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Advanced antenna systems for 5G networks

Recent technology developments have made advanced antenna systems (AAS) a viable option for large scale deployments in existing 4G and future 5G mobile networks. AAS enables state-of-the-art beamforming and MIMO techniques that are powerful tools for improving end-user experience, capacity and coverage. As a result, AAS significantly enhances network performance in both uplink and downlink. Finding the most suitable AAS variants to achieve performance gains and cost efficiency in a specific network deployment requires an understanding of the characteristics of both AAS and of multi-antenna features.

Introduction

End-user performance requirements continue to increase, putting high demands on the radio access network (RAN) to deliver increased coverage, capacity and end-user throughput. Since data usage is currently increasing at a much faster rate than corresponding revenue, mobile network operators (MNOs) must evolve the RAN in a way that enables a reduced cost per bit while meeting new demands for end-user performance. The timing is now right for the telecom industry to make the technology shift to advanced antenna systems (AAS). The key reasons for this technology shift are the superior performance of AAS in both uplink (UL) and downlink (DL) [2] [3] [4] and the feasibility of building AAS cost-effectively. The shift to AAS is enabled by technology advances in the integration of baseband, radio, and antenna, and a reduction in the digital processing cost of advanced beamforming and MIMO.

AAS is a powerful option for MNOs that want to improve coverage, capacity and user performance using existing network sites. Many MNOs choose this strategy as it is often difficult, time consuming and expensive to acquire and deploy new sites. Another main driver for AAS is the need to meet coverage requirements on new and higher frequency bands. This is particularly important when introducing 5G on existing site grids.

Key terms

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

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

AAS = AAS radio + AAS features

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

Dual-polarized antenna element = Combination of two antenna elements with orthogonal polarizations with the purpose of enabling diversity and doubling the number of antenna elements on a given physical area

What is an advanced antenna system?

An advanced antenna system (AAS) is a combination of an AAS radio and a set of AAS features. An AAS radio consists of an antenna array closely integrated with the hardware and software required for transmission and reception of radio signals, and signal processing algorithms to support the execution of the AAS features. Compared to conventional systems, this solution provides much greater adaptivity and steerability, in terms of adapting the antenna radiation patterns to rapidly time-varying traffic and multi-path radio propagation conditions. In addition, multiple signals may be simultaneously received or transmitted with different radiation patterns.

Multi-antenna techniques

Multi-antenna techniques, here referred to as AAS features, include beamforming and MIMO. Such features are already used with conventional systems in today's LTE networks. Applying AAS features to an AAS radio results in significant performance gains because of the higher degrees of freedom provided by the larger number of radio chains, also referred to as Massive MIMO.

Beamforming

When transmitting, beamforming is the ability to direct radio energy through the radio channel toward a specific receiver, as shown in the top left quadrant of **Figure 1**. By adjusting the phase and amplitude of the transmitted signals, constructive addition of the corresponding signals at the UE receiver can be achieved, which increases the received signal strength and thus the end-user throughput. Similarly, when receiving, beamforming is the ability to collect the signal energy from a specific transmitter. The beams formed by an AAS are constantly adapted to the surroundings to give high performance in both UL and DL.

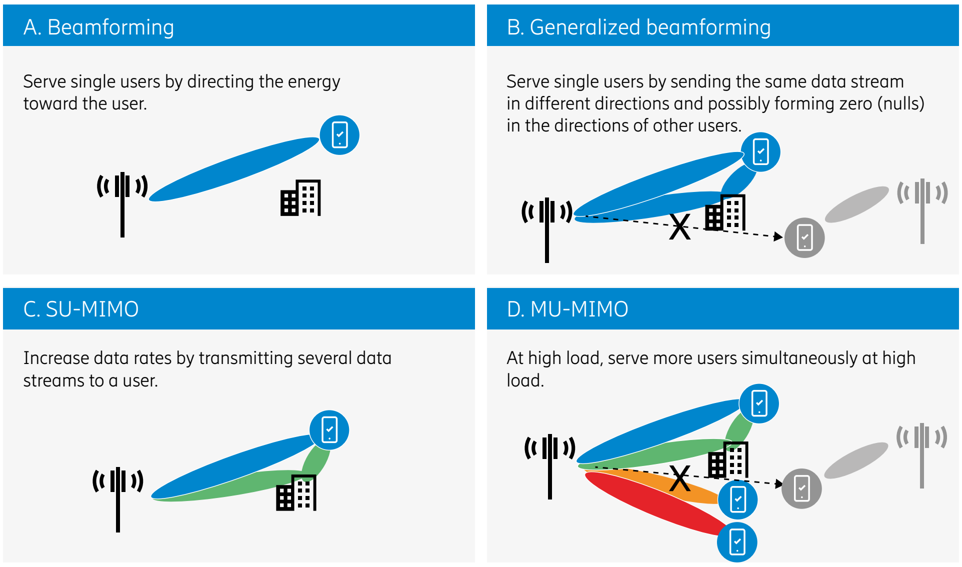


Figure 1: Beamforming and MIMO, with the different colors of the filled beams representing streams.

Although often very effective, transmitting energy in only one direction does not always provide an optimum solution. In multi-path scenarios, where the radio channel comprises multiple propagation paths from 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 [5]. This is referred to as generalized beamforming, as shown in the upper right quadrant of Figure 1. 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 the interfered UEs.

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. The purpose of MIMO is to increase throughput. 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 streams do not interfere with each other. The potential diminishes when the mutual interference between streams increases. MIMO works in both UL and DL, but for simplicity the description below will be based on the DL.

Single-user MIMO (SU-MIMO) is the ability to transmit one or multiple data streams, called layers, from one transmitting array to a single user. SU-MIMO can thereby increase the throughput for that user and increase the capacity of the network. The number of layers that can be supported, called the rank, depends on the radio channel. To distinguish between DL layers, a UE needs to 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 AAS and the UE, by sending different layers on different propagation paths, as shown in the bottom left quadrant of Figure 1.

In multi-user MIMO (MU-MIMO), which is shown in the bottom right quadrant of Figure 1, the AAS simultaneously sends different layers in separate beams to different users using the same time and frequency resource, thereby increasing the network capacity. In order 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. 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 different 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.

It should be noted that the practical benefits of many layers in MU-MIMO are limited by the fact that, in today's real networks, even with a high number of simultaneous connected users, there tends not to be many users who want to receive data simultaneously. This is due to the bursty (chatty) nature of data transmission to most users. Since the AAS and the transport network must be dimensioned for the maximum number of layers, the MNO needs to consider how many layers are required in their networks. In typical MBB deployments with the current 64T64R AAS variants, the vast majority of the DL and UL capacity gains can be achieved with up to 8 layers.

Acquiring channel knowledge for AAS

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 AAS 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 in the case of MU-MIMO.

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 in terms of null forming for MU-MIMO is even more challenging, since more channels typically need to be characterized with high granularity and accuracy. There are two basic ways of acquiring the DL channel knowledge between the UEs and the AAS: UE feedback and UL channel estimation.

For UE feedback, the base station transmits known signals in the DL that UEs can use for channel estimation and generation of feedback that is transmitted on control channels in the UL to the AAS.

For the case of UL channel estimation, there are differences depending 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. DL 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 offers 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.

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. The gain is achieved, in both UL and DL, by constructively combining signals from a number of antenna elements. 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 so-called sub-arrays (groups of non-overlapping elements), as shown in section C of Figure 2, and by applying two dedicated radio chains per sub-array (one per polarization) to enable control, as shown in section D. In this way it is possible to control the direction and other properties of the created antenna array beam.

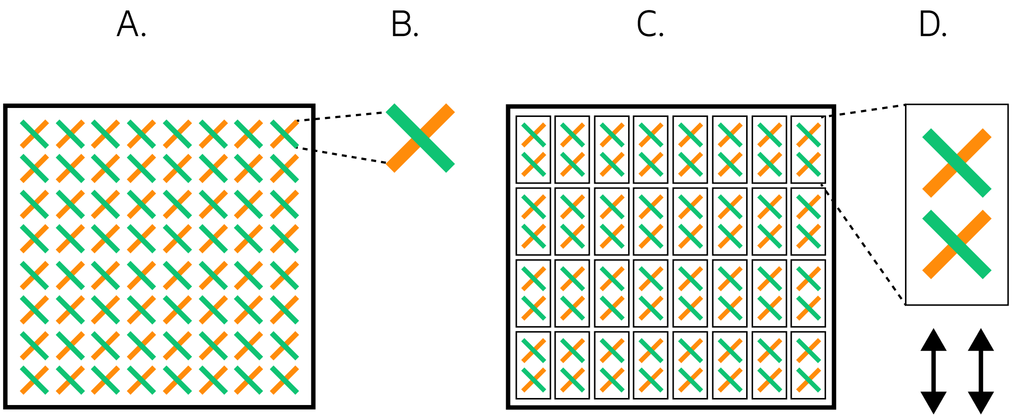


Figure 2: A typical antenna array (A) is made up of rows and columns of individual dual-polarized antenna elements (B). Antenna arrays can be divided into sub-arrays (C), with each sub-array (D) connected to two radio chains, normally one per polarization.

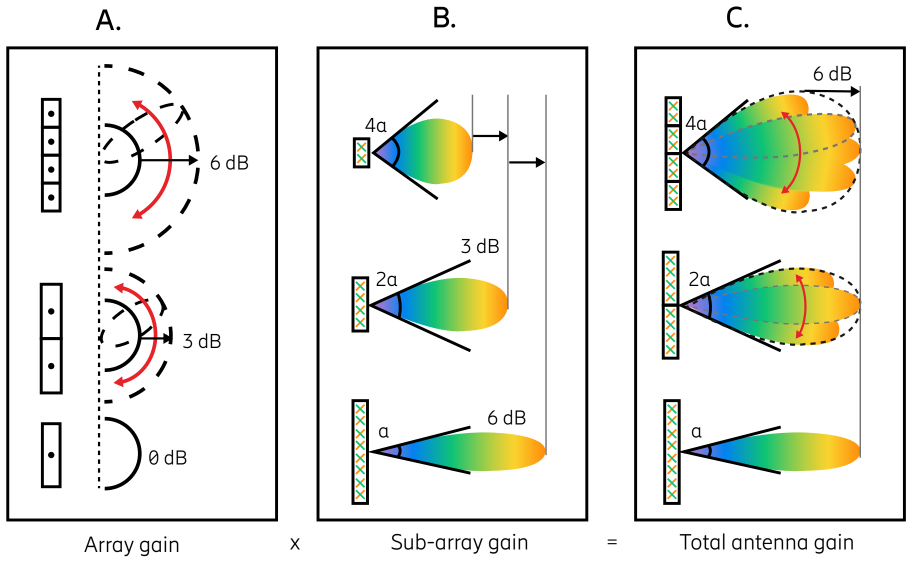
To see how an antenna array creates steerable high-gain beams, we start with an antenna array of a specific size, which is then divided into sub-arrays of different sizes. For illustrative purposes, we describe only one dimension. The same principles do, however, apply to both vertical and horizontal dimensions.

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 gives 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, as shown in section A of **Figure 3.**

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, as illustrated in section B of Figure 3.

The total antenna gain is the product of the array gain and the sub-array gain, as shown in section C of Figure 3. The total number of elements determines the maximum gain and the sub-array partitioning allows 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 section C of Figure 3). This has an implication on how to choose 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.



Deployment scenarios

Determining what kind of AAS 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 AAS features, particularly the need for vertical steerability of beams, the applicability of reciprocity-based beamforming and the gain from MU-MIMO.

We have chosen three typical use cases that illustrate different aspects of AAS deployment: rural/suburban, urban low-rise and dense urban high-rise. The scenarios, including relevant characteristics, suitable AAS configurations, and performance potential are depicted in **Figure 4**. More elaborate evaluations of the performance achievable with AAS are available in reference [4].

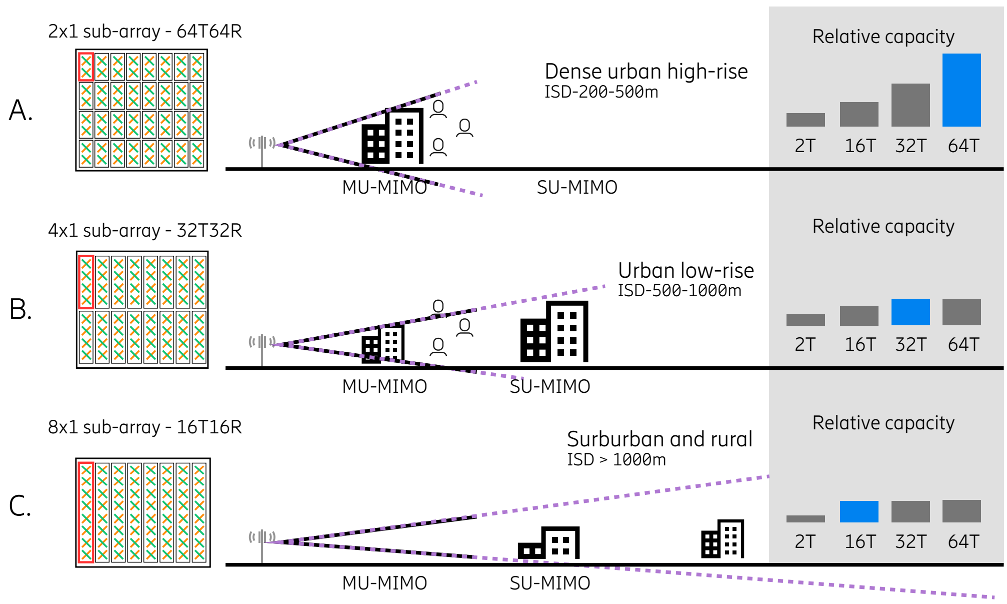


Figure 4: Suitable AAS configurations, schematic MU-MIMO and SU-MIMO usage ranges, and typical capacity gains in different deployment scenarios

Deployment scenario #1: Dense urban high-rise

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

For conventional non-beamformed systems such as 2T2R, the vertical spread of users in combination with the small ISD creates a situation where many users are outside the vertical main beam of the nearest base station. Together with the high site density, this leads to a situation where the signals from interfering base stations are strong, and severe interference problems may occur.

Desired AAS characteristics in the dense urban high-rise scenario include an antenna area large enough to ensure sufficient coverage (UL cell-edge data rate). Further, 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. Partitioning the antenna into small sub-arrays results in high-gain beams that can be steered over a large range of angles and effectively addresses the interference problems seen with conventional systems. The AAS 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 mean that the potential for reciprocity-based beamforming and MU-MIMO with a relatively large number of multiplexed users is high, and the AAS 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 illustrated in section B of Figure 4 represents many of the larger cities around the world, including the 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 AAS 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 decreased vertical spread of users (lower buildings), the vertical coverage range can be decreased compared to dense urban high-rise; hence, larger vertical sub-arrays can be used and there is less gain from vertical beamforming. Using larger sub-arrays for a given antenna area means that fewer radio chains are required. Horizontal beamforming is a very effective feature that provides large gains. Reciprocity-based beamforming schemes will work for most users, but there will be users with poor coverage that need to rely on techniques such as 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 an AAS with 16 to 32 radio chains.

Deployment scenario #3: Rural/suburban

Rural or suburban macro scenarios, as depicted in section C of Figure 4, 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 an AAS 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 appropriate. Reciprocity-based beamforming is supported for a smaller fraction of users than in the other scenarios, and MU-MIMO gains are more limited. A good trade-off between complexity and performance is an AAS with 8 to 16 radio chains.

Conclusion

Recent technology developments have made advanced antenna systems (AAS) a viable option for large-scale deployments in existing 4G and future 5G mobile networks. AAS enables state-of-the-art beamforming and MIMO techniques that are powerful tools for improving end-user experience, capacity and coverage. As a result, AAS significantly enhances network performance in both uplink and downlink.

In dense urban high-rise scenarios with tall buildings and high subscriber density, an AAS with beamforming capabilities in both vertical and horizontal directions is the most beneficial option. In suburban/rural scenarios, where vertical beamforming is usually not needed, the performance of a more cost-efficient AAS with fewer radio chains is often sufficient. High AAS performance can be achieved without the need for many MIMO layers.

A small number of AAS variants 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 AAS across their networks. As a result, the importance of AAS is likely to increase rapidly in future radio network deployments.

Glossary

5G	5th Generation (mobile system technology)
AAS	Advanced Antenna System
BB	Baseband
DL	Downlink
FDD	Frequency Division Duplex
HW	Hardware
ISD	Inter-site Distance
MBB	Mobile Broadband
MIMO	Multiple Input Multiple Output
MU-MIMO	Multi-User MIMO
mmW	Millimeter Wave
MNO	Mobile Network Operator
NR	New Radio
R	Receiver (part of the radio chain)
RAN	Radio Access Network
SU-MIMO	Single-User MIMO
SW	Software
TDD	Time Division Duplex
T	Transmit (part of the radio chain)
UE	User Equipment
UL	Uplink

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Further reading

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