 3GPP

6.1 OMA

6.1.1 Description

The transmitter processing for OMA is presented in Figure 6.1-1. OMA allows transmissions without inter-user interference between messages for the scheduled UEs.

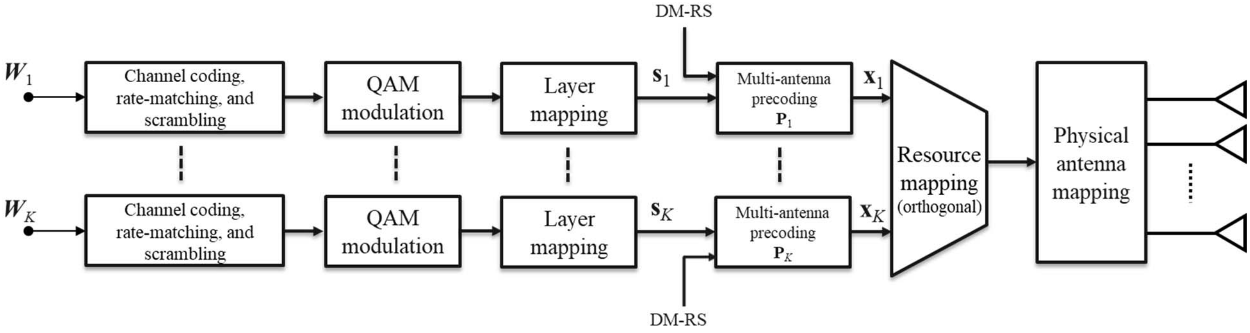


Figure 6.1-1: Transmit processing for OMA

$W_1, \ldots, W_K$, are messages to UE$_1$, …, UE$_K$, respectively. As specified in [i.10], [i.13], each of the messages is channel coded to generate codewords, rate-matched to the available resources for transmission, scrambled to randomize interference and QAM modulated. Layer mapping allocates modulation symbols from the codewords across L_k MIMO transmission layers ($k \in \{1, \ldots, K\}$). DM-RS are used for channel estimation at the receivers for coherent demodulation. A different orthogonal DM-RS is used for each of the transmission layers. Each transmission layer and corresponding DM-RS is mapped to an antenna port as specified in [i.10].

Multi-antenna precoding can be applied independently to the modulated symbols for each of the messages $W_1, \ldots, W_K$. DM-RS are also processed with the same multi-antenna precoding, which means that at the receiver the combination of the multi-antenna precoding and channel is seen as an effective channel. Therefore, multi-antenna precoding is transparent to the receivers. For OMA, multi-antenna precoding mainly aims to increase the data rate of the target UE.

The resource mapping allocates, as assigned by the scheduler, modulation symbols for each transmission layer to the available time-frequency resources - i.e. resource blocks as defined in [i.10]. In OMA, messages for different UEs are mapped to orthogonal time-frequency resources (i.e. only one UE message in a given time-frequency resource). If the number of MIMO layers $L_j > 1$ for UE$_j$, the message W_j is transmitted over multiple transmission layers and it is referred to as Single-User MIMO (SU-MIMO).

After resource mapping, the symbols at each transmission layer are OFDM modulated (not represented in Figure 6.1-1) and mapped to the physical antennas.

6.1.2 Transmit and receive expressions

For the OMA transmitter in Figure 6.1-1 the transmit signal $\mathbf{x}_k$ can be expressed as (for simplicity it is assumed that $L_k = L$):

$$\mathbf{x}_k = \mathbf{P}_k \mathbf{s}_k = \sum_{n=1}^{L} \mathbf{p}_n s_{n,k},$$

where:

$\mathbf{s}_k \in \mathbb{C}^{L\times 1}$ are modulated symbols of the message for UE$_k$,

$\{\mathbf{p}_1, \cdots, \mathbf{p}_L\} \in \mathbb{C}^{N_T\times 1}$ are precoding vectors,

$\mathbf{P}_k = [\mathbf{p}_1 \cdots \mathbf{p}_L] \in \mathbb{C}^{N_T\times L}$ is the precoding matrix, and

$\mathbf{x}_k \in \mathbb{C}^{N_T\times 1}$ are the pre-coded symbols.

The corresponding OMA receive signal $\mathbf{y}$ at UE$_k$ can be expressed as:

$$\mathbf{y}_k = \mathbf{H}_k \mathbf{x}_k + \mathbf{n}_k = \sum_{n=1}^{L} \mathbf{H}_k \mathbf{p}_n s_{n,k} + \mathbf{n}_k,$$

where:

$\mathbf{y}_k \in \mathbb{C}^{N_R\times 1}$ received signal vector of UE$_k$,

$\{\mathbf{h}_{1,k}, \cdots, \mathbf{h}_{N_R,k}\} \in \mathbb{C}^{N_T\times 1}$ channel vectors at each receive antenna of UE$_k$,

$\mathbf{H}_k = \left[\mathbf{h}_{1,k} \cdots \mathbf{h}_{N_R,k}\right]^H \in \mathbb{C}^{N_R\times N_T}$ channel matrix of UE$_k$ (where $(\cdot)^H$ is the Hermitian operator), and

$\mathbf{n}_k \in \mathbb{C}^{N_R\times 1}$ noise vector of UE$_k$.

In the receive signal $\mathbf{y}_k$, the term $\sum_{n=1}^{L} \mathbf{H}_k \mathbf{p}_n s_{n,k}$ is the wanted signal for UE$_k$ with inter-layer interference but without any inter-user interference from the messages from other UEs. Inter-layer interference can be managed with receive processing with multiple receive antennas. [i.14] defines demodulation requirements for MMSE-IRC and R-ML receiver with enhanced inter-layer interference mitigation for SU-MIMO.

6.2 MU-MIMO

6.2.1 Description

The transmitter processing for MU-MIMO is presented in Figure 6.2-1. MU-MIMO allows the spatial multiplexing of the messages for various UEs into the same time-frequency resources.

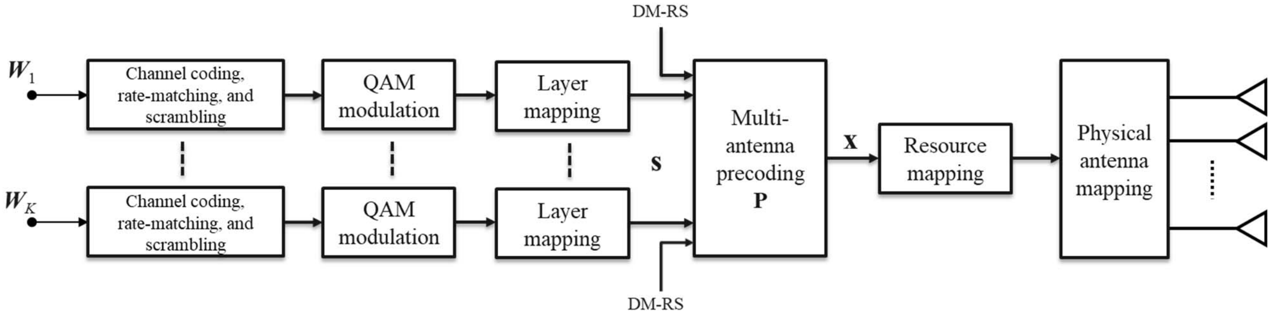


Figure 6.2-1: Transmit processing for MU-MIMO

W_1 ,…, W_K, are messages to UE$_1$, …, UE$_K$, respectively. As specified in [i.10], [i.13], each of the messages is channel coded to generate codewords, rate-matched to the available resources for transmission, scrambled to randomize interference and QAM modulated. Layer mapping allocates modulation symbols from the codewords across L_k MIMO transmission layers ($k \in \{1, \ldots, K\}$). If the number of MIMO layers $L_j > 1$ for UE$_j$, the message W_j is transmitted over multiple transmission layers. DM-RS are used for channel estimation at the receivers for coherent demodulation. A different orthogonal DM-RS is used for each of the transmission layers. Each transmission layer and corresponding DM-RS is mapped to an antenna port as specified in [i.10].

Multi-antenna precoding can be applied jointly to the modulated symbols of the messages W_1, …, W_K. DM-RS are also processed with the same multi-antenna precoding, which means that at the receiver the combination of the multi-antenna precoding and channel is seen as an effective channel. Therefore, multi-antenna precoding is transparent to the receivers. For MU-MIMO, multi-antenna precoding allows the efficient spatial multiplexing of the messages for various UEs into the same time-frequency resources. This is different from OMA where only one UE message is allocated in a given time-frequency resource.

The resource mapping allocates, as assigned by the scheduler, modulation symbols for each transmission layer to the available time-frequency resources - i.e. resource blocks as defined in [i.10].

After resource mapping, the symbols at each transmission layer are OFDM modulated (not represented in Figure 6.2-1) and mapped to the physical antennas.

6.2.2 Transmit and receive signal expressions

For the MU-MIMO transmitter in Figure 6.2-1 with L_k=1 (for all k), for a given time-frequency resource, the transmit signal **x** can be expressed as:

$$\mathbf{x} = \mathbf{P}\mathbf{s} = \sum_{k=1}^{K} \mathbf{p}_k s_k,$$

where:

$\mathbf{s} \in \mathbb{C}^{K\times 1}$ are modulated symbols from the K messages W_1, …,W_K,

$\{\mathbf{p}_1, \cdots, \mathbf{p}_K\} \in \mathbb{C}^{N_T\times 1}$ are precoding vectors,

$\mathbf{P} = [\mathbf{p}_1 \cdots \mathbf{p}_K] \in \mathbb{C}^{N_T\times K}$ is the precoding matrix, and

$\mathbf{x} \in \mathbb{C}^{N_T\times 1}$ are the pre-coded symbols.

The corresponding MU-MIMO receive signal $\mathbf{y}_k$ at UE$_k$ can be expressed as:

$$\mathbf{y}_k = \mathbf{H}_k\mathbf{x} + \mathbf{n}_k = \mathbf{H}_k\mathbf{p}_k s_k + \sum_{j\neq k}^{K} \mathbf{H}_k\mathbf{p}_j s_j + \mathbf{n}_k,$$

where:

$\mathbf{y}_k \in \mathbb{C}^{N_R\times 1}$ received signal vector of UE$_k$,

$\{\mathbf{h}_{1,k}, \cdots, \mathbf{h}_{N_R,k}\} \in \mathbb{C}^{N_T\times 1}$ channel vectors at each receive antenna of UE$_k$,

$\mathbf{H}_k = \left[\mathbf{h}_{1,k} \cdots \mathbf{h}_{N_R,k}\right]^H \in \mathbb{C}^{N_R\times N_T}$ channel matrix of UE$_k$, and

$\mathbf{n}_k \in \mathbb{C}^{N_R \times 1}$ noise vector of UE$_k$.

In the receive signal $\mathbf{y}_k$, the term $\mathbf{H}_k \mathbf{p}_k s_k$ is the desired signal for UE$_k$ and the term $\sum_{j\neq k}^{K} \mathbf{H}_k \mathbf{p}_j s_j$ is the inter-user interference.

NOTE: If the number of MIMO layers $L_j > 1$ for UE$_j$, the message W_j is transmitted over multiple transmission layers. The desired signal for UE$_j$ would also include interference among the MIMO layers of UE$_j$ (see clause 6.1 OMA) and the expressions above can be expanded accordingly.

6.2.3 MU-MIMO with TIN

The inter-user interference in MU-MIMO is controlled at the transmitter by multi-antenna precoding. At the receivers, a common approach is to treat the residual inter-user interference as if it were assumed to be noise, referred to as TIN. For K=2, the received signal for UE$_1$ is:

$$\mathbf{y}_1 = \underbrace{\mathbf{H}_1 \mathbf{p}_1 s_1}_{\text{desired}} + \underbrace{\mathbf{H}_1 \mathbf{p}_2 s_2 + \mathbf{n}_1}_{\substack{\text{asssumed} \\ \text{as noise}}}.$$

6.2.4 MU-MIMO with MMSE-IRC receivers

Void.

6.2.5 MU-MIMO with advanced receivers (R-ML)

To enhance inter-user interference mitigation for MU-MIMO, [i.15] and [i.14] study and specify R-ML receivers. R-ML receivers jointly demodulate the desired signal and the inter-user interference. For K=2, the received signal for UE$_1$ is:

$$\mathbf{y}_1 = \underbrace{\mathbf{H}_1 \mathbf{p}_1 s_1 + \mathbf{H}_1 \mathbf{p}_2 s_2}_{\text{joint demodulation}} + \mathbf{n}_1,$$

where the R-ML receiver does a joint demodulation of s_1 and s_2.

Without explicit knowledge of the co-scheduled UE, an approach would be for the scheduled UE to blindly try different modulation orders to improve the mitigation of inter-user interference. However, [i.15] and [i.13] study and specify, respectively, assistance information to the scheduled UE about the modulation order used by the co-scheduled UE within the same time-frequency resources. The assistance information does not include information about the LDPC channel code-rate used by the co-scheduled UE. Therefore, an R-ML receiver is not expected to carry out LDPC decoding the interference from the co-scheduled UE.

6.3 MUST

6.3.1 Description

MUST is a downlink multiple access technique studied and standardized by 3GPP in Releases 13 and 14 as part of LTE-Advanced enhancements [i.17], [i.22]. MUST leverages the concept of superposition coding to serve the messages for various UEs into the same time-frequency resources. Its main purpose is to increase spectral efficiency and improve user fairness, particularly benefiting users at the cell-edge who typically suffer from poor signal conditions. It is mainly considered for asymmetric downlink scenarios consisting of active cell-edge and cell-centre UEs.

There are three cases for MUST that were standardized by 3GPP [i.19], [i.22]:

- Case 1: Superposed PDSCHs are transmitted using the same transmission scheme and the same spatial precoding vector.
- Case 2: Superposed PDSCHs are transmitted using the same transmit diversity scheme.
- Case 3: Superposed PDSCHs are transmitted using the same transmission scheme, but their spatial precoding vectors are different.

NOTE 1: In LTE, there are 10 TMs for the downlink as defined by [i.20]. Case 1 is applicable for modes with spatial multiplexing precoding (such as TM 3, 4) while Case 2 is applicable for modes with transmit diversity (such as TM 2 with frequency-based version of Alamouti codes, i.e. SFBC and FSTD). Case 3 is applicable to modes with spatial multiplexing precoding schemes such as TM 8, 9, 10 where multiple transmit layers for different users are transmitted via different spatial precoding vectors.

For Case 1 and Case 2, MUST superposes in the power domain the messages for two UEs with different channel conditions by adjusting its power levels. There are two types of UEs considered in MUST Case 1 and Case 2:

- MUST-far UEs: UEs at cell-edge with weak channel conditions. A higher power level is allocated to the message for the UE with a weaker channel. The modulation for a MUST-far UE is fixed to QPSK.
- MUST-near UEs: UEs at cell-centre with stronger channel conditions. A lower power level is assigned to the message of the UE with a stronger channel. The modulation for a MUST-near UE can be QPSK, 16QAM or 64QAM.

The transmit processing for MUST Case 1 and Case 2 is presented in Figure 6.3-1. This figure shows an example with two messages associated to two UEs. W_1 and W_2 are messages to UE_1 and UE_2, respectively. Each of the messages is channel coded to generate codewords, rate-matched to the available resources for transmission, scrambled to randomize interference and QAM modulated. Layer mapping allocates modulation symbols from the codewords across L_k MIMO transmission layers ($k \in \{1,2\}$). If the number of MIMO layers $L_j > 1$ for UE_j, the message W_j is transmitted over multiple transmission layers. Power scaling is applied at the layers by means of power splitting coefficients [i.21], which will be described in clause 6.3.2. Multi-antenna precoding can be applied jointly to the modulated symbols of the messages W_1, W_2. For Case 1 and 2, the same multi-antenna precoding is applied to the modulated symbols including both UE messages.

Regarding assistance information form the transmitter to the UEs for Case 1 and Case 2 [i.18]:

- A MUST-far UE does not receive any assistance information and can decode its signal treating the interference from the MUST-near UE as noise.
- A MUST-near UE receives assistance information from the transmitter to indicate the existence of MUST interference and the transmission power ratio. There is no need to signal the constellation of the interference (MUST-far UE) since it is fixed to QPSK. With this assistance information the UE can improve the performance by using advanced receivers such as R-ML by jointly demodulating MUST-far and MUST-near UE symbols [i.18].

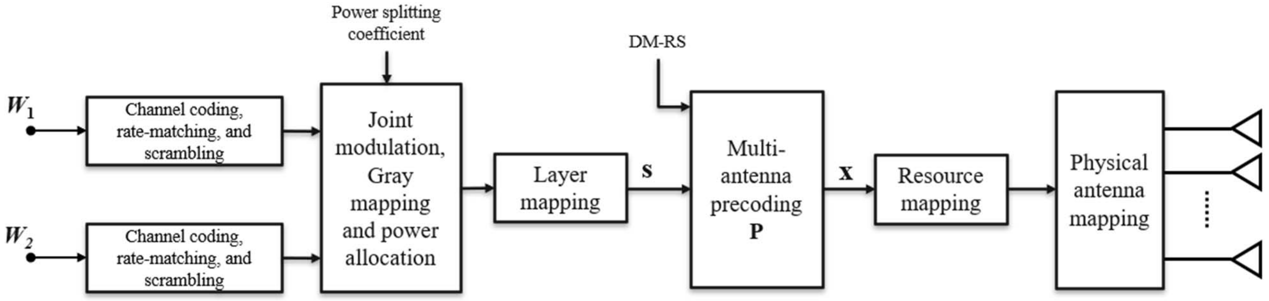


Figure 6.3-1: Transmit processing for MUST Case 1 and Case 2

NOTE 2: TM 2,3,4 do not precode the reference signals, however, this figure is aligned with the transmit processing architectures in other clauses.

For Case 3, each UE message can be transmitted using a different precoding vector and UEs are not classified as a MUST-far UE or MUST-near UE. The transmitter processing for MUST Case 3 is presented in Figure 6.3-2, which describes the same transmitter processing as for MU-MIMO in clause 6.2.1.

Regarding assistance information from the transmitter to the UEs for Case 3 [i.18], UEs implementing advanced receivers (such as R-ML) receive assistance information that includes "interference existence" and "modulation order". With this assistance information the UE implementing an advanced receiver can jointly demodulate the desired signal and the inter-user interference and improve the performance of its intended message. MUST Case 3 provides similar functionality as MU-MIMO with advanced receivers as described in clause 6.2.5.

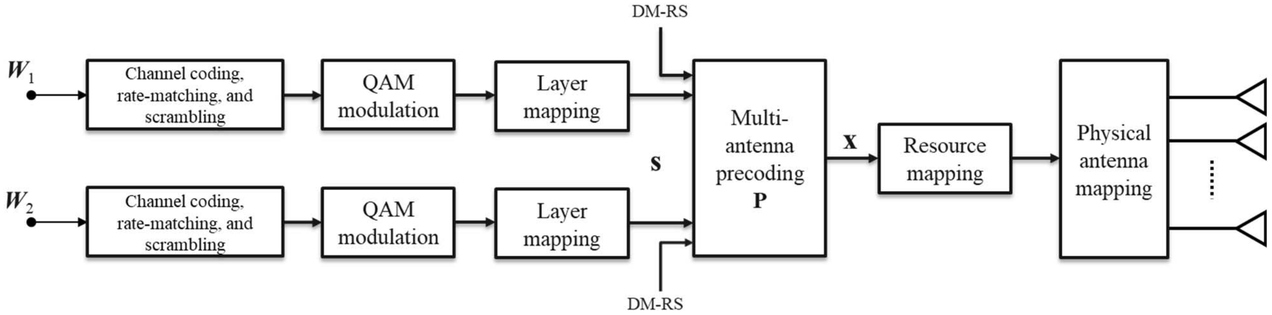


Figure 6.3-2: Transmit processing for MUST Case 3

NOTE 3: According to [i.18], MUST Case 3 can support up to 4 UEs. This figure illustrates the two UE case.

6.3.2 Transmit and receive signal expressions

For MUST Case 1 and Case 2, the information bits from the two UEs are combined using power allocation and jointly mapped into a custom modulation as defined by [i.21]. The bits are combined so that the resulting mapping is Gray-coded and the two leftmost bits are allocated for the MUST-far UE.

The custom modulation for MUST Case 1 and Case 2 with a MUST-far UE and MUST-near UE is:

$$s = e^{j\varphi_1\pi}c(I-d) + e^{j(\varphi_2+0.5)\pi}c(Q-d),$$

where φ_1, φ_2 are information bits for the MUST-far UE, I and Q are real and imaginary parts which are determined by the information bits of the MUST-near UE, and scalars c, d are power allocation coefficients that adjust the constellation diagram of the custom modulation and are determined by a control parameter MUSTIdx [i.21].

The composite constellation can also be expressed as:

$$s = \sqrt{\alpha}s_1' + \sqrt{1-\alpha}s_2,$$

where s_1' is the constellation for the MUST-near UE, s_2 is the constellation of the MUST-far UE and α is the power ratio for the MUST-near UE. The term s_1' is used to express a non-standard QPSK, 16QAM or 64QAM modulation where s follows a Gray-mapped composite constellation.

NOTE: The composite constellation expression $s = \sqrt{\alpha}s_1' + \sqrt{1-\alpha}s_2$ is not used explicitly in the 3GPP technical specifications to describe the MUST operation but it is used here for clarity of the presentation. The mapping of s_1' would be a function of s_2.

The transmitted signal expression for Case 1 is given as:

$$\mathbf{x} = \mathbf{p}s = \mathbf{p}\left(\sqrt{\alpha}s_1' + \sqrt{1-\alpha}s_2\right)$$

where:

s $\in \mathbb{C}$ is combined modulated symbol including bits of both MUST-far UE and MUST-near UE,

$\mathbf{p} \in \mathbb{C}^{N_T\times 1}$ is the common precoding vector,

$\mathbf{x} \in \mathbb{C}^{N_T\times 1}$ are the precoded symbols.

The corresponding MUST Case 1 receive signal $\mathbf{y}_k$ at UE$_k$ can be expressed as

$$\mathbf{y}_k = \mathbf{H}_k\mathbf{x} + \mathbf{n}_k = \mathbf{H}_k\mathbf{p}\mathrm{s} + \mathbf{n}_k,$$

where:

$\mathbf{y}_k \in \mathbb{C}^{N_R\times 1}$is the received signal vector of UE$_k$,

$\{\mathbf{h}_{1,k}, \cdots, \mathbf{h}_{N_R,k}\} \in \mathbb{C}^{N_T\times 1}$ channel vectors at each receive antenna of UE$_k$,

$\mathbf{H}_k = \left[\mathbf{h}_{1,k} \cdots \mathbf{h}_{N_R,k}\right]^H \in \mathbb{C}^{N_R \times N_T}$ channel matrix of UE$_k$, and

$\mathbf{n}_k \in \mathbb{C}^{N_R \times 1}$ noise vector of UE$_k$.

The transmitted signal expression for Case 2 is given as:

$$\mathbf{x} = \tilde{\boldsymbol{s}}$$

where:

$\tilde{\boldsymbol{s}}$ is the combined modulated symbol including bits of both MUST-far UE and MUST-near UE after transmit diversity scheme,

$\mathbf{x} \in \mathbb{C}^{N_T \times 1}$ are the transmit symbols.

Here, either SFBC (two transmit antennas) or FSTD (4 transmit antennas) schemes are considered depending on the total number of transmit antennas. The vector $\tilde{\boldsymbol{s}}$ includes a mixture of multiple subcarriers and multiple transmit antennas. This operation can be considered as a special precoding including diversity over space and frequency and hence the architecture given in Figure 6.3-1 can be used for both Case 1 and Case 2.

MUST Case 1 and Case 2 can be considered a precursor to power domain NOMA as they both share the concept of power domain multiplexing as described in clause 7.1.

The corresponding MUST Case 2 receive signal $\mathbf{y}_k$ at UE$_k$ can be expressed as

$$\mathbf{y}_k = \mathbf{H}_k \mathbf{x} + \mathbf{n}_k = \mathbf{H}_k \tilde{\boldsymbol{s}} + \mathbf{n}_k.$$

For the MUST Case 3 transmitter in Figure 6.3-2 with L_k=1 (for $k = \{1, 2, \dots, K\}$), for a given time-frequency resource, the transmit signal $\mathbf{x}$ can be expressed as:

$$\mathbf{x} = \mathbf{P}\mathbf{s} = \sum_{k=1}^{K} \mathbf{p}_k s_k,$$

where:

K is the total number of UEs which can be at most 4 for MUST Case 3,

$\mathbf{s} \in \mathbb{C}^{K \times 1}$ are modulated symbols from the messages W_1, W_2,…, W_K

$\{\mathbf{p}_1, \mathbf{p}_2, \dots, \mathbf{p}_K\} \in \mathbb{C}^{N_T \times 1}$ are the precoding vectors,

$\mathbf{P} = [\mathbf{p}_1, \mathbf{p}_2, \dots, \mathbf{p}_K] \in \mathbb{C}^{N_T \times K}$ is the precoding matrix, and

$\mathbf{x} \in \mathbb{C}^{N_T \times 1}$ are the precoded symbols.

The corresponding MUST receive signal $\mathbf{y}_k$ at UE$_k$ can be expressed as:

$$\mathbf{y}_k = \mathbf{H}_k \mathbf{x} + \mathbf{n}_k = \mathbf{H}_k \mathbf{p}_k s_k + \sum_{j \neq k}^{K} \mathbf{H}_k \mathbf{p}_j s_j + \mathbf{n}_k.$$

6.3.3 MUST receivers for Case 1

This clause focuses on MUST Case 1. The MUST-far UE decodes its signal without any assistance information from the transmitter about the MUST-near UE signal. The received signal for MUST-far UE is:

$$\mathbf{y}_2 = \mathbf{H}_2 \mathbf{p} \mathrm{s} + \mathbf{n}_2 = \underbrace{\mathbf{H}_2 \mathbf{p} \sqrt{1-\alpha}\, s_2}_{\text{desired}} + \underbrace{\mathbf{H}_2 \mathbf{p} \sqrt{\alpha}\, s_1' + \mathbf{n}_2}_{\text{assumed as noise}},$$

where the desired signal is demodulated and decoded treating the interference from the MUST-near UE as noise.

NOTE: The constellation is designed in such a way that all constellation points in upper right region of the Cartesian plane have the same bit sequence for MUST-far UE (e.g. all four symbols in x > 0, y > 0 region have the same "00" bits for MUST-far UE). Therefore, MUST-far UE can apply QPSK demodulation without any side information.

The MUST-near UE uses the assistance information from the transmitter to suppress the interference from the MUST-far UE. The received signal for the MUST-near UE is:

$$\mathbf{y}_1 = \mathbf{H}_1\mathbf{p}s + \mathbf{n}_1 = \underbrace{\mathbf{H}_1\mathbf{p}\sqrt{\alpha}s_1' + \mathbf{H}_1\mathbf{p}\sqrt{1-\alpha}s_2}_{\text{joint demodulation}} + \mathbf{n}_1\ ,$$

where the R-ML receiver does a joint demodulation of s_1' and s_2.

It is important to highlight that assistance information from the transmitter only includes information about the existence of MUST interference and transmission power ratio. (MUST-near UE can assume QPSK constellation for MUST-far UE.) To be able to implement Successive Interference Cancellation (SIC) type receivers to decode and cancel the interference, additional assistance information such as TBS would also need to be signalled to calculate the corresponding code-rate of the MUST-far UE [i.17].

6.3.4 MUST receivers for Case 3

For MUST Case 3 (assuming K=2) the received signal for UE$_1$ is:

$$\mathbf{y}_1 = \underbrace{\mathbf{H}_1\mathbf{p}_1 s_1 + \mathbf{H}_1\mathbf{p}_2 s_2}_{\text{joint demodulation}} + \mathbf{n}_1,$$

where the R-ML receiver does a joint demodulation of s_1 and s_2.

It is important to highlight that assistance information from the transmitter only includes "interference existence" and "modulation order". To be able to implement SIC type receivers to decode and cancel the interference, additional assistance information such as TBS would also need to be signalled to calculate the corresponding code-rate of the co-scheduled UE.

7 Candidate MAT baseline architectures

7.1 Power domain NOMA

7.1.1 Description

Power domain NOMA relies on SC at the transmitter and SIC at the receivers [i.23]. Unlike OMA techniques, where the message of each UE occupies separate time-frequency resources, power domain NOMA enables the multiplexing of the messages for various UEs into the same time-frequency resources. Other variants for NOMA exist, such as code domain NOMA [i.24], however, the focus in the present document is on power domain NOMA.

The key distinguishing feature lies in assigning different power levels to different UEs based on their channel conditions and employing SIC at the receivers to separate the superimposed signals. UEs with weaker channel conditions are allocated more transmit power, while users with stronger channels are allocated less power. This results in a composite signal consisting of data from multiple UEs, each modulated with a distinct power level. At the receivers, UEs employ SIC to process their received signals. A UE with stronger channel condition decodes and cancels interference signals from weaker UEs before decoding its own data. The weaker UE, on the other hand, directly decodes its own signal while treating stronger UE interference signal as noise. This decoding strategy is viable only when there is a sufficiently large disparity in channel condition between users, and when the receiver has the necessary processing capability for SIC.

NOTE 1: Alternatives to SIC receivers are also possible as discussed in clause 7.1.4.

Figure 7.1-1 depicts a conventional power domain NOMA transmitter in multi-antenna systems. $W_1,\ldots, W_K$ are messages to UE$_1$, …, UE$_K$, respectively. Each of the messages is channel coded to generate codewords, rate-matched to the available resources for transmission, scrambled to randomize interference and QAM modulated. Layer mapping allocates modulation symbols from the codewords across L_k MIMO transmission layers ($k \in \{1, \ldots, K\}$). If the number of MIMO layers $L_j > 1$ for UE$_j$, the message W_j is transmitted over multiple transmission layers. A different orthogonal DM-RS can be used for each of the transmission layers. Different power levels are assigned to each transmission layer according to the different UE channel conditions, and multi-antenna precoding can be applied jointly to the modulated symbols of the messages W_1, …, W_K.

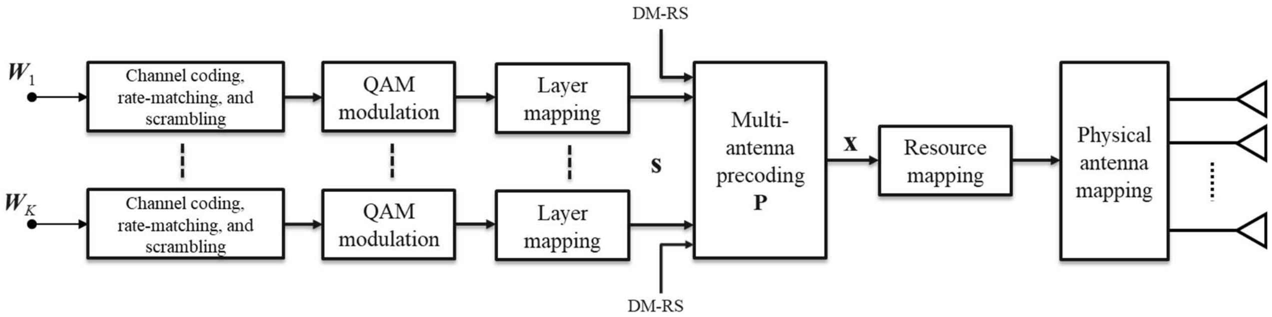


Figure 7.1-1: transmit processing for power domain NOMA

NOTE 2: Figure 7.1-1 contains the same processing as Figure 6.2-1 for MU-MIMO.

Different approaches for multi-antenna precoding have been proposed for NOMA. A typical multi-antenna NOMA downlink scenario with K UEs is to split UEs into groups where each group includes UEs with different channel conditions. The multi-antenna precoding is used to suppresses the inter-group interference, while within each group the UE signals are superimposed with different power levels and UEs employ SIC operation to decode their signals [i.25], [i.26]. Another approach is to use different precoding vectors for each of the UE signals with different power levels and UEs employing SIC operation to decode their signals. The present document focuses on the later approach for the discussion on power domain NOMA.

MUST Case 1 and Case 2, as discussed in clause 6.3, are a special case of power domain NOMA with K=2 UEs and a single group. The transmit processing architecture for NOMA in Figure 7.1-1 follows the same processing blocks as the transmit processing for MU-MIMO discussed in clause 6.2. More discussion on commonalities and differences with MUST and MU-MIMO is provided in the next clauses. Required assistance information for power domain NOMA is discussed in clauses 7.1.3 and 7.1.4.

7.1.2 Transmit and receive signal expressions

For the power domain NOMA transmitter in Figure 7.1-1 with L_k=1 (for all k), for a given time-frequency resource, the transmit signal $\mathbf{x}$ can be expressed as:

$$\mathbf{x} = \mathbf{P}\boldsymbol{s} = \sum_{k=1}^{K} \mathbf{p}_k s_k,$$

where:

$\mathbf{s} \in \mathbb{C}^{K\times 1}$ are modulated symbols from the K messages $W_1, \ldots, W_K$,

$\{\mathbf{p}_1, \cdots, \mathbf{p}_K\} \in \mathbb{C}^{N_T\times 1}$ are precoding vectors,

$\mathbf{P} = [\mathbf{p}_1 \cdots \mathbf{p}_K] \in \mathbb{C}^{N_T\times K}$ is the precoding matrix, and

$\mathbf{x} \in \mathbb{C}^{N_T\times 1}$ are the pre-coded symbols.

The corresponding power domain NOMA receive signal $\mathbf{y}_k$ at UE$_k$ can be expressed as:

$$\mathbf{y}_k = \mathbf{H}_k\mathbf{x} + \mathbf{n}_k = \mathbf{H}_k\mathbf{p}_k s_k + \sum_{j\neq k}^{K} \mathbf{H}_k\mathbf{p}_j s_j + \mathbf{n}_k,$$

where:

$\mathbf{y}_k \in \mathbb{C}^{N_R\times 1}$ received signal vector of UE$_k$,

$\{\mathbf{h}_{1,k}, \cdots, \mathbf{h}_{N_R,k}\} \in \mathbb{C}^{N_T\times 1}$ channel vectors at each receive antenna of UE$_k$,

$\mathbf{H}_k = \left[\mathbf{h}_{1,k} \cdots \mathbf{h}_{N_R,k}\right]^H \in \mathbb{C}^{N_R\times N_T}$ channel matrix of UE$_k$, and

$\mathbf{n}_k \in \mathbb{C}^{N_R\times 1}$ noise vector of UE$_k$.

NOTE: If the number of MIMO layers L_j > 1 for UE$_j$, the message W_j is transmitted over multiple transmission layers. The desired signal for UE$_j$ would also include interference among the MIMO layers of UE$_j$ (see clause 6.1 OMA) and the expressions above can be expanded accordingly.

It is important to highlight that in power domain NOMA the power levels and bitrates of modulated symbols s_k (for all k) are designed so that UEs can use SIC techniques to sequentially decode and cancel interference signals while treating previously undecoded signals as noise. To illustrate the conditions imposed by power domain NOMA, $R(k,i)$ is defined as an achievable bitrate of s_k at UE$_i$. Assuming that UEs are indexed according to their decoding order (i.e. UE$_1$ decodes and cancels all interfering signals $s_K, s_{K-1}, \dots, s_2$ before decoding its intended message s_1, UE$_2$ decodes and cancels interference signals $s_K, s_{K-1}, \dots, s_3$ before decoding its intended message s_2, etc.), $R(k,i)$ can be expressed as a function of the decoded message s_k and the sum of UE interference signals that are treated as noise:

$$\begin{cases} R(1,1) = C(s_1, 0) \text{ for } k = 1 \\ R(k,i) = C\left(s_k, \sum_{j=1}^{k-1} \mathbf{H}_i \mathbf{p}_j s_j\right) \text{ for } k \geq 2 \end{cases}$$

where $k \in \{1, \dots, K\}$ and $i \in \{1, \dots, k\}$. In power domain NOMA, the bitrates R_k of s_k (for all k) need to meet the following conditions so UEs can sequentially decode and cancel interference signals:

$$R_k = \min_{i=1,\dots,k} R(k,i).$$

As a clarifying example for $K = 3$, the bitrates for messages s_1, s_2 and s_3 need to meet the following conditions:

$$\begin{cases} R_3 = \min\{R(3,1), R(3,2), R(3,3)\} \\ R_2 = \min\{R(2,1), R(2,2)\} \\ R_1 = R(1,1) \end{cases},$$

since s_3 is decoded by all UEs, s_2 is decoded by UE$_1$ and UE$_2$, and s_1 is only decoded by UE$_1$ without additional interference.

As discussed in a previous clause, power domain NOMA has similar processing blocks to MU-MIMO. In fact, the transmit signal $\mathbf{x}$ and receive signal $\mathbf{y}_k$ also have the same form as for MU-MIMO. However, the key difference between the two techniques is that MU-MIMO is not usually designed to meet the additional conditions on power levels and bitrates of modulated symbols s_k (for all k) as discussed in the paragraphs above.

As discussed in previous clause, with $K = 2$ and $\mathbf{p}_1 = \mathbf{p}_2$, MUST Case 1 and Case 2 can be considered a special case of power domain NOMA from the precoding and signal power levels point of view. (The details of the joint modulation and Gray mapping are omitted in the discussion.) The power domain NOMA case considered in the present document is more flexible than MUST Case 1 and Case 2 since $\mathbf{p}_1$ and $\mathbf{p}_2$ do not need to be the same.

7.1.3 NOMA with SIC receivers

Figure 7.1-2 depicts the receiver side operations for power domain NOMA for UE$_k$. SIC is employed at the receiver side to decode the intended message for a particular user. Specifically, each UE performs signal decoding and interference cancellation according to a decoding order to decode the stronger interfering signals intended for UEs with poorer channel conditions before decoding its own message. The decoding is performed by treating all other interference signals as noise. For UE$_k$, the messages of all UEs with larger decoding order indexes are decoded, reconstructed and cancelled from the overall received message until the intended message is decoded to obtain $\widehat{W}_k$.

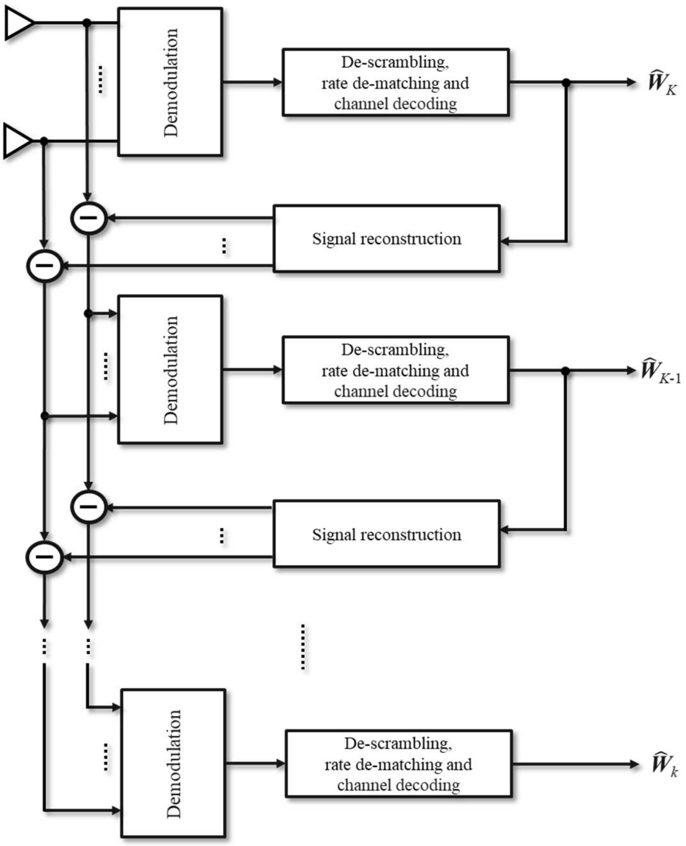


Figure 7.1-2: NOMA receiver architecture for UE*k*

As an illustrative example, for $K = 2$, the receive signal at UE_2 with the weaker channel conditions i:s

$$\mathbf{y}_2 = \mathbf{H}_2\mathbf{Ps} + \mathbf{n}_2 = \underbrace{\mathbf{H}_2\mathbf{p}_2 s_2}_{\text{desired}} + \underbrace{\mathbf{H}_2\mathbf{p}_1 s_1 + \mathbf{n}_2}_{\text{assumed as noise}},$$

where modulated symbols s_2 are decoded treating the interference signal $\mathbf{H}_2\mathbf{p}_1 s_1$ from UE_1 as noise.

UE1 with a stronger channel condition, first decodes modulated symbols s_2 intended for UE_2 treating its own intended received signal $\mathbf{H}_1\mathbf{p}_1 s_1$ as noise:

$$\mathbf{y}_1 = \mathbf{H}_1\mathbf{Ps} + \mathbf{n}_1 = \underbrace{\mathbf{H}_1\mathbf{p}_2 s_2}_{\text{desired}} + \underbrace{\mathbf{H}_1\mathbf{p}_1 s_1 + \mathbf{n}_1}_{\text{assumed as noise}}.$$

After successful decoding and cancellation of the $\mathbf{H}_1\mathbf{p}_2 s_2$ term, the resulting signal at $UE_{1:}$

$$\mathbf{y}_1' = \mathbf{H}_1\mathbf{p}_1 s_1 + \mathbf{n}_1$$

is used to decode its intended signal $\mathbf{H}_1\mathbf{p}_1 s_1$ free from interference.

Regarding assistance information for power domain NOMA, all UEs that perform SIC need information about modulation order and channel code-rate to decode and cancel the interfering signals. In particular, the assistance information at UE_k may include assistance information from $K - k$ interfering UEs.

NOTE: Information about the modulation order of some of the weaker UEs may not need to be transmitted if it is fixed to a particular modulation order such as in MUST Case 1 and Case 2.

7.1.4 NOMA with R-ML receivers

As discussed in clause 6.3.3 regarding MUST receivers for Case 1, an alternative to SIC operation is to implement R-ML receivers where interference is not decoded but supressed. Following the example of the previous clause, for UE$_1$ with a stronger channel condition the received signal is:

$$\mathbf{y}_1 = \mathbf{H}_1\mathbf{P}\mathbf{s} + \mathbf{n}_1 = \underbrace{\mathbf{H}_1\mathbf{p}_2 s_2 + \mathbf{H}_1\mathbf{p}_1 s_1}_{\text{joint demodulation}} + \mathbf{n}_1,$$

where the R-ML receiver does a joint demodulation of s_1 and s_2. For this type of receiver, assistance information about the channel code-rate of the interfering signals would not be necessary.

7.2 RSMA

7.2.1 Description

RSMA is a multiple access technique for multi-antenna communications that relies on the concept of rate-splitting at the transmitter and partial interference decoding at the receivers [i.27]. RSMA allows the spatial multiplexing of the messages for various UEs into the same time-frequency resources. An RSMA transmitter adapted from [i.28] is depicted in Figure 7.2-1.

NOTE 1: The present document focuses on the RSMA variant where messages can be split onto one common part and one private part. However, as detailed in [i.27], other variants exist where messages are split into multiple common and private parts.

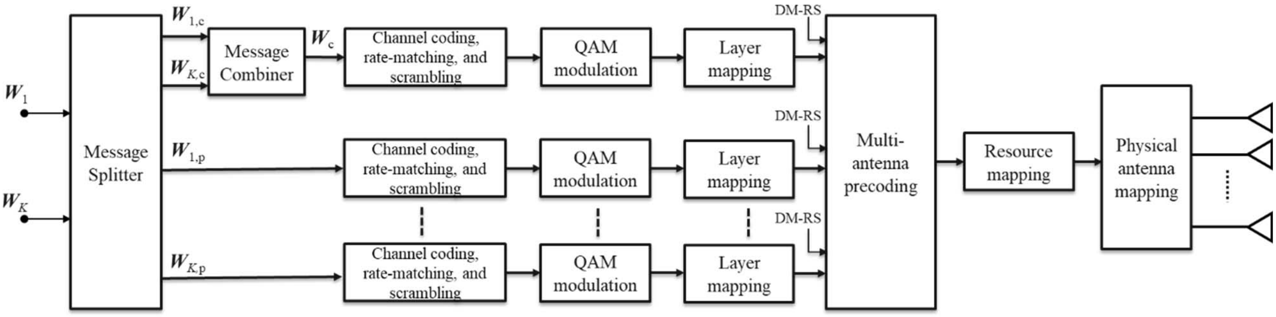


Figure 7.2-1: Transmit processing for RSMA

W_1, … W_K are messages to UE$_1$, …, UE$_K$, respectively. Each of the messages can be split into one common part and one private part, $W_{k,c}$ and $W_{k,p}$, $k \in \{1, \dots, K\}$, respectively. The split common parts are then combined to obtain a single common message W_c. This common message is intended to be decoded by all UEs.

NOTE 2: The main parameters of the Message Splitter in Figure 7.2-1 are: the selection of UE messages W_1, … W_K that are to be split, the total number of bits from each split message that are allocated to each common message part, and the bit indices from the split message that are allocated to the common message part.

For example, the Message Splitter could be configured such that only the first message is split and where half the number of bits of the message are allocated to the common message part. In another example it could be configured such that all messages are split and where each split message allocates a different number of bits to each common message part.

Regarding the bit indices from the split message that are allocated to the common message part, in one example the Message Splitter could allocate every other bit from the split message to the common message part, or in another example the Message Splitter could allocate the first *n* bits of the split message to the common message part.

How the Message Splitter is configured will depend on the specific channel conditions and the selected objective such as maximizing the cell throughput or maximizing the fairness in the throughput provided to UEs in the cell.

> For the Message Combiner depicted in Figure 7.2-1, there can also be multiple options as to how to combine the common message parts into a single common message. For example, the Message Combiner could concatenate each common message part to form a single common message. Alternatively, the Message Combiner could interleave the bits from the common message parts according to a specific interleaving sequence to form a single common message. A specific example for the Message Splitter and Message Combiner can be found in [i.27].

The common message and the private messages are independently channel coded to generate codewords, rate-matched to the available resources for transmission, scrambled to randomize interference and QAM modulated. Layer mapping allocates modulation symbols from private messages $W_{k,\mathrm{p}}$ across L_k MIMO transmission layers and allocates modulation symbols from the common message W_c across L_c MIMO transmission layers. If the number of MIMO layers $L_j > 1$ for $W_{j,\mathrm{p}}$, the private message $W_{j,\mathrm{p}}$ is transmitted over multiple transmission layers. If the number of MIMO layers $L_\mathrm{c} > 1$ for W_c, the common message W_c is transmitted over multiple transmission layers. A different orthogonal DM-RS can be used for each of the transmission layers.

Multi-antenna precoding can be applied jointly to the modulated symbols of the messages W_c, $W_{1,\mathrm{p}}$, …, $W_{K,\mathrm{p}}$. For RSMA, multi-antenna precoding allows the efficient spatial multiplexing of the messages for various UEs into the same time-frequency resources. This is different from OMA where only one UE message is allocated in a given time-frequency resource. For RSMA the existence of a mixture of common and private messages provides flexibility and improved interference management capability.

Detailed discussion on commonalities and differences with MU-MIMO and power-domain NOMA is provided in the next clause. Required assistance information from the transmitter to the UEs for RSMA is discussed in clauses 7.2.3 and 7.2.4.

7.2.2 Transmit and receive signal expressions

In RSMA, the transmitter divides each UE's message into a common part and a private part, where all common parts are combined into a single common message. RSMA allows partial decoding of the interference at the UEs, rather than treating all interference as either fully decodable or purely as noise. For the RSMA transmitter in Figure 7.2-1 with L_k=1 (for all k) and L_c=1, for a given time-frequency resource, the transmit signal $\mathbf{x}$ can be expressed as [i.29] and [i.30]:

$$\mathbf{x} = \mathbf{P}\mathbf{s} = \mathbf{p}_\mathrm{c} s_\mathrm{c} + \sum_{k=1}^{K} \mathbf{p}_k s_k,$$

where:

$\mathbf{s} = [s_\mathrm{c}, s_1, \dots, s_K]^T \in \mathbb{C}^{(K+1)\times 1}$ (where $(\cdot)^T$ is the transpose operator) are modulated symbols of the common and K private messages W_c, $W_{1,\mathrm{p}}$, … $W_{K,\mathrm{p}}$,

$\{\mathbf{p}_\mathrm{c}, \mathbf{p}_1, \cdots, \mathbf{p}_K\} \in \mathbb{C}^{N_T\times 1}$ are precoding vectors,

$\mathbf{P} = [\mathbf{p}_\mathrm{c}, \mathbf{p}_1 \cdots \mathbf{p}_K] \in \mathbb{C}^{N_T\times (K+1)}$ is the precoding matrix, and

$\mathbf{x} \in \mathbb{C}^{N_T\times 1}$ are the pre-coded symbols.

The corresponding RSMA receive signal $\mathbf{y}_k$ at UE$_k$ can be expressed as:

$$\mathbf{y}_k = \mathbf{H}_k\mathbf{x} + \mathbf{n}_k = \mathbf{H}_k\mathbf{p}_\mathrm{c} s_\mathrm{c} + \mathbf{H}_k\mathbf{p}_k s_k + \sum_{j\neq k}^{K} \mathbf{H}_k\mathbf{p}_j s_j + \mathbf{n}_k,$$

where:

$\mathbf{y}_k \in \mathbb{C}^{N_R\times 1}$ received signal vector of UE$_k$,

$\{\mathbf{h}_{1,k}, \cdots, \mathbf{h}_{N_R,k}\} \in \mathbb{C}^{N_T\times 1}$ channel vectors at each receive antenna of UE$_k$,

$\mathbf{H}_k = \left[\mathbf{h}_{1,k} \cdots \mathbf{h}_{N_R,k}\right]^H \in \mathbb{C}^{N_R\times N_T}$ channel matrix of UE$_k$, and

$\mathbf{n}_k \in \mathbb{C}^{N_R\times 1}$ noise vector of UE$_k$.

For the received signal $\mathbf{y}_k$, the term $\mathbf{H}_k\mathbf{p}_\mathrm{c} s_\mathrm{c}$ is the desired common message signal, $\mathbf{H}_k\mathbf{p}_k s_k$ is the desired private message signal for UE$_k$, and the term $\sum_{j\neq k}^{K} \mathbf{H}_k\mathbf{p}_j s_j$ is the inter-user interference.

NOTE: If the number of MIMO layers $L_j > 1$ for $W_{j,\mathrm{p}}$ and/or $L_\mathrm{c} > 1$ for W_c, the private message $W_{j,\mathrm{p}}$ and/or the common message W_c is transmitted over multiple transmission layers. The desired private message signal and/or the desired common message signal for UE$_j$ would include interference among the MIMO layers (see clause 6.1 OMA) and the expressions above can be expanded accordingly.

It is important to highlight that for RSMA the precoding vector $\mathbf{p}_\mathrm{c}$ and bitrate of modulated symbols s_c are designed so that the common message can be decoded by the K scheduled UEs. To illustrate this condition imposed by RSMA, $R(s_\mathrm{c}, i)$ is defined as an achievable bitrate of the common message s_c at UE$_i$. Assuming UEs decode the common message s_c treating the sum of private message interference signals as noise, $R(s_\mathrm{c}, i)$ can be expressed as:

$$R(s_\mathrm{c}, i) = C\left(s_\mathrm{c}, \textstyle\sum_{j=1}^{K} \mathbf{H}_i \mathbf{p}_j s_j\right),$$

where $i \in \{1, \dots, K\}$. In RSMA, the bitrate R_c of the common message s_c needs to meet the following condition to enable all UEs to decode the common message:

$$R_\mathrm{c} = \min_{i \in \{1,\dots,K\}} R(s_\mathrm{c}, i).$$

As can be seen from the transmitter diagram in Figure 7.2-1 and transmit signal $\mathbf{x}$, a key difference between RSMA and MU-MIMO (as described in clause 6.2) is that RSMA includes a message splitter/combiner and the processing of an additional encoded common message s_c with a precoding vector $\mathbf{p}_\mathrm{c}$. The message spitter/combiner, common message precoding vector $\mathbf{p}_\mathrm{c}$, and bitrate of the common message s_c can all be designed according to the channel conditions and/or specific fairness criteria. For example, if no bits are allocated to the common message and/or $\mathbf{p}_\mathrm{c} = 0$, then no common message s_c is transmitted and the transmit processing is identical to that for MU-MIMO.

The design of the message split and the power allocation to the common message parts and the private message parts allow RSMA to operate across different points including the operation provided by other MAT discussed in the present document. Figure 2 in [i.31] shows for K=2 how different allocation of messages to common and private message parts map to the operation of other MAT discussed in the present document.

7.2.3 RSMA with SIC receivers

At the receiver side, each UE aims to demodulate the common part and private part of its message. SIC is a candidate method that can be employed at the receivers. Figure 7.2-2 depicts the SIC operations for RSMA.

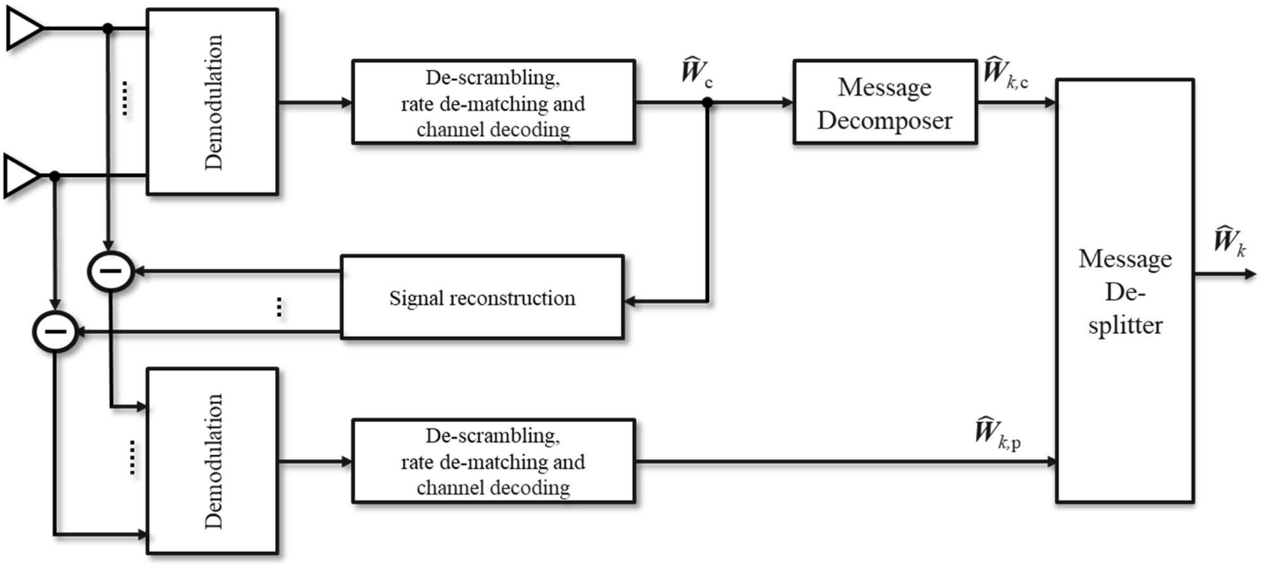


Figure 7.2-2: Example receive processing for RSMA based on SIC

First, each UE decodes the common message and extracts the common part of its intended message $\widehat{W}_{k,\mathrm{c}}$ $(k \in \{1, \dots, K\})$ by treating the interference from all private messages as noise. Accordingly, the received signal $\mathbf{y}_k$ for UE$_k$ can be expressed as:

$$\mathbf{y}_k = \underbrace{\mathbf{H}_k \mathbf{p}_\mathrm{c} s_\mathrm{c}}_{\text{desired}} + \underbrace{\textstyle\sum_{n=1}^{K} \mathbf{H}_k \mathbf{p}_n s_n + \mathbf{n}_k}_{\substack{\text{asssumed} \\ \text{as noise}}}.$$

After decoding, and cancelling of the $\mathbf{H}_k\mathbf{p}_\mathrm{c}s_\mathrm{c}$ term, the resulting signal at each UE can be expressed as:

$$\mathbf{y}'_k = \underbrace{\mathbf{H}_k\mathbf{p}_k s_k}_{\text{desired}} + \underbrace{\sum\nolimits_{j\neq k}^{K} \mathbf{H}_k\mathbf{p}_j s_j + \mathbf{n}_k}_{\substack{\text{asssumed}\\ \text{as noise}}},$$

where each UE then decodes their respective intended private message $\widehat{W}_{k,\mathrm{p}}$ while treating the remaining interference from other private messages as noise. Finally, the overall decoded message $\widehat{W}_k$, is reconstructed by combining the decoded common message part $\widehat{W}_{k,\mathrm{c}}$ and the decoded private message part $\widehat{W}_{k,\mathrm{p}}$.

Regarding assistance information from the transmitter to the UEs, all UEs require the knowledge of physical layer parameters necessary to decode the common message W_c including modulation order and channel code-rate. UEs also need the knowledge of the location and size of the common message part $W_{k,\mathrm{c}}$ in the common message W_c.

7.2.4 RSMA with R-ML receivers

For RSMA, an alternative to SIC operation is to implement R-ML receivers [i.32] as shown in Figure 7.2-3.

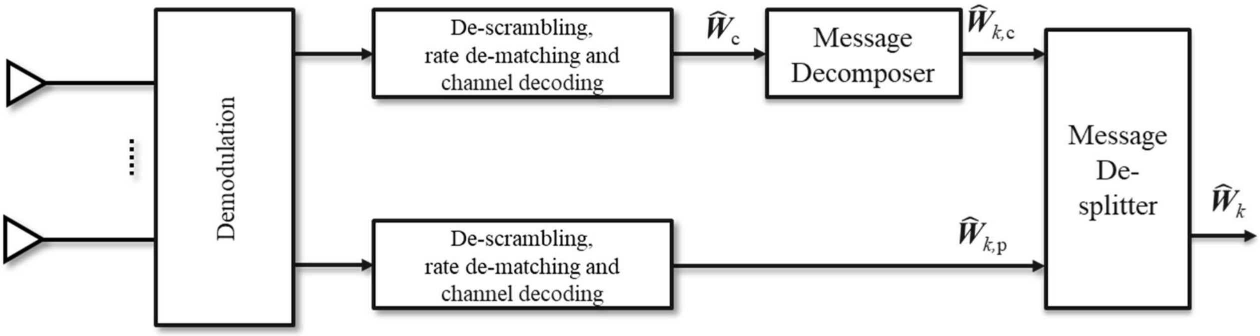


Figure 7.2-3: Example receive processing for RSMA with R-ML receivers (without SIC)

For the received signal $\mathbf{y}_k$ at UE*k*:

$$\mathbf{y}_k = \underbrace{\mathbf{H}_k\mathbf{p}_\mathrm{c}s_\mathrm{c} + \mathbf{H}_k\mathbf{p}_k s_k}_{\text{joint demodulation}} + \underbrace{\sum\nolimits_{j\neq k}^{K} \mathbf{H}_k\mathbf{p}_j s_j + \mathbf{n}_k}_{\text{assumed as noise}},$$

the R-ML receiver performs a joint demodulation of the common message s_c and the intended private message s_k assuming the remaining interference from other private messages as noise. The common message demodulated information is decoded and the common message part $\widehat{W}_{k,\mathrm{c}}$ $(k \in \{1, \ldots, K\})$ is extracted. The private message demodulated information is decoded to obtain $\widehat{W}_{k,\mathrm{p}}$. Finally, the overall decoded message $\widehat{W}_k$ is reconstructed by combining the decoded common message part $\widehat{W}_{k,\mathrm{c}}$ and the decoded private message part $\widehat{W}_{k,\mathrm{p}}$.

Regarding assistance information from the transmitter to the UEs, same assistance information as for previous clause 7.2.3 is needed, including the channel code-rate since the common message is still decoded.

7.3 Cache-aided MU-MIMO

7.3.1 Description

CA MU-MIMO is based on the paradigm of coded caching [i.16], where memory at the receivers is used to store the cache. The caches contain specific parts (subpackets) of files from a common library that are distributed prior to transmission. Every UE can independently request a file from the library and those UEs are scheduled together for a CA MU-MIMO transmission. Hence, in a CA MU-MIMO transmission, the interfering data of a subset of scheduled UEs is stored in the caches and is available at the respective receivers for interference cancellation.

CA MU-MIMO uses conventional MU-MIMO as a building block. More precisely, CA MU-MIMO super-imposes multiple MU-MIMO transmissions, i.e. effectively scheduling more UEs than the number of transmit antennas N_T. This overloading will typically result in inter-user interference even with precoding with perfect CSI. Perfect interference cancellation at the receivers is difficult because the receivers are non-cooperative, i.e. UEs cannot exchange information during the demodulation process. However, in CA MU-MIMO the resulting inter-user interference is cancelled by re-encoding and re-modulating the *known* interfering data and subtracting the interfering symbols from the received signal prior to decoding the desired data stream. Unlike other transmission schemes, e.g. RSMA and NOMA, the interfering data are known a priori to the respective receivers and do not need to be decoded.

The system model at the physical layer can be expressed as a super-position of G MU-MIMO transmissions as depicted in Figure 7.3-1.

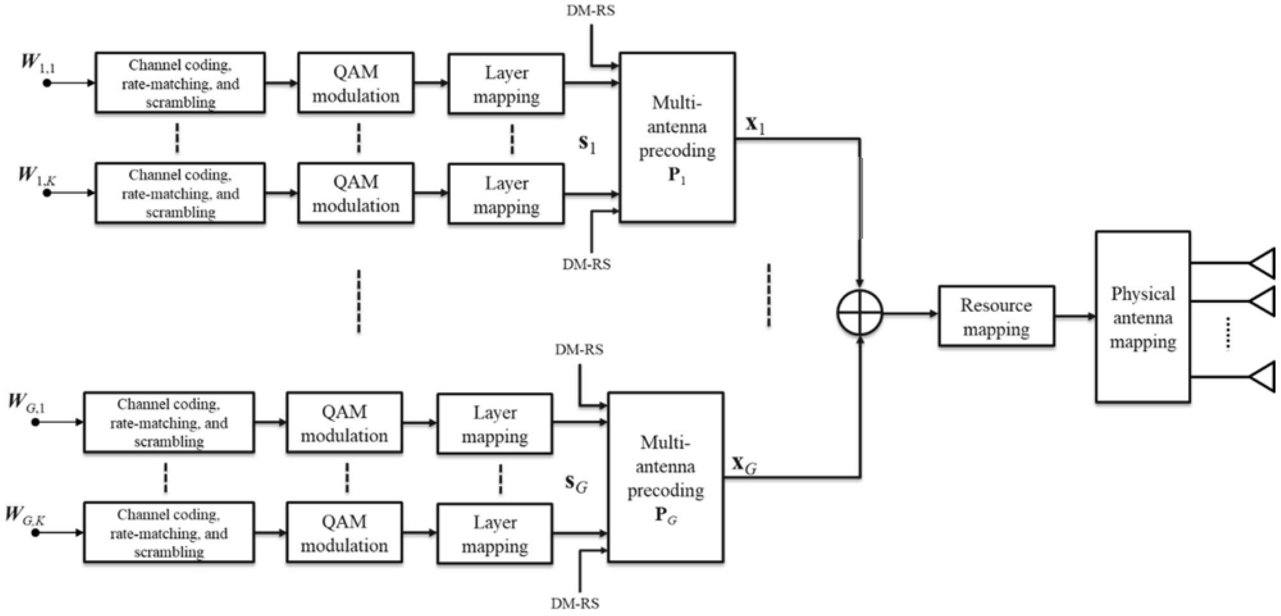


Figure 7.3-1: Transmit processing for CA MU-MIMO

7.3.2 Transmit and receive signal expressions

The transmit signal $\mathbf{x} \in \mathbb{C}^{N_T \times 1}$ with a single layer per UE (i.e. $L_k = 1, \forall k$) is given by:

$$\mathbf{x} = \sum_{g=1}^{G} \mathbf{x}_g \ \text{ with } \mathbf{x}_g = \mathbf{P}_g \mathbf{s}_g,$$

where:

$N_T \geq K$ and (note that each group g may consist of a different number of UEs K_g. For simplicity $K_g = K, \forall g$ is assumed),

$\mathbf{s}_g \in \mathbb{C}^{K \times 1}$ are modulated symbols from the K messages $\boldsymbol{W}_g = [W_{g1}, W_{g2}, \dots, W_{gK}]$ of MU-MIMO transmission g,

$\{\mathbf{p}_{g1}, \cdots, \mathbf{p}_{gK}\} \in \mathbb{C}^{N_T \times 1}$ is the set of precoding vectors of MU-MIMO transmission g, and

$\mathbf{P}_g = [\mathbf{p}_{g1} \cdots \mathbf{p}_{gK}] \in \mathbb{C}^{N_T \times K}$ is the precoding matrix of MU-MIMO transmission g.

Each of the GK transmission layers is associated with a different DM-RS and thus GK DM-RS are required for the CA MU-MIMO transmission.

The corresponding CA MU-MIMO receive signal $\mathbf{y}_{g,k}$ at UE$_k$ belonging to group g can be expressed as:

$$\mathbf{y}_{g,k} = \mathbf{H}_k\mathbf{x} + \mathbf{n}_k = \underbrace{\mathbf{H}_k\mathbf{p}_{g,k}s_{g,k}}_{desired\ signal} + \underbrace{\sum\nolimits_{j\neq k}^{K}\mathbf{H}_k\mathbf{p}_{g,j}s_{g,j}}_{intra-group\ interference} + \underbrace{\sum\nolimits_{l\neq g}^{G}\mathbf{H}_k\mathbf{P}_l\mathbf{s}_l}_{inter-group\ interference} + \mathbf{n}_k,$$

where:

$\mathbf{y}_{g,k} \in \mathbb{C}^{N_R\times 1}$ is the received signal vector of UE$_k$,

$\{\mathbf{h}_{1,k}, \cdots, \mathbf{h}_{N_R,k}\} \in \mathbb{C}^{N_T\times 1}$ is the set of channel vectors at each receive antenna of UE$_k$,

$\mathbf{H}_k = \left[\mathbf{h}_{1,k} \cdots \mathbf{h}_{N_R,k}\right]^H \in \mathbb{C}^{N_R\times N_T}$ is the channel matrix of UE$_k$,

$\hat{\bar{\mathbf{h}}}_{g,k}$ is the estimate of the effective channel $\bar{\mathbf{h}}_{g,k} = \mathbf{H}_k\mathbf{p}_{g,k} \in \mathbb{C}^{N_R\times 1}$ of UE$_k$ in group g, and

$\mathbf{n}_k \in \mathbb{C}^{N_R\times 1}$ is the noise vector of UE$_k$.

In the receive signal $\mathbf{y}_{g,k}$, the term $\mathbf{H}_k\mathbf{p}_{g,k}s_{g,k}$ is the desired signal for UE$_k$ and the term $\sum_{j\neq k}^{K}\mathbf{H}_k\mathbf{p}_{g,j}s_{g,j}$ is the inter-user interference within the MU-MIMO transmission of UE$_k$. The additional term $\sum_{l\neq g}^{G}\mathbf{H}_k\mathbf{P}_l\mathbf{s}_l$ is the inter-group interference between the multiple MU-MIMO transmissions. The effective channels $\bar{\mathbf{h}}_{g,k} = \mathbf{H}_k\mathbf{p}_{g,k}$, $g = 1,2,\ldots,G$, $k = 1,2,\ldots,K$ can be estimated via DM-RS.

7.3.3 CA MU-MIMO receiver architecture

A potential receiver block-diagram is shown in Figure 7.3-2.

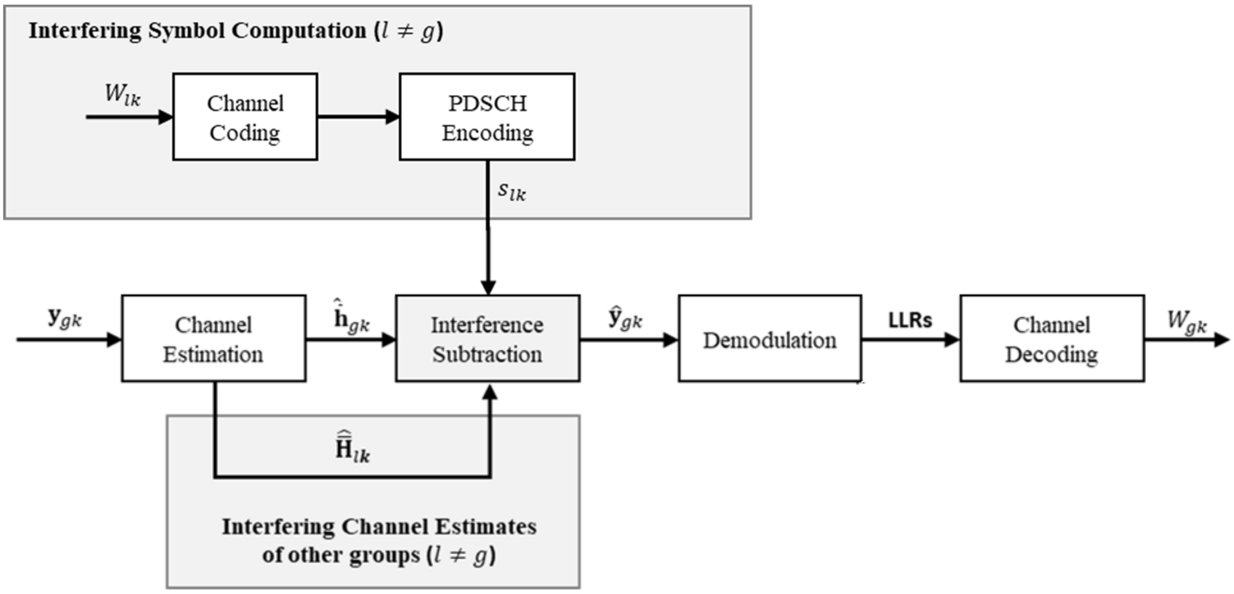


Figure 7.3-2: Receive processing for CA MU-MIMO transmission

The interference subtraction stage at UE$_k$ computes an estimate $\hat{\bar{\mathbf{H}}}_{l,k}$ of the effective channel $\bar{\mathbf{H}}_{l,k} = \mathbf{H}_k\mathbf{P}_l = [\bar{\mathbf{h}}_{l,k,1}, \bar{\mathbf{h}}_{l,k,2}, \ldots, \bar{\mathbf{h}}_{l,k,K}] \in \mathbb{C}^{N_R\times K}$, containing the interfering channel of each of the K UEs of interfering group $l \neq g$, from known DM-RS. Subsequently, the interfering modulated symbols $\mathbf{s}_l$ are obtained by encoding and modulating in the *known* (stored in the cache) messages $W_{l,k}$ $(k = 1,2,\ldots,K)$ of the UEs in group l. The resulting inter-group interference is then subtracted from the received signal $\mathbf{y}_{gk}$ resulting in an interference-mitigated received signal $\hat{\mathbf{y}}_{gk}$ as:

$$\hat{\mathbf{y}}_{gk} = \mathbf{y}_{gk} - \underbrace{\sum\nolimits_{l\neq g}^{G}\hat{\bar{\mathbf{H}}}_{l,k}\mathbf{s}_l}_{\substack{estimated\\ inter-group\\ interference}}.$$

To decode the desired signal within a MU-MIMO transmission in $\hat{\mathbf{y}}_{gk}$, the remaining intra-group interference can be treated as noise (see clause 6.2.3 MU-MIMO with TIN receivers) or via joint demodulation (see clause 6.2.5 MU-MIMO with R-ML receivers). The former does not require the estimation of the intra-group effective channels $\bar{\mathbf{h}}_{g,k'}, k' \neq k$.

The crucial aspect is that the data underlying the interfering symbols $\mathbf{s}_l$ is known to the receivers. In fact, the data transmitted with CA MU-MIMO is cachable, i.e. slowly varying in time, e.g. data from video-on-demand or virtual reality applications. As an example, consider a library of the most popular movies of the month. Every movie is split into subpackets that are subsequently distributed and stored at the UE in an intelligent manner. The UEs can request any movie from the library and the transmissions are scheduled with CA MU-MIMO in such a way that every scheduled UE has the interfering subpackets stored and ready for interference cancellation. As a result, KG UEs can be efficiently spatially multiplexed instead of only K UEs.

NOTE: RSMA can also be used as a building block of a cache-aided transmission. Similar to super-imposed MU-MIMO transmissions, multiple RSMA transmissions are super-imposed at the transmitter. At the receiver, the interfering symbols of the other RSMA transmissions are regenerated and subtracted from the received signal. Compared to MU-MIMO, CA RSMA requires more DM-RS, because each RSMA transmission needs an additional DM-RS for the common message.

8 Basic performance evaluation

8.1 Evaluation results

This clause provides evaluation results for MAT specified in 3GPP technical specifications and candidate MAT. The performance evaluation follows the system model and assumptions detailed in clause 5, with $K = 2$, $N_T = 4$, $N_R = 1$ and $L_1 = L_2 = 1$ i.e. a transmitter with 4 antennas and 2 single antenna UEs where each UE receives a single transmission layer. Details on evaluation methodology, including channel model, precoding design and bitrate expressions are provided in Annex A.

Table 8.1-1 presents precoding design assumptions and considerations; Table 8.1-2 presents the channel model parameters and Table 8.1-3 presents the evaluation criteria. The bitrates for the evaluated MAT are calculated with channel capacity expressions that assume infinite block length and Gaussian signals. The relation between bitrates calculated with channel capacity expressions and the different receiver architectures for the evaluated MAT is presented in Table 8.1-4.

Figures 8.1-1 to 8.1-4 present MAT performance evaluation results for maximum sum-rate optimization criterion. Figures 8.1-5 to 8.1-8 present MAT performance evaluation results for maximum weak UE bitrate optimization criterion. All the results in Figures 8.1-1 to 8.1-8 have been verified by multiple independent implementations.

Table 8.1-1: Precoder design assumptions

MAT	Precoder design	Optimization parameters	Considerations (note 1)
MU-MIMO	MMSE with equal power across precoding vectors	None	Low complexity precoder with closed form expression and improved performance over Zero Forcing (ZF) and Maximum Ratio Transmission (MRT). Equal power across precoding vectors is used to reduce complexity of precoder calculations.
OMA	MRT	$\alpha \in [0,1]$ fraction of total time resources allocated to the UE$_1$. $(1-\alpha)$ fraction of total time resources allocated to UE$_2$.	Low complexity precoder with closed form expression. Signals from all antennas arrive constructively at the UE resulting in the highest SNR. Precoder does not need to remove interference of other UEs due to orthogonal allocation of resources between UEs.
MUST Case 1 (note 2)	Dominant right singular vector of normalized concatenated channel matrix for both UEs, $\mathbf{H}_\text{a} = \begin{bmatrix}\mathbf{h}_{1,1}^H \\ \mathbf{h}_{1,2}^H\end{bmatrix}$.	$t \in [0,1]$ fraction of total power allocated to the near-UE transmission layer. $(1-t)$ fraction of total power allocated to the far-UE transmission layer.	To exploit near-UE and far-UE conditions where near-UE suppresses/cancels far-UE signal, dominant right singular vector of concatenated channel is used to maximize overall received power across both UEs. Both UEs use the same precoding vector. After near-UE suppression/cancellation of far-UE interference, near-UE decodes its own message.
NOMA	MRT for UE$_1$ (near-UE). Dominant right singular vector of normalized concatenated channel matrix for both UEs $\mathbf{H}_\text{a} = \begin{bmatrix}\mathbf{h}_{1,1}^H \\ \mathbf{h}_{1,2}^H\end{bmatrix}$ for UE$_2$ (far-UE).	$t \in [0,1]$ fraction of total power allocated to the precoder vector of near-UE. $(1-t)$ fraction of total power allocated to precoder vector of far-UE.	To exploit near-UE and far-UE conditions where near-UE suppresses/cancels far-UE signal, dominant right singular vector of concatenated channel is used to maximize overall received power across both UEs. After near-UE suppression/cancellation of far-UE interference, low complexity MRT precoder makes signals from all antennas arrive constructively at the UE resulting in the highest SNR.
RSMA	MMSE with equal power across precoding vectors for private streams. Dominant right singular vector of normalized concatenated channel matrix of both UEs $\mathbf{H}_\text{a} = \begin{bmatrix}\mathbf{h}_{1,1}^H \\ \mathbf{h}_{1,2}^H\end{bmatrix}$ for the common stream.	$t \in [0,1]$ fraction of the total power given to the common stream. $(1-t)$ fraction of total power given to all private streams. Common stream bitrate allocation to individual UEs.	Low complexity precoder with closed form expression and improved performance over ZF and MRT for private streams. Equal power across precoding vectors for private streams is used to reduce complexity of precoder calculations. Since the common stream is decoded by both UEs, dominant right singular vector of concatenated channel is used to maximize overall received power across both UEs. The common stream bitrate can be allocated to the UEs to equalize the bitrates across UEs and increase the fairness. Closed form expression for *K*=2.

NOTE 1: Performance results with non-equal power allocation and optimal (high complexity) precoders can be found in [i.33].

NOTE 2: Simulation results for MUST Case 1 are optimized for $t \in [0,1]$ and are not restricted to the specific values specified in ETSI TS 136 211 [i.21].

Table 8.1-2: LOS channel parameters

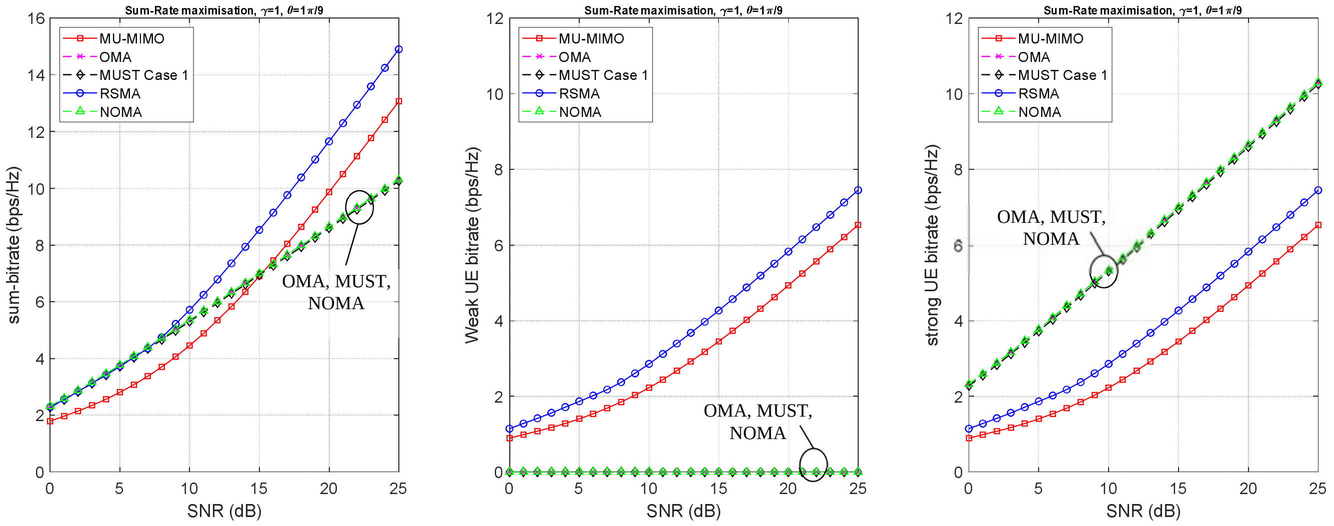
Parameter	Values	Explanation
γ	$\{1, 0{,}3\}$	Controls channel strength of UE$_2$ where channel strength of UE$_1$ is fixed to 1. $\gamma = 0{,}3$, studies the scenario of channel imbalance between UEs.
θ	$\{\frac{\pi}{9}, \frac{3\pi}{9}\}$	Parameter related to the angular separation between the UEs, which allows to study impact of correlation on performance. $\theta = \frac{\pi}{9}$ provides a high correlated channel ($\text{Corr} = 0{,}86$), while $\theta = \frac{3\pi}{9}$ provides a low correlated channel ($\text{Corr} = 0{,}19$).

Table 8.1-3: Evaluation criteria

Criterion	Expression	Explanations
Sum-rate	$\max \sum_{k=1}^{K} R_k$	Maximizes aggregate bitrate across all UEs. It favours allocating resources to UEs with better channel conditions at the expense of UEs with worse channel conditions.
Maximum weak UE bitrate	$\max \min\{R_1, R_2, \ldots, R_K\}$	Also known as Max Min Fairness (MMF) criterion. Allocation of resources is optimized so the weak UE bitrate is maximum - strong UE bitrate will be at least the bitrate of the weak UE bitrate.

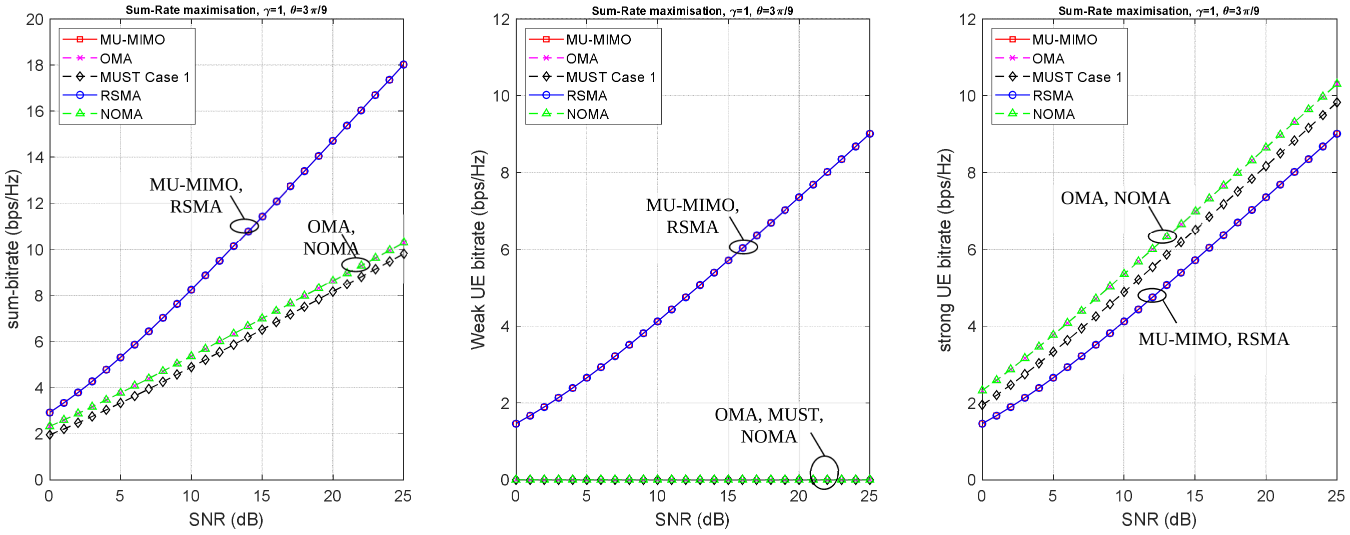
Table 8.1-4: Relation between bitrates calculated with channel capacity expressions in Annex A and evaluated MAT

MAT	Receiver types (note)	Receiver types considered in the evaluation	Explanations
MU-MIMO	TIN, MMSE-IRC, R-ML	TIN	Channel capacity expression assumes interference is not decoded and is treated as noise (TIN).
MUST Case 1	Far-UE: TIN	Far-UE: TIN	Channel capacity expression for far-UE assumes interference is not decoded and is treated as noise (TIN). Channel capacity expression for near-UE assumes interference from far-UE is decoded and cancelled before decoding its own signal, i.e. SIC receiver. However, as discussed in clause 6.3, assistance information does not include sufficient information to derive the code-rate of the interferer and implement SIC. Hence, the channel capacity expression used to calculate the MUST Case 1 bitrate provides an upper bound performance for R-ML receivers.
	Near-UE: R-ML	Near-UE: SIC	
NOMA	Far-UE: TIN	Far-UE: TIN	Channel capacity expression for far-UE assumes interference is not decoded and is treated as noise (TIN). Channel capacity expression for near-UE assumes interference from far-UE is decoded and cancelled before decoding its own signal, i.e. SIC receiver.
	Near-UE: SIC, R-ML	Near-UE: SIC	
RSMA	Common stream: TIN	Common stream: TIN	Channel capacity expressions for common stream for both UEs assumes interference is not decoded and is treated as noise (TIN). Channel capacity expressions for the private streams for both UEs assume interference from common stream is decoded and cancelled before decoding its own private stream, i.e. SIC receiver.
	Private streams: SIC, R-ML	Private streams: SIC	
NOTE: Code Word Interference Cancellation (CWIC) terminology is used in 3GPP TR 36.866 [i.34] to describe SIC receiver architectures.			



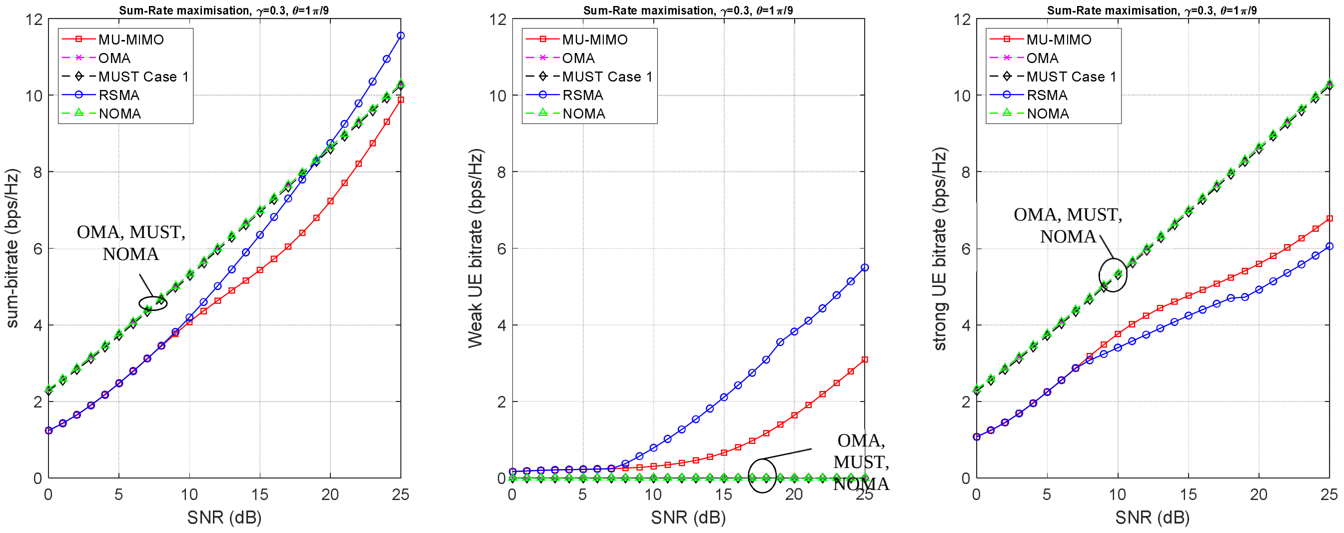
NOTE: The two UEs have the same channel strength and high channel correlation, $\mathbf{Corr} = \mathbf{0,86}$. MAT optimized to maximize the sum-rate.

Figure 8.1-1: Spectral efficiency (bps/Hz) vs. SNR (dB) for $\gamma = 1$ and $\theta = \frac{\pi}{9}$



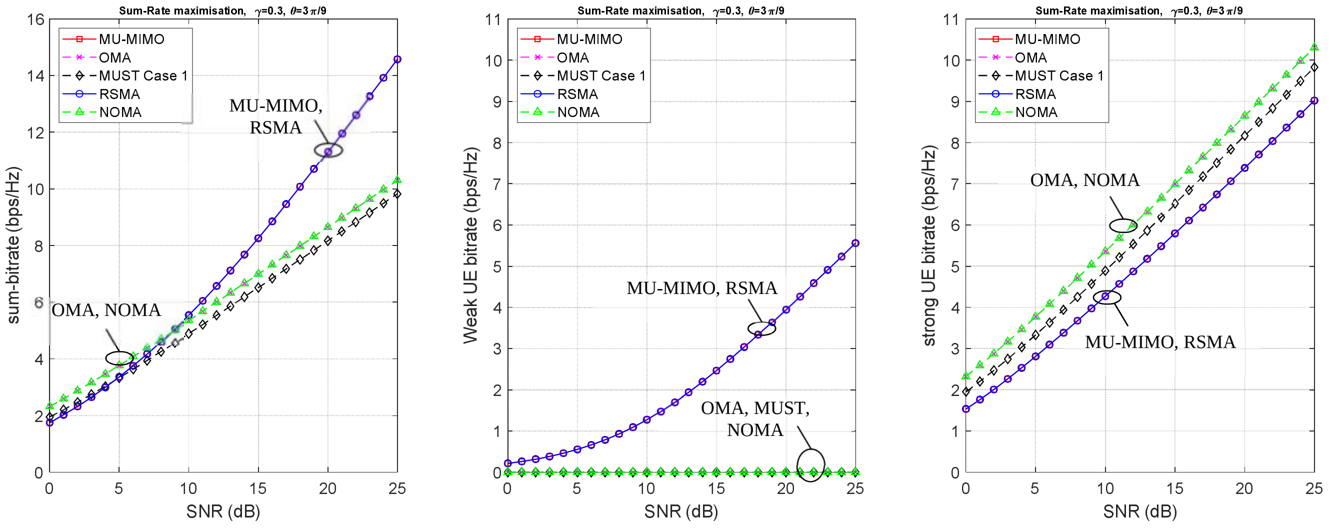
NOTE: The two UEs have the same channel strength and low channel correlation, $\mathbf{Corr} = \mathbf{0,19}$. MAT optimized to maximize the sum-rate.

Figure 8.1-2: Spectral efficiency (bps/Hz) vs. SNR (dB) for $\gamma = 1$ and $\theta = \frac{3\pi}{9}$



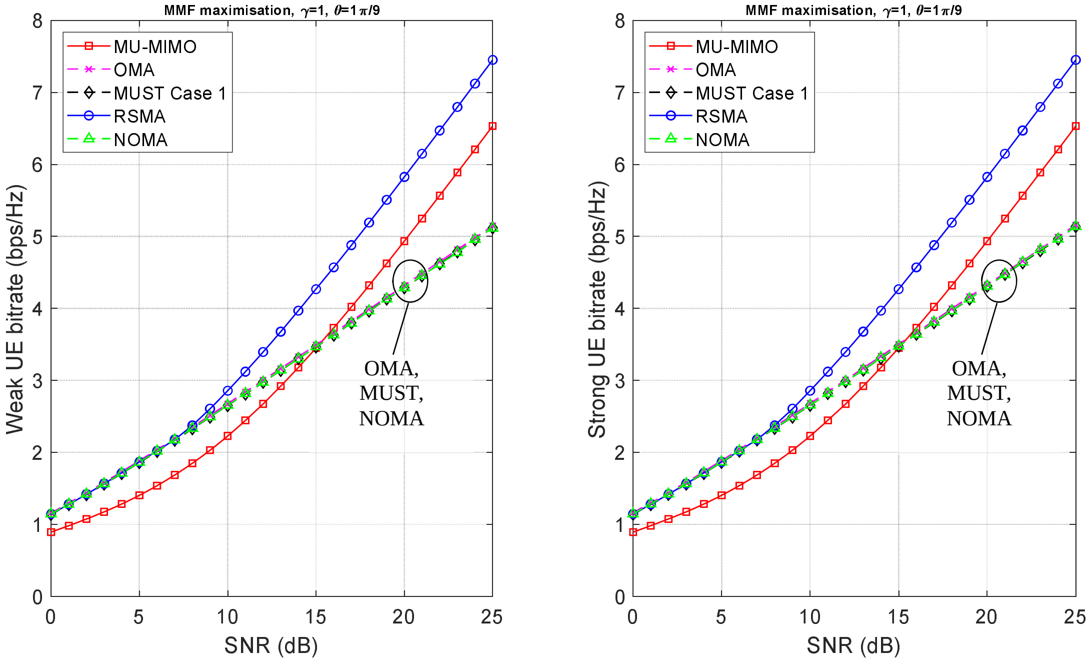
NOTE: The two UEs have channel strength imbalance and high channel correlation, $\mathbf{Corr} = \mathbf{0,86}$. MAT optimized to maximize the sum-rate.

Figure 8.1-3: Spectral efficiency (bps/Hz) vs. SNR (dB) for $\gamma = 0,3$ and $\theta = \frac{\pi}{9}$



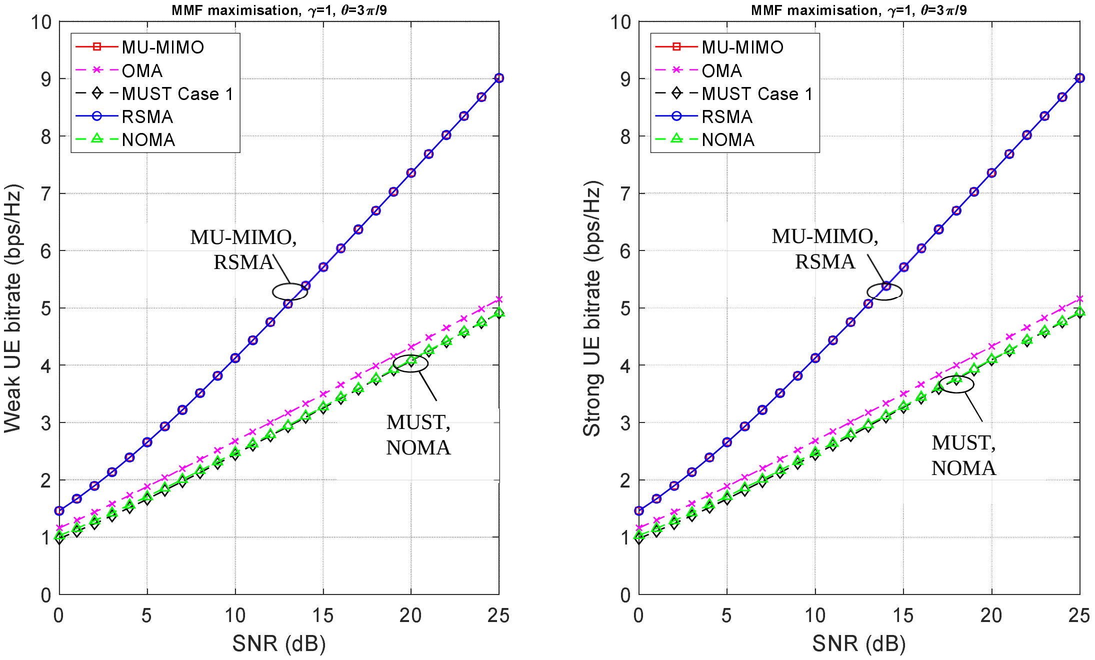
NOTE: The two UEs have channel strength imbalance and low channel correlation, $\mathbf{Corr} = \mathbf{0,19}$. MAT optimized to maximize the sum-rate.

Figure 8.1-4: Spectral efficiency (bps/Hz) vs. SNR (dB) for $\gamma = 0,3$ and $\theta = \frac{3\pi}{9}$



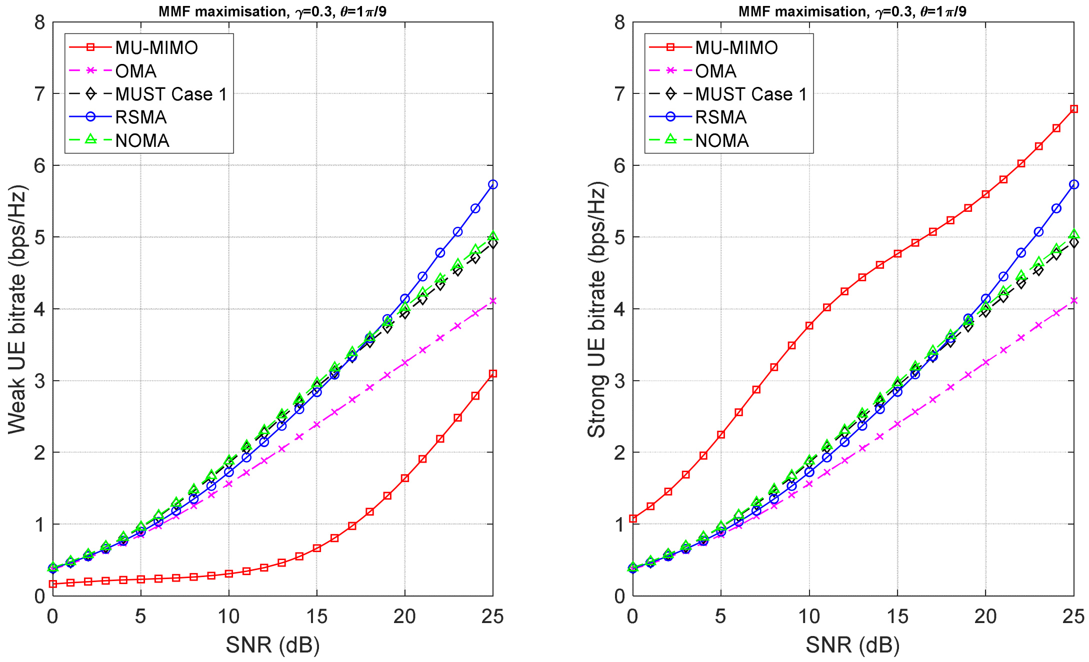
The two UEs have the same channel strength and high channel correlation, $\mathbf{Corr} = \mathbf{0{,}86}$. MAT optimized to maximize the weak UE bitrate.

Figure 8.1-5: Spectral efficiency (bps/Hz) vs. SNR (dB) for $\gamma = 1$ and $\theta = \frac{\pi}{9}$



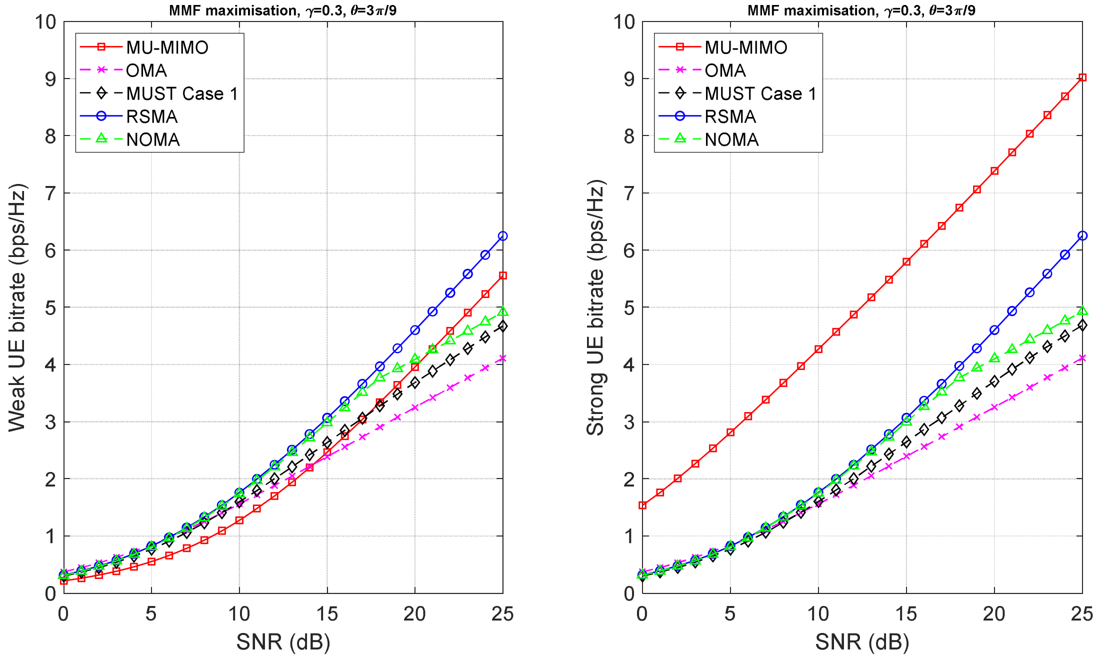
NOTE: The two UEs have the same channel strength and low channel correlation, $\mathbf{Corr} = \mathbf{0{,}19}$. MAT optimized to maximize the weak UE bitrate.

Figure 8.1-6: Spectral efficiency (bps/Hz) vs. SNR (dB) for $\gamma = 1$ and $\theta = \frac{3\pi}{9}$



NOTE: The two UEs have channel strength imbalance and high channel correlation, $\mathbf{Corr} = \mathbf{0,86}$. MAT optimized to maximize the weak UE bitrate.

Figure 8.1-7: Spectral efficiency (bps/Hz) vs. SNR (dB) for $\gamma = 0,3$ and $\theta = \frac{\pi}{9}$



NOTE: The two UEs have channel strength imbalance and low channel correlation, $\mathbf{Corr} = \mathbf{0,19}$. MAT optimized to maximize the weak UE bitrate.

Figure 8.1-8: Spectral efficiency (bps/Hz) vs. SNR (dB) for $\gamma = 0,3$ and $\theta = \frac{3\pi}{9}$

8.2 Observations

Based on the assumptions and the evaluations results presented in clause 8.1, the following observations are made:

- Regarding the impact of channel parameters (angular separation and power imbalance between UEs) and optimization criteria (maximum sum-rate vs. maximum weak UE bitrate) for the different MAT:
    - MU-MIMO:
        - performance generally degrades with increasing channel correlation (UEs with smaller angular separation);
        - Since equal power across precoding vectors is used, a higher bitrate is achieved by the stronger UE when there is power imbalance between the UEs.
    - OMA:
        - its performance is invariant to the channel correlation (angular separation between UEs);
        - for sum-rate maximization, it allocates all the resources to the stronger UE where the weaker UE is allocated zero bitrate;
        - for maximum weak UE bitrate maximization, the same bitrate is achieved by both UEs.
    - MUST Case 1:
        - performance degrades slightly with decreasing channel correlation (UEs with higher angular separation);
        - for sum-rate maximization, it allocates all the resources to the stronger UE where the weaker UE is allocated zero bitrate;
        - for maximum weak UE bitrate maximization, the same bitrate is achieved by both UEs.
    - Power-domain NOMA:
        - for sum-rate maximization, it allocates all the resources to the stronger UE where the weaker UE is allocated zero bitrate;
        - for maximum weak UE bitrate maximization, performance degrades slightly with decreasing channel correlation (UEs with higher angular separation) only when there is no power imbalance between UEs.
    - RSMA:
        - performance generally degrades with increasing channel correlation (UEs with smaller angular separation). However, the performance loss due to increasing channel correlation is smaller for RSMA than for MU-MIMO.
- Regarding the performance comparison between different MAT:
    - For sum-rate maximization:
        - without power imbalance between UEs and with high channel correlation (UEs with smaller angular separation):
            - RSMA provides the best sum-rate performance and the best weak UE bitrate performance.
        - without power imbalance between UEs and with low channel correlation (UEs with higher angular separation):
            - MU-MIMO and RSMA both provide the best sum-rate performance and the best weak UE bitrate performance.

    - with power imbalance between UEs and with high channel correlation (UEs with smaller angular separation):
        - OMA, MUST Case 1 and power-domain NOMA provide the best sum-rate performance below 20 dBs of SNR. From 20 dBs of SNR, RSMA provides the best sum-rate performance;
        - RSMA provides the best weak UE bitrate performance where OMA, MUST Case 1 and power-domain NOMA assign zero bitrate to the weak UE.
    - with power imbalance between UEs and with low channel correlation (UEs with higher angular separation):
        - below 8 dBs of SNR all schemes provide similar sum-rate performance. From 8 dBs of SNR, MU-MIMO and RSMA both provide the best sum-rate performance;
        - MU-MIMO and RSMA both provide the best weak UE bitrate performance where OMA, MUST Case 1 and power-domain NOMA assign zero bitrate to the weak UE.
- For maximum weak UE bitrate maximization:
    - without power imbalance between UEs and with high channel correlation (UEs with smaller angular separation):
        - RSMA provides the best performance for both weak UE bitrate and strong UE bitrate.
    - without power imbalance between UEs and with low channel correlation (UEs with higher angular separation):
        - MU-MIMO and RSMA both provide the best performance for both weak UE bitrate and strong UE bitrate.
    - with power imbalance between UEs and with high channel correlation (UEs with smaller angular separation):
        - for weak UE bitrate, MUST Case 1, power-domain NOMA and RSMA provide similar performance up to 20 dBs of SNR. From 20 dBs of SNR, RSMA provides the best performance;
        - MUST Case 1, power-domain NOMA and RSMA provide significant gains against MU-MIMO at all SNRs;
        - MUST Case 1, power-domain NOMA and RSMA provide relevant gains against OMA in mid to high SNRs;
        - MU-MIMO provides the best strong UE bitrate performance.
    - with power imbalance between UEs and with low channel correlation (UEs with higher angular separation):
        - for weak UE bitrate, power-domain NOMA and RSMA provide the best performance up to 17 dBs of SNR. From 17 dBs of SNR, RSMA provides the best performance;
        - for weak UE bitrate, RSMA provides a relevant gain against MU-MIMO at all SNRs;
        - for weak UE bitrate, RSMA provides an increasing gain with increasing SNR against OMA and MUST Case 1;
        - MU-MIMO provides the best strong UE bitrate performance.

9 Classification of MAT

Table 9-1 provides a classification of MAT based on main characteristics discussed in previous clauses.

Table 9-1: Classification of MAT assuming *K* scheduled UEs where each UE receives one transmission layer

	MAT		Transmitted signal		Number of orthogonal DM-RS	Assistance information from network to UE	Interference suppression / cancellation capability (note 1)
			Expression	Key feature			
MAT specified at 3GPP	MU-MIMO	TIN Rx	$\mathbf{x} = \sum_{k=1}^{K} \mathbf{p}_k s_k$	Information messages from multiple UEs are multiplexed in the spatial domain with different precoding vectors within the same time-frequency resources.	K	None	None
		R-ML Rx				UEs implementing R-ML receiver, receive modulation order of co-scheduled UEs.	Interference suppression. Interference is not decoded and is not cancelled.
	OMA		$\mathbf{x} = \mathbf{p}_k s_k$	Information messages from multiple UEs are multiplexed in orthogonal time-frequency resources.	1	None	None. No interference between information messages from multiple UEs due to orthogonal time-frequency allocation.
	MUST Case 1 (note 2)		$\mathbf{x} = \mathbf{p}\left(\sqrt{\alpha} s_1' + \sqrt{1-\alpha} s_2\right)$	Information messages from *K*=2 UEs are transmitted through same precoding vector within the same time-frequency resources. It exploits near-UE and far-UE condition. Near-UE suppresses interference signal from far-UE before decoding its own signal. Far-UE decodes its signal while treating the interference signal from near-UE as noise.	1 (note 3)	Far-UE, receives no assistance information. Near-UE receives "existence of MUST interference" and "transmission power ratio". Modulation order of the interference is not signalled since it is fixed to QPSK.	Interference suppression. Interference is not decoded and is not cancelled.

	MAT		Transmitted signal		Number of orthogonal DM-RS	Assistance information from network to UE	Interference suppression / cancellation capability (note 1)
			Expression	**Key feature**			
Candidate MAT	Power Domain NOMA	SIC Rx	$\mathbf{x} = \sum_{k=1}^{K} \mathbf{p}_k s_k$	Information messages from multiple UEs are multiplexed in the spatial domain with different precoding vectors within the same time-frequency resources. It exploits near-UE and far-UE conditions. The power levels and bitrates of modulated symbols s_k (for all *k*) need to meet specific conditions such that UEs can use SIC techniques to sequentially decode and cancel interference signals while treating previously undecoded signals as noise (see clause 7.1.2). For example (for $K = 3$), s_3, s_2, s_1 need to meet bitrate constraints such that s_3 is decodable by all UEs, s_2 is decodable by UE$_1$ and UE$_2$, and s_1 is decodable by UE$_1$.	*K*	All UEs that perform SIC need information about modulation order and channel code-rate to decode and cancel the interfering signals. In particular, the assistance information at UE$_k$ (for all *k*) may include assistance information from $K - k$ interfering UEs.	Interference cancellation. Interfering signals are decoded and cancelled.
		R-ML Rx				Same as for SIC receivers, but for R-ML receivers assistance information about the channel code-rate of the interfering signals would not be necessary.	Interference suppression. Interference is not decoded and is not cancelled.
	RSMA	SIC Rx	$\mathbf{x} = \mathbf{p}_{\mathrm{c}} s_{\mathrm{c}} + \sum_{k=1}^{K} \mathbf{p}_k s_k$	Information messages from multiple UEs are multiplexed in the spatial domain with different precoding vectors within the same time-frequency resources. Each of the messages can be split into one common part and one private part, $W_{k,\mathrm{c}}$ and $W_{k,\mathrm{p}}$, (for all *k*), respectively. Then, the split common parts are combined to obtain a single common message W_{c}. The precoding vector $\mathbf{p}_{\mathrm{c}}$ and bitrate of modulated symbols s_{c} need to meet specific conditions such that the common message s_{c} can be decoded by the *K* scheduled UEs (see clause 7.2.2). For example (for $K = 3$), s_{c} needs to meet the bitrate constraint such that s_{c} is decodable by UE$_1$, UE$_2$ and UE$_3$.	*K*+1	All *K* scheduled UEs receive assistance information including modulation order and channel code-rate of the common message.	The common message containing parts of co-scheduled UE's information messages is decoded and cancelled.
		R-ML Rx				Same as for SIC receivers since common message is still decoded.	The common message containing parts of co-scheduled UE's information messages is decoded but it is not cancelled.

	MAT		**Transmitted signal**		**Number of orthogonal DM-RS**	**Assistance information from network to UE**	**Interference suppression / cancellation capability (note 1)**
			Expression	**Key feature**			
Candidate MAT	CA MU-MIMO	TIN Rx	$\mathbf{x} = \sum_{g=1}^{G}\sum_{k=1}^{K}\mathbf{p}_{g,k}s_{g,k}$	Superposition of *G* MU-MIMO transmissions groups where the inter-group interference can be cancelled with known a priori (stored in the cache) information symbols. Intra-group interference can be handled as conventional MU-MIMO transmission with TIN or R-ML receivers. Crucial aspect is that information symbols causing inter-group interference are cached a priori of the transmission, e.g. data from video-on-demand or virtual reality applications (see clause 7.3).	*GK*	For both TIN and R-ML receivers, prior to the transmission, specific parts (subpackets) of files from a common library are distributed to the receiver and stored using coded caching. The known information messages are used to handle inter-group interference. To handle intra-group interference with TIN receivers, no assistance information is required. To handle intra-group interference with R-ML receivers, UEs receive modulation order of co-scheduled UEs.	For both TIN and R-ML receivers, inter-group interference is cancelled using encoded known (a priori) messages stored in the receiver cache. Intra-group interference with TIN receivers, no interference cancellation nor interference suppression capability. Intra-group interference with R-ML receivers, interference suppression. Interference is not decoded and is not cancelled.
		R-ML Rx					

NOTE 1: Interference suppression means the process where a UE uses assistance information about the modulation of the interferer to improve the performance with e.g. R-ML receivers. However, it does not decode and cancel the interference. Interference cancellation means the process where the UE uses assistance information about the modulation and channel code-rate of the interferer to decode and cancel the interference and improve the performance.

NOTE 2: MUST Case 3 provides similar functionality as MU-MIMO with advanced receivers (R-ML).

NOTE 3: MUST Case 1 was only specified for *K*=2 UEs.

10 Conclusions

The present document studies candidate MAT for 6G in the downlink that improve spectral efficiency in the presence of inter-user interference. The candidate MAT considered in this study, i.e. power-domain NOMA, RSMA and CA MU-MIMO, are compared against MAT specified in the 3GPP technical specifications, i.e. OMA, MU-MIMO and MUST. The conclusions of the present document are as follows.

3GPP technical specifications include techniques to cancel/supress inter-user interference, such as MU-MIMO with advanced receivers (R-ML) and MUST. In particular:

- MU-MIMO with advanced receivers requires assistance information from network to UEs implementing R-ML receiver.
- MUST Case 1 requires assistance information from network to near-UE implementing R-ML receiver. It also requires that near-UE suppresses interference signal from far-UE before decoding its own signal.
- MUST Case 3 provides similar functionality with similar requirements to MU-MIMO with R-ML receivers.

For the considered candidate MAT, the following are the main conclusions in terms of performance evaluation, requirements on additional processing, number of DM-RS, and assistance information from network to UEs.

Power-domain NOMA:

- In terms of performance evaluation for the considered scenario, power-domain NOMA provides gains against specified MAT when there is power imbalance between the scheduled UEs. In particular:
    - For sum-rate maximization, power-domain NOMA provides the same performance as specified OMA. Both techniques allocate all bitrate to the strong UE while the weak UE is allocated zero bitrate.
    - For weak UE bitrate maximization (max-min fairness), power-domain NOMA provides gains against specified OMA when there is power imbalance between the two scheduled UEs. Power-domain NOMA provides gains against specified MU-MIMO with TIN receivers when there is power imbalance between the two scheduled UEs and when the channels between the scheduled UEs are highly correlated (e.g. UEs with small angular separation).
- In terms of requirements on additional processing, number of DM-RS, and assistance information compared with MU-MIMO with TIN receivers:
    - In power-domain NOMA the bitrates of scheduled UEs need to meet specific conditions such that UEs can use SIC techniques to sequentially decode and cancel interference signals while treating previously undecoded signals as noise.
    - Power-domain NOMA requires the same number of DM-RS as specified MU-MIMO.
    - Power-domain NOMA requires assistance information from network to UEs, so UEs can use SIC or R-ML receivers.

RSMA

- In terms of performance evaluation for the considered scenario, RSMA provides gains against specified MAT when the channels between the scheduled UEs are highly correlated (e.g. UEs with small angular separation) or when there is power imbalance between scheduled UEs. In particular:
    - When the channels between the scheduled UEs are highly correlated (e.g. UEs with small angular separation), RSMA provides significant gains against MU-MIMO with TIN receivers for both sum-rate performance and weak-UE bitrate performance. This is the case for both considered optimization criteria (sum-rate maximization and weak UE bitrate maximization) and both cases of power imbalance between scheduled UEs (with and without power imbalance).
    - When the channels between the scheduled UEs are uncorrelated (e.g. UEs with large angular separation), RSMA generally provides the same performance as MU-MIMO with TIN receivers. However, for weak UE bitrate maximization, RSMA can also provide gains against MU-MIMO with TIN receivers when there is a power imbalance between the two scheduled UEs.

- In terms of requirements on additional processing, number of DM-RS, and assistance information compared with MU-MIMO with TIN receivers:
    - RSMA requires the implementation of message splitter and message combiner processing blocks to generate the common message.
    - In RSMA the bitrate of the common message needs to meet specific conditions such that the common message can be decoded by the K scheduled UEs.
    - RSMA requires an additional DM-RS for the common message compared to specified MU-MIMO.
    - RSMA requires assistance information from network to UEs, so UEs can use SIC or R-ML receivers to decode the common message.

CA MU-MIMO

- The performance of CA MU-MIMO has not been evaluated in the present document because simplified performance metrics are not available.
- In terms of requirements on additional processing, number of DM-RS, and assistance information compared with MU-MIMO with TIN receivers:
    - CA MU-MIMO requires the same number of DM-RS as specified MU-MIMO.
    - CA MU-MIMO applies only to cacheable content, e.g. data from video-on-demand or virtual reality applications. This content constitutes a common library and is constant over long periods of time. Specific parts (subpackets) of files from a common library are distributed to the receivers and stored using coded caching.
    - CA MU-MIMO requires a receiver that uses the cache to mitigate inter-group interference which allows for an efficient scheduling of many UEs even with a limited number of transmit antennas.

Due to the current limitations in the evaluation methodology, specified MAT and candidate MAT with R-ML receivers have not been evaluated. These evaluations would require link level simulations with specified constellations (i.e. QAM modulation) and specified channel codes (i.e. polar codes and LDPC codes) that could be considered in next revisions of the present document.

Annex A:
Evaluation methodology

A.1 Channel model

The channel is modelled with a simple Line of Sight (LOS) as in equation 37 of [i.33]. The channel vector at UE$_1$ and UE$_2$ are $\mathbf{h}_1 = [1,1,1,1]^H$ and $\mathbf{h}_2 = \gamma \times \left[1, e^{j\theta}, e^{j2\theta}, e^{j3\theta}\right]^H$, where γ controls the channel strength of UE$_2$ and the variable θ is related to the angular separation between the UEs. In the evaluations γ takes the values $\{1,0,3\}$ and θ takes the values $\{\frac{\pi}{9}, \frac{3\pi}{9}\}$. The channel correlation between the channel vectors at each UE is measured as $\mathrm{Corr} = \frac{|\mathbf{h}_1^H \mathbf{h}_2|^2}{\|\mathbf{h}_1\| \|\mathbf{h}_2\|}$. The noise $\mathrm{n}_k \in \mathbb{C}^{1\times 1}$ at UE$_k$ is modelled as additive white Gaussian noise (AWGN) with distribution $CN(0, \sigma_k^2)$, where $\sigma_1^2 = \sigma_2^2 = 1$.

A.2 Precoder design and bitrate expressions

A.2.1 OMA

Let $\bar{H} = \left[\bar{\mathbf{h}}_1\ \bar{\mathbf{h}}_2 \ldots \bar{\mathbf{h}}_K\right]$ where $\bar{\mathbf{h}}_k = \frac{\mathbf{h}_k}{\|\mathbf{h}_k\|}$ ($\bar{H}$ is $N_T \times K$ normalized channel matrix). Maximum Ratio Transmission (MRT) is used for the precoder design for OMA, where $[\bar{\mathbf{p}}_1 \quad \cdots \quad \bar{\mathbf{p}}_K] = \bar{H}$. The precoder and modulated modulated symbols of the message from UE$_k$, follow the constraint $\mathbb{E}[|s_k|^2] = 1$, and $P = \|\mathbf{p}_k\|^2$.

The bitrate at UE$_k$ is calculated as:

$$R_k = \alpha_k \log_2(1 + |\mathbf{h}_k^H \mathbf{p}_k|^2),\ k = 1, 2, \ldots, K,$$

where:

α_k denotes a fraction of total resources allocated to the k^{th} user ($\alpha_1 + \alpha_2 + \cdots + \alpha_K = 1$), and

$\mathbf{p}_k = \sqrt{P}\bar{\mathbf{p}}_k$, for $k = 1, \ldots, K$.

The sum-rate, weak UE bitrate and strong UE bitrate are calculated as $\sum_{k=1}^{K} R_k$, $\min\{R_1, R_2, \ldots, R_K\}$, and $\max\{R_1, R_2, \ldots, R_K\}$, respectively. α_k is optimized to maximize either the sum-rate or the weak UE bitrate.

A.2.2 MU-MIMO

Let $\bar{H} = \left[\bar{\mathbf{h}}_1\ \bar{\mathbf{h}}_2 \ldots \bar{\mathbf{h}}_K\right]$ where $\bar{\mathbf{h}}_k = \frac{\mathbf{h}_k}{\|\mathbf{h}_k\|}$ ($\bar{H}$ is $N_T \times K$ normalized channel matrix). Minimum Mean Squared Error (MMSE) is used for the precoder for MU-MIMO with TIN receivers:

$$[\mathbf{v}_1 \quad \cdots \quad \mathbf{v}_K] = H\left(H^H H + \frac{1}{\xi(t)} I\right)^{-1}$$

where $\xi(t) = \frac{P}{K}$ is the regularization term [i.35]. The normalized precoding vectors are $[\bar{\mathbf{p}}_1 \quad \cdots \quad \bar{\mathbf{p}}_K] = \left[\frac{\mathbf{v}_1}{\|\mathbf{v}_1\|} \quad \cdots \quad \frac{\mathbf{v}_K}{\|\mathbf{v}_K\|}\right]$. The precoder and modulated symbols follow the constraints $\mathbb{E}\{\mathbf{s}\mathbf{s}^H\} = \mathbf{I}$, and $P = \sum_{n=1}^{K} \|\mathbf{p}_n\|^2$.

The bitrate at UE$_k$ is calculated as:

$$R_k = \log_2\left(1 + \frac{\left|\mathbf{h}_k^H \mathbf{p}_k\right|^2}{\sum_{j\neq k}\left|\mathbf{h}_k^H \mathbf{p}_j\right|^2 + 1}\right), k = 1,2, \ldots, K,$$

where:

$$\mathbf{p}_k = \sqrt{\frac{P}{K}}\,\bar{\mathbf{p}}_k, \text{ for } k = 1, \ldots, K.$$

The sum-rate, weak UE bitrate and strong UE bitrate are calculated as $\sum_{k=1}^{K} R_k$, $\min\{R_1, R_2, \ldots, R_K\}$, and $\max\{R_1, R_2, \ldots, R_K\}$, respectively.

A.2.3 MUST Case 1

It is assumed that UE$_1$ is the near-UE with capability to supress/cancel interference from UE$_2$, and that UE$_2$ is a far-UE that treats interference from UE$_1$ as noise (TIN receiver).

Let $\bar{H} = \left[\bar{\mathbf{h}}_1\ \bar{\mathbf{h}}_2 \ldots \bar{\mathbf{h}}_K\right]$ where $\bar{\mathbf{h}}_k = \frac{\mathbf{h}_k}{\|\mathbf{h}_k\|}$ ($\bar{H}$ is $N_T \times K$ normalized channel matrix). The precoding vector $\bar{\mathbf{p}}$ for UE$_1$ and UE$_2$ is designed as the dominant right singular vector of $\bar{H}^H$. The precoder and modulated symbols follow the constraints $\mathbb{E}[\mathbf{s}\mathbf{s}^H] = \mathbf{I}$, and $P = \sum_{n=1}^{K}\|\mathbf{p}_n\|^2$.

The bitrate at UE$_1$ and UE$_2$ are calculated as:

$$R_1 = \log_2(1 + |\mathbf{h}_1^H \mathbf{p}_1|^2),$$

$$R_2 = \min\left(\log_2\left(1 + \frac{\left|\mathbf{h}_1^H \mathbf{p}_2\right|^2}{1 + \left|\mathbf{h}_1^H \mathbf{p}_1\right|^2}\right), \log_2\left(1 + \frac{\left|\mathbf{h}_2^H \mathbf{p}_2\right|^2}{1 + \left|\mathbf{h}_2^H \mathbf{p}_1\right|^2}\right)\right),$$

where:

$$\mathbf{p}_k = \sqrt{t_k P}\,\bar{\mathbf{p}}, \text{ for } k = 1, \ldots, K,$$

and $t_1 + t_2 + \cdots + t_K = 1$.

The sum-rate, weak UE bitrate and strong UE bitrate are calculated as $\sum_{k=1}^{K} R_k$, $\min\{R_1, R_2, \ldots, R_K\}$, and $\max\{R_1, R_2, \ldots, R_K\}$, respectively.

The power allocation to the UE$_k$ precoder is controlled by the variable t_k, i.e. $t_k P$ power allocated to UE$_k$ precoder vector. Optimal $t_k$can be found by exhaustive search between $[0,1]$ to maximize either sum-rate or weak UE bitrate.

A.2.4 NOMA

It is assumed that UE$_1$ is the near-UE with capability to supress/cancel interference from UE$_2$, and that UE$_2$ is a far-UE that treats interference from UE$_1$ as noise (TIN receiver).

Let $\bar{H} = \left[\bar{\mathbf{h}}_1\ \bar{\mathbf{h}}_2 \ldots \bar{\mathbf{h}}_K\right]$ where $\bar{\mathbf{h}}_k = \frac{\mathbf{h}_k}{\|\mathbf{h}_k\|}$ ($\bar{H}$ is $N_T \times K$ normalized channel matrix). The precoding vector for UE$_1$ is designed as a maximum ratio transmission (MRT) where $\bar{\mathbf{p}}_1 = \bar{\mathbf{h}}_1$, and the dominant right singular vector of $\bar{H}^H$ is chosen as the precoder for UE$_2$. The precoder and modulated symbols follow the constraints $\mathbb{E}[\mathbf{s}\mathbf{s}^H] = \mathbf{I}$, and $P = \sum_{n=1}^{K}\|\mathbf{p}_n\|^2$.

The bitrate at UE$_1$ and UE$_2$ are calculated as:

$$R_1 = \log_2(1 + |\mathbf{h}_1^H \mathbf{p}_1|^2),$$

$$R_2 = \min\left(\log_2\left(1 + \frac{|\mathbf{h}_1^H \mathbf{p}_2|^2}{1+|\mathbf{h}_1^H \mathbf{p}_1|^2}\right), \log_2\left(1 + \frac{|\mathbf{h}_2^H \mathbf{p}_2|^2}{1+|\mathbf{h}_2^H \mathbf{p}_1|^2}\right)\right),$$

where:

$\mathbf{p}_k = \sqrt{t_k P}\,\bar{\mathbf{p}}_k$, for $k = 1, \dots, K$,

and $t_1 + t_2 + \cdots + t_K = 1$.

The sum-rate, weak UE bitrate and strong UE bitrate are calculated as $\sum_{k=1}^{K} R_k$, $\min\{R_1, R_2, \dots, R_K\}$, and $\max\{R_1, R_2, \dots, R_K\}$, respectively.

The power allocation to the UE$_k$ precoder is controlled by the variable t_k, i.e. $t_k P$ power allocated to UE$_k$ precoder vector. Optimal $t_k$can be found by exhaustive search between $[0,1]$ to maximize either sum-rate or weak UE bitrate.

A.2.5 RSMA

Let $\bar{H} = [\bar{\mathbf{h}}_1\ \bar{\mathbf{h}}_2 \dots \bar{\mathbf{h}}_K]$ where $\bar{\mathbf{h}}_k = \frac{\mathbf{h}_k}{\|\mathbf{h}_k\|}$ ($\bar{H}$ is $N_T \times K$ normalized channel matrix). MMSE is used for the precoder of the private streams for RSMA:

$$[\mathbf{v}_1 \quad \cdots \quad \mathbf{v}_K] = H\left(H^H H + \frac{1}{\xi(t)} I\right)^{-1}$$

where $\xi(t) = \frac{P(1-t)}{K}$ is the regularization term [i.35] and t is the fraction of power given to the common stream. The normalized precoding vectors for the private streams are $[\bar{\mathbf{p}}_1 \quad \cdots \quad \bar{\mathbf{p}}_K] = \left[\frac{\mathbf{v}_1}{\|\mathbf{v}_1\|} \quad \cdots \quad \frac{\mathbf{v}_K}{\|\mathbf{v}_K\|}\right]$. The dominant right singular vector of $\bar{H}^H$ is chosen as the common stream precoder $\bar{\mathbf{p}}_{\mathrm{c}}$. The precoder of the private streams, common stream and modulated symbols follow the constraints $\mathbb{E}\{\mathbf{s}\mathbf{s}^H\} = \mathbf{I}$, and $P = \|\mathbf{p}_{\mathrm{c}}\|^2 + \sum_{n=1}^{K} \|\mathbf{p}_n\|^2$.

The bitrate of the private streams is calculated as:

$$R_{\mathrm{p},k} = \log_2\left(1 + \frac{|\mathbf{h}_k^H \mathbf{p}_k|^2}{\sum_{j\neq k} |\mathbf{h}_k^H \mathbf{p}_j|^2 + 1}\right), k = 1,2, \dots, K,$$

where:

$\mathbf{p}_k = \sqrt{\frac{P(1-t)}{K}}\,\bar{\mathbf{p}}_k$, for $k = 1, \dots, K$.

The bitrate of the common stream is calculated as:

$$R_{\mathrm{c}} = \min_{k=1,2,\dots,K} \log_2\left(1 + \frac{|\mathbf{h}_k^H \mathbf{p}_{\mathrm{c}}|^2}{\sum_{j=1}^{K} |\mathbf{h}_k^H \mathbf{p}_j|^2 + 1}\right)$$

where:

$\mathbf{p}_{\mathrm{c}} = \sqrt{Pt}\,\bar{\mathbf{p}}_{\mathrm{c}}$,

the common stream may be split among users: $\{R_{\mathrm{c},1}, R_{\mathrm{c},2}, \dots, R_{\mathrm{c},K}\}$ so that $R_{\mathrm{c},1} + \cdots + R_{\mathrm{c},K} = R_{\mathrm{c}}$, and

the individual bitrate at UE$_k$ is calculated as $R_k = R_{\mathrm{p},k} + R_{\mathrm{c},k}$, $k = 1,2, \dots, K$.

The sum-rate, weak UE bitrate and strong UE bitrate are calculated as $\sum_{k=1}^{K} R_k = \left(\sum_{k=1}^{K} R_{\mathrm{p},k}\right) + R_{\mathrm{c}}$, $\min\{R_1, R_2, \dots, R_K\}$, and $\max\{R_1, R_2, \dots, R_K\}$, respectively.

The power allocation between the common and private streams is controlled by the variable $t \in [0,1]$, where Pt is the power of the common stream and $\frac{P(1-t)}{K}$ is the power for each private stream. Optimal t can be found by exhaustive search between $[0,1]$ to maximize either the sum-rate or the weak UE bitrate.

The rate of the common stream may be split between the UEs in any way without changing the sum-rate. For fairness, it may be desirable to allocate larger fraction of the common stream to UEs with lower rates to better equalize the rates between the UEs. For $K = 2$, let $R_1 = R_{\mathrm{p},1} + \tau R_{\mathrm{c}}$ be the UE_1 bitrate and $R_2 = R_{\mathrm{p},2} + (1-\tau)R_{\mathrm{c}}$ be UE_2 bitrate. $\tau \in [0,1]$ is the fraction of the common rate given to UE_1.

Step 1) Choose τ so that $R_1 = R_2$. If τ falls out of $0 \leq \tau \leq 1$ range, then this is not feasible.

Step 2) If $R_{\mathrm{p},1} - R_{\mathrm{p},2} > R_{\mathrm{c}}$, then give all common stream to user 2 by setting $\tau = 0$.

Step 3) If $R_{\mathrm{p},1} - R_{\mathrm{p},2} < -R_c$, then give all common stream to user 1 by setting $\tau = 1$.

In summary, $\tau = \frac{1}{2} - \frac{R_{\mathrm{p},1} - R_{\mathrm{p},2}}{2R_{\mathrm{c}}}$. If $\tau > 1$, then set $\tau = 1$. If $\tau < 0$, then set $\tau = 0$.

Annex B:
Change history

Date	Version	Information about changes
September 2025	0.01	First draft including MAT(25)02_010r3, MAT(25)09004, MAT(25)10003r2, MAT(25)10004r1
September 2025	0.0.2	Clean version
October 2025	0.0.3	Inclusion of MAT(25)13002, MAT(25)13003r1, MAT(25)13004, MAT(25)14004r2
October 2025	0.0.4	Updated based on the comments in MAT#3
November 2025	0.0.5	Inclusion of MAT(25)14002r9, MAT(25)16003r2, MAT(25)18003r1
November 2025	0.0.6	Inclusion of MAT(25)18004r1
December 2025	0.0.7	Inclusion of MAT(25)19003r1
December 2025	0.0.8	Inclusion of MAT(25)21005 and revision changes in MAT(25)21004r2

History

Version	Date	Status
V1.1.1	January 2026	Publication