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5G 및 Beyond 5G를 위한 고용량 제약 조건에서 다중 안테나 기술에 대한 NOMA와 OMA 비교

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NOMA and OMA Comparison for Multiple Antenna Technologies under high Capacity Constraints for 5G and Beyond

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요 약

비-직교 다중 접속 (NOMA, Non-orthogonal Multiple Access) 은 대규모 연결, 낮은 지연시간, 향상된 전송률을 요구하는 5G 무선 통신 네트워크의 유력한 후보다. 기존 문헌에서 직교 다중 접속 (OMA, Orthogonal Multiple Access) 은 채널 용량 및 합 용량에 대해 NOMA와 비교되며, 여기서 NOMA는 비-직교성으로 인하여 채널 용량 및 연결성 측면에서 OMA를 능가한다. 그러나 이 비교들은 단일 안테나 시스템 또는 제한된 수의 다중 송신 안테나에 대해 수행된다. MIMO(Multiple-Input-Multiple-Output) 시스템에 대해, 전송 안테나 수보다 많은 사용자 수가 있는 경우와 그 반대의 경우에서 NOMA와 OMA의 용량 비교 결과는 상당히 다르다. 본 논문에서는 중요한 요구 사항 (예 : 채널 용량, 합 용량, 대규모 연결)에서 대규모 MIMO 시나리오에 대한 다중 액세스 기술의 역할이 무엇인지에 대한이 질문에 답한다. 하이브리드 시스템으로 OMA와 NOMA를 함께 사용하거나 물리적 계층에서 OMA와 NOMA로 전환하는 것의 중요성을 강조하기 위해 일부 특수한 경우도 정의한다.

Key Words : Non-orthogonal Multiple Access (NOMA), Massive MIMO, Successive Interference Cancellation (SIC), Fifth Generation (5G), Random Access Technologies (RATs)

ABSTRACT

Non-orthogonal Multiple Access (NOMA) is always considered the best candidate for Fifth-Generation (5G) wireless communication network as it demands mass connectivity, low latency and increased data rate. In the literature, Orthogonal Multiple Access (OMA) is compared with NOMA for the sum rate and capacity, where NOMA leads the OMA in terms of capacity and huge connectivity due to the freedom of non-orthogonality. However, these comparisons are carried out rather for single antenna system or a limited number of multiple transmitting antennas. For multiple-input-multiple-output (MIMO) system, the capacity comparison is quite different for NOMA and OMA, especially where the number of users out-number the transmitting antenna. This paper answers this query that what is the role of multiple access techniques for massive MIMO scenarios under vital requirements i.e. increased channel capacity, sum rate, and mass connectivity. Some special cases are also identified to highlight the importance of using both OMA and NOMA together as a hybrid system or switching to either of it at the physical layer.

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Ⅰ. Introduction

Non-Orthogonal Multiple Access (NOMA) has attracted the attention of the researchers since very long because of its spectral efficiency and ability to handle mass connectivity by its non-orthogonality[1]. To meet the 5G cellular network requirement along with NOMA, several technologies have been investigated to increase the capacity and spectral efficiency of the wireless communication system. Among those technologies, the massive MIMO is one the most highlighted solution that is presented in the literature, which refers to a large number of antenna arrays at the Base Station (BS)[2]. After the standardization, where the first release of 5G consists of many other features, one of the most prominent feature was combined structure of NOMA and massive MIMO, which raises the most general question about choosing the best technology which can enhance the data rate, increased demand of connections and spectral efficiency. In this article, the answer to this query is presented by considering both NOMA and massive MIMO for 5G wireless communication network.

The concept of NOMA is very simple as it holds the capability for multi-user transmission allocating the same frequency, time or code resources to all the users simultaneously. Superposition algorithm is applied to merge the user's data by allocating the different power levels to each user and the combined signal is transmitted in the same beam-forming scheme. In NOMA, users are grouped because of different channel condition at each user, typically the poor channel gain is assumed at the far user because its distance from the BS is larger, while the channel at the near user is assumed to be the better and these two users are grouped in the system. Far user is located at the edge of the cell, far from BS and the near user is usually located at the centre of the cell, near to the BS. Far users are allocated with high transmission power because of the poor channel gains, and it needs to suppress the interferences occurred due to the presence of other user's signal in the same transmission. At the receiver side, NOMA implies successive interference cancellation (SIC) technique to decode the signal. Usually, the user near to the BS will decode the high-power user's data first and its interference is cancelled out using SIC[3]. Therefore, in the power domain NOMA, it is not necessary to assign high power to the user near to the BS to achieve increased data rate. To perform SIC, accurate channel state information (CSI) is compulsory to assume that there must not be any significant remaining interference at the user performing SIC. That is why the process of SIC depends on the perfect channel quality estimation using downlink pilot signalling at the BS[4]. For SIC process, near user needs to decode the high-power signal first which requires buffering to execute the SIC completely. But these complexities and buffer storage could only be the concern for application-specific devices where low cost and less power consuming system is required, hence these both are not assumed here.

NOMA exploits the power allocation procedure and allows multiple users data combinedly transmitted which is a completely different case compared to orthogonal multiple access (OMA) technology. In OMA, the users are allocated undivided transmit power therefore, no intra-cell interference occur in OMA based communication system. However, for conventional OMA systems, the spectral efficiency lags in comparison to NOMA, where almost twice the bandwidth efficiency can be achieved[5]. OMA is considered a benchmark to compare the performance and characteristics of a wireless communication system with NOMA for modern wireless communication networks. Specifically, when the wireless communication has entered into the age of 5G and beyond 5G technologies and NOMA has been presented as a best possible candidate to serve 5G requirements for modern cellular networks, NOMA is always assessed with its comparison to OMA. There are a lot of researches which present the comparison of both OMA and NOMA with different setups and assumptions[6]. This paper specifically focuses to compare conventional OMA scheme with the most researched NOMA scheme under high capacity requirement and assuming massive MIMO setup. In massive MIMO the BS is equipped with a large number of antennas (M), and the setup includes a huge figure of active users (K). If the number of antennas at the BS are greater than the number of active users, it gives a high spatial resolution to spatially combine the user in the same resource block[7]. Dedicated beam assigning to each user helps to attain antenna array gain for the intended signal and to reduce inter-user interference (IUI)[8]. To overcome this IUI, Zero-forcing (ZF) beam-forming is considered as a moderate scheme which also performs well under incomplete channel state information scenarios. Most of the literature work considers NOMA system with a single transmitting antenna only, but some researches present the NOMA system with multiple antennas at the BS[9]. This study focuses on the performance of both the schemes NOMA and OMA for high capacity demands of 5G and B5G systems. Generally, each work presented in the comparison of NOMA and OMA, both the techniques are considered as multiple access technique and ZF beam-forming is included to make the setup spectrally confined for multi-user scenarios. We demonstrate that for a massive MIMO system where users are assumed to be greater in number and affect the capacity of the system, the proposed NOMA scheme with MIMO setup can enhance the capacity of the system to a significant gain. Furthermore, the results show that NOMA with massive MIMO setup has the potential to cater to high data-rate by significantly taking the lead over conventional OMA system.

Ⅱ. Literature Study

In the previous studies [10], [11], [12], MIMO-NOMA application is described for the rate gap between NOMA and OMA. Typically, these studies consider either a single antenna at the BS or the users in the setup is equal to the number of BS antennas, which is not the definition of massive MIMO setup. Similarly, various research works i.e. [13] consider massive MIMO setups for a larger number of transmitting antennas at the BS as compared to users in a cell. The presented work in [12] focuses on the convex solution for the NOMA scheme i.e. power allocation strategies and optimization of power towards increased gain. Similarly, in [13] the comparison of massive MIMO technique and NOMA is presented to justify the selection of either scheme or opting hybrid system based on the application dependent scenario. Furthermore, [14] gives insight about the design hierarchy for massive MIMO NOMA system to prevent users from going fade and outage probabilities have been discussed. In this research work, we have investigated the performance comparison of conventional OMA scheme aided with beam-forming with the typical NOMA scheme. The interest of this research is to highlight the potential of NOMA scheme in massive MIMO scenarios to provide better user induction and remarkable performance in terms of capacity which is an essential requirement of 5G cellular system. Moreover, both line of sight (LOS) and non-line of sight (NLOS) models are considered. This work also gives support to the argument made in [13] that both the schemes can be utilized in a hybrid way to support mass connectivity demands for 5G and B5G networks. This performance analysis gives better insight to gain benefits from both conventional OMA and the NOMA techniques in terms of the average sum rate. However, the superiority of either scheme depends on the user location, the number of antennas at the BS and the number of users in a single cell. That is why we present this work to put emphasis that habitually the NOMA scheme in massive MIMO scenarios can outperform conventional OMA for any power split considerations specifically when there are multiple users in the cluster or grouping is sought in system design. Since massive MIMO setups carry random interference which causes the fluctuation in the signal propagates over the channel. If the ratio of these fluctuations is very small then there is channel hardening effect on the setup, which can be minimized by increasing the transmitting antennas at the BS. Because, by doing so, the channel hardening factor averages out over the antennas and the variance decays with the number of antenna increment. This is the reason; the channel hardening is higher at the far users as compared to the near users and the far users will also get affected by shadowing for this reason. But, the NOMA system has the potential to reduce the effect of channel hardening at the far user which benefits the system for enhanced throughput and leads to the increased capacity. Fading factors have also been considered to take independent realization for each coherence interval. Results verify that NOMA achieves higher sum rate, channel capacity and increased user fairness than conventional OMA.

The rest of the paper is as follows. Section III provides the details about system setup. Comparison results are provided in Section IV, while conclusion and future trends are briefly discussed in Section V.

Ⅲ. System Setup

Downlink multiuser MIMO setup is considered in this research, which represents a BS with M transmitting antennas, K number of users having N receiving antennas at each user. The channel is assumed to be quasi-static and equally distributed.

For NOMA system, the users are divided into two categories, near users and far users. According to the assumption, K number of users are considered in a single cell, where half of the users $(K/2)$ are taken as the near users and other half $(1-K/2)$ are considered as the far users. For power domain NOMA, near user experience better channel gain (h) compared to the far user. Based on this channel gain, power factors (α) are assigned to the users which helps to perform SIC and decode the signal at the near user and far user respectively. This channel gain is modelled as (h_k), for K number of users:

$$h_k = \sqrt{\beta_k} h_k \ , \quad k = 1,2,...,K \tag{1}$$

where, β_k represents large scale fading factor which is known at the BS. On the other hand, for the conventional massive MIMO OMA setup, beam-forming is considered as a common assumption because in literature [19], it is optimal for the system with many antennas. However, unlike NOMA there are no groups, and beam-forming vectors are selected based on the K channels instead of considering $K/2$ channels. v_k is the beam-forming vector associated to the K users in this setup. Hence, BS needs to know K channels to implement this approach. For massive MIMO OMA setup, beam-forming must satisfy:

$$v_j^H h_i = 0, \qquad \text{for } all \quad i \neq j \tag{2}$$

For LOS scenario, channel is deterministic and can be easily known at the BS with negligible estimation overhead. For NLOS scenario, block fading model is considered, while the resources are distributed into coherence intervals. Our setup is assumed to be time-division-duplex (TDD) in order to utilize channel reciprocity at the BS to estimate channel for uplink pilots.

NOMA scheme has been analyzed by various researchers in the literature [14], [15], based on the aforementioned studies, there are assumptions made in the setup e.g. the total number of users are grouped into two, with $K/2$ users in each group and for NOMA the interferences among the groups can be minimized either by allocating different power levels to the users or assigning beam-forming vectors for each group. So, the beam-forming is utilized depending on the near user's channel gain to cancel the effect of users on each other [16], [17];

$$v_i^H h_j \qquad \text{if} \quad j \neq i \tag{3}$$

where, v_i is the beam-forming vector for corresponding group. The motivation behind this is actually to make sure that near users would be able to do SIC, because near users have to cancel the interference of corresponding high-power users while near user itself is prone to interference. BS can only know the channel gains for near users by implementing this type of zero-forcing beam-forming, because this technique does not provide array gain to far users. It is necessary to assume here that there are two users and one beam vector for each group which is based on the linear combination of the channels[18]. This linear combination should be estimated in order to implement this approach. Channel estimation overhead can not be neglected for NLOS scenarios, where we need to estimate channel recurrently.

3.1 Performance Analysis

In the conventional OMA system, in which TDD is considered, coherence interval takes three steps which includes uplink training, uplink data transmission and downlink data transmission. In this setup, downlink data transmission is the main focus. That is why, for uplink training, near users will transmit uplink pilot sequences and BS estimates the channel based on these pilots. and beam-forming vectors are generated accordingly. It is important to notice that for NOMA scheme $K/2$ pilots are needed to estimate the channel. While, in order to perform SIC it is inevitable to estimate far user's channel and it is done by beam-forming because in this way NOMA gives an edge over conventional OMA techniques[20].

Since, beam-forming is carried out by estimation of near user's signal so the far user's channel will fluctuate timely on the assumption that the phase will be distributed from -π to +π. Taking the insight from blind estimation, BS needs to transmit $K/2$ pilots in the downlink to let the users estimate channel gains. However, in massive MIMO OMA scenario no downlink pilots are needed but K uplink pilots are used instead to estimate the channel of the users. To estimate channel for massive MIMO OMA the signal at the BS is given as:

$$Y=\sqrt{K}\sum_{k'\in K}\sqrt{q_{k'}}\,h_{k'}\phi_{k'}^{H}+Z \tag{4}$$

where, $\sqrt{k}\,\phi_{k'}^{H}$ is the pilot sequence, $q_{k'}$ is the power of pilot symbol and Z is the noise matrix. Similarly, for NOMA scenario the channel estimation of users is carried out by the following signal received at the BS:

$$Y=\sqrt{K/2}\sum_{k'\in K_{near}}\sqrt{q_{k'}}\,h_{k'}\phi_{k'}^{H}+Z \tag{5}$$

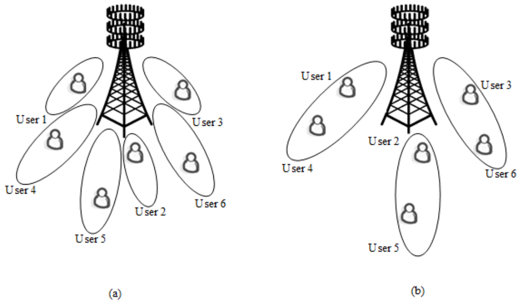

Fig. 1. (a) separate (mMIMO) beam-forming vectors are generated for each user through estimation of their channels, (b) NOMA users are paired via the same beam-forming vector in each group.

where, for uplink training only the near users will transmit the pilot sequences while far users will remain silent. Minimum-mean-square-error (MMSE) channel estimation is considered in this setup for both conventional OMA and NOMA schemes.

In order to perform SIC, near user must have to decode the signal intended for the far user and to do so, near user has to be able to get the achievable rate greater than the ergodic achievable rate of cell edge user. Because if this condition does not satisfy then it will be difficult to decode the signal of far user, hence SIC would fail at near user effecting the overall capacity and performance of the system. Therefore, under this assumption the ergodic sum rate for NOMA is given by:

$$R_k^{NOMA} = (1-\frac{K}{T})\boldsymbol{E}\left[\log_2\left(1+\frac{p_k\beta_k pk'|h_k^T v_k|^2}{\beta_k\sum_{\substack{k'\neq k,\\ k'\neq k+K/2}}^{K} pk'|h_k^T v_k{}'|^2+1}\right)\right] \tag{6}$$

where, R_k^{NOMA} is the ergodic sum rate at the intended user k and $(1-K/T)$ is the ratio of coherence interval for data. The data rate for the user placed at the edge of the cell is given by:

$$R_k^{NOMA} = (1-\frac{K}{T})E[\log_2(1+SNR_{k+K/2})] \tag{7}$$

where, $SNR_{k+K/2}$ is the fraction of the received signal at the intended user to the collective sum of all the users superposed by the superposition algorithm. For massive MIMO conventional scheme, the zero-forcing beam-forming is considered in NLOS scenarios and ergodic sum rate for OMA is given by:

$$R_k^{mMIMO} = (1-\frac{K}{T})\log_2\left(1+\frac{(M-K)p_k\beta_k\gamma_k^{mMIMO}}{\beta_k(1-\gamma_k^{mMIMO})\sum_{k'=1}^{K}p_{k'}+1}\right) \tag{8}$$

The conventional massive MIMO OMA scheme fully compresses the interferences at each user. While, in NOMA the interference is suppressed only at one user in a group i.e. near user. Each user is having a rate as a function of the number of antennas at the BS, which escalates as the BS antenna increases, and this is known as an array gain. Where, in NOMA it only happens at the near user which is performing SIC.

This research also compares the CDF for massive MIMO OMA and NOMA to justify the gains for NOMA over OMA under mass connectivity. The cumulative distribution function (CDF) is the probability to have the users with throughput smaller equal to the assumed value. To express the CDF for massive MIMO case it depends on the number of users and the cell radius. For the target throughput (x) the CDF is given by:

Table 1. Simulation parameters for multi-user massive MIMO setup

Parameters	Value
Users(K)	6
Cell Radius	1000m
Beam-forming	Zero-Forcing
Equalization	MMSE
Transmit Antenna(M)	8, 16, 32, 64, 128
Receiver Antenna (N)	2

$$CDF = \frac{N_x}{N} \tag{9}$$

where, N is the total users in the cell. For the number of users in a cell N_x/N depends on the radius of the cell which is given by:

$$\frac{N_x}{N} = 1 - R/R_c^2 \tag{10}$$

For the given parameters shown in the Table 1, the CDF is calculated and briefly discussed in the section IV. The following section also includes the performance comparison for massive MIMO OMA and NOMA, followed by the conclusion and future work as Section V.

Ⅳ. Experimental Results

Notice that in the previous discussion the intuition has described the achievable capacity for OMA and NOMA for massive MIMO network, now the performance in terms of capacity is compared in this section. Mat-Lab is used as a software tool to carry out the simulations. For a single cell scenario, the multi-user system is sought, where the superposition algorithm is applied to combine user's data in a non-orthogonal manner. Moreover, user pairing is carried out based on the channel gain i.e. $(|h_n| > |h_f|)$. The transmitted data is added with noise due to channel impairments.

The received data is then processed by minimum-mean-square-error (MMSE) equalization technique for channel equalization. After serial to parallel conversion of data, the near user will perform SIC to retrieve the signal of high power (near) user and it will subtract the retrieved data from the superposed signal. While high power (far) user will directly decode its own data by cancelling out the other user's data as noise. The same process is carried out for the OMA system, but the user's data is combined by keeping the orthogonality maintained.

In Figure 2 and Figure 3, the cumulative distributive function (CDF) for massive MIMO

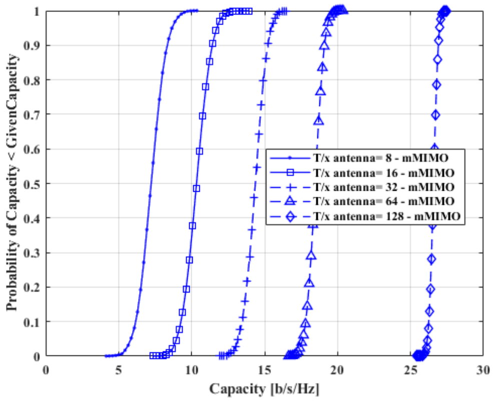

Fig. 2. Cumulative distributive function (CDF) for multi-user massive MIMO OMA

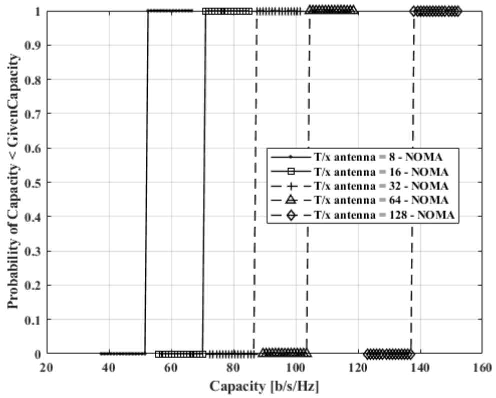

Fig. 3. Cumulative distributive function (CDF) for multi-user massive MIMO NOMA

OMA and NOMA is given respectively, which shows that the capacity for 6 users in the same cell having the radius of 1000m gives rise to the achieved capacity with the increased amount of transmit antennas at the BS. For NOMA, Figure 3 shows that the upper bound of the capacity is achieved more accurately as compared to the conventional MIMO OMA, as shown in Figure 2. It is the inheritance of massive MIMO scheme that the increased number of transmission antenna increases the probability that users might have similar channel conditions which can deteriorate the performance of the system where such researches are mentioned in Section II presenting almost orthogonal conditions are presented to minimize the similar channel interferences. But NOMA gives the edge cutting solution to this problem where it is inevitable that two users might have identical channels so the beam-forming vector can accommodate both the users in the system and the channel hardening coefficients. Hence, in the massive MIMO scheme, we can get benefits from implementing NOMA, specifically when users have parallel channels in LOS or NLOS scenario.

Moreover, for the increased number of transmit antenna Figure 4 and Figure 5 show that array gain for NOMA is higher than the OMA, as the number of transmit antenna is in an order of 8, 16, 32, 64 and 128 respectively. Capacity versus signal to noise ratio (SNR) in Figure 4 and Figure 5 confirms that for 128 transmit antenna at 20 dB, the capacity for OMA is 47.6 bps/Hz while for NOMA we can achieve 200 bps/Hz respectively. Similarly, for the 8 transmit antenna at 5 dB the achieved capacity for

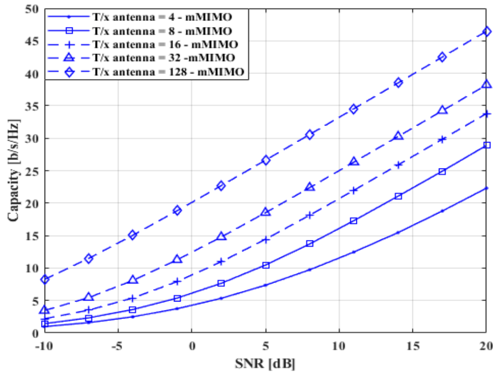

Fig. 4. Impact of increasing transmission antenna on the capacity in single cell, multi-user mMIMO scenario

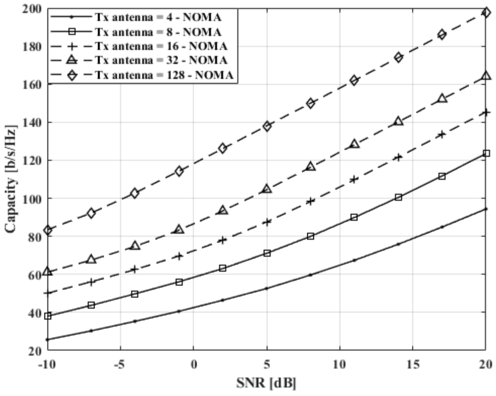

Fig. 5. Impact of increasing transmission antenna on the capacity in single cell, multi-user NOMA system

OMA is 7.8 bps/Hz and for NOMA is 50.3 bps/Hz. Hence, it provides a significant gain for massive MIMO NOMA which is almost 4 times as compared to the conventional massive MIMO OMA scheme. An overview of considered parameters for the performance of NOMA for multi-user modern wireless communication network under high capacity demand has been presented in this research. Conventional NOMA and NOMA have been compared in the context of capacity, and the impact of increased transmitting antenna at the BS. It is important to notice that this research explicitly considers two user grouping for NOMA. However, if the two users fit well and perform better in the system under high capacity constraints then more users can be added in the group to get the benefits for NOMA scheme. Furthermore, a hybrid system using OMA and NOMA both as multiple access techniques could be the solution to maintain user fairness and system's efficiency for specific scenarios. Generally, the system's complexity escalates for ultra-dense networks, where mass connectivity is the actual concern. NOMA provides the cutting-edge solution in such cases where users are grouped, usually in a pair of two users that are near and far users. For the lesser dense environment, OMA based cellular system can be a fair choice to provide maximum transmit power to each user at the cost of reduced data rate, which can be enhanced utilizing efficient filter banks or improved channel coding to reduce the BER, at the physical layer.

Ⅴ. Conclusion

In this work, we have investigated the gains that NOMA can provide in massive MIMO scenario with multiple antennas. To sum up more accurately, this research compares two schemes such as OMA and NOMA for multi-user massive MIMO networks and in this comparison, we have shown the practical importance of these schemes, since there are already multiple antennas have been deployed at the BS for LTE and fourth-generation (4G) wireless communication networks. This comparison is important for implementation ready deployment since LTE has already been deployed with 64 antennas at the BS. Similarly, for 5G and beyond, the massive antenna will be the norm typically when the reduced latency, increased capacity and a huge number of user connectivity is inevitable. The intuition behind this research is favourable channel propagation consideration that appears in massive MIMO systems to achieve considerable gains of NOMA as the most favourable multiple access techniques for modern 5G cellular networks. Multi-cell scenarios with imperfect SIC at the Near user can be considered for future advancements. More importantly, other beam-forming or interference cancellation schemes can be compared to infer better results for the future 5G and beyond wireless communication networks. Furthermore, after all the Random Access Technologies (RATs) and Multiple Access Technologies (MACs), what is next!

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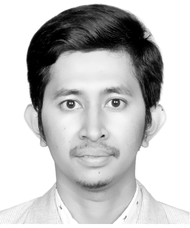

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