# Massive MIMO for 5G Cellular Networks: Potential Benefits and Challenges

Bekele Mulu Zerihun(✉) and Yihenew Wondie

School of Electrical and Computer Engineering, AAiT, AAU, Addis Ababa, Ethiopia
{bekele.mulu,yihenew.wondie}@aait.edu.et

**Abstract.** The concept of deploying multiple antenna arrays in the base station (i.e. massive MIMO) among other technologies, such as millimeter wave communication and network densification, that it is one of the key enabling methods in the design and development of future cellular networks. Massive MIMO is a disruptive technology; it is considered as a cornerstone in the design of future cellular networks. In this paper, we investigate the benefits of massive MIMO in terms of capacity and energy efficiency. Performance evaluation of massive MIMO is also presented with respect to spectral efficiency and energy efficiency. Moreover, the major challenges for practical deployment of massive MIMO are discussed in details.

**Keywords:** Massive MIMO · 5G · Cellular network · Capacity
Network efficiency

## 1 Introduction

In recent years, cellular network operators are facing challenges to satisfy the exponential traffic growth due to the popularity of smart devices. This exponential data traffic growth and continuous emergence of various services and applications triggered the investigation of the fifth generation (5G) for future cellular systems [1].

To address the future high traffic demands, 5G networks is required to be designed to improve the network performance in terms of capacity, energy efficiency, latency, network security and robustness at large [1, 13]. However, the dramatic network performance improvement targeted by 5G could not be achieved by a mere evolution of the legacy network architecture. Therefore, the future cellular network architecture is required to incorporate different new radio access technologies. Thus, 5G is not only envisioned as an evolution of LTE, but it should also consider new potential technologies that were not included in the previous networks. There are many new applications that should be served in 5G, such as machine type communications (MTC), Internet of things (IoT), tactile Internet, connected vehicles etc. [1, 3].

These services and 5G requirements set by 5G-PPP were defined in different test cases, each of them aiming at representing one possible deployment and utilization of 5G. According to different research results, the standardization of 5G will be composed of two radio access technologies: an evolution of LTE, and new radio systems. The


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main concept of the new radio system is to use higher frequency bands. Utilization of unlicensed band is also expected in 5G, as used in LTE-Unlicensed.

Software-defined networking (SDN), network function virtualization (NFV), and network slicing and spectrum sharing can be used to improve the network efficiency and minimize the cost of network operators, and in turn for users. To that end, the future 5G cellular network should exploit the potential gains from different emerging technologies including massive antenna arrays (i.e., massive MIMO technologies), deployment of ultra-dense small cells, and utilization of millimeter wave frequency bands.

The rest of this paper is organized as follows: In Sect. 2, we describe the details of five key emerging technologies towards the development of the future 5G cellular network. Comprehensive discussions on basics of massive MIMO, its benefits, associated research challenges, and performance evaluations are then presented in Sect. 3. Finally, a concluding remark is drawn in Sect. 4.

## 2 Emerging Technologies Towards 5G Cellular Networks

To satisfy the ambitious goals set by 5G-PPP, it is required to evaluate the potential technologies to investigate and produce solutions, architectures, and standards for 5G. As explained in the introductory part, 5G will be composed of different emerging technologies which will bring a revolutionary change in cellular principles. İn this section, we describe five disruptive technologies which lead to both architectural and component design changes, as depicted in Fig. 1.

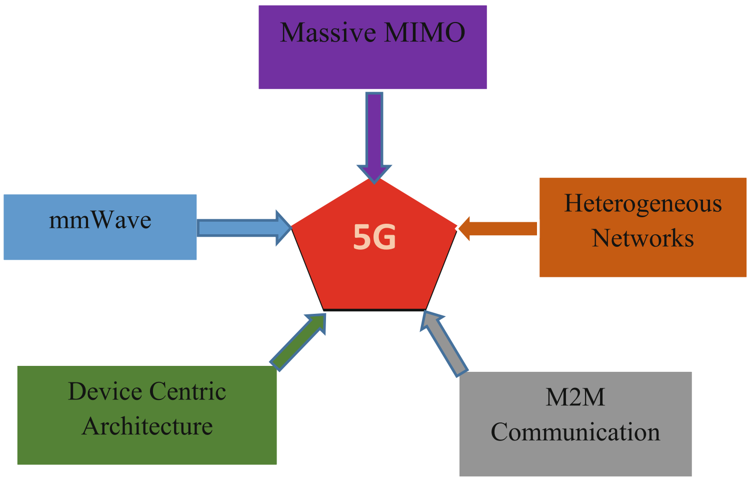


**Fig. 1.** Five new technologies for the design of future 5G cellular networks.

**Device Centric Architecture.** In previous network design, the network structure is based on cells in the radio access network. However, in future 5G cellular network design, a device-centric architecture is required. Device centric architecture changes the traditional view, where users and network providers are two different entities. İn device centric architecture, nodes might serve as a relay between a user equipment and BS. For example, with connected vehicles, both vehicle to vehicle and vehicle to infrastructure communications will be important, either to serve users in the vehicle or for new services such as collision avoidance for unmanned cars. Device centric architectural network design will compensate multiple transmission by resource aggregation [2].

**Millimeter Wave (mmWave).** The frequency spectra in the microwave range currently in use for cellular communication is almost saturated. Therefore, most of the studies consider the millimeter waves as the best candidate to achieve a bandwidth in gigabit range. Millimeter waves refer to the frequency bands in the 3–300 GHz range. Theoretical and experimental studies have been carried out to determine which band is the most suitable within this range. The exponential growing traffic demand in mobile communications and bandwidth limit in RF range has recently drawn increased attention to use spectrum in the millimeter wave bands. Using millimeter wave will increase network capacity in 5G more than 100 times compared to current 4G cellular network [3].

**Heterogeneous Networks (HetNets).** HetNets are composed of a macro layer, with traditional BSs and small cells using different cell size or coverage within the same network installed in strategic locations. HetNets can be seen as a concept designed for LTE. However, HetNets were used only to improve the network performance locally, whereas ultra-dense network is seen as a cornerstone of future deployments. Ultra-dense networks can be considered as one of the most promising technique to meet the new requirements. While this paradigm is seen as a cornerstone of 5G, densified networks were already present in the existing cellular networks. İn ultra-dense networks, small cells can be deployed within macro-coverage to serve small areas with hotspots. Solutions like carrier aggregation or dual connectivity can be used to boost system performance [4, 5].

**Machine-to-Machine (M2M) Communication.** Including M2M communication in the design of 5G will change the network architecture and help to satisfy the high data rate requirements using; (i) large number of devices to be connected and operated without human intervention, (ii) guaranteed minimum data rate in all conditions, (iii) data could be transferred in a very short transmission time interval. In M2M, nodes can serve as a relay, or two equipment might communicate together without using the serving base station.

**Massive MIMO.** Massive MIMO is considered as a promising technology to improve the network performance in the next generation of cellular systems. The gains promised by massive MIMO are augured to overcome the capacity crunch in today's mobile networks and to pave the way for the ambitious goals set for 5G. The details of massive MIMO is presented in Sect. 3.

# 3 Massive MIMO

## 3.1 Basics of MIMO Technology

In conventional point-to-point MIMO, user equipment, and BSs are equipped with more than one transmitter and receiver. MIMO is used for spatial multiplexing to improve the data rate where messages transmitted at the same time. However, MIMO technology was fundamentally designed to serve a single user at a time. Massive MIMO is a large-scale MIMO, with hundreds of antenna elements in single BS. A large number of users can be served simultaneously [6].

Massive MIMO is one of the promising technology in the design and development of the future 5G cellular network. İt is expected to increase the network capacity by 10 times and energy efficiency by 1000 times compared with the conventional MIMO. Massive MIMO offers numerous advantages. İt can be built with inexpensive, low-power transceivers make it robust, secure and use spectrum efficiently. However, high mobility is a challenge in massive MIMO since channel estimation and spatial beamforming required a lot of signaling. A typical massive MIMO network is depicted in Fig. 2. İn recent years, Massive MIMO attracts the attention of many researchers due to its promising capability of improving spectral efficiency, energy efficiency, and robustness of the system [6, 7].

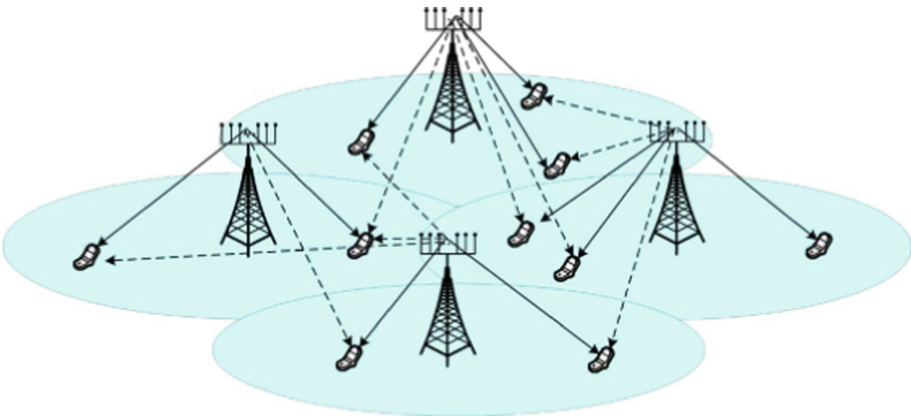

**Fig. 2.** Illustration of massive MIMO systems.

## 3.2 Benefits of Massive MIMO for 5G HetNet

As explained in the introductory section, the future 5G cellular network requires new technologies to provide extra high throughput for many users simultaneously. Among these new technologies, massive MIMO takes the lion's share. Using massive MIMO, we can achieve a huge energy efficiency and spectral efficiency when the array and multiplexing gains are large. These gains are obtained under favorable propagation conditions and using optimal signal processing technique at the BS [8]. Therefore, one of the important benefits from massive MIMO is to improve the network throughput by serving many users in the same frequency band and time frame, which is a very critical requirement in 5G.

Another major benefit from massive MIMO is improved energy efficiency and reduced cost. Since it can be built with inexpensive low-power components, circuit complexity and cost will be highly reduced. İn addition, energy consumption will be reduced using beamforming techniques, where each transmitter emits only some portion of its transmit power directed to the location of active users. This, in turn, minimizes the operational cost of the network and reduce carbon emissions [7]. Moreover, massive MIMO is very useful in interference management. Since BSs are equipped with very large antenna elements compared to the number of user equipment in a given cell region, transmitted signals can be easily shaped to null interference [9].

Massive MIMO improves not only the network performance and energy efficiency, but also it increases the system robustness. İntentional jamming and cyber security threat is a serious issue in wireless systems. Since massive MIMO offers an excess degree of freedom, it could be used as the best tool to cancel signals from intentional jammers [10].

Generally, deploying multiple antenna elements in a BS will highly improve the overall network performance and energy efficiency. Especially, a 1000 times energy efficiency requirement set by 5G can be easily achieved by implementing massive MIMO in the new architectural design of future cellular networks.

### 3.3 Performance Analysis of Massive MIMO

Since the number of antenna elements is very large, the channel vectors between the BS and user equipment are orthogonal. Considering the data transmission in favorable propagation conditions, the performance of massive MIMO can be evaluated using simple linear signal processing techniques, such as MRC, ZF, and MMSE in the receiver section. A comparison among these receivers in realistic test-case is presented in [11]. İn the following, we evaluate the performance of massive MIMO using simple linear processing techniques and analyze some numerical results in terms of sum rate, spectral efficiency, and energy efficiency.

Figure 3 shows that the performance of massive MIMO using different linear processing techniques in terms of the achievable sum rate. Where K is a multiplexing gain and $P_u$ is the uplink power. As clearly observed from Fig. 3, we can give the following analysis. The achievable sum rate increases exponentially as the number of antenna elements increased in the BS. On the other hand, as the number of BS antennas increased, the spectral efficiency with linear receivers is almost the same with Shannon sum capacity achieved by optimal receivers.

The other basic parameter to evaluate the performance of massive MIMO is energy efficiency. Fundamentally, the significant improvement of energy efficiency in massive MIMO can be obtained by extremely sharpening the radiated energy from the transmitter to focus into small regions where active user equipment located. By using a

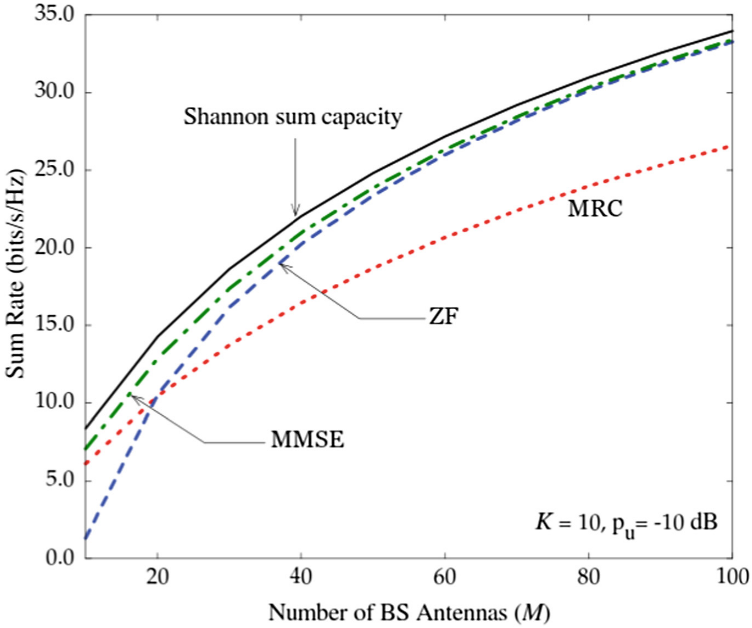


**Fig. 3.** Performance of linear receivers [10].

beamforming technique the transmitted signals emitted by all antenna elements at the BS can be constructively added and directed into the location of intended user equipments.

Strictly speaking, the energy efficiency and spectral efficiency are two trade-off parameters. Since spectral efficiency is directly proportional to the transmit power, to improve the spectral efficiency of the system the signal power is required to be increased. On the other hand, as the signal power increased, the power consumption in the system will increase and in turn reduce the energy efficiency. However, by using moderately large antenna arrays we can jointly improve spectral efficiency and energy efficiency in orders of magnitude compared with a single antenna system.

Figure 4 shows the trade-offs between the spectral efficiency and energy efficiency with 100 antennas at the BS using different linear processing techniques. In Fig. 4 it is clearly observed that ZF processing performs strictly better than MRC processing in a wider range. However, in the lower region of spectral efficiency, we can achieve a better energy efficiency using MRC processing.

Generally, using appropriate signal processing technique we can jointly achieve a better energy efficiency and spectral efficiency by deploying a moderately large number of antenna arrays at the BS.

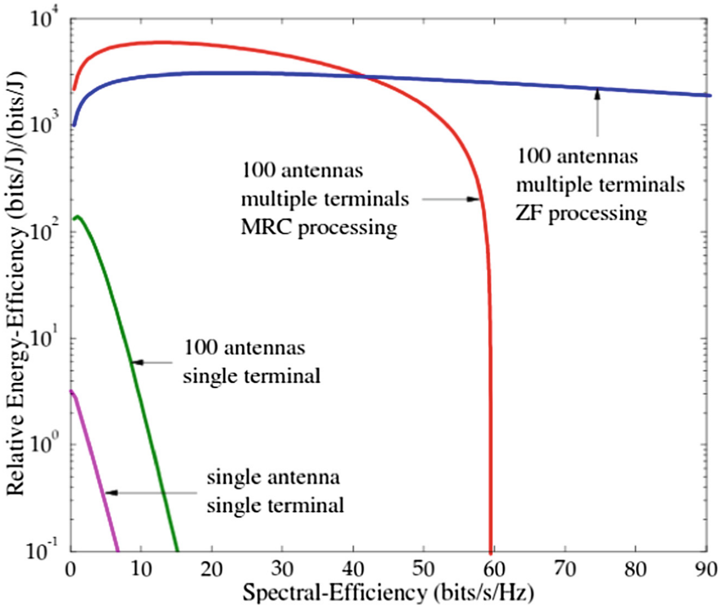


**Fig. 4.** Trade-offs between energy efficiency and spectral efficiency [10].

### 3.4 Research Challenges

Despite the fact that massive MIMO has numerous advantages to meet the ambitious requirements of 5G, a number of issues and challenges are required to be investigated. There are many open research directions and various challenges to be addressed before its practical deployment. In the following, some of the key challenges related to the practical implementation of massive MIMO and the potential solution approaches are discussed.

**Pilot Contaminaton.** Pilot contamination is one of the fundamental limitations which significantly reduces the performance of massive MIMO. Pilot contamination is the effect of interference from other cells during the pilot training sequences. In multi-cell systems, we cannot assign orthogonal pilot sequences for each user in all cells. One of the best methods to minimize the pilot contamination effect is to use high frequency-reuse factors. But, this will degrade the spectral efficiency of the system [12]. An appropriate design of frequency-reuse factor during the pilot sequence and power control to reduce pilot contamination effect is an important research direction.

**Radio Resource Management.** The future 5G cellular network is required to fully exploit all available resources at a maximum level. Current approaches to resource management and scheduling algorithms will not be the best solution for future networks. To properly coordinate and utilize all available resources, a new radio resource management technique is required. Some advanced technologies, such as cloud based radio access networks are proposed to centrally cooperate all network elements. Centralized cloud based radio access network is the best method to efficiently centralize resources and brings flexible options for radio resource management. İn cloud based radio access network architecture design, adaptive and intelligent technologies, such as NFV and SDN can be included. However, the current mobile networks are designed based on the 3GPP standards, both network architecture and radio access are an evolution from it. Therefore, the future network architecture is expected to support both central and distributed radio access control system. This will create a trade-off between centralized radio resource management as in cloud based network architecture and decentralization as in the current networks' resource management system. Further research is required to address this trade-off and to design optimal resource management technique.

**Beamforming and CSI Acquisition.** The acquisition of CSI is very important in massive MIMO. In massive MIMO, the BS needs a perfect CSI to detect the signals transmitted from the users. Each user is assigned an orthogonal pilot sequence and sends this pilot sequence to the BS. Beamforming and CSI are the two very important tools in the design of future 5G cellular network which highly affect the network efficiency. Acquisition of CSI is an energy consuming technique and equipments are very expensive. CSI acquisition vary depending on the channel estimation techniques and system duplexing mode [13]. In this regard, many problems are not yet addressed. How to optimally assign a pilot sequence for new users? Which pilot sequences should be used? These are some of the problems related to CSI acquisition. Therefore, the design of low-cost CSI acquisition system and optimal assignment of pilot sequences is a good research direction.

**Hardware Impairements.** Massive MIMO will be built with inexpensive low-power components. Ultra-linear high power equipment used in the previous system will be replaced by this inexpensive low-power equipment. However, the design of future cellular network is required to be backward compatible and seamlessly support the legacy network. Therefore, there will be a potential challenge to practically implement and integrate massive MIMO with the physical layer of the current technology. Designing a new efficient system to smoothly combine these technologies will be a good research area.

## 4 Conclusion

In this paper, the benefits of massive MIMO as a promising technology for the design of future 5G networks is highlighted. The technology offers huge advantages in terms of network efficiency, robustness, and reliability. As the performance evaluation result shows by deploying a large number of antenna arrays in the BS, spectral and energy efficiency can be improved in a significant level. However, to fully exploit the numerous advantages of massive MIMO, further research is required to address some challenges such as pilot contamination, hardware impairments, radio resource management, beamforming, and channel state information acquisition.

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