Performance Analysis of NOMA for Massive MIMO Systems*

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Abstract. Non-Orthogonal Multiple Access (NOMA) and massive Multiple Input Multiple Output (mMIMO) have been addressed as a promising candidates for fifth generation (5G) networks and beyond 5G. In this paper, we have analyzed the performance of downlink NOMA for massive MIMO Systems in contrast to conventional MIMO systems. Furthermore, we have also explored the performance gains of MIMO NOMA compared to its traditional MIMO OMA counterpart. Users are grouped into different clusters by combining any two users with same spatial direction or having higher correlation between their channels but having different channel conditions. In addition, we have investigated the performance of two user per cluster in downlink NOMA with a base station equipped with large number of antennas. We have used 64 number of antennas at the BS in the case of massive MIMO NOMA, but in the case of multiuser MIMO NOMA, we used three different configurations of antennas at the BS, i.e., three number of antennas at the BS and at the user side. Perfect channel state information is assumed in both massive MIMO NOMA and multiuser MIMO NOMA, and we have allocated less power for the near users where we have allocated more power for the weak users. The numerical conclusions reveal that multiuser MIMO NOMA outperforms multiuser MIMO OMA. Moreover, we have also noticed that massive MIMO NOMA outperforms MIMO NOMA.

Keywords: NOMA · massive MIMO · MIMO-NOMA.

1 Introduction

We are on the dawn of 5G cellular communication technology that will transform the way we are communicating, it is a dramatic change of wireless communication systems in terms data rate, latency and number of devices connected together. In each decade of mobile communications, there is an emergence of new generation of cellular technology, in the initial of 1980's, the first generation (1G) of cellular technology was announced. The primary focus of this generation was transmitting a voice with a peak data rate of 2.4kbps. In 1990's, the second generation (2G) was launched which supports an improved voice and text

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messages. The mobile data access was the main target use case of third generation (3G) cellular technologies in 2000's with both circuit switched and packet switched core network. For the last decade, fourth generation (4G) was emerged with a target use case of growing data rates and a broadband connectivity. However, 5G will introduce huge and extremely data rates with ultra-dense wireless networks, massive device to device communication. To meet this paradigm and seismic shift, 5G is being designed to encounter the new IMT 2020 and beyond targets in [1]. IMT 2020 and beyond can be summarized into three service types: massive Machine Type Communications (mMTC), enhanced Mobile Broadband (eMBB), and Ultrahigh Reliable and Low Latency Communications (URLLC).

IMT 2020 and beyond is envisioned to support an enhanced network capability in comparison to the capabilities of current networks. It will support a maximum data rate of 20Gbps in downlink communication and 10Gbps in uplink case. But the user experienced data rates of fifth generation will be 100 fold of the current communication technologies. 5G is aimed or designed to reduce the latency up to 1ms with very high dense environment that can support 1 million devices in each km^2.

When considering the requirements for IMT 2020 and beyond, it becomes apparent to develop new technologies that boosting the system throughput or capacity in order to achieve these target scenarios. So, in terms of wireless communication resources, different innovations and key technologies have been suggested or proposed and developed for 5G wireless networks. Non- Orthogonal Multiple Access (NOMA) and massive Multiple Input Multiple Output (mMIMO) are the main candidates for the fifth-generation networks in order to enable a paradigm shift of 1000-fold data rate.

NOMA has been emerging as a key enabling technology for the fifth generation wireless networks to enlarge the network density by enlarging the number of nodes or users, enhance or promote the spectral efficiency by allowing or letting more than one mobile subscriber or user to share one wireless resource block simultaneously. Moreover, NOMA improves system latency and user fairness. To meet these heterogeneous demands, NOMA is a vital or essential and promising technology by comparison with conventional OMA systems. The conventional OMA schemes such as FDMA for 1G systems, TDMA for 2G systems, CDMA for 3G systems and OFDMA for 4G system are based on a common and key concept of serving one user in each resource block by orthogonalizing the signals of different users. This concept limits the system capacity in terms of network densification and spectral efficiency. Furthermore, the link establishment and random access phases are the major causes of the latency in the traditional OMA schemes. In addition to these improvements, fifth generation networks will support massive connectivity in order to ensure some of the new technologies such as Internet of Things (IoT). Thus, NOMA is indispensable for the forthcoming 5G networks.

Massive MIMO is another emerging technology for the fifth generation networks that significantly enhances the system throughput. Massive MIMO will meet the desirable requirements of the next decade wireless networks, such as, huge spectral efficiency and also energy efficient networks. Massive MIMO uses hundreds of antenna arrays at the BS or at the transmitter sector, and sometime at the receiving devices with the goal of enhancing the system throughput. Massive MIMO is dependent on the spatial multiplexing which in turn relies on the knowledge of base station to the operating environment. Massive MIMO system is an enlarged conventional MIMO system. The concept of unlimited or massive number of antenna arrays at the BS was first coined by Marzetta in [2]. Nevertheless, the integration of NOMA and massive MIMO systems is expected to boost the system efficiency in terms of spectral efficiency and also in terms of energy efficiency.

2 Literature Review

In [3], it is considered the utilization of NOMA in multiuser MIMO with shared pilots within each cluster, and compares the achievable performance with a comparable conventional network with orthogonal pilots. However, locating more clusters inside the cell diminishes the performance gain. The performance of MIMO-NOMA is conducted in [4] by considering a randomly deployed multiple users. In [5], it is conducted fully or complete non-orthogonal communication for both channel estimation and multiple access technology to tackle conventional orthogonal channel estimation methods that are not applicable for the future wireless networks and the impact of imperfect SIC that degrades performance, since there a leakage of interference even when the SIC is applied. But, the performance decreases in highly overloaded conditions.

The authors in [6] explored the role that can NOMA play in or carry out in massive MIMO systems. In addition, it is compared the performance of massive MIMO NOMA over the standalone NOMA and massive MIMO. In [7], a limited or low feedback NOMA design is proposed, where the massive MIMO system is decomposed into a multiple SISO NOMA channels for the simplification of design complexity. Reference [8] explores the characteristics of finite resolution beamforming under millimeter wave massive MIMO with NOMA. A single cell equipped with a large number of antennas at the base station is conducted in [9] for the sake of capacity under millimeter wave conditions. however, only single cell is studied. In [10], it is considered a low complexity algorithm of Passing Gaussian Messages for uplink multi-user discovery in overloaded conditions of massive MIMO NOMA. Most the antecedent works of [7]-[10], assumed that the BS has perfect CSI.

The authors in [11] proposed an efficient antenna selection mechanism and user scheduling methods for the maximizing of the sum rate in massive MIMO-NOMA systems. In [12], the authors targeted to achieve multiuser gain which is difficult to achieve unless accurate CSI is found. To tackle this issue, it is proposed IDMA and iterative data aided channel estimation which results high data throughput, and it is robust to pilot contamination. In reference [13], the performance yield of NOMA for massive MIMO systems is considered with spatially distributed users that are grouped into several clusters based on the information of spatial-direction for both finite and infinite antennas at the base station. To the most of prior works i.e. [3], [5]-[9], were concentrated in downlink communication scenario, thereby, the authors in [13] discussed the performance of NOMA with massive MIMO systems in uplink communication scenario. The main contribution of our study is analyzing the performance of massive MIMO NOMA by comparing multiuser MIMO NOMA.

3 System Design

We have considered single cell downlink communication scenario. The number of antennas at the base station is very larger than the number of antennas at the user equipment. The number of antennas at the user equipment is single antenna ($N = 1$) where the number of antennas at the base station is about 64 antennas ($M = 64$). So, M is very larger than N ($M \gg N$). The users are grouped into multiple clusters where each cluster consists of two users. Half of the users are located at the cell edge where the rest of the users are located at the cell center. Based on this, users are classified strong users and weak users since their distances to the base station is different.

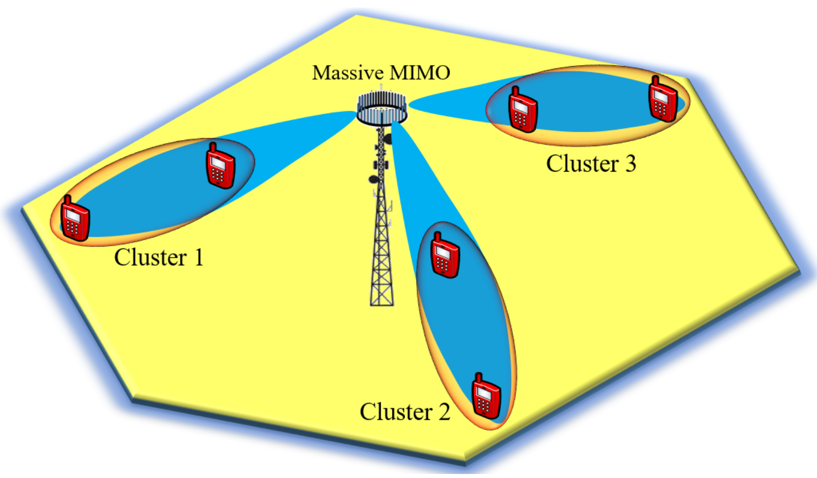

Fig. 1. System model of NOMA with massive MIMO systems

The users near to the base station have strong channel gains where users at the cell edge has weak channel gains since they experience more interference from the neighboring cells and its cell itself. The concept of superposition coding is implemented at the base station and successive interference cancellation is being applied at the receiving units to combat the intra-cluster interference. For the sake of simplicity and convenience of analysis, we have assumed the channel status information of the system to be perfect.

The base station processes a power multiplexed signal for the users in the m-th cluster by making use of the concept of superposition coding

$$x_m = \sum_{k=1}^{K} \sqrt{\alpha_{m,k}} s_{m,k} \tag{1}$$

Where $s_{m,k}$ is the information bearing signal of k-th user in m-th cluster, i.e. for the first cluster $x_1 = (\sqrt{\alpha_{1,1}} s_{1,1} + \sqrt{\alpha_{1,2}} s_{1,2})$ where $\alpha_{m,k}$ is power allocated to the k-th user in m-th cluster. Herein, $s_{1,1}$ and $s_{1,2}$ is the strong and weak signals respectively that are transmitted towards the first cluster where $\alpha_{1,1}$ and $\alpha_{1,2}$ are their corresponding allocated powers respectively. By the applying the rule of NOMA, $\alpha_{1,1} + \alpha_{1,2} = 1$.

The base station transmits the superimposed signal (x_m) with the transmit beam (φ_m) for specific spatial direction based on the concept of the users that have different channel gains. So, the total transmit signal that is transmitted by the base station is equivalent to $\mathbf{x}$:

$$\mathbf{x} = \sum_{m=1}^{M} \varphi_m \sum_{k=1}^{K} \sqrt{\alpha_{m,k}} s_{m,k} \tag{2}$$

We can simply write this expression by combining equation (3.15xxxxx) and (3.16xxxxxxx) in [31].

$$\mathbf{x} = \sum_{m=1}^{M} \varphi_m x_m \tag{3}$$

The observed signal by k-th user in m-th cluster is given by the following expression in [31].

$$y_{m,k} = \sqrt{\alpha_{m,k}} \mathbf{h}_{m,k}^H \mathbf{x} + n_{m,k} \tag{4}$$

Where $n_{m,k}$ is the additive white Gaussian noise in the system with a variance of one. There are m-th clusters inside the cell with two users in each, so there is intra-cluster interference, inter-cluster inference and unwanted signals along with desired signal. Intra-cluster interference is used to mitigate by the use of SIC where the inter-cluster interference is used to mitigate spatial beams intended to the clusters. $\alpha_{m,k}$ from equation (3.18) is the path-loss and shadowing fading coefficient where $\mathbf{h}_{m,k}^H$ is the channel vector of fast fading coefficient related to the downlink transmission from the base station to the user equipment in m-th cluster. $\alpha_{m,k}$ is considered to be constant during a relatively long time where $\mathbf{h}_{m,k}^H$ fades over time independently.

The received signals by the user equipment do not consist of the desired signals only, but we receive it along with undesired signals such as interference signals from the users inside the cluster and interference from other clusters, moreover the noise is along with each receiving signal. The observed signal along with the other signals can be expressed as follows

$$y_{m,k} = \sqrt{\beta_{m,k}}\mathbf{h}_{m,k}^{H}\varphi_m\sqrt{\alpha_{m,k}}s_{m,k}+\textstyle\sum_{l=1l\neq k}^{K}\sqrt{\beta_{m,k}}\mathbf{h}_{m,k}^{H}\varphi_m\sqrt{\alpha_{m,l}}s_{m,l}$$
$$+\sum_{j=1j\neq m}^{M}\sum_{l=1}^{K}\sqrt{\beta_{m,k}}\mathbf{h}_{m,k}^{H}\varphi_j\sqrt{\alpha_{j,l}}s_{j,l}+n_{m,k} \quad (5)$$

The users inside the same cluster perform successive interference cancellation algorithm to mitigate the intra-cluster interference, in order to perform this technique at the user equipment, without loss of generality, we assumed to have descending order of user ordering. Every weak user (cell-edge user) is allocated higher power where the strong user (cell-center user) is allocated less power, this is the concept that power-domain NOMA. In our system model, each cluster consist of only two user equipment, thereby the effective channel gains of the users in the m-th cluster can be given by

$$\sqrt{\beta_{m,1}}\mathbf{h}_{m,1}^{H}\varphi_m|^2 \;\; \geq \;\; |\sqrt{\beta_{m,2}}\mathbf{h}_{m,2}^{H}\varphi_m|^2 \quad (6)$$

However, the achievable rates of k-th user in the m-th cluster is given by the bellow expression

$$R_{m,k} = \left(1-\frac{\tau}{\tau_c}\right)log_2(1+\gamma_{m,k}) \quad (7)$$

$1-\dfrac{\tau}{\tau_c}$ is the pre-log factor, Pre-log factor is the fraction of downlink samples per coherence block that are used for the downlink transmission. Pre-log factor increase if we decrease the size of the length of the pilots sequences which means reducing the pilot overhead, moreover, decreasing the number of samples used for the downlink transmission (τ_d) in massive MIMO systems with NOMA increases the pre-log factor. $\gamma_{m,k}$ is the observed or received signal to interference plus noise ratio (SINR) corresponding to the k-th user in the m-th cluster in the cell.

4 Results and Discussions

In here, we have the simulation results of massive MIMO systems with NOMA compared to that of conventional multiuser MIMO with NOMA. The performance comparison between massive MIMO NOMA and conventional multiuser MIMO NOMA is not yet considered. So, in here, we have explored the performance comparison between conventional multiuser MIMO systems with NOMA and massive MIMO systems with NOMA. The bandwidth used for the simulation of the system is 10 MHz, and the power allocated to the near user is 0.2 where the power allocated to the far user is 0.8. The number of antennas at the base station is $M = 64$. Zero-forcing precoding is performed at the transmitter side. So, the following figure explores the performance of massive MIMO NOMA with ZF precoding at the transmitter side.

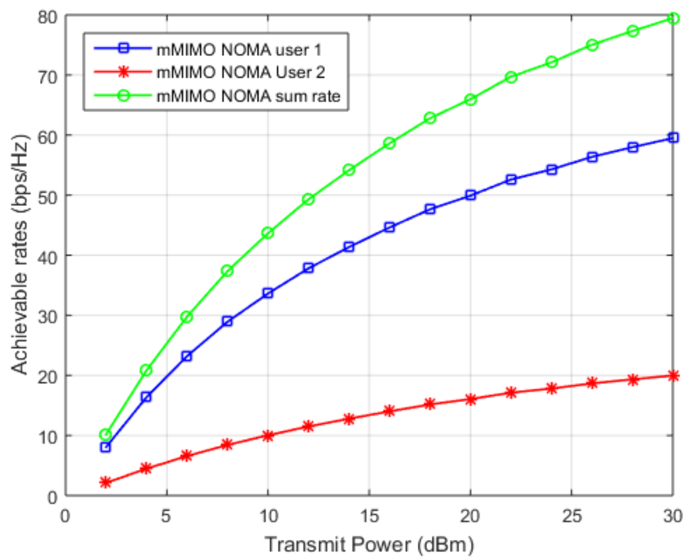

Fig. 2. Achievable rates of massive MIMO NOMA users

From figure 4.27, we have demonstrated the performance yields of massive MIMO NOMA users. The spectral efficiency of the users increases with transmit power as shown in the figure. The achievable rate of the near user is higher than the achievable or attainable rate of the far user, because of the interference.

If we compare the sum rate between massive MIMO NOMA users to that of conventional multiuser MIMO NOMA users which we have previously discussed, there is big capacity difference between the two sum rates as shown in figure 4.28. As shown in figure 4.28, the performance of massive MIMO with NOMA is more than the performance of conventional multiuser MIMO with NOMA. In figure 4.28, we have considered three different configurations of antennas at the BS and at the user side. First we have considered three number of antennas at the BS and at the user side, then we have increased the number of antennas at the BS and at the user side upto six and twelve number of antennas, and we have revealed how big the performance gap between these conventional MIMO NOMA and massive MIMO NOMA. In conventional multiuser MIMO NOMA, as the number of antennas at the radio BS and at the receiving units increase, the spectral efficiency of the system also increases.
The following figure depicts the individual achievable rates of the near users and far users in both massive MIMO systems with NOMA and conventional multiuser MIMO systems with NOMA in a single plot. So, the attainable rates of conventional multiuser MIMO systems with NOMA are very lower than the achievable or attainable rates of massive MIMO systems with NOMA as shown in figure 4.29. The far user in MIMO NOMA experiences a lot interference, and

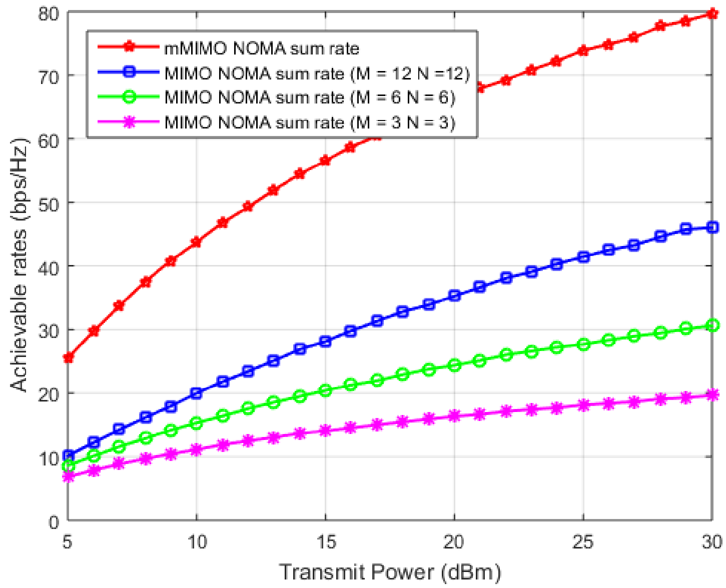

Fig. 3. mMIMO NOMA vs MIMO NOMA

that is why it is appearing as a saturating line. In figure 4.29, we have discussed the performance comparison of individual achievable rates and the sum rate comparison between massive MIMO systems with NOMA and conventional multiuser MIMO systems with NOMA. So, massive MIMO systems with NOMA can achieve higher throughput rate than multiuser MIMO with NOMA.
The following figure depicts when we increase the number of users from two user equipments up to six number of users, for the previous figure, the achievable rates that we have discussed was based on per cluster capacity. So, in the following figure, we have considered the whole capacity of the system, which means that we have three number of clusters and each cluster consist of two UEs, therefore the total number of UEs in the system is six. The achievable rates of the system is being explored by figure 4.30.

The following figure depicts when we have used twelve number of users, the achievable rates of the users by considering all the different configurations of antennas in the case of conventional multiuser MIMO NOMA by comparison with massive MIMO NOMA which we have considered a large number of antennas at the base station.

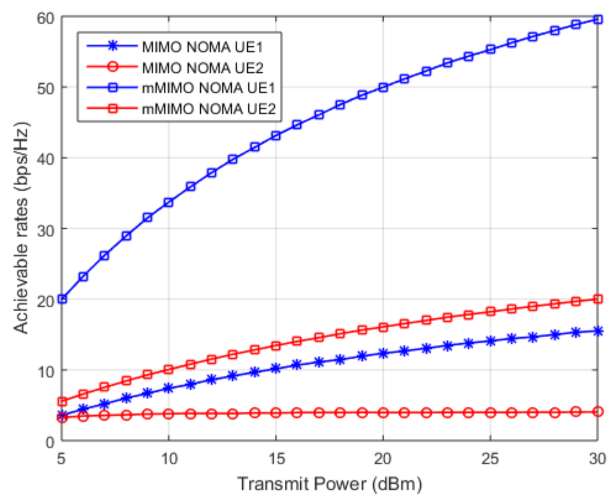

Fig. 4. mMIMO NOMA vs MIMO NOMA

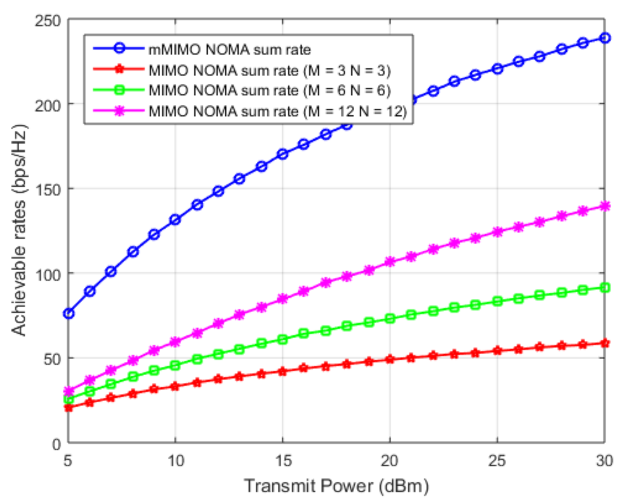

Fig. 5. mMIMO NOMA vs MIMO NOMA (6 Users)

5 Conclusion

We have discussed the performance of NOMA for massive MIMO systems in contrast to conventional multiuser MIMO systems. We have considered a large number of antennas and zero-forcing precoding at the transmitter side. Then we have compared the performance of massive MIMO NOMA with that of multiuser

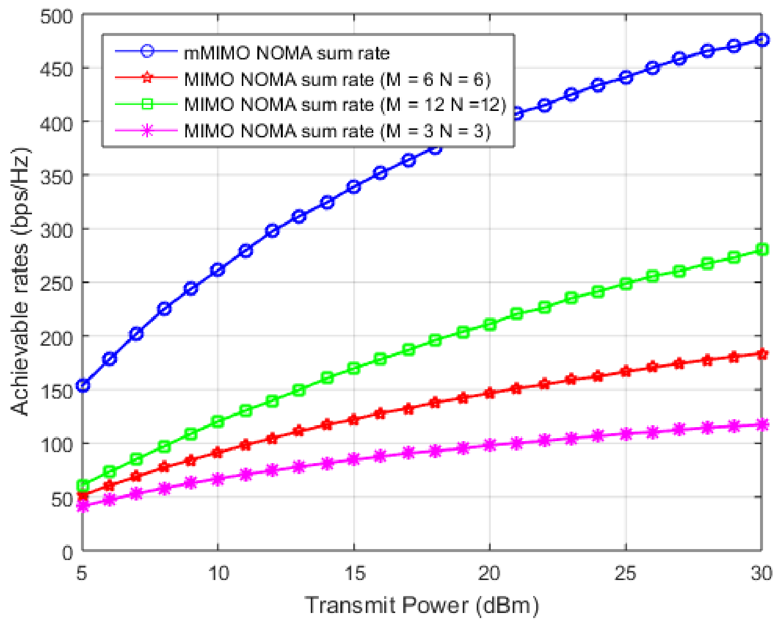

Fig. 6. mMIMO NOMA vs MIMO NOMA (12 Users)

MIMO NOMA. We noticed that massive MIMO NOMA outperforms multiuser MIMO NOMA. lastly, we conclude that standalone NOMA outperforms standalone OMA, and multiuser MIMO NOMA outperforms multiuser MIMO OMA, and massive MIMO NOMA outperforms multiuser MIMO NOMA.

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