

Massive MIMO for superior network performance

Recent technology developments have made Massive MIMO a viable option for large scale deployments in mobile networks. Massive MIMO enables state-of-the-art beamforming and MIMO techniques that are powerful tools for improving user experience, capacity and coverage. As a result, Massive MIMO significantly enhances network performance in both uplink (UL) and downlink (DL). Finding the most suitable Massive MIMO variants to achieve the potential performance gains and cost efficiency in a specific network deployment requires an understanding of the characteristics of both array antennas and of multi-antenna features.

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Introduction

User requirements continue to evolve [1], putting high demands on the radio access network (RAN) to deliver increased network performance. Since data usage is currently increasing at a faster rate than corresponding revenue, communications service providers (CSPs) must evolve the RAN in a way that enables a reduced cost per bit while meeting increasing demands for user performance. Even as a relatively new technology, Massive MIMO solutions have already proven to be essential in today's 5G mid-band deployments to meet the network requirements. Most Massive MIMO solutions have already undergone several hardware and software generations, making them highly competitive in terms of size, weight, cost, performance, energy efficiency, and ease-of-deployment.

Key terms

Massive MIMO radio

Hardware unit that comprises an antenna array, radio chains and parts of the baseband, all tightly integrated to facilitate Massive MIMO features

Massive MIMO feature

A multi-antenna feature (such as beamforming and MIMO) that can be executed in the Massive MIMO radio, in the baseband unit or both

Massive MIMO solution

Massive MIMO radio + Massive MIMO features

Conventional system

Passive antenna + remote radio unit comprising a low number (2, 4 or 8) of radio chains

Dual-polarized antenna element pair

Pair of two antenna elements with orthogonal polarizations with the purpose of enabling diversity and spatial multiplexing, and doubling the number of antenna elements on a given physical area

What is a Massive MIMO solution?

Massive MIMO (also known as advanced antenna system, or AAS) is a technology that makes use of a large number of controllable antennas to implement multi-antenna techniques to improve network performance. A Massive MIMO solution is a combination of a Massive MIMO radio and a set of Massive MIMO features, implementing the multi-antenna techniques. Compared to conventional systems, Massive MIMO provides much greater flexibility, in terms of adapting the antenna radiation patterns to rapidly time-varying traffic and multi-path radio propagation conditions.

Multi-antenna techniques

Multi-antenna techniques (here referred to as Massive MIMO features) include all variants of beamforming, null-forming, and MIMO. Applying Massive MIMO features to a Massive MIMO radio results in significant performance gains because of the higher degrees of freedom provided through the use of many radio chains and a large antenna aperture.

Beamforming

During transmission, beamforming is the ability to direct transmit power through the radio channel toward a specific receiver, see Figure 1, part A. By adjusting the phase and amplitude of the transmitted signals, constructive addition of the corresponding signals at the user equipment receiver can be achieved which increases the received signal strength and, thus, the user throughput. Similarly, during reception, beamforming is the ability to collect the signal power from a specific transmitter. The beams formed are constantly adapted to the surroundings to give high performance in both UL and DL.

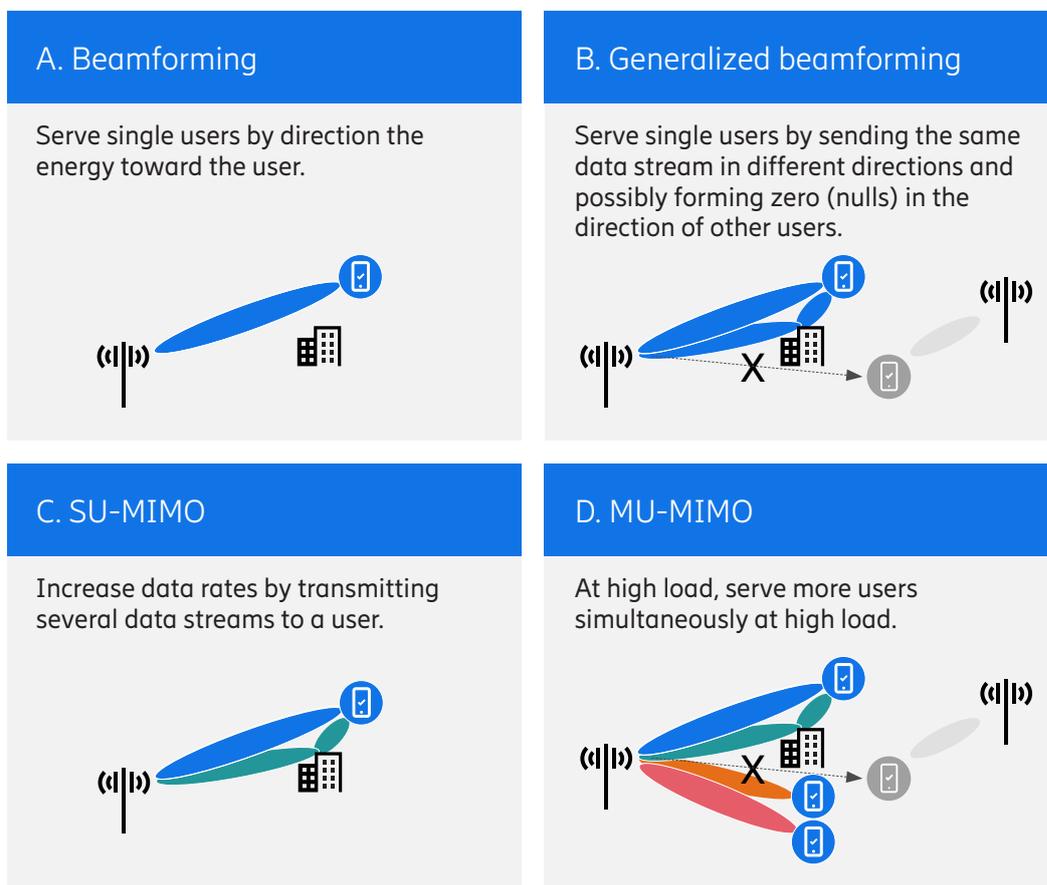


Figure 1: Beamforming and MIMO with the different colors of the filled beams that represent different data streams.

Although often very effective, transmitting power in only one direction does not always provide an optimum solution. In multi-path scenarios, where the radio channel comprises multiple propagation paths from the transmitter to receiver through diffraction around corners and reflections against buildings or other objects, it is beneficial to send the same data stream in several different paths (direction and/or polarization) with phases and amplitudes controlled in a way that they add constructively at the receiver, see [2] for further details. This is referred to as generalized beamforming, see Figure 1, part B. It should be noted that beams do not always correspond to single directions, as indicated in the figure, but can have arbitrary shapes, see [2, ch. 6].

Null-forming

As part of generalized beamforming, it is also possible to reduce interference to other UEs, which is known as null-forming. This is achieved by controlling the transmitted signals in a way that they cancel each other out at UEs that would otherwise be interfered.

MIMO (Multiple Input, Multiple Output) techniques

Spatial multiplexing, here referred to as MIMO, is the ability to transmit multiple data streams, using the same time and frequency resource, where each data stream can be beamformed differently. The purpose of MIMO is to increase user throughput and capacity. MIMO builds on the basic principle that when the received signal quality is high, it is better to receive multiple streams of data with reduced power per stream, than one stream with full power.

The potential is large when the received signal quality is high, and the beams carrying the data streams are designed not to interfere with each other. MIMO works in both UL and DL, but for simplicity, the description below will be based on the DL. More details can be found in [2, Ch. 6].

Single-user MIMO (SU-MIMO) is the ability to transmit one or multiple data streams, also called layers, from one transmitting array to a single user. The number of layers that can be supported, called the rank, depends on the radio channel and the minimum number of antennas on each side. To distinguish between DL layers, a UE must have at least as many receiver antennas as there are layers.

SU-MIMO can be achieved by sending different layers on different polarizations in the same direction. SU-MIMO can also be achieved in a multi-path environment, where there are many radio propagation paths of similar strength between the Massive MIMO radio and the UE, by sending different layers on different propagation paths, Figure 1, part C.

In multi-user MIMO (MU-MIMO), Figure 1, part D, different layers are transmitted to different users using the same time and frequency resource, thereby increasing the network capacity. To use MU-MIMO, the system needs to find two or more users that need to transmit or receive data at the very same time. Also, for efficient MU-MIMO, the interference between the users should be kept low relative to noise and intercell interference. This can be achieved by using generalized beamforming with null forming such that when a layer is sent to one user, nulls are formed in the directions of the other simultaneous users.

The achievable capacity gains from MU-MIMO depend on receiving each layer with good signal-to-interference-and-noise-ratio (SINR). As with SU-MIMO, the total DL power is shared between the layers, and therefore the power (and thus SINR) for each user is reduced as the number of simultaneous MU-MIMO users increases. Also, as the number of users grows, the SINR will further deteriorate due to mutual interference between the users. Therefore, the network capacity typically improves as the number of MIMO layers increases to a point at which power sharing and interference between users result in diminishing gains and eventually also losses.

Acquiring channel knowledge for Massive MIMO

Knowledge of the radio channels between the antennas of the user and those of the base station is a key enabler for beamforming and MIMO, both for UL reception and DL transmission. This allows the Massive MIMO solution to adapt the number of layers and determine how to beamform them.

For UL reception of data signals, channel estimates can be determined from known signals received on the UL transmissions. Channel estimates can be used to determine how to combine the signals received to improve the desired signal power and mitigate interfering signals, either from other cells or within the same cell.

DL transmission, on the other hand, is typically more challenging than UL reception because channel knowledge needs to be available before transmission. Whereas basic beamforming has relatively low requirements on the necessary channel knowledge, generalized beamforming has higher requirements as more details about the multi-path propagation are needed. Furthermore, mitigating interference by using null-forming for MU-MIMO is even more challenging, since more details of the channels typically need to be characterized with high granularity and accuracy. There are two basic ways of acquiring DL channel knowledge: UE feedback and UL channel estimation.

To acquire DL channel knowledge based on UE feedback, the base station transmits known signals in the DL that UEs can use for channel estimation. Relevant channel information is then extracted from the channel estimates and fed back to the base station.

What type of DL channel knowledge can be acquired based on UL channel estimation, also referred to as UL sounding, depends on whether time division duplex (TDD) or frequency division duplex (FDD) is used. For TDD, the same frequency is used for both UL and DL transmission. Since the radio channel is reciprocal (the same in UL and DL), detailed short-term channel estimates from UL transmission of known signals can be used to determine the DL transmission beams. This is referred to as reciprocity-based beamforming. For full channel estimation, signals should be sent from each UE antenna and across all frequencies.

For FDD, where different frequencies are used for UL and DL, the channel is not fully reciprocal. Longer-term channel knowledge (such as dominant directions) can, however, be obtained by suitable averaging of UL channel estimate statistics. The suitable channel knowledge scheme to use depends on UL coverage and UE capabilities. In cases where UL coverage is limiting, UE feedback may offer more robust operation, whereas full UL channel estimation is applicable in scenarios with good coverage. In short, both reciprocity and UE feedback-based beamforming are needed.

The achievable performance gains depend on the channel estimates. Particularly, the gains of MU-MIMO, see above, rely on accurate and timely channel knowledge for multiplexed users, which in practice for the DL often is more challenging for more bursty (chatty) traffic. This can cause a dependency of the practical benefits achievable for MU-MIMO on the traffic pattern.

Antenna array structure

The purpose of using a rectangular antenna array, as shown in section A of Figure 2, is to enable high-gain beams and make it possible to steer those beams over a range of angles in horizontal and vertical directions. The gain is achieved, in both UL and DL, by constructively combining signals from several antenna elements. Typically, the more antenna elements there are, the higher the gain. Steerability is achieved by individually controlling the amplitude and phase of smaller parts of the antenna array. This is usually done by dividing the antenna array into sub-arrays (groups of non-overlapping elements pairs), Figure 2, section C, and by applying two dedicated radio chains per sub-array (one per polarization) to enable control, Figure 2 section D. In this way, it is possible to control the properties of the created beam.

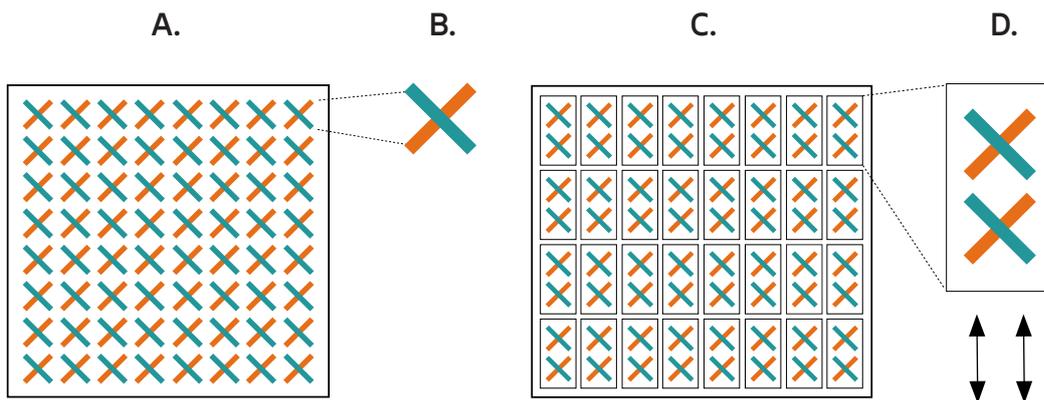


Figure 2: A typical antenna array (A) is made up of rows and columns of individual dual-polarized antenna element pairs (B). Antenna arrays can be divided into sub-arrays (C), with each sub-array (D) connected to two radio chains, normally one per polarization.

Some key properties of an array of subarrays are illustrated below. For simplicity, a linear antenna array (only one dimension) is considered.

The array gain is referred to as the gain achieved when all sub array signals are added constructively (in phase). The size of the array gain, relative to the gain of one sub-array, depends on the number of sub-arrays – for example, two sub-arrays give an array gain of 2 (i.e. 3 dB). By changing the phases of the sub-array signals in a certain way, this gain can be achieved in any direction, see Figure 3, section A.

Each sub-array has a certain radiation pattern describing the gain in different directions. The gain and beam width depend on the size of the sub-array and the properties of the individual antenna elements. There is a trade-off between sub-array gain and beam width

– the larger the sub-array, the higher the gain and the narrower the beam width, Figure 3, section B. The total antenna gain is the product of the array gain and the sub-array gain, Figure 3, section C. The total number of elements determines the maximum gain and the sub-array partitioning allows the steering of high-gain beams over the range of angles. Moreover, the sub-array radiation pattern determines the envelope of the narrow beams (the dashed shape in Figure 3, section C). This has an implication on how to choose an antenna array structure in a real deployment scenario with specific coverage requirements. Since each sub-array is normally connected to two radio chains and each radio chain is associated with a cost in terms of additional components, it is important to consider the performance benefits of additional steerability when choosing a cost-efficient array structure.

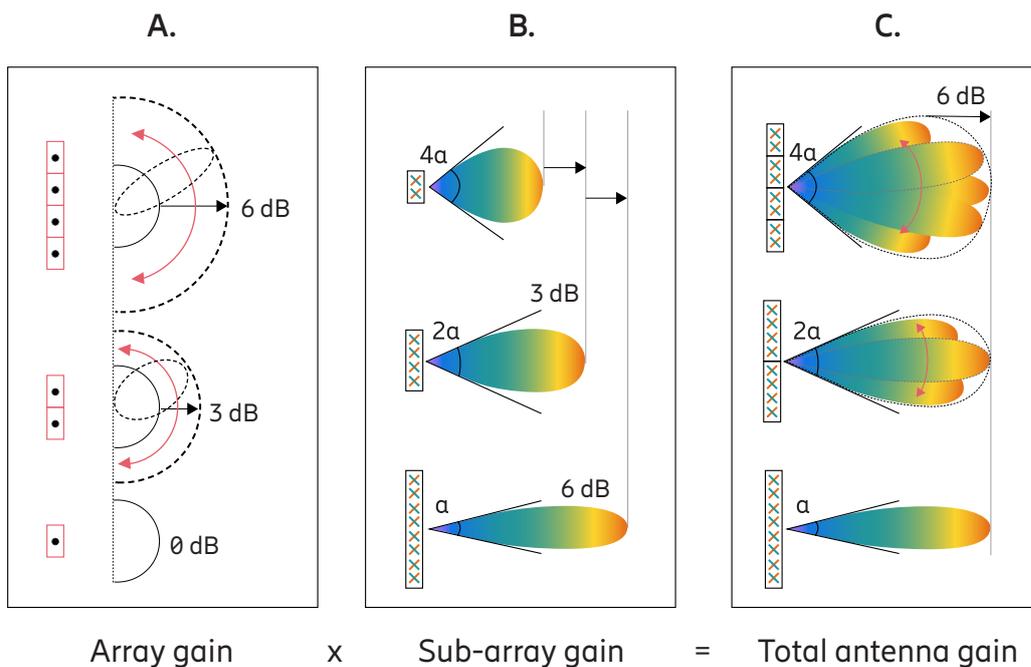


Figure 3: An array of sub-arrays supporting high total antenna gain and steerability.

Spectrum aspects

The total propagation loss tends to increase as the carrier frequency increases. To maintain coverage when increasing the carrier frequency, one possibility is to increase the antenna gain. As antenna size typically is proportional to the wavelength, more elements can fit a given physical size as the frequency increases. For example, by doubling the carrier frequency, four times more antenna elements can fit in a planar antenna array with a fixed physical size, resulting in 6 dB more antenna gain. In most situations, however, when increasing the carrier frequency, the propagation loss outweighs the additional gain an antenna of fixed physical size provides, hence a physically larger antenna is needed to fully compensate for the propagation loss. An alternative is to rely on frequency interworking and let lower frequency bands handle users with poor coverage. To keep similar properties of the antenna in terms of beamforming flexibility when adding more antenna elements, the number of radio chains needs to increase correspondingly. This increase is not sustainable and new building practices, possibly including a hybrid architecture with a mix of digital and analog beamforming, is needed. For mmWave (24-52 GHz; FR2 in 3GPP) an implementation based only on analogue beamforming is very common.

Deployment scenarios

Determining what kind of Massive MIMO configuration is most appropriate and cost effective for a particular deployment scenario requires a mix of knowledge about the scenario, possible site constraints, and available Massive MIMO features, particularly the need for vertical steerability of beams, the expected performance of reciprocity-based beamforming and the gain from MU-MIMO. It should be noted that horizontal beamforming provides large gains in all scenarios as the users are generally spread in the horizontal dimension. Therefore, it is beneficial to have many antenna columns in all scenarios.

Three typical use cases are chosen to illustrate different aspects of Massive MIMO deployment: rural/suburban, urban low-rise, and dense urban high-rise. The scenarios, including relevant characteristics, suitable Massive MIMO configurations, and performance potential are depicted in Figure 4. More elaborate evaluations of the performance achievable with Massive MIMO are available in [2] and [3].

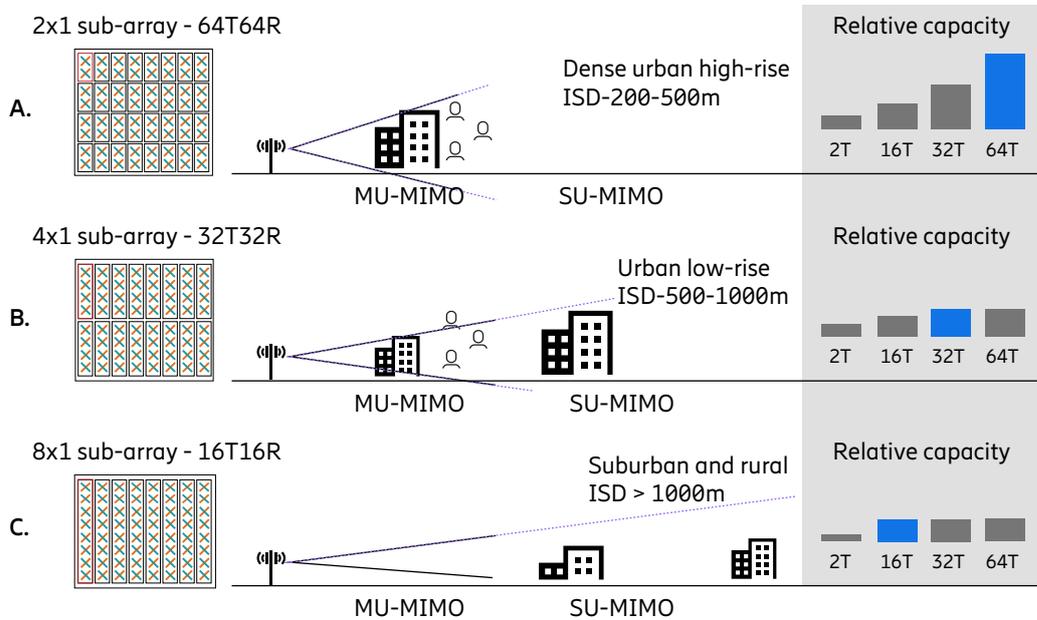


Figure 4: Suitable Massive MIMO configurations, schematic MU-MIMO and SU-MIMO usage ranges, and typical capacity gains in different deployment scenarios.

Deployment scenario #1: Dense urban high-rise

The dense urban high-rise scenario, Figure 4, section A, is characterized by high-rise buildings, short inter-site-distances (ISDs) of 200-500 m, large traffic volume, and high subscriber density with significant user spread in the vertical dimension. The main network evolution driver is increased capacity and high user throughput.

The desired Massive MIMO characteristics in the dense urban high-rise scenario include an antenna area large enough to ensure sufficient coverage (UL cell-edge data rate). The vertical coverage range needs to be large enough to cover the vertical spread of users. This calls for small sub-arrays, which have a wide beam in the vertical direction. Small vertical sub-arrays results in high-gain beams that can be steered over a large range of angles provides good coverage for the buildings in the target area. The Massive MIMO radio needs to have a sufficient number of radio chains to support the relatively large number of sub-arrays. The good coverage and large spread of users imply that the potential for reciprocity-based beamforming and MU-MIMO are high, and the Massive MIMO radio should support these techniques. A good trade-off between complexity and performance could be achieved with 64 radio chains controlling small sub-arrays.

Deployment scenario #2: Urban low-rise

The urban low-rise scenario, see Figure 4 section B, represents many larger cities and outskirts of many high-rise cities. Base stations are typically deployed on rooftops, with inter-site distances of a few hundred meters. Compared to the dense urban high-rise scenario, traffic per area unit is lower. There is generally a mix of building types, which creates multipath propagation between the Massive MIMO radio and the UE. Maximizing the antenna area is important for improving the UL cell-edge data rates, especially for higher frequency bands employing TDD. Due to larger ISDs and lower buildings, the vertical coverage range can be decreased compared to dense urban high-rises; hence, larger vertical sub-arrays, can be used and there is less gain from vertical beamforming. Reciprocity-based beamforming schemes will work for most users, but there will also be users with poor coverage that need feedback-based beamforming. MU-MIMO is also appropriate at high loads due to the multi-path propagation environment, good link qualities, and UE pairing opportunities. A good trade-off between complexity and performance is a Massive MIMO radio with 32 radio chains.

Deployment scenario #3: Rural/suburban

Rural or suburban macro scenarios, see Figure 4 section C, are characterized by rooftop or tower-mounted base stations with inter-site distances ranging from one to several kilometers, low or medium population density and very small vertical user distribution. This scenario calls for a Massive MIMO radio with a large antenna area and the ability to support horizontal beamforming. Vertical beamforming, however, does not provide any significant gains as the vertical user spread is low. Therefore, large vertical sub-arrays with small vertical coverage areas are possible. A good trade-off between complexity and performance is a Massive MIMO radio with 16 radio chains.

Evolution of Massive MIMO

Massive MIMO is currently (2026-Q1) used mainly for TDD mid-band (2.6-7 GHz). Massive MIMO products at this frequency range can support antenna arrays of reasonable size with many radio chains, hence a high degree of freedom for Massive MIMO features, using a fully digital beamforming architecture. In many TDD mid-band networks, Massive MIMO radios constitute a significant part of all new deployments. Massive MIMO is also used at lower frequencies and for FDD, where its usage is growing as the latest products are significantly more efficient than earlier generations. Due to the lower attenuation on lower bands and to the use of FDD, these bands, especially in the uplink, provide better coverage than higher bands using TDD, and thus are important for the overall system coverage. Massive MIMO is also used for millimeter wave (mmWave) bands (24-58 GHz), particularly for areas that require extremely high capacity and for fixed wireless access (FWA). The current use is however limited due to the challenging wave propagation properties on these bands.

The evolution of Massive MIMO is very rapid, and several tracks are being investigated to achieve higher performance. A few examples include the use of higher numbers of radio chains, larger array panels, the use of new and higher frequencies, and the use of multiple transmission points (multi-TRP). In particular, the cmWave range (7-15 GHz) could provide new spectrum where Massive MIMO is a key technology to achieve high capacity and good coverage. There may be regional needs to co-exist with incumbent systems, e.g. terrestrial radio links, satellite ground stations and satellites, for some of the cmWave frequencies, which may require new solutions.

In addition to advancements in technologies specific to Massive MIMO, the use of interworking between frequency bands adds additional capacity beyond the sum of the capacity on each band. Other developing technologies, e.g. artificial intelligence and machine learning (AI/ML) will also be applied in Massive MIMO to improve performance. Yet other technology developments, relating to, for example energy performance, cost efficiency, and site deployment, are coming into use to make Massive MIMO a highly competitive and commercially viable option for mass deployment in a large variety of scenarios. Massive MIMO is also used to support a growing number of services in addition to MBB. Massive MIMO is already used for FWA, IoT and new industries and soon also XR services. With the development of private networks, the number of services supported is expected to grow fast.

Conclusion

Massive MIMO is a preferred option for large-scale deployments in many of today's 5G mobile networks. Massive MIMO enables state-of-the-art beamforming and MIMO techniques that are powerful tools for improving user experience, capacity, and coverage. As a result, Massive MIMO significantly enhances network performance in both uplink and downlink.

The Massive-MIMO solution toolbox is versatile and the selection of a suitable Massive MIMO solution depends on aspects such as deployment environment, traffic load variations and ease-of-deployment. Massive MIMO products provide significant benefits across a very wide range of deployment scenarios, making it possible for mobile network operators to enjoy the benefits of cost-efficient Massive MIMO across their networks. Massive MIMO solutions have already proven highly valuable in many deployments, and their importance will increase even further in future network deployments.

Further reading

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Authors



Peter von Butovitsch joined Ericsson in 1994 and currently serves as Principal Researcher in the Business Area Networks. He has held various positions in Ericsson Research, Radio Access Network (RAN) development and customer units (in Japan and China). He holds an MSc in engineering physics and a PhD in signal processing, both from KTH, Royal Institute of Technology in Stockholm, Sweden. In 2016 he earned an MBA from University of Leicester, School of Business, in the United Kingdom.



David Astely is currently a Principal Researcher with Ericsson Research in the radio area. He received his PhD in signal processing from KTH Royal Institute of Technology in 1999 and has been with Ericsson since 2001, where he has held various positions in both research and product development.



Anders Furuskär joined Ericsson Research in 1997 and is currently a senior expert focusing on radio resource management and performance evaluation of wireless networks. He has an M.Sc. in electrical engineering and a Ph.D. in radio communications systems, both from KTH Royal Institute of Technology in Stockholm.



Bo Göransson is the Senior Expert in Multi Antenna Systems & Architectures. He joined Ericsson Research in 1998, where he worked with research and standardization of 3G and 4G physical layer with a special interest in MIMO and beamforming technologies. He later moved to Business Area Networks to work closer to the implementation of multi antenna technologies. He holds an M.Sc. in electrical engineering and engineering physics from Linköping University (Sweden) and a Ph.D. in signal processing from KTH Royal Institute of Technology in Stockholm. Since 2019 he is also an adjunct professor at KTH Royal Institute of Technology.



Billy Hogan joined Ericsson in 1995. His current position is Head of Radio Access and Propagation, Concepts and Algorithms within Business Area Networks, where he leads a group that is researching radio network algorithms and concepts for 6G. Previously he had held various senior technical and leader positions within core and Radio Access Network Systemization and Design, including the role of Principal Engineer for Massive MIMO technology and strategy. He holds a BE in electronic engineering from the University of Galway, Ireland, and a MEng in electronic engineering from Dublin City University, Ireland.



Jonas Karlsson joined Ericsson in 1993. Since then, he has held various technical and leader positions in Ericsson covering both radio access research and system management in product development. He is currently an Expert in Multi-Antenna Systems at Business Area Networks. He holds an MSc in electrical engineering and engineering physics from Linköping University, Sweden, and a PhD in electrical engineering from the University of Tokyo, Japan.



Erik Larsson joined Ericsson in 2005. He is currently a Senior Specialist in RAN evaluations at Business Area Networks working with concept development and network performance for 6G. He holds both an MSc in engineering physics and a PhD in electrical engineering, specializing in signal processing, from Uppsala University, Sweden.