SEYBOLD Report
https://seyboldreport.net/
ISSN: 1533 - 9211

A STUDY OF MASSIVE MIMO SYSTEMS TO DETERMINE RECENT TRENDS, SCOPE, AND PROBLEMS FOR 5G COMMUNICATIONS

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ABSTRACT
Future 5G systems will benefit from massive MIMO's ability to increase data throughput and spectral efficiency while supporting a huge user population. In addition, it supports 3D beamforming, which may increase the number of high-throughput users and give additional degrees of freedom. Compared to other alternatives, massive MIMO is predicted to provide better benefits in terms of energy and spectral efficiency. Increased capacity over a traditional antenna system means spectral efficiency up to 50 times that of current 4G technology is possible. “However, to fully use this technology and to overcome the problems of deployment in a real setting, a complex radio system is necessary.” Here, we provide a high-level summary of the foundational technologies needed to support 5G and 6G networks, focusing on massive MIMO. We cover the whole scope of the issues that might arise in a massive MIMO system, including pilot contamination, channel estimation, precoding, user scheduling, energy efficiency, and signal detection, as well as some of the most cutting-edge methods for dealing with them. “In this article, we provide an overview of current developments in massive MIMO systems, including terahertz communication, ultra-massive MIMO (UM-MIMO), visible light communication (VLC), machine learning, and deep learning.” To round off the article, we go through some of the most pressing unanswered questions that will shape the direction of future research in large MIMO systems for 5G and beyond networks.
Keywords: “5G, 6G, beamforming, channel estimation, massive MIMO, millimeter waves, pilot contamination, signal detection, spectral efficiency, and terahertz spectrum”.

I. INTRODUCTION
Beginning in the 1980s with 1G analog systems, the cellular infrastructure has progressed to 2G digital systems like GSM, in which the baseband unit, a digital unit linked to the telecom network, was co-located with the analog radio head unit in a shelter at the foot of the antenna tower. These were connected to antennas atop a tall tower through thick, low-loss coaxial cables and amplifiers to compensate for the power loss in the cables. Distributed networks are employed in modern 3G and 4G systems, as opposed to the centralised networks used in earlier generations (1G and 2G). Separated from the baseband unit, the radio unit in dispersed networks

is located atop the antenna tower and is responsible for transmission and reception. Digital information is now sent to the tower through fiberfront hauls rather than the previously used long-distance coaxial cables, which are lossy at high frequencies. Due to the strategic placement of the radio head about the antennas, a significant link gain is realised in this design. The baseband processing unit will be centrally located in 4.5G and 5G networks [1]. "Massive Multiple-Input Multiple-Output (MIMO) will be formed when the distant radio unit is directly integrated with hundreds of antenna components (Fig. 1)."

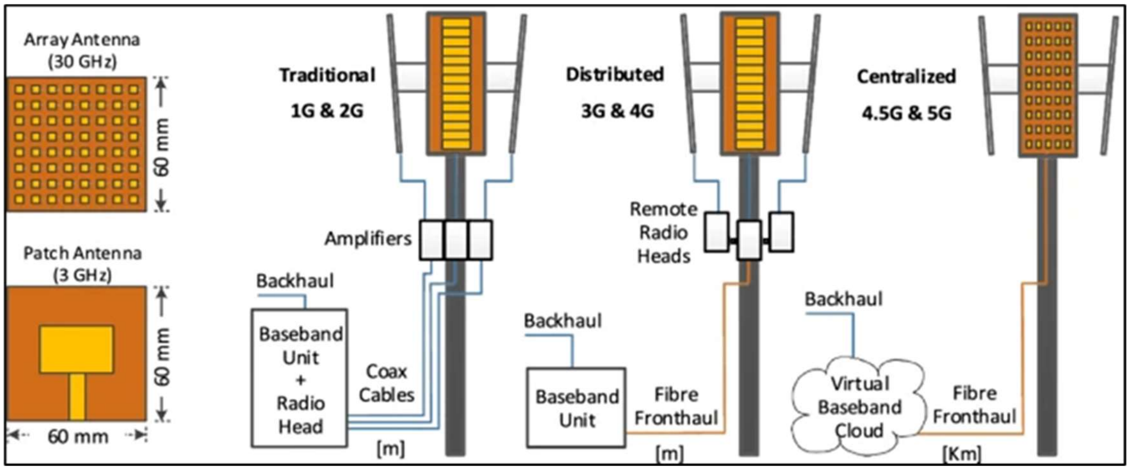


Figure 1: "Antenna array for mm-Wave frequencies and the cellular infrastructure evolution"

The extreme strain has been placed on the world's wireless communication networks due to the meteoric rise in wireless data traffic. Due to spectrum scarcity, telecom engineers focus on millimeter-wave frequencies, which call for very compact antennas [2]. The large-scale antenna arrays are a promising technology since the reduction in antenna element size makes them suitable for massive MIMO [3]. In addition, the performance and signal-to-interference-plus-noise ratio rise with the number of antenna components (SINR). The maximum antenna element in a standard MIMO system is 8, with 8 elements at the transmitter and 8 at the receiver (8 8 MIMO system). Massive MIMO, on the other hand, will allow up to 256 BS antennas and 32 UE antennas in the 5G new radio, depending on the prototype implemented [4]. Improvements in cellular networks' speed and coverage may be accomplished by increasing the number of components in the antenna array.

Furthermore, the increased path loss at higher frequencies may be compensated for by combining energy in the necessary directions from several antenna components. This significantly improves spectrum efficiency since beamforming methods are used in MIMO, focusing radio energy in smaller angular sectors. Massive MIMO is a new promising approach that uses the elevation angle in addition to other spatial dimensions. Using antenna components in both the horizontal and vertical planes results in three-dimensional multiple-input multiple-output, or 3D MIMO. 3D beamforming is necessary for 3D MIMO as it allows the base station to adapt and adjust the broadcast directions in azimuth and elevation. "With this, the system's performance is enhanced, and the rising demand for capacity is met [5]."

II. SINGLE USER-MIMO & MULTIPLE USER-MIMO

Single-user MIMO (SU-MIMO, version 8) is the simplest form of MIMO, in which both the user equipment (UE) and the base station (BS) make use of multiple antennas. Because of this, they can accommodate various forms of transmission in response to changes in the channel (Fig. 2). In transmit diversity, identical data is broadcast over numerous antennas to improve the signal-to-noise ratio. Different data streams are sent over each antenna in spatial multiplexing to enhance capacity [6].

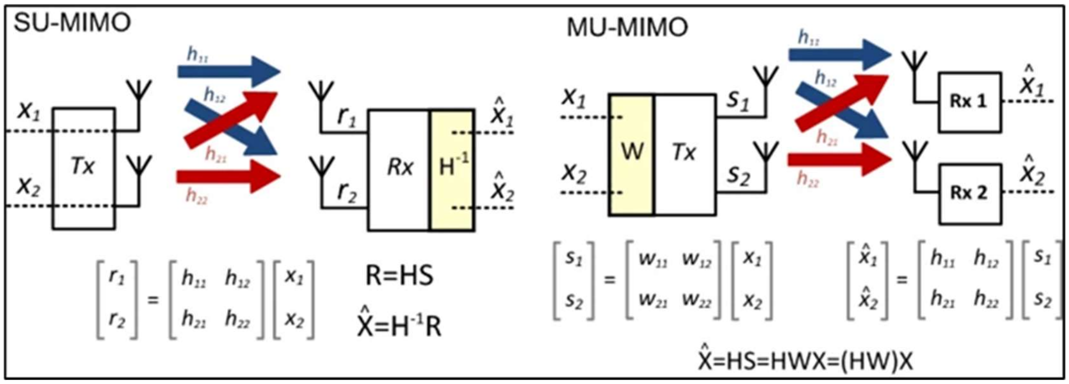


Figure 2: SU-MIMO vs. MU-MIMO

Today's LTE networks use SU-MIMO. "This scheme's complexity stems from the UE receiver, which must parse the many incoming data streams (interference due to multi stream transmission)." Examples include situations when knowledge of the channel matrix H (a matrix consisting of channel route coefficients) is unnecessary on the transmitter side but necessary on the receiver side for decoding the received signals. The receiver learns about the channel by decoding the initial preamble or pilot information. In order to construct the inverse channel matrix H1 on the receiving end, a large amount of processing power is required. Unfortunately, when the receiver is a mobile device, there is insufficient power to do all these computations efficiently. The base station, which often has higher processing capability, takes on some complexity in a multiple-input multiple-output system. In this scenario, data is pre-weighted using a matrix W applied at the transmitter end [7]. During the channel coherence period, all UEs simultaneously broadcast a set of uplink pilots used to calculate the channel matrix W. "All the base station antennas receive the uplink pilots, and the pre-weighting matrix W is calculated, the data streams are precoded and sent to each antenna port based on the measured magnitude and phase, owing to the distance from each user to each element of the antenna array." Therefore, each user equipment (UE) gets the data separately from the other UEs with a higher signal-to-interference ratio (SNR) since the receiver does not have to deal with multi-user spatial layer separation.

III. FROM MU-MIMO TO MASSIVE MIMO

Beamforming plays a crucial role in the system since it allows for varied SINRs across different users within the same cell, which is necessary because different users have varying SINR needs based on the application (e.g., video downloading, internet surfing, messaging, etc.). The purpose of using beamforming algorithms in mm-Wave wireless communication networks is to locate the least-destructive route to users while minimizing interference [8].

Beam steering (Fig. 3a) involves pointing the antenna's primary lobe in the desired direction before beamforming. Several techniques, such as sending orthogonal pilot signals in each possible transmitter direction, are utilized to determine which of these directions must be used. The UE then relays information to the serving cell BS about which signal it receives at maximum strength. With beam steering, signal strength may be increased in omnidirectional antenna cells, where it typically declines from the cell's center to its edges. By focusing all of its power in one direction, the cell can increase its signal-to-noise ratio (SNR) at the cell's periphery while also allowing several autonomous cells to operate in the same area close to one another without the need for any coordination or collaboration (Fig. 3b). The radiation is focused in one direction using beam steering from a collection of transmit antennas that are all physically placed in the exact physical location. At the same time, side lobe interference is an issue; co-location benefits the signal-to-noise ratio (SNR) near the cell's edge. For this reason, antennas with minimal side lobes are necessary [9].

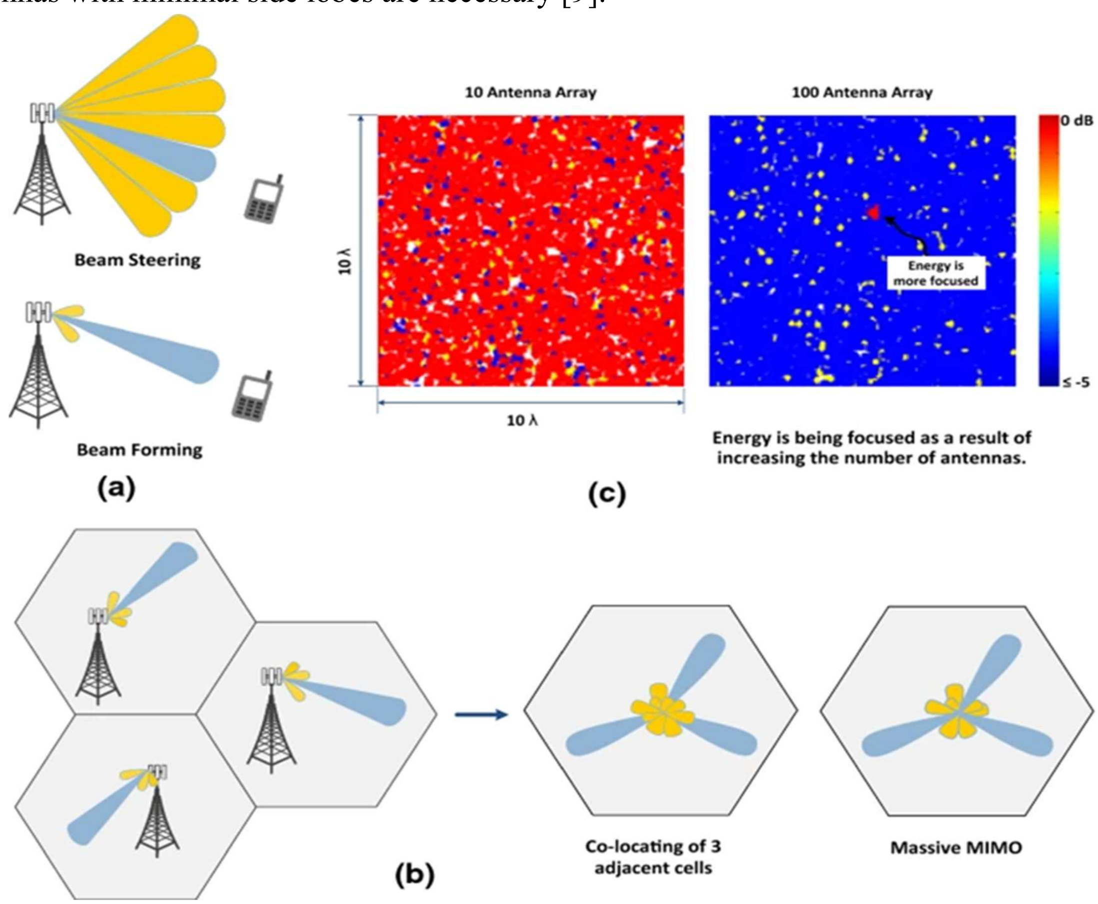


Figure 3: Massive MIMO scheme

Channel estimation, on the other hand, is used in beamforming. In contrast to beam steering, which randomly selects one of many possible beam directions, antenna weighting correction is used in real-time to generate a beam aimed at the user of interest.

In order to implement beamforming, there must be ten times as many antennas at the base station as there are UEs with a single antenna inside the cell.[10]. This massive MIMO (large-scale MIMO) uses a novel structure similar to co-location, allowing transmitters to concentrate their power in a small region using beamforming. By adding more antennas, we can concentrate the power in a smaller beam, as illustrated in Fig. 3c, which means that every given user will experience a more robust signal at their receiver than they would otherwise. Beamforming drastically reduces the amount of energy lost within the coverage zone. With spatial multiplexing, this means less interference and better spectral efficiency. In turn, this contributes to significant electricity savings [11].

The massive MIMO system's channel estimation (also called channel training) time is proportional to the number of base station antennas deployed. These antennas receive a certain number of pilots proportional to the total number of UEs, and the base stations learn simultaneously by comparing the signals they get from various UEs. Moreover, the total number of client terminals grows linearly with the coherence period. There will be more people who can utilize a cell if the coherence time is longer.

Time Division Duplex (TDD) systems use a channel state information (CSI) parameter in UE-network communication to characterize the channel quality and advice on an appropriate precoding matrix during channel training [12]. Measuring the uplink channel with the users' sent pilots approximates the downlink channel's CSI [13]. For this reason, the system uses channel reciprocity when TDD [14] is in play. Uplink and downlink channels in an FDD system undergo separate training procedures. Therefore, training the downlink channel takes time proportional to the number of antennas. As a result, substantial antenna arrays are not recommended for use with FDD. Therefore, an effective alternative method is required to enable CSI estimate in an FDD system [15].

IV. MASSIVE MIMO IS BECOMING MORE IMPORTANT FOR 5G NETWORKS AND BEYOND

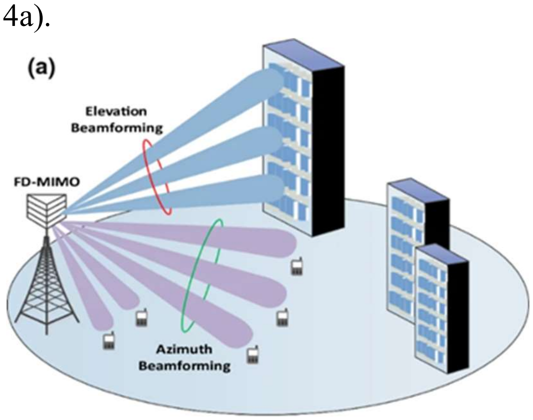
The Massive MIMO idea has been around for a while, but it has continued to grow and expand throughout that time. Due to its importance in 5G standards has become a hot issue in wireless communication research. However, the present MIMO systems have been overwhelmed by the rapid growth of wireless data traffic. “The existing system is unable to achieve the necessary spectral efficiency when new technologies emerge, such as the Internet of Things (IoT), machine-to-machine communication, virtual reality (VR), and augmented reality (AR)." Recent trials using the extensive MIMO system have shown its utility by achieving unprecedented levels of spectral efficiency. “In 2015, researchers from Lund University and Bristol University used a shared 20 MHz radio channel at 3.51GHz and 128 antennas at the base station to achieve spectral efficiency of 145.6 bits/s/Hz for 22 users modulating using 256-Quadrature Amplitude Modulation (256-QAM) [16]”. Compared to the current advanced standard for 4G set by the International Telecommunications Union (ITU), which is 3 bit/s/Hz, the increase in spectral efficiency was substantial.

Multiple indoor and outdoor settings have verified significant MIMO's efficacy in operation. Massive MIMO systems have been shown to perform reliably while using minimally sophisticated radio frequency and baseband circuits [17]. Successful tests have also been conducted on the underlying hardware of a massive MIMO system, demonstrating that such systems can be constructed with meager complicated and low-cost hardware for both digital baseband and analog RF chains [17]. “Several algorithms for precoding, detection, scheduling, and equalisation have been developed to cut down on expenses and energy use.” With all the

recent improvements and advancements in massive MIMO, the technology is now more appealing to implement than ever before, which is essential for the rollout of 5G and beyond wireless networks.
China and Japan are the first to deploy 4G LTE networks that use Massive MIMO. In 2016, Japanese telecom company Soft Bank Group Corp. implemented massive MIMO into its network. In 2017, Vodafone and Huawei collaborated on a field test of Massive MIMO technology, during which they reached speeds of 717 Mbps. The ReefShark chipset, developed by Nokia in 2018, is a lightweight and power-efficient solution for huge MIMO antenna designs. This chipset is one of the most promising technologies for deploying Huge MIMO [18] since it has the potential to cut in half the size of the massive MIMO antennas. By conducting experiments in a packed stadium in South Korea, Samsung also showed that massive MIMO could deliver simultaneous high-speed video streaming without delay in a crowded area [19]. "Sprint Mobile made history in January 2019 by making the first commercial 5G data call across the 2.5 GHz band utilising Massive MIMO on the 3GPP 5G New Radio network [20]." Massive MIMO networks may, in theory, use an unlimited number of base station antennas. However, in large-scale MIMO base stations, 64-128 antennas are typically employed. "Together with industry heavyweights including Ericsson, Nokia, and Samsung Electronics, Sprint Network has recently installed 128 antennas huge MIMO systems (64 antennas to receive signal and 64 antennas to transmit signal)". Massive MIMO's main benefit is that it only requires complex gear at the base station, allowing the UE to use a single antenna with a straightforward design. This means that a more significant number of antennas are required only at the base station but not at the UE to support massive MIMO. The antenna count on today's smartphones ranges from 2 to 4. Even though modern smartphones contain anywhere from two to four antennas, a single antenna at the UE is all that's needed for massive MIMO.

V. 3D MIMO

The goal of 3D MIMO is to address the relevant issue of a large number of antenna components (32, for example, with a spacing of 0.5) in the given area, making it a potential solution for meeting the future needs of massive MIMO. By adjusting the excitation weights of the antenna array components, the radiation pattern in a 3D MIMO system may be steered about azimuth and elevation angles (Fig. 4a).



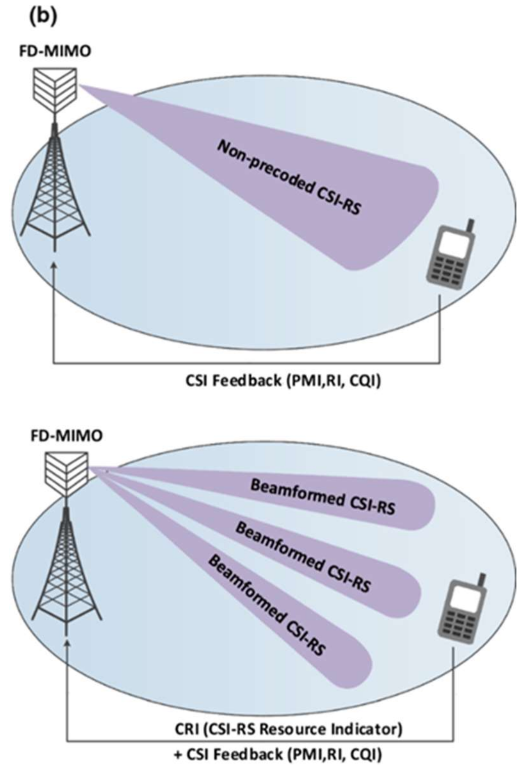


Figure 4: "a. Azimuth and elevation beamforming b Non-precoded CSI-RS (top) vs. beamformed CSI-RS (bottom)"

Elevation-azimuth exploitation improves average-cell and cell-edge performance in 4G-LTE networks compared to traditional MIMO systems [26]. Field testing has shown that TDD 3D-gain MIMOs are more significant than conventional 2D-MIMO, thanks to the utilisation of channel reciprocity. However, these benefits need a precise three-dimensional operation, which introduces additional difficulties [21].

Transceiver units (TXRUs) are added to the transmitter in order to handle the amplitude and phase of the excitation weights, allowing for elevation beamforming with FD-MIMO and providing more precise control over the beamforming direction. We require CSI reporting techniques with higher amplitude and phase granularity and CSI feedback with a high degree of accuracy [22] because "a large TXRU count leads in a considerable CSI-RS overhead and unnecessary CSI-RS resource use [23]". Because several approaches are useful for 3D MIMO but show different throughput increases, further study is needed to determine the efficacy and practicality of elevation beamforming for 3D MIMO (Fig. 8b). But the amount of TXRUs matters for the best option [24]. Many CSI-RS ports in a non-precoded scheme share a single, broad beam; in a beam formed system, each CSI-RS port utilizes its own, narrow beam; and in a hybrid scheme, both non-precoded and beam formed approaches are employed to achieve CSI [25].

Future systems must minimise mismatches and conform to older systems [26] to realize the promised advantage for 3D-MIMO. As a result, 3D-MIMO has a long way to go before it reaches its full potential in terms of its specifications [27].

Three-dimensional multiple-input multiple-output (3D MIMO) increases the efficiency of the cell spectrum, allowing the eNB to schedule more users. The need for reference signals by users and eNBs to estimate the channel grows in tandem with the number of connected users. That means more users would need access to reference signals, or the number of users may be capped [28].

Future MIMO mobility situations were considered to create trustworthy transmission systems. Future research problems for LTE include improving beam management, recovering from beam failure, and transmitting mm-wave signals with low latency and high reliability. Rel-16 [29].

VI. CHALLENGES IN MASSIVE MIMO

A. Pilot contamination

We have already discussed single-cell systems. Although, functional cellular networks often include a large number of cells. Many cells must share the same time-frequency resources due to the scarcity of the frequency spectrum. Consequently, it is essential to think about multi-cell configurations. Due to the channel coherence interval constraint, it is impossible to assign orthogonal pilot sequences to all users in all cells in multi-cell systems. “To go from one cell to the next, orthogonal pilot sequences must be recycled. Therefore, pilots sent by users in other cells will taint the channel estimate calculated in a specific cell. Pilot contamination, the impact caused by this, lowers the system's efficiency [30]”. Massive MIMO suffers from a severe inherent constraint due to the influence of pilot contamination [1]. Even if there are an infinite amount of BS antennae, it will not go away. There have been significant efforts to mitigate this result. “To this end, [31] present Eigen value decomposition-based channel estimation, pilot decontamination, and pilot contamination precoding techniques.” In [30], the authors demonstrated that a covariance-aware pilot assignment system among the cells effectively reduces pilot contamination under certain circumstances of the channel covariance. Numerous studies are still being conducted here [1].

B. Unfavorable propagation

For massive MIMO to function, the propagation conditions must be just right. On the other hand, there are real-world propagation situations where channels are less than ideal. “A poor channel exists, for instance, in propagation conditions where the number of scatterers is low in comparison to the number of users, or if the channels from different users to the BS share some common scatterers [31]”. "One possibility to tackle this problem is to distribute the BS antennas over a large area" [1].

C. New standards and designs are required.

Massive MIMO's efficiency would skyrocket if it could be used in preexisting systems like LTE. However, the LTE specification specifies a cap of 8 on the number of BS antenna connectors. Additionally, LTE uses assumed channel knowledge. As an example, the base station (BS) in an LTE downlink could use several fixed beams to broadcast reference signals. Finally, the users report the strongest beam back to the BS. In the downlink direction, the BS will focus on this beam. On the other hand, Massive MIMO makes advantage of predicted channel data (measured). Accordingly, new standards are needed to bring Massive MIMO down to practice. Massive MIMO, on the other hand, allows for a considerable number of low-power and affordable antennas to take the place of a single high-powered transceiver of 40

Watts. It is also essential to think about the hardware in question. There must be a massive effort from the academic and business communities to accomplish this. [32].

VII. BENEFITS OF MASSIVE MIMO FOR 5G NETWORKS AND BEYOND

Here are just a few of how huge MIMO technology excels:

- Spectral Efficiency: Improved spectrum efficiency is another benefit of Massive MIMO, which is made possible by the system's ability to direct tiny beams of radio waves toward individual users. The existing MIMO technology used for 4G/LTE may be improved by 10 or more, allowing for much higher spectral efficiency.
- Energy Efficiency: Since the antenna array is concentrated in one tiny area, much less power is emitted, making massive MIMO systems more energy efficient.
- High Data Rate: With massive MIMO, data rates and capacities of wireless systems may be increased because of array gain and spatial multiplexing.
- User Tracking: Because massive MIMO directs narrow signal beams at the user, user tracking can be improved.
- Low Power Consumption: Power consumption is reduced because of massive MIMO's use of linear amplifiers with much lower power output and because there is no need for significant, bulky electrical components. There is room for improvement here in terms of power use.
- Less Fading: Massive MIMO is resistant to fading because of the large number of antennas at the receiver, which reduces the amount of signal attenuation [33].
- Low Latency: Massive MIMO decreases air-interface latency. Therefore it is faster.
- Robustness: For one thing, Massive MIMO systems are resistant to both external interference and internal Jamming. Due to the enormous antennas, these systems can withstand the loss of communication from even a small number of antennas [34].
- Reliability: Massive MIMO uses many antennas to improve connection dependability to maximise diversity gain [35,36].
- Enhanced Security: Massive MIMO's narrow beams and orthogonal mobile station channels improve physical security.
- Low Complex Linear Processing: More antennas at the base station mean simpler signal detectors and precedes may be used, reducing the complexity of the linear processing required by the system [37].

VIII. CONCLUSION

In this study, we have covered the history and potential benefits of massive MIMO networks of the future. "The investigation indicates good performance due to the employed methods for the downlink channel such as user grouping and group-based feedback schemes." When massive MIMO is implemented using the pattern/polarisation antenna array concept, the number of possible channels configurations increases, leading to higher channel capacities.

Upgrading the present implementation and allowing for versatile azimuth and elevation radiation patterns is possible by adding 3D MIMO to the existing technology. Three-Hop Joint Project (3GPP) has improved the MIMO relevant reference signal and CSI reporting method to provide specification support for FD-MIMO. “Finally, as the number of antennas per UE increases, the ability to execute uplink beamforming and channel reciprocity use at the UE side becomes more feasible."

This article thoroughly introduces large MIMO systems, focusing on the technologies that will be essential to the success of 5G and beyond networks. Massive MIMO can potentially significantly improve 5G and 6G networks, but it faces several obstacles in its widespread use. "These include issues with pilot contamination, channel estimate, precoding, user scheduling, hardware impairments, energy efficiency, and signal identification." Also discussed are new developments like terahertz communication, UM-MIMO, VLC, and machine learning and deep learning in massive MIMO systems. Our goal in writing this study was to inspire academics in the area of 5G and beyond networks to explore novel avenues and unanswered questions in the future years.

REFERENCES

[1] Zhang, C., Huang, Y., Sheikh, F., & Wang, Z. (2017). Advanced baseband processing algorithms, circuits, and implementations for 5g communication. IEEE Journal on Emerging and Selected Topics in Circuits and Systems, 7(4), 477–490Return to ref 1 in the article

[2] Lin, Z., Du, X., Chen, H., Ai, B., Chen, Z., & Wu, D. (2019). Millimeter-wave propagation modeling and measurements for 5g mobile networks. IEEE Wireless Communications, 26(1), 72–77

[3] Han, S., et al. (2015). Large-scale antenna systems with hybrid analog and digital beamforming for millimeter wave 5G. IEEE Communications Magazine, 53(1), 186–194

[4] CATR. (2016). Discussion on the frame structure design for NR. 3GPP TDocs TSG RAN WG1, Busan, Korea, Tech. Rep. R1–163132, April.

[5] Zhang, J., Yu, X., &Letaief, K. B. (2020). Hybrid beamforming for 5G and beyond millimeter-wave systems: A holistic view. IEEE Open Journal of the Communications Society, 1, 77–91

[6] Guo, W., Fan, J., Li, G. Y., Yin, Q., & Zhu, X. (2017). Adaptive SU/MU-MIMO scheduling schemes for LTE-A downlink transmission. IET Communications, 11(6), 783–792

[7] Clerckx, B., &Oestges, C. (2013). MIMO Wireless Networks: Channels Techniques and Standards for Multi-Antenna, Multi-User and Multi-Cell Systems. Cambridge: Academic Press.

[8] Zhou, I., Ramírez, G. A., Montero, L., Blanch, S., Romeu, J., &Jofre, L. (2020). 3D Beamsteering low complexity reconfigurable multilevel antenna. IEEE Antennas and Wireless Propagation Letters, 19(6), 1017–1021

[9] Han, C., Xiao, L., Chen, Z., & Yuan, T. (2020). Co-located self-neutralized handset antenna pairs with complementary radiation patterns for 5G mimo applications. IEEE Access, 8, 73151–73163

[10] National Instruments, "Overview of massive MIMO for NR," 3GPP TDocs TSG RAN WG1, Nanjing, China, Tech. Rep. R1–164117, May 2016.

[11] Zhang, W., Xia, X., Fu, Y., &Bao, X. (2019). Hybrid and full-digital beamforming in mm-wave massive MIMO systems: A comparison considering low-resolution ADCs. China Communications, 16(6), 91–102

[12] Li, Q., Zhang, A., Liu, P., Li, J., & Li, C. (2020). A Novel CSI feedback approach for massive MIMO Using LSTM-attention CNN. IEEE Access, 8, 7295–7302

[13] Luo, C., Ji, J., Wang, Q., Chen, X., & Li, P. (2020). Channel state information prediction for 5G wireless communications: A deep learning approach. IEEE Transactions on Network Science and Engineering, 7(1), 227–236

[14] Raeesi, O., Gokceoglu, A., Zou, Y., Björnson, E., &Valkama, M. (2018). Performance analysis of multi-user massive MIMO downlink under channel non-reciprocity and imperfect CSI. IEEE Transactions on Communications, 66(6), 2456–2471

[15] Liao, Y., Yao, H., Hua, Y., & Li, C. (2019). CSI Feedback is based on deep learning for massive MIMO systems. IEEE Access, 7, 86810–86820

[16] Makowsky S., Vieira J., Liu L., Harris P., Nieman K., Kundargi N., Wong I.C., Tufvesson F., Öwall V., Edfors O. The World's First Real-Time Testbed for Massive MIMO: Design, Implementation, and Validation. IEEE Access. 2017;5:9073–9088. doi: 10.1109/ACCESS.2017.2705561

[17] Massive MIMO Enables Fixed Wireless Access. [(accessed on 25 January 2020)]; Available online: http://www.massive-mimo.net

[18] Massive MIMO for 5G. [(accessed on 25 January 2020)]; Available online: https://futurenetworks.ieee.org/tech-focus/march-2017/massive-mimo-for-5g

[19] 52. What is Massive MIMO Technology? [(accessed on 25 January 2020)]; Available online: https://5g.co.uk/guides/what-is-massive-mimo-technology

[20] 53. Sprint Completes World's First 5G Data Call Using 2.5 GHz and Massive MIMO on Commercial Network. [(accessed on 25 January 2020)]; Available online: https://newsroom.sprint.com

[21] hafin, R., & Liu, L. (2019). Multi-cell multi-user massive FD-MIMO: Downlink precoding and throughput analysis. IEEE Transactions on Wireless Communications, 18(1), 487–502

[22] Media Tek. (2018). "Views on REL-16 MIMO enhancements," 3GPP TDocs TSG RAN, Chennai, India, Tech. Rep. RP-180352, March.

[23] Samsung. (2016). "Enhancements on full-dimension (FD) MIMO for LTE", 3GPP TDocs TSG RAN, Göteborg, Sweden, Tech. Rep. RP-160623, March.

[24] Huawei, HiSilicon (2018). "DL MIMO efficiency enhancements for LTE FDD" 3GPP TDocs TSG RAN, Chennai, India, Tech. Rep. RP-180367, March. 2018.

[25] Samsung. (2015). "Elevation beamforming/full-dimension (FD) MIMO for LTE", 3GPP TDocs TSG RAN, Malmö, Sweden, Tech. Rep. RP-150784, June.

[26] Samsung, "Mismatched FD-MIMO configuration fields between RAN1 and RRC," 3GPP TDocs TSG RAN WG1, St Julian's, Malta, Tech. Rep. R1–160520, Feb. 2016.

[27] Huawei, HiSilicon, "New WI proposal on SRS enhancements for LTE" 3GPP TDocs TSG RAN WG1, Dubrovnik, Croatia, Tech. Rep. RP-170345, 2017.

[28] 3GPP. (2019). "Maintenance of SRS (sounding reference signal) switching between LTE component carriers," TSG-TSG RAN, Athens, Greece, Tech. Rep. R1–1903266.
[29] ZTE, (2015). "Discussion on SRS Enhancements," 3GPP TDocs TSG RAN, Fukuoka, Japan, Tech. Rep. RP-152983, May.
[30] Huawei.,HiSilicon., (2018). "Motivation for new WI proposal on DL MIMO efficiency enhancements for LTE TDD," 3GPP TDocs TSG RAN, Chennai, India, Tech. Rep. RP-180366, March.
[31] Huawei, HiSilicon, (2018). "Motivation for new WI proposal on NR MIMO enhancements," 3GPP TDocs TSG RAN, Chennai, India, Tech. Rep. RP-180387, 2018.
[32] Hien Quoc Ngo, 2015. Massive MIMO: Fundamentals and System Designs, Linkoping Studies in Science and Technology Dissertations, No. 1642.
[33] Nguyen M. Massive MIMO: A Survey of Benefits and Challenges. ICSES Trans. Comput. Hardw. Electr. Eng. 2018;4:1–4.
[34] 43. Hoydis J., Hosseini K., Brink S.T., Debbah M. Making smart use of excess antennas: Massive MIMO, small cells, and TDD. Bell Labs Tech. J. 2013;18:5–21. doi: 10.1002/bltj.21602.
[35] Jungnickel V., Manolakis K., Zirwas W., Panzner B., Braun V., Lossow M., Sternad M., Apelfrojd R., Svensson T. The role of small cells, coordinated multipoint, and massive MIMO in 5G. IEEE Commun. Mag. 2014;52:44–51. doi: 10.1109/MCOM.2014.6815892.
[36] Marzetta T.L. Noncooperative cellular wireless with unlimited numbers of base station antennas. IEEE Trans. Wirel. Commun. 2010;9:3590–3600. doi: 10.1109/TWC.2010.092810.091092.
[37] Popovski P., Stefanović Č., Nielsen J.J., De Carvalho E., Angjelichinoski M., Trillingsgaard K.F., Bana A.S. Wireless Access in Ultra-Reliable Low-Latency Communication (URLLC) IEEE Trans. Commun. 2019;67:5783–5801. doi: 10.1109/TCOMM.2019.2914652.