World Academy of Science, Engineering and Technology
International Journal of Electronics and Communication Engineering
Vol:13, No:4, 2019

Open Science Index, Electronics and Communication Engineering Vol:13, No:4, 2019 publications.waset.org/10010248/pdf

Performance Analysis in 5th Generation Massive Multiple-Input-Multiple-Output Systems

Jihad S. Daba, Jean-Pierre Dubois, Georges El Soury

Abstract**—**Fifth generation wireless networks guarantee significant capacity enhancement to suit more clients and services at higher information rates with better reliability while consuming less power. The deployment of massive multiple-input-multiple-output technology guarantees broadband wireless networks with the use of base station antenna arrays to serve a large number of users on the same frequency and time-slot channels. In this work, we evaluate the performance of massive multiple-input-multiple-output systems (MIMO) systems in 5th generation cellular networks in terms of capacity and bit error rate. Several cases were considered and analyzed to compare the performance of massive MIMO systems while varying the number of antennas at both transmitting and receiving ends. We found that, unlike classical MIMO systems, reducing the number of transmit antennas while increasing the number of antennas at the receiver end provides a better solution to performance enhancement. In addition, enhanced orthogonal frequency division multiplexing and beam division multiple access schemes further improve the performance of massive MIMO systems and make them more reliable.

Keywords—Beam division multiple access, D2D communication, enhanced OFDM, fifth generation broadband, massive MIMO.

I. INTRODUCTION

MOBILE telecommunication networks owe its rapid evolution and ubiquitous infrastructure to multiple-input-multiple-output (MIMO) systems which were first used in 3G telecommunication technology and then adapted in 4G networks. MIMO structures are employed to combat fading in the wireless channel and improve the performance of wireless communication systems in terms of speed and quality of service. Massive MIMO systems are the latest advanced wireless technology that gave rise to the successful implementation of the fifth generation (5G) wireless communication standard that will become ubiquitous in 2020.

In addition to improving data rates of up to 10 Gbps and reducing latencies below 1 ms, massive MIMO technology is able to build a network of connected machines and devices that operate between regular subscribers. This will give rise to new communication technologies like device-to-device communication (D2D). 5G networks will transform the conventional cell architecture from multiple macro- and micro-cells covering large areas to multiple small pico- and femto-cells, which can yield higher capacity and provide better services to the users with minimal transmission power. By utilizing the millimeter wave band, 5G networks benefit from larger bandwidth and higher data rates. However, the use of high frequencies imposes additional constraints on the system. To resolve this problem, massive MIMO systems are implemented because they allow for parameters adaptation of the transmitted signals to cancel out the effects of the millimeter wave channel.

This paper starts with a literature survey of massive MIMO systems followed by a section on mathematical modeling of these systems. The highlight of the research is a performance analysis of the capacity and bit error rate (BER) of 5G networks by studying several cases with varying numbers of antennas at both transmitting and receiving ends.

II. LITERATURE SURVEY

Lim et al. [1] studied downlink and uplink channels connecting 3 radio units (RUs) to a digital unit (DU). The DU serves multiple user equipment (UEs) at the cell-boundary using the same time-frequency slot. A single-cell massive MIMO consisted of multiple RUs connected to each other by optical fibers and connected to a centralized DU as illustrated in Fig. 1. Received diversity signals were processed using zero-forcing (ZF) and maximum ratio transmission (MRT) techniques.

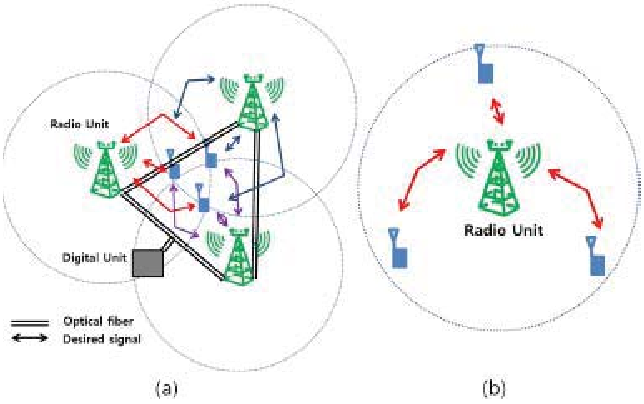

Fig. 1 Massive MIMO with cell-boundary users of multi-RU in (a) and single-RU in (b)

Lim et al. [1] showed that massive MIMO systems maximize network capacity and conserve transmit energy with a power scaling law of $1/M$ under ideal channel state information (CSI) and $1/\sqrt{M}$ under imperfect CSI at the base station (BS), where

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M is the number of BS antennas. The authors also demonstrated that MRT is better for cell center users at high SNR and for cell-boundary users at low SNR in downlink systems.

Filho et al. examined two scenarios in [2], the first one where the number of users and the number of receiver antennas at the BS grow at the same rate, and the second one where the number of antennas at the BS approaches infinity and the number of users is fixed. Under an environment with intercell interference and perfect CSI, the BER was shown to be very high for the 1st scenario using precoding techniques and much worse using ZF technique. In the 2nd scenario, all techniques resulted in a better performance as the number of antennas was increased. With imperfect CSI, the system's performance using all techniques was nearly the same.

Misilmani et al. considered D2D communication in [3] with BS and D2D communication with device controlled link as depicted in Figs. 2 and 3, respectively. The main focus of their study was to control the global arrangement of the massive MIMO antennas to reduce interference and be able to communicate over long distance at high frequencies. This arrangement is affected by the array configuration, the distance that separates antenna elements, the phase and the amplitude of different elements, and the corresponding pattern of each element. The authors recommended that the configuration should be chosen, taking into consideration the total number of antenna components and the radiation features such as radiation pattern, gain and beamwidth. In addition, the mutual coupling between components and their influence on the power of the received signal, the coverage, and the channel capacity should also be taken into consideration. The authors also advised that a study be conducted on several operating frequencies of the 5G technology, 6 GHz, 27 to 28 GHz, and 60 to 70 GHz bands. Different types of antennas could be used in the arrays, such as microchip antennas, printed, horn, or dipoles antennas.

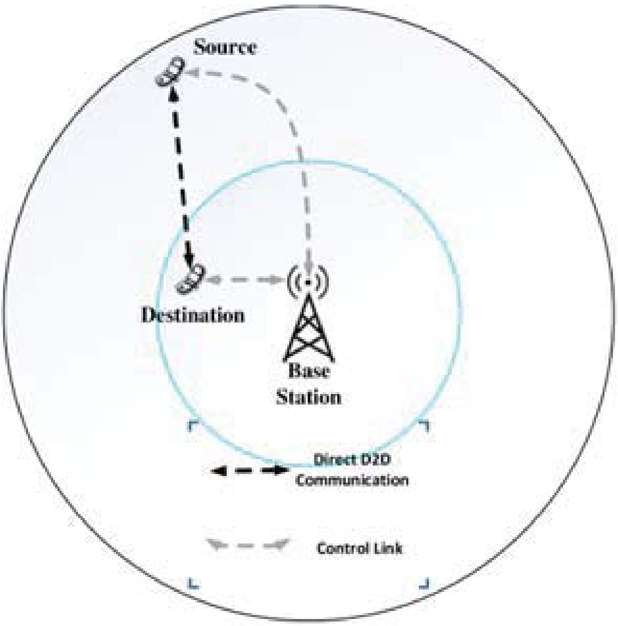

Fig. 2 D2D communication with BS

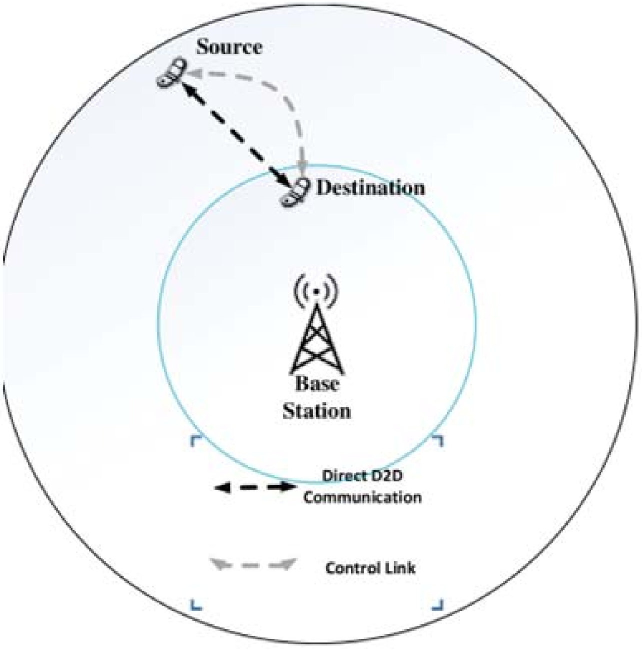

Fig. 3 D2D communication with device controlled link

In [4], Gupta and Jha considered massive MIMO systems with arrays containing couple of hundred antennas in the same time and frequency slot serving many tens of user terminals. Massive MIMO depends on spatial multiplexing, which additionally relies on the BS having channel state data, both in the downlink and uplink channels. In the case of downlink, it is very difficult to obtain channel state data, but in the case of uplink the terminals send pilots and channel state data can be attained. As a result, massive MIMO systems require an expansive number of similar slots when compared to the basic MIMO system. In addition, increasing the number of BS antennas causes the number of channel estimates to also increase for each terminal, thus requiring hundreds of uplink slots to feedback the channel responses to the BS. The solution to this problem is to operate massive MIMO systems under Time Division Duplexing (TDD) mode as opposed to Frequency Division Duplexing (FDD) mode.

There are several application scenarios for multi-user massive MIMO systems. The first application, the multi-beam satellite system, shown in Fig. 4, is one of the main scenarios for massive MIMO because of the large number of antenna elements exceeding one hundred. The major advantage of satellite communication systems is that they serve all the users at the same cost within the coverage region.

The second application scenario is mobile cellular network beyond LTE-A as illustrated in Fig. 5. In this kind of network, massive MIMO could play a main role with the deployment of tens and hundreds of antenna elements at the BS (on the roof of buildings) and a small number of antenna elements at the user terminals. In this network, it is better to operate under TDD mode to perform accurate uplink channel estimation.

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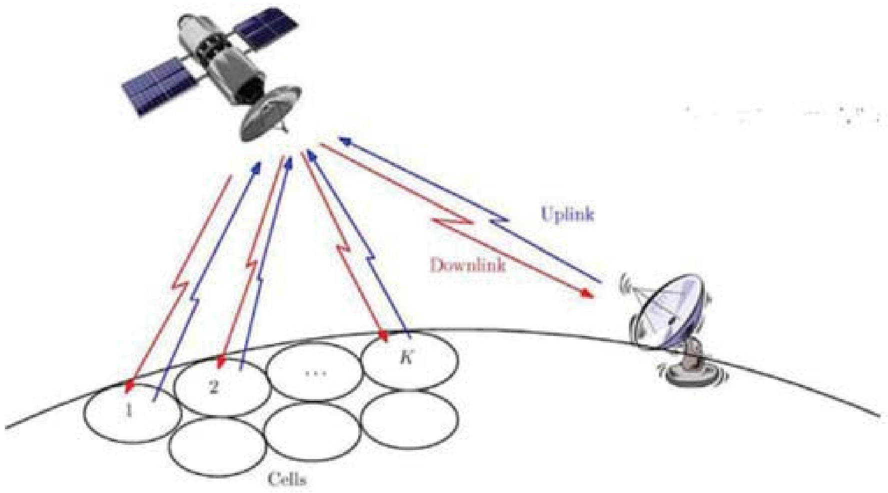

Fig. 4 A multi-beam satellite network

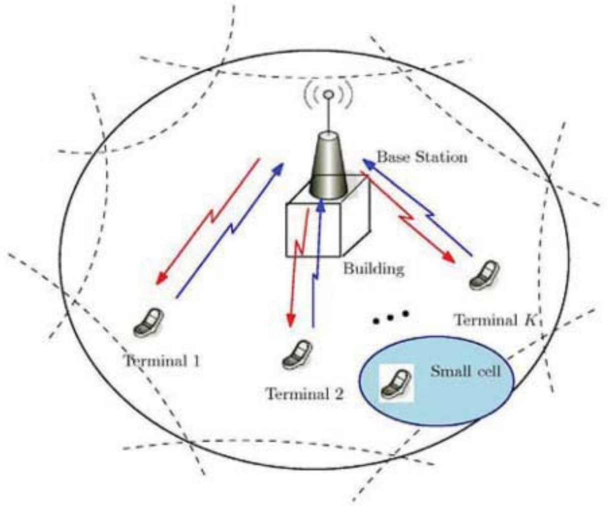

Fig. 5 A mobile 5G cellular network

III. MASSIVE MIMO MODELING

Massive MIMO is the most suitable technology for TDD operation with large number of active terminal antennas. The use of large number of antennas allows for the concentration of energy into small regions of space to give huge improvements in throughput and energy efficiency. Other benefits of massive MIMO include extensive use of inexpensive low-power components, reduced latency, simplification of the MAC layer, and robustness against intentional jamming. As a result, massive MIMO could improve the radiated energy efficiency by 100 times.

The most notable advantages of massive MIMO are significant increase in capacity and large reduction in BER. This can be achieved because massive MIMO uses spatial multiplexing techniques where orthogonal multiple faded signal paths are combined using zero-forced (ZF), MRT, or maximum ratio combining (MRC) schemes. Accurate CSI must be estimated to achieve these benefits. However, since the channel coefficients are estimated from orthogonal pilot sequences, and since the reuse of pilot sequences of several co-channel cells creates pilot contamination in a multi-cell setup, the performance of massive MIMO is significantly reduced due to imperfect CSI.

A. Received Signal Model

In massive MIMO systems, a mobile user sends multiple signals to the BS using many transmit antennas. The transmitted signals go through a channel matrix which consists of all the paths between the transmitting antennas and the receiving antennas. The BS receives the signal vector and decodes it into the original signal data. The received signal model at a single BS for uplink is

$$\mathbf{Y_u} = \sqrt{\rho_u}\,\mathbf{H}\,\mathbf{X_u} + \mathbf{n_u}, \tag{1}$$

where $\mathbf{X_u}$ is the signal vector from users, $\mathbf{H}$ is the uplink channel matrix, $\mathbf{n_u}$ is a zero mean noise vector with Gaussian distribution, and ρ_u is the uplink transmit power. Similarly, the received signal vector at a single BS for downlink is

$$\mathbf{Y_d} = \sqrt{\rho_d}\,\mathbf{H}\,\mathbf{X_d} + \mathbf{n_d}, \tag{2}$$

where $\mathbf{X_d}$ is the signal vector from BS, $\mathbf{H}$ is the downlink channel matrix, $\mathbf{n_d}$ is a zero mean noise vector with Gaussian distribution, and ρ_d is the downlink transmit power. The complete massive MIMO channel model is depicted in Fig. 6.

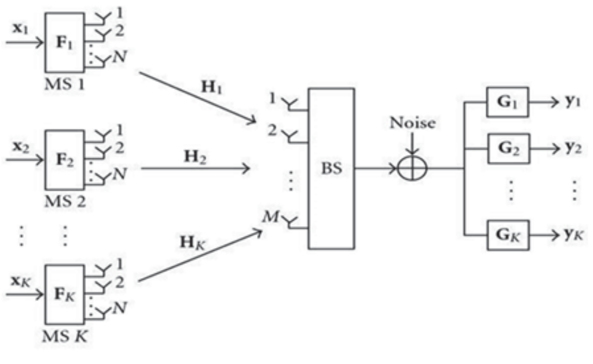

Fig. 6 Massive MIMO channel model

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B. Link Capacity

The data capacity is a main measure which quantifies the maximum value of information transferable across a channel's reliably. The channel capacity of massive MIMO systems for uplink is

$$C = \max\left(E\left[\log_2\left(\det\left(\mathbf{I}+\rho_u\mathbf{H}^H\ \mathbf{H}\right)\right)\right]\right), \quad (3)$$

where **H** is the channel matrix and *H* is the Hermitian operator. For downlink, the BS allocates power such that the transmission rate sum is maximized. The downlink capacity with power allocation is

$$C = \max\left(E\left[\log_2\left(\det\left(\mathbf{I}+\rho_d\,\mathbf{H}\,\mathbf{P}\,\mathbf{H}^H\right)\right)\right]\right), \quad (4)$$

where **P** is the power allocation matrix.

C. BDMA and Enhanced OFDM

Massive MIMO systems employ Beam Division Multiple Access (BDMA) transmission. Numerical simulations prove that the performance of BDMA transmission is near optimal [5]. In addition, using 64-QAM modulation improves the BER performance and approaches ideal channel estimation with negligible loss [6]. A block diagram of a BDMA transmission system is shown in Fig. 7.

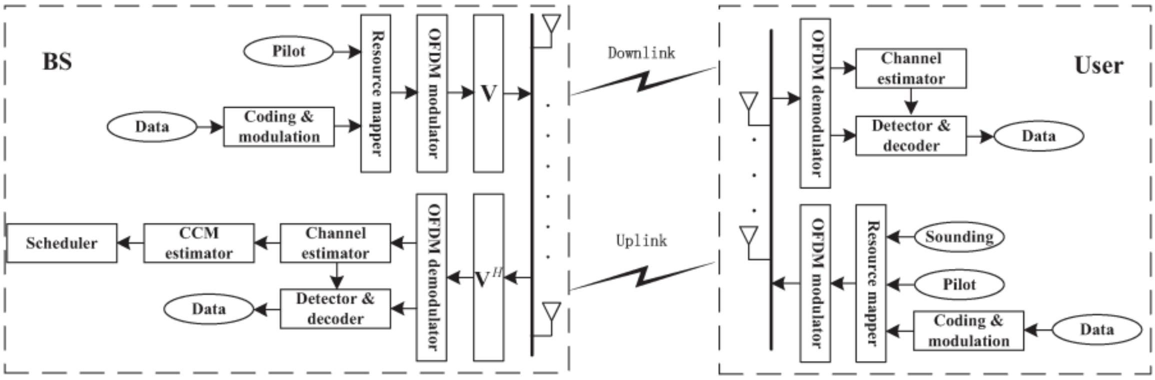

Fig. 7 Block diagram of a BDMA transmission scheme.

In addition to BDMA, massive MIMO uses Orthogonal Frequency Division Multiplexing (OFDM), which remains one of the best multiplexing techniques till date. The main reason behind using OFDM in 5G networks is to offer higher data rates and extensive networking services. Some studies found that OFDM suffers from some weak points [3], but simple updates in the form of waveform or access option can add more benefits to OFDM and enable it to provide maximized spectral efficiency, asynchronous multiplexing, minimal out-of-band emission, minimal complexity, and minimal consumption power [2]. Fig. 8 shows different implementation methods of OFDM. Information data enter a serial-to-parallel block, followed by zero-tail padding, then it is subjected to DFT precoding operation that precedes IFFT operation. Cyclic Prefix (CP) is optional, followed by windowing and a Band Pass filter, which is then subjected to radio frequency (RF).

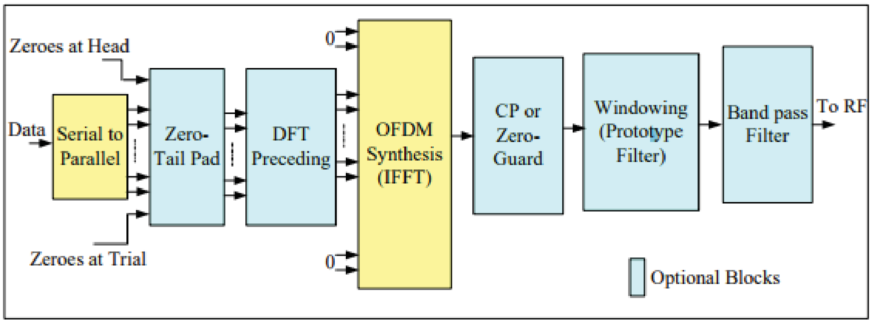

Fig. 8 Implementation of OFDM

IV. SIMULATION AND RESULTS

MATLAB simulations were conducted to demonstrate the performance of massive MIMO systems in terms of BER and capacity efficiency. We consider the channel matrix **H** to follow Rayleigh fading and the noise at each antenna as additive zero-mean white complex Gaussian. Simulations were performed for 3 cases using enhanced OFDM and BMDA driven by 64-QAM at the transmitter, and using ZF decoding at the receiver: (1) the number of transmit antenna N_t = 10 and number of receive antenna N_r = 10 (i.e. 10x10), (2) N_t = 5 and N_r = 20 (5x20), and

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(3) $N_t = 2$ and $N_r = 50$ (2x50).

The BER and capacity efficiency (in bits/sec/Hertz) curves versus the SNR (in dB) are shown in Figs. 9 and 10 respectively.

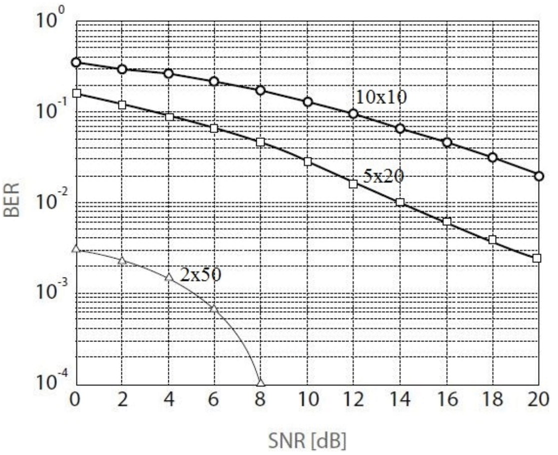

Fig. 9 Comparison of the BER versus SNR for different number of transmitting and receiving antennas

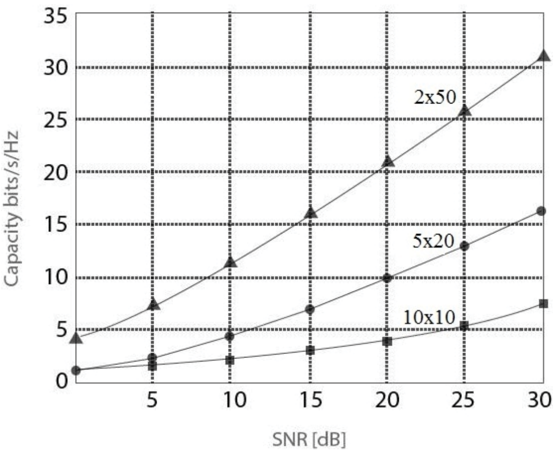

Fig. 10 Comparison of the capacity efficiency versus the SNR for different number of transmitting and receiving antennas

As expected, the BER decreases as the SNR is increased, with the rate of decrease being larger when the number of transmit antennas is small (for the same product $N_t \times N_r$). In addition, the capacity efficiency increases as the SNR is increased, with the rate of increase being larger when the number of transmit antennas is small (for the same product $N_t \times N_r$). Most notably, we observe that, unlike classical OFDM driven MIMO systems [7]-[15], the performance is not identical for the same product of transmitting and receiving antennas, that is, a 10x10 system does not produce the same performance as a 5x20 or a 2x50 system. In fact, the performance is much better for a smaller number of transmitting antennas and a large number of receiving antennas, assuming perfect CSI [16]-[22]. This is explained by the fact that a smaller number of transmit antennas reduces inter-symbol interference (ISI) between users. The number of antennas is not the only factor that drives massive MIMO to outperform classical MIMO. BDMA and enhanced ODFM (as opposed to traditional ODFM) play a significant role in causing massive MIMO to be more reliable than conventional MIMO systems. All this is contingent upon accurate stochastic modeling of the fading scattering channel, and efficient detection and estimation algorithms [23]-[29] that are needed to determine the CSI.

V. CONCLUSIONS

Massive MIMO is a scalable and flexible technology where any number of BS antennas can be usefully employed with no tightening of array. Massive MIMO is at the core of 5th generation broadband wireless networks and guarantees significant capacity enhancement to suit more clients and services at higher information rates with better reliability while consuming less power.

In this work, we analyzed the performance of massive MIMO systems in 5G networks in terms of capacity and BER as a function of received signal-to-noise ratio. We studied and analyzed several scenarios with different number of antennas at both transmit and receive ends to compare the performance of massive MIMO systems. Most notably, our case studies demonstrated that massive MIMO performance is not identical when the product of transmitting and receiving antennas remains the same, that is, a 10x10 system does not produce the same performance as a 5x20 or a 2x50 system. This is a major deviation from established performance analysis findings of classical MIMO systems used in 4G networks. In fact, we observed that the BER and capacity efficiency in bps per bandwidth are significantly better for a smaller number of transmitting antennas, provided that the reduced number of transmit antennas is compensated for by a significant increase in the number of receiving antennas at the BS. ISI between the users at the transmit antennas is significantly reduced with the implementation of BDMA and enhanced OFDM which further enhances the performance of massive MIMO systems and makes them more reliable than traditional 4G MIMO systems under a perfect CSI environment [30]-[36].

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