On Performance of multi-user Massive MIMO for 5G and Beyond

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***Abstract*—5G New Radio (NR) is the latest radio access technology (RAT) developed by 3GPP for the 5G mobile network. 5G NR and beyond is expected to play a key role in Cyber-Physical Systems as it will deliver significantly faster, more reliable and much lower latency connections to enable wireless control applications. 5G will support three fundamental application scenarios, enhanced Mobile BroadBand (eMBB), Ultra-Reliable and Low deployment Latency Communication (URLLC), and massive Machine-Type Communication (mMTC). mMTC is of particular importance as it forms the basis of IoT, whereas URLLC will support mission-critical applications such as autonomous robotics. The commercial roll-out of 5G is planned in phases with challenging new vertical deployments as the technology is still evolving and little practical experience is available yet. Massive MIMO is a vital enabling technology for 5G NR, enhancing reliability and data rates in challenging environments. It is one of the technologies having a low carbon emission rate as it exploits the resources in an optimal way, hence enabling more sustainable and greener networks. In this paper, we investigate the performance of two MIMO precoding techniques in terms of achievable sum rates for massive MIMO. Simulation experiments show that Zero Forcing (ZF) precoding outperforms Maximum Ratio Transmission (MRT) precoding for the given scenario and assumed conditions.**

***Index Terms*—5G NR, massive MIMO, Zero Forcing (ZF), Maximum Ratio Transmission (MRT), Precoding techniques**

I. INTRODUCTION

5G is looked at as a key enabler for mobile communication system based automation applications in smart manufacturing, industrial Internet of Things (IIoT), smart cities and autonomous vehicles and robotics. With such heterogeneous use cases, the deployment of a 5G network has become a challenge. Fifth-generation wireless (5G) networks will play an important role for future Cyber Physical Manufacturing Systems (CPMS) [1]. With the rapid increase in new use cases and applications, 5G's New Radio (NR) technology promises to support 100–1000x gains in terms of network capacity, one million connections per kilometre-square, 10 Gbit/s peak data rates with 1 ms latency, system spectral efficiency of 10 (bit/s)/Hz/cell, energy efficiency $> 90\%$ improvement over LTE, 500 km/h mobility and with extreme reliability. These high performing 5G networks will play a key role in industrial automation, high-speed V2X connectivity and autonomous driving, and similar applications [2]. In order to support these enhanced requirements, large-scale or massive Multiple-Input Multiple-Output (MIMO) systems are employed at base stations (BSs). They employ antenna arrays that have an order of magnitude more elements (one hundred or more antenna elements) than traditional MIMO systems. While on the other hand, mobile stations (MSs) use single antennas. Massive MIMO works on the principle of favourable propagation, which occurs when the channel vectors between the BS and each MS are nearly orthogonal as the number of BS antennas are increased [2]. We examine the performance of massive MIMO systems in 5G in this paper for two MIMO pre-coding techniques, zero forcing (ZF) and maximum ratio combining (MRT). We show that ZF exhibits significantly better performance than MRT for the chose use case.

The rest of this paper is structured as follows. Related work is presented in Section II. The system model is described in Section III. In Section IV, results are presented followed by a discussion. Lastly, conclusions are drawn in Section V.

II. RELATED WORK

Related work includes [3] where an evaluation of the performance of two linear precoding technologies, namely Zero-Forcing (ZF) and Maximum Ratio Transmission (MRT) for the downlink massive MIMO was carried out using two normalization methods namely vector and matrix normalization to eliminate or mitigate the Multi user Interference. The authors concluded that vector/matrix normalization for ZF performs better at high power, while MRT performs better at low power. Also, according to their findings, the ZF precoding technique is superior than MRT for users near the cell centre (high power), whereas MRT is superior to ZF for users at the cell boundary (low power). Another comparable study is reported in [4], where a performance analysis and comparison of ZF and MRT based downlink massive MIMO systems was carried out focused on achievable data rate plus energy efficiency aspect and the required transmit power simultaneously, under same conditions / assumptions. Parameters which were studied are the achievable sum rate and the total downlink transmit powers, results showed that ZF achieves higher data rates and is also more power efficient than MRT. All these studies assumed a single-cell downlink massive MIMO system. The study in [5] used spectrum efficiency and energy efficiency as metrics to examine the performance of large-scale multi-user MIMO systems. They used the Open Source Lena 5GNR and NS3-MmWave simulators and claimed that it is a first of its kind work reported. Compared with the MRT-MRC precoder, the ZF precoder has better performance. In [6], relative performance analysis of linear precoding in downlink multi-user MIMO was examined and it was shown that the ZF precoding gives a better reachable sum rate (bits/s/Hz). Not only does the low complexity implementation of MIMO systems, such as hybrid beamforming, become more significant as the number of antennas increases, but the spatial features of wireless communications channels also become more critical. To allow reliable performance prediction and research of large-scale MIMO systems, effects including large scale and small scale fading must be accurately and consistently modelled. The research presented in this paper aims to address performance of linear precoding / beamforming techniques under such conditions as defined in the simulation parameters table II.

III. System Model

A MU-MIMO system is one in which the base station allows for multiple parallel communications to occur in the same time and frequency resource, which is known as Space Division Multiple Access (SDMA). The MU-MIMO system has numerous advantages, including increased data rate, link reliability, and improved energy efficiency [7]. In this work, we consider a MU-MIMO downlink system.

A. Beamforming / Precoding Techniques

The precoder takes the output of the layer mapper and maps it to the different antennas. The pre-coding can be configured in different ways, corresponding to different transmission schemes. We investigate the performance of linear precoding in order to analyse massive MU-MIMO downlink systems. Linear precoding is a simple process that involves multiplying the information data vector by a linear precoding matrix to obtain the transmission signal vector. We use two precoding techniques, Zero Forcing (ZF) and Maximum Ratio Transmission (MRT) as they are common for massive MIMO. ZF minimizes inter-beam interference assuming that the base station has perfect channel state information for the downlink, which is the ideal case. In ZF the inter-user interference can be cancelled out at each user. We also assume that in our simulation each of the base stations receives pilot signals from user equipment and is able to determine perfect channel state information (CSI). We then calculate signal to interference plus noise ratio (SINR) and throughput for each of the users in the cells. ZF precoding is assumed to implement a pseudo-inverse of the channel matrix [8].

$$A_{ZF} = (1/\beta)H^*(H^T/H^*)^{-1} \tag{1}$$

where

$$\beta = \sqrt{tr(BB^H)/P_{tr}} \tag{2}$$

with

$$B = H^*(H^T H^*)^{-1} \tag{3}$$

where A is a precoding matrix, β is the scalar of a Wiener filter. P_{tr} is the average power constraint.

ZF sets beamforming weights to minimize interference to all other users in a cell, placing them within local nulls. Both of these techniques are show in Figure 1.

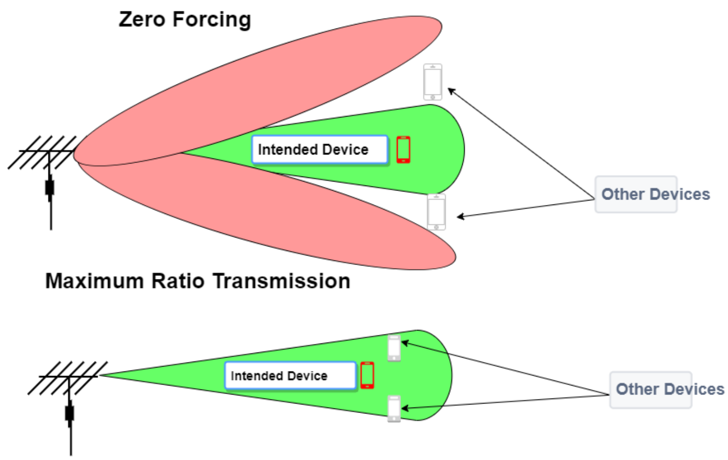

Fig. 1: Illustration of Zero Forcing and Maximum Ratio Transmission Beamforming Techniques.

ZF attempts to minimize the amount of interference that the beam causes to other users while maximizing the signal strength to an intended user equipment. Maximum ratio transmission (MRT) simply tries to form the strongest beam that it can to one of the intended devices without any concern for how much this may cause interference to other devices. MRT can cause significant interference to other users and is not the best way to form the beams for multiuser MIMO, but it works quite well if there is only a single user. In simple words, MRT maximizes the SNR.

$$A_{MRT} = (1/\beta)H^* \tag{4}$$

where

$$\beta = \sqrt{tr(BB^H)/P_{tr}} \tag{5}$$

with

$$B = H^* \tag{6}$$

In our model uplink and downlink transmissions are performed on different frequency bands at the same time in the traditional FDD mode. There is no correlation between their wireless channels if the frequency separation between uplink and downlink bands is large. As a result, for the FDD mode, we assume the uplink and downlink channels are independent and generate them separately.

B. Simulation Setup

In this study, we performed our simulations using the Vienna 5G link level simulator [9]. Because the goal of the link level simulation is to obtain the average link performance, each scenario requires a large number of random channel realisations. Because there is no network geometry, there is no path loss model. A cell should be viewed as a network of nodes rather than a physical space.

The path loss of a link is an input parameter that determines the average signal-to-noise ratio (SNR) of the user. Channel pathloss is 100dB per link. As a result, while the channel model only includes small scale fading effects, this parameter governs the average channel power. For channel modeling we have employed a tapped delay line (TDL) with frequency selectivity and the channel is generated using this model.

We calculated the beamforming with weights, SINR for MIMO streams and MIMO throughput. The scenario consists of two independent base stations (BSs). In our system model, to simulate multiuser MIMO, we placed eight individual user equipments (UEs), four are associated with one base station and the next four users are associated with the other base station. Each BS performs a downlink transmission to connected users using massive MIMO for connected users. The first BS employs ZF precoding, while the second BS employs MRT. UE1 to UE4 are associated with BS1 which uses ZF whereas UE5 to UE8 are latched to BS2 which uses MRT, both for downlink as well as for uplink. To disable interference between BS1 and BS2, we have set an inflated attenuation level to virtually divide the two BSs. The two cells only serve to simulate two different multi-user MIMO modes in one simulation to allow for comparison of simulation results.

The UE distribution and association is given in table I.

TABLE I: The UE distribution and association

MIMO Mode	User /BS
ZF-MU-MIMO	UE1/BS1
ZF-MU-MIMO	UE2/BS1
ZF-MU-MIMO	UE3/BS1
ZF-MU-MIMO	UE4/BS1
MRT-MU-MIMO	UE5/BS2
MRT-MU-MIMO	UE6/BS2
MRT-MU-MIMO	UE7/BS2
MRT-MU-MIMO	UE8/BS2

We have considered and averaged over different random deployments for each of these scenarios to estimate the average behaviour. For the ZF scenario beams are formed to each user simultaneously while trying to form nulls to the other users. Each base station forms 4 beams simultaneously and tries to form those beams such that they would form nulls simultaneously to the other 3 users within the cell. We simulated this scenario in the Vienna 5G Link Level Simulator. The MRT technique tries to generate the maximum beam to any point throughout the cell. Small scale fading results due to the dynamic scattered path and "constant scattered path". The small-scale fading is modelled as Rayleigh fading. The centre frequency is set to 2.5 GHz. Note that the centre frequency only impacts the channel model in terms of the maximum Doppler shift. It is important to mention here that small-scale fading does not depend on movement of UE, where normalized Jake's Doppler power spectrum is given analytically by:

$$S(f) = 1/\pi f_d \sqrt{1-(f/f_d)^2}, |f| \leq f_d \tag{7}$$

where the max Doppler frequency is f_d

The parameters of the simulation are given in table II.

TABLE II: Simulation Parameter's

Parameter	Value	Parameter	Value
Frequency	2.5 GHz	Channel pathloss (dB)	100 per link
Antenna Configuration	[4, 4] per BS	Doppler Model	Jake's
Number of antennas at the BS	16 per BS	Time Subsampling Factor [for time-varying channels]	10
Channel Coding	Turbo	Number of propagation paths for the Doppler model	50
Channel Decoding	Max-Log-MAP	Antenna Spacing	1/2
Number of UE's per Base Station	4	Modulation cqi	QPSK to 64-QAM
Modulation waveform	OFDM	Number of used subcarriers	72
Transmission Mode BS 1	Downlink: (ZF-MUMIMO)	Transmission Mode BS 2	Downlink: (MRT-MUMIMO)
Pilot Pattern Uplink / Downlink	LTE Uplink	User Velocity	5km/h
Feedback	Channel Quality Indicator (CQI)	Duplexing Mode (Frame Structure)	FDD
Small Scale Fading	Rayleigh fading	MIMO detector / Receiver Type	MMSE
Power Delay Profile	Pedestrian A	Channel estimator	Approximate-Perfect

IV. Results And Discussions

The ZF precoder cancels the interference between users, whereas the MRT maximizes the received power and does not cancel the interference. As the number of antennas becomes very large, the channel vectors between the BS and the UEs are nearly orthogonal (aka favorable propagation). For a large number of antennas, the post-equalization interference is very small for both precoders. Therefore, both schemes saturate at the maximum throughput.

In Figure 2 we show Downlink Throughput per user and in Figure 3 we show the downlink sum throughput comparison by plotting against the variation of the number of Base Station Antennas, for ZF beamforming and MRT respectively. The results show the performance of ZF to be significantly better than MRT.

Figure 4 shows uplink throughput per user against Number of BS antennas for both beamforming strategies and Figure 5 shows the comparison in Uplink Sum Throughput. The results show ZF exhibits improvement as far as throughput is concerned over MRT.

The confidence intervals are calculated via bootstrapping. By default, a 95% confidence level is used. Large confidence intervals correspond to uncertain results, meaning that if we repeat the simulation, we are less likely to get a similar

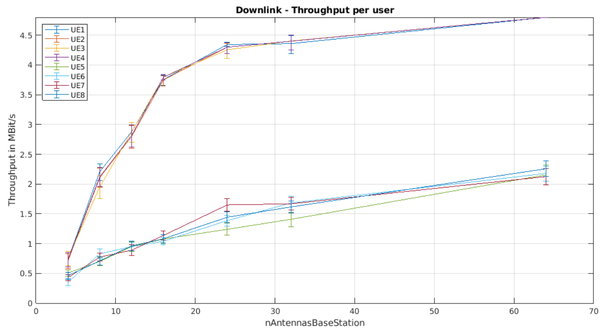

Fig. 2: Downlink Throughput per user over Number of Base Station Antennas for the two considered Beamforming strategies.

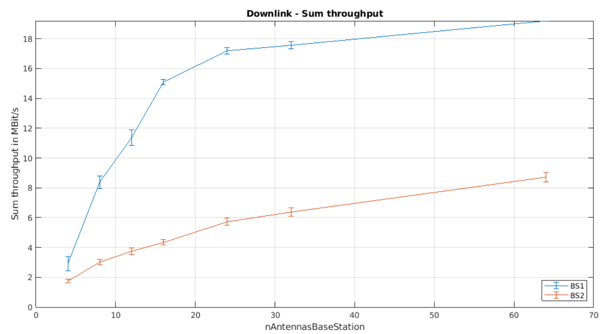

Fig. 3: Downlink Sum Throughput over Number of Base Station Antennas for the two considered Beamforming strategies.

average value (of the throughput for example). To make them smaller, and therefore make the results more accurate and representative, we have increased the number of simulation samples by increasing the number of simulated frames to a larger value in the scenario. Experimental results show that ZF beamforming outperforms MRT beamforming.

Spectral efficiency is also an important parameter in a wireless system. Spectral efficiency always improves by increasing antennas as it helps in getting larger array gain and also because

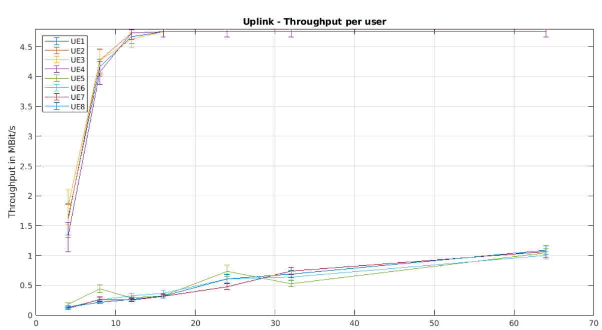

Fig. 4: Uplink Throughput per user over Number of Base Station Antennas for the two considered Beamforming strategies.

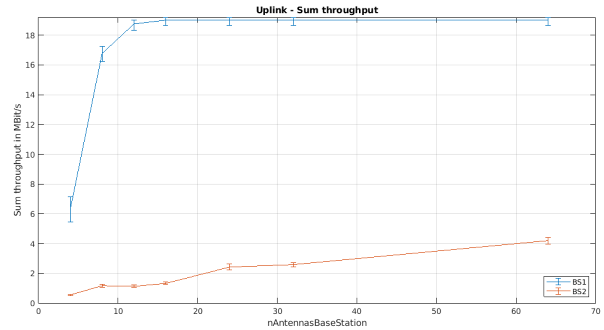

Fig. 5: Uplink Sum Throughput over Number of Base Station Antennas for the two considered Beamforming strategies

of favourable propagation properties [10]. Spectral efficiency is directly proportional to service antennas as they add larger array gain. For this reason, massive MIMO is a system with at least an order of magnitude more antennas than UEs. In our scenario, M is the number of antennas and K is the number of terminals. M ranges from 4 to 64 whereas K is 4. Figure 6 shows the spectral efficiency versus the number of antennas. It shows spectral efficiency for ZF and MRT reusing the method as described by [10]. Power control is applied to provide an SNR of 5 dB for each terminal. By increasing the number of antennas, spectral efficiency with linear precoding improved significantly.

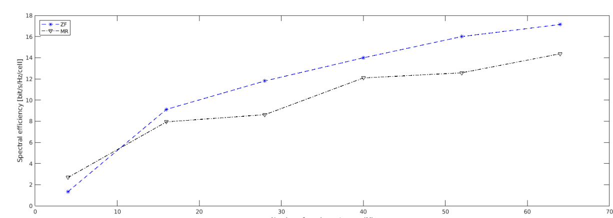

Fig. 6: Sum spectral efficiency for Rayleigh fading channels in environments, such as buildings, stadiums and other indoor environments with linear processing. When M = K, the loss incurred by linear processing is large, but it quickly decreases as the number of antennas increases.

V. Conclusions

This work analysed performance of Massive Multiple-Input Multiple-Output (MIMO) systems in 5G. The ZF precoder cancels the interference between users, whereas the MRT maximizes the received power and does not cancel the interference. As the number of antennas becomes very large, the channel vectors between the BS and the UEs are nearly orthogonal (aka favorable propagation). For a large number of antennas, the post-equalization interference is very small for both precoders. Therefore, both schemes saturate at the maximum throughput. Experimental results show that Zero Forcing (ZF) beamforming outperforms Maximum Ratio Transmission (MRT) beamforming at a small as well as large number of antennas.

While both sum throughput plots, from cell one and cell two, do of course increase with an increasing number of antennas, the ZF cell throughput attains saturation value for a smaller number of antennas compared to the MRT cell. Besides, the sum throughput of MRT approaches close to that of ZF with the increase in Base Station antennas. Spectral efficiency analysis shows ZF has high spectral efficiency for large number of service antennas.

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