5G AMERICAS WHITE PAPER

ADVANCED ANTENNA SYSTEMS FOR 5G

August 2019

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1. INTRODUCTION

As the demand for throughput, improved user experience and ubiquitous coverage from consumers and corporations continues to grow, operators are quickly improving and expanding coverage and capacity in their wireless network in a cost-effective way. Recent technology developments have made advanced antenna systems (AASs) a viable option for large scale deployments in existing 4G and 5G mobile networks. AASs enable state-of-the-art beamforming and multiple-input, multiple-output (MIMO) techniques that are powerful tools for improving end-user experience, capacity and coverage. These advances have brought mmWave communications, untenable almost two decades[1] ago, to manageable today. 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.

The goal of this paper is to clarify why AAS is being commercialized now, to describe AAS and how it works, and to explain the relevant complexity/performance drivers. Finally, this paper examines how AAS is used in real deployments, for both sub-6 GHz and mmWave, and which AAS parameters impact performance in different environments.

The paper is organized into six broad sections, Introduction being the first one. The second section of this paper is titled as Challenges Addressed by 5G Antenna Methods, which will review how passive antennas, MIMO and beamforming are used today. The technology and challenges in the network are discussed as well as two examples on how grating lobes can impact performance.

The next section, Review of 4G Antennas, highlights passive versus active antennas and why a tighter integration of RF electronics and antennas is necessary for massive MIMO (mMIMO) and mmWave antennas. This will highlight how this integration makes antenna testing more complex. Certain trade-offs of different MIMO antennas that are considered are highlighted.

The fourth section, Current Enhancements to the Antenna Side of the Network, includes Chapters 4 through 13. It explains capacity and better utilization of spectrum at both sub-6 GHz and mmWave frequencies. Additionally, Beamforming and Beam management are techniques that allow for higher capacity are explained.

The fifth section includes Chapters 14 and 15. It presents use cases, simulations and trial data for AAS in different deployment scenarios for urban, suburban, and rural cases, including both macro and small cell usage. Results reflect the potential of AAS for the wireless industry to improve throughput, capacity and coverage.

The last section reviews and summarizes the white paper.

2. CHALLENGES ADDRESSED BY 5G ANTENNA METHODS

Network traffic continues to grow rapidly; end-user performance demands continue to increase, straining the Radio Access Network (RAN) to deliver increased coverage, capacity and end-user throughput.[2] This requires the wireless operators' networks to deliver gradually higher capacity over time. Since data usage is currently increasing at a much faster rate than corresponding revenue, mobile network operators (MNOs)

[1] *Hope for LMDS Dwindles*, eWeek Networking, August 6, 2001.
[2] *Ericsson Mobility Report*, Ericsson, December 2018.

must evolve the RAN in a way that enables both a reduced cost per bit and provides the required end-user performance increases. The timing is now right for the telecom industry to make a technology shift to AASs. The shift is driven by the superior performance of AAS in both uplink (UL) and downlink (DL),[3,4,5] and the feasibility to build AAS cost effectively. This is supported by technology advances in integration of baseband, radio, and antenna, and a reduction in the digital processing cost to perform advanced beamforming and MIMO.

The operators adopt new technologies and spectrum as they become available and subsequently accommodate some of the capacity needs. The capacity requirements tend to grow even faster and thus, the operators need additional means to meet the capacity demands. It is usually both difficult and expensive to grow the number of sites. The availability of attractive sites is limited, and the cost and lead time for acquiring a new site is significant. Therefore, operators typically focus on maximizing the use of existing sites before expanding the site grid. AAS is a way to increase Signal to Interference+Noise Ratio (SINR) at the receivers and ultimately increase spectral efficiency. The efficiency of AAS, and particularly the cost efficiency and its advantages to other deployment options, depend on the deployment scenarios.

5G New Radio (NR) enables new bands in the frequency range above 6 GHz, FR2, by adding flexibility and scalability in the numerology. For example, in the mmWave bands allocations at 28 GHz and 39 GHz, very wide operational bandwidths of the order of GHz are made available which support the need for capacity. The radio propagation is much more challenging at mmWave bands in comparison with lower bands in the range of 1-3 GHz carrier frequencies. To secure the reach of the mmWave signals, AASs play an important role to enable coverage via beamforming gain. AASs are enabling enhancements both for capacity and coverage. For lower bands, FR1 (below 6 GHz), the capacity enhancement is more essential due to the more interference limited environment. For the higher spectrum, FR2 (above 6 GHz), coverage enhancement is more essential due to the more challenging propagation and path loss conditions.

3. REVIEW OF 4G ANTENNAS

MIMO and Smart Antenna for Mobile Broadband Systems,[6] published in July 2013 by 4G Americas, provided practical details based upon the latest LTE information through 3GPP Release 10, on the system performance improvements possible via the efficient use of MIMO for different antenna schemes for broadband demand.

In the 2013 white paper, fundamental antenna characteristics with regards to base station antenna capabilities were considered. Then, the transmission modes 1-9 (SISO through 8x8) as defined by 3GPP through Release 10 were reviewed. Considerations for antenna configurations and capabilities were examined on DL. Some of the salient features were:

1. Open and Closed loop MIMO
2. SU-MIMO and MU-MIMO
3. Angle of Arrival beamforming
4. Different antenna configurations and for different environments

Alternate methods for increasing capacity, sector splitting and multibeam antennas, were then discussed. Finally, system performance of these different configurations was considered for Nx2, 2x4 and 4x4 MIMO

[3] *5G NR: The Next Generation Wireless Access Technology*, 1st Edition, Dahlman, E; Parkvall, S; Sköld, J. August 2018,
[4] *NR - The New 5G Radio-Access Technology,* Stefan Parkvall, Erik Dahlman, Anders Furuskär, Mattias Frenne, 2018 IEEE 87th Vehicular Technology Conference: VTC2018-Spring, 3–6 June 2018, Porto, Portugal.
[5] *The Advantages of Combining NR with LTE at Existing Sites*, Fredric Kronestedt, Henrik Asplund, Anders Furuskär, Du Ho Kang, Magnus Lundevall, Kenneth Wallstedt.
[6] *MIMO and Smart Antennas for Mobile Broadband Systems*, 5G Americas. June 2013.

in both UL and DL. The relative advantages of closely spaced Clustered Linear Arrays were shown compared with diversity schemes with more widely spaced antenna radomes. The close performance seen with arrays of vertical antennas versus cross polarized antennas was examined and explained. The tradeoffs between antenna radome size and performance were also considered. When possible, simulations and from field measurements were utilized to highlight results. Towards the end of the previous white paper, calibration methods, complexities and tradeoffs for different antennas were also described.

4. CURRENT ENHANCEMENTS TO THE ANTENNA SIDE OF THE NETWORK

4.1 WHAT 5G PROMISES AND HOW ANTENNAS WILL GET US THERE

The work of 3GPP has led to the very successful LTE system of today through Release 15 and this work continues. The next generation of air interface standardization, 5G NR, is following two parallel paths:

- 5G Phase 1 with Release 15 in 2019. This covers the so-called Non-Stand Alone (NSA) option where devices will need Dual Connectivity for LTE and 5G NR link
- 5G Phase 2 with Release 16 in 2020. This covers the Stand Alone (SA) option where both data and control use the 5G NR link. In Phase 2, mmWave and sub-6GHz can be combined with Carrier Aggregation (CA)[7]

There is no obvious impact of NSA versus. SA for Advanced Antennas Systems (AAS). The following text discusses the features of Release 15 and 5G Phase 1 (NSA).[8]

Release 15 promises a number of features including Base Station Antennas. Among many enhancements, 5G NR brings the ability to exploit beamforming in more channels (control and broadcast) compared to LTE, which already offered support for beamforming in data channels. 5G NR beamforming capabilities may be used in most systems comprising 4T4R, 8T8R, 16T16R, 32T32R, 64T64R and larger transceiver/antenna counts, both in passive and active systems. For the 5G NR mid bands identified for initial deployments, the mobile industry has focused efforts into two main families of passive and active antennas:

- 8T8R passive antennas with calibration circuits (to be able to exploit channel reciprocity in Time Division Duplexing [TDD] and beamforming)
- 16T16R, 32T32R, 64T64R, active antennas (with integrated radio and antennas)

For the high bands (mmWave), the initial deployments for fully integrated transceivers and antennas include many antenna elements (>100). This enables high beamforming gains to support coverage enhancement in the more challenging propagation environment.

The support for 5G NR beamforming features in terminals guarantees coverage and capacity benefits from day one.

[7] https://www.3gpp.org/specifications/67-releases.
[8] TR 21.915 “3rd Generation Partnership Project; Technical Specification Group Services and System Aspects; Release 15 Description; Summary of Rel-15 Work Items (Release 15)”, 2019, 3GPP.

Table 4.1: Features of 5G NR Release 15. [9]

Feature	Technology Examples	Change versus. 4G (S/M/L))	BSA relevance (L/M/H)	Comments
Enhanced Mobile Broadband (eMBB)	DL: 8 streams, peak data rat 20 Gbits/s[10] UL: 4 streams peak data rate 10 Gbits/s	Medium	Large	Active antennas with 2D BF (Beamforming)
Critical Communications (CC) and Ultra Reliable and Low Latency Communications (URLLC)	low latency	Medium	Small	Requires coverage, may drive low band deployment of 5G
Massive Internet of Things (mIoT)		Medium	Medium	Requires coverage, may drive low band deployment of 5G
Flexible network operations (including scalability	100 MHz bandwidth at 3.5 GHz, scalable OFDM air interface	Large	Medium	New frequency bands, possibly stable performance over wide bandwidth

4.2 SPECTRUM EXTENSION (SUB-6 GHZ AND MMWAVE)

5G NR will not only be deployed in TDD bands, but also in mmWave and <3 GHz Frequency Division Duplex (FDD) bands. For mmWave bands today, active antennas commonly use hybrid beamforming for cost and efficiency reasons. Beam selection and tracking procedures defined by the 3GPP address terminal mobility.

In <3 GHz spectrum, some but not all, operators will be able to use dedicated bands for 5G NR. However, in both cases, existing <3 GHz bands will be essential to supporting 5G NR deployments—via 5G NR-only mode, supplementary uplink mode, carrier aggregation or by using dynamic spectrum sharing techniques. Therefore, the importance of high performing passive antennas will continue to be crucial in the next wireless generation.

4.3 ACTIVE ANTENNAS

5G will require a toolbox of passive and active solutions in <6GHz bands, both in FDD and TDD. Some key criteria for the selection in a given site/cluster/area are listed here:

- Performance versus cost
- OPEX
- EMF considerations
- Time to benefits
- Deployment constraints
- Predictability
- Elevation plane beamforming
- Antenna or site sharing strategies
- Impact on existing technologies

[9] IMT-2020 requirement, see 3GPP TS 23.501 and TS 23.502.

4.4 NETWORK DEPLOYMENT AND DENSIFICATION

5G NR sites are expected to have a combination of passive and active antennas with the mix being a result of a continuous assessment of the previously mentioned metrics. Presumably, the initial deployment of 5G will re-use existing sites and implement three main strategies:

- N+1:
  - No change to existing antennas to support all legacy bands and/or legacy technologies
  - 5G NR high bands deployed in a separate antenna (either passive or active)
- 1+1:
  - Existing antenna(s) replaced by a new one to support all legacy bands and/or legacy technologies, to support 4T4R in high/low bands and new LTE bands
  - 5G NR mid bands deployed in a separate antenna (either passive or active)
  - 5G NR low bands in the same radome as LTE low bands
- All-in-One:
  - Full consolidation of all legacy bands and/or legacy technologies and new 5G NR bands into one radome
  - One antenna per sector supporting FDD/TDD
    - Full passive antenna (available today): 4T4R 700/850/1900/AWS/1800/2100/2600 + 8T8R3500
    - Passive/Active antenna (mid/long term expectation): 4T4R 700/850/1900/AWS/1800/2100/2600 + 16T16R/32T32R/64T64R 3500

5. MULTI-ELEMENT ARRAY ANTENNA

There are many ways of utilizing the multi-element antenna array. An antenna array can be partitioned into subarrays known as an array of subarrays (AOSA). The number of sub-arrays in the partition will determine the degrees of freedom in which antenna elements may interact with each other to provide the beamforming capabilities of the entire antenna array.

In practice, the actual antenna array design depends on the beamforming capabilities required, along with a system's total complexity and budget considerations influenced by factors such as steering and cost.

The number of sub-array antennas determines the degree of freedom. In this way, the partition determines the beamforming capabilities of the antenna array, coupled with the total complexity and steering versus cost.

5.1 ANTENNA TECHNOLOGY FUNDAMENTALS AND CHALLENGES

Antennas are an integral part of all mobile communication systems. In the last five years or so, the functionality of the individual components of passive antennas have been refined to meet today's higher capacity requirements. For example, cross polarized radiating elements feed networks, variable phase shifters for electrical down tilt, and etcetera. To this end, the number of arrays in a base station antenna have grown considerably without relaxing the RF or mechanical specifications of the antennas. Two to three array macro antennas—commonly known as Quad-port and Hex-port (4 and 6 port)—were the norm in 12”-15” wide platforms, shown in Figure 5.1.

Today, passive antennas can have five or more arrays in a 15”-20” wide platform. Bandwidths of arrays have grown from 698-960 MHz to 617-960 MHz and additional bands have been added for CBRS (3550-3700 MHz). Along with increasing bandwidth, weight has also increased with some antennas weighing in excess of 66 lbs (40 kg).

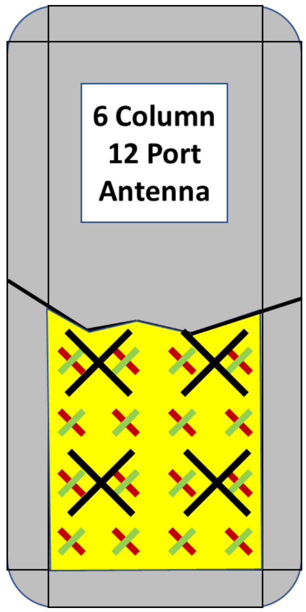


Figure 5.1. Sketch of 12 Port Macro Antenna.

Note: The mid-band elements are in green and red (equivalent to 8 ports), the low band elements are in black (equivalent to 4 ports).

Throughput is increased to the user by taking advantage of MIMO and carrier aggregation with a high port count antenna. Furthermore, a single or pair of high port count antenna can reduce the number of antennas enclosures on a tower. Ideally, the tower constraints will be maintained by keeping the weight and wind load of the new antennas the same or less than the antennas they displace. Not all high port count antenna can keep this last promise.

Massive MIMO has been shown to enhance network capacity by taking the MIMO technology one step further with the integration and use of more than 8 radio T/R (transmit/receive) modules within an antenna. For any given spectrum, antennas will stay the same size or grow physically larger with the addition of massive MIMO. In addition to increased size, weight also increases due to the integrated electronics. RF losses and passive intermodulation (PIM) are much better controlled due to the RF front end being integrated into the antenna. However, the power consumption and heat dissipation of the massive MIMO antenna becomes larger as the number of T/R increase.

Small cell antennas were added in Release 8 of the 3GPP specification.[11] They are typically low power access nodes that are deployed to increase cellular network capacity via network densification in a region, or to fill in whitespaces in a macrocell. Additional functionality has been added to the small cells through

[11] *From Macro to Small Cells: Enhancements for Small Cells in 3GPP*, Matthew Baker.

different releases. They are referred to as small cell antennas for their shorter height compared to macrocell antennas. These heights range from 12’ to 50’ and are advantageous for mmWave antenna deployment. Small cells, shown in Figure 5.2 are typically camouflaged to blend into their environment and are sometimes called Street Macros. They operate on both licensed and unlicensed spectrum and cover less range than their macrocell counterparts.

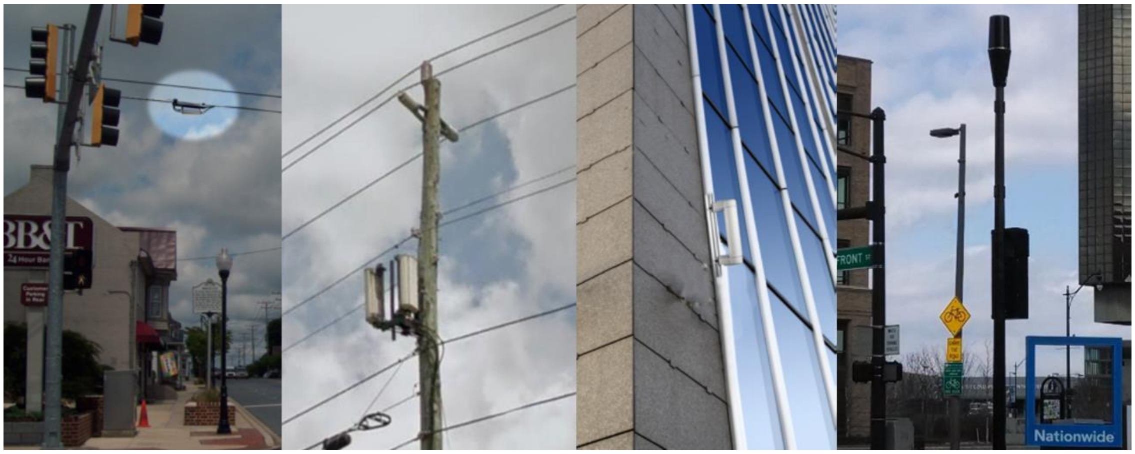


Figure 5.2. Examples of Different Types of Small Cells in the Field.

Some small cells are shared by different operators to reduce costs. Although they share an antenna, unlike distributed antenna systems (DAS), each tenant utilizes its own set of arrays under the radome. This scenario has led to increased port count on small cell antennas.

Small Cells today use sub-6 GHz spectrum, both licensed and unlicensed bands. The unlicensed band is the 5 GHz Unlicensed National Information Infrastructure (UNII) band and is used Licensed Assisted Access (LAA) with carrier aggregation typically to supplement downlink speeds. Even though the UNII bands are unlicensed, care must be taken to ensure the FCC emission requirements are satisfied.[12]

Antenna technology for wireless systems has again progressed due to customer and industry needs, with key drivers like:

- Continuing addition of cellular frequency bands
- Integration of more functionality into single radome housing
- Antenna techniques that contribute additional capacity to cellular networks

5.2 ARRAY THEORY – GRATING LOBES

Grating lobes is a well-known problem of phased arrays, and in mobile communications it has mostly been a concern regarding the elevation pattern. For beamforming and mMIMO antennas, grating lobes can also occur in the azimuth plane.

The element spacing is key for both azimuth and elevation pattern performance. For azimuth beamforming, each column can be seen as an element. For elevation beamforming, the vertically separated sub-arrays are considered the elements. The case of azimuth beamforming, using a number of horizontally separated

[12] United States CFR Title 47 (Telecommunication), Part 15 - Radio Frequency Devices, Subpart E - Unlicensed National Information Infrastructure Devices, Paragraph 15.407 - General technical requirements.

columns, is shown in the following example. It is well known that a uniformly spaced array with a spacing *d* will have an Array Factor of:

$$AF(\phi) = \sum_n w_n \, e^{jkd(n-1)\sin\phi}$$

which repeats itself in the $\sin\phi$ domain when:

$$kd\sin\phi_1 - kd\sin\phi_2 = \pm m\,2\pi$$

$$\sin\phi_1 - \sin\phi_2 = \pm m\,\frac{\lambda}{d}$$

This means that the Array Factor will repeat itself with a periodicity of $\frac{\lambda}{d}$, and this is completely independent of the complex array weights applied. The above also leads to the well-known condition for no grating lobes: if $\lambda/d \geq 2$ or $d \leq \frac{\lambda}{2}$, the pattern will not repeat itself in the so-called visible space $(-1 < \sin\phi < 1)$ and there are no multiple maxima ⇔ grating lobes.

This theory is illustrated in Figure 5.3. For the total pattern, the element factor, which in this case is the azimuth radiation pattern of a single column, is considered. The element factor will usually help to suppress unwanted grating lobes as seen in the bottom of Figure 5.3. However, this is of less help when scanning out large angles, for example, ±45°, since a wide scan angle also requires a relatively wide element factor.

The presence of a grating lobe has two major detrimental effects:

1. Secondary maxima will reduce the directivity of the main beam (in the extreme case, the radiated
2. Grating lobe typically occurs near or outside the nominal cell edge at +/-60°. This can cause significant interference in neighboring cells or having a UE in a neighboring cell be picked up by the initial beam scan.

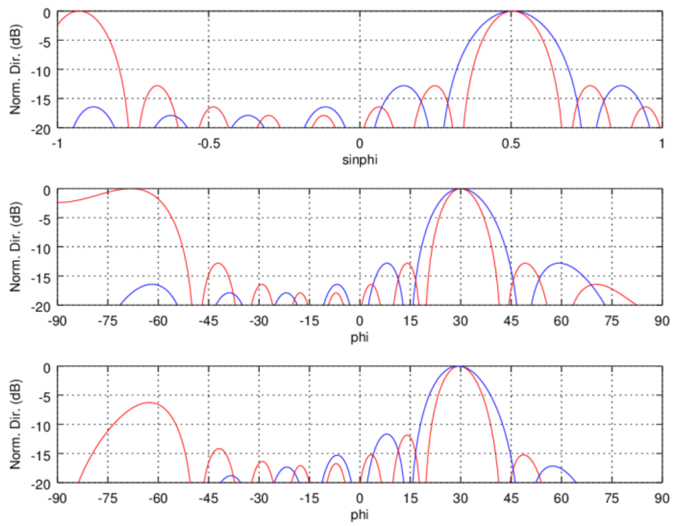


Figure 5.3. Radiation Patterns of 8-Element Arrays.

Note: **with 0.5λ (blue) and 0.7λ spacing (red). The top plot shows the Array Factor** versus**. $AF(sin\phi)$, the center figure shows $AF(\phi)$, and the bottom figure shows the total pattern $AF(\phi)EF(\phi)$ with $EF(\phi) = sin\,\phi$ corresponding to 90° half-power beamwidth.**

5.3 ONE AND TWO-DIMENSIONAL BEAMFORMING EXAMPLES

There are several examples of 1D (one dimensional) and 2D beamforming with mMIMO arrays such as the case of multiple beams transmitted from a single mMIMO array, one beam containing a desired signal, and one or two beams containing interfering signals (therefore, signals intended for other users). The parameters are as follows:

- *f* = 3500 MHz
- 8 x 8 elements with horizontal and vertical spacing $d_y = 42$ mm, $d_z = 58$ mm, respectively
- uniform amplitude (full power)
- progressive phase shift in horizontal and vertical direction to steer the beam to (θ_0, ϕ_0). (a somewhat ideal situation)
- base station height *h* = 50 m
- maximum range = 1000 m
- P_{TX} = 20 W
- free space propagation (Line of Sight)

The first example is beamforming with scan in azimuth.Figure 5.4 and Figure 5.5 show the signal strength on the ground for beams scanned to -30°, 0°, +30° in azimuth. Since the beams are rather narrow, HPBW of 13-14°, the Signal-to-Interference Ratio (SIR) is quite good in the center beam (within ±15°). This SIR is calculated from the P_S and P_I shown in the top left and right plots of Figure 5.5.

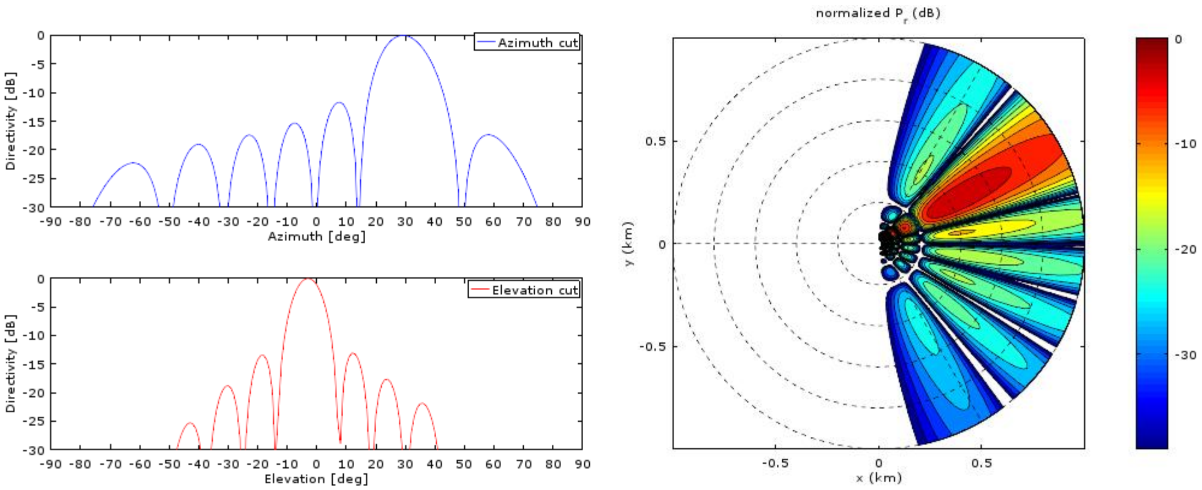


Figure 5.4. Example of 1D Beam Steering Using an 8 x 8 Array.

Note: The beam is scanned to $(\boldsymbol{\theta_0}, \boldsymbol{\phi_0}) = (\mathbf{93°}, \mathbf{30°})$ which means pointing to the 1 km boundary. The 2D plot shows the normalized received power on the ground with each contour being a step of 3 dB. The first lower null at EL = -14° ⇔ r = 200 m (the white ring close to the center).

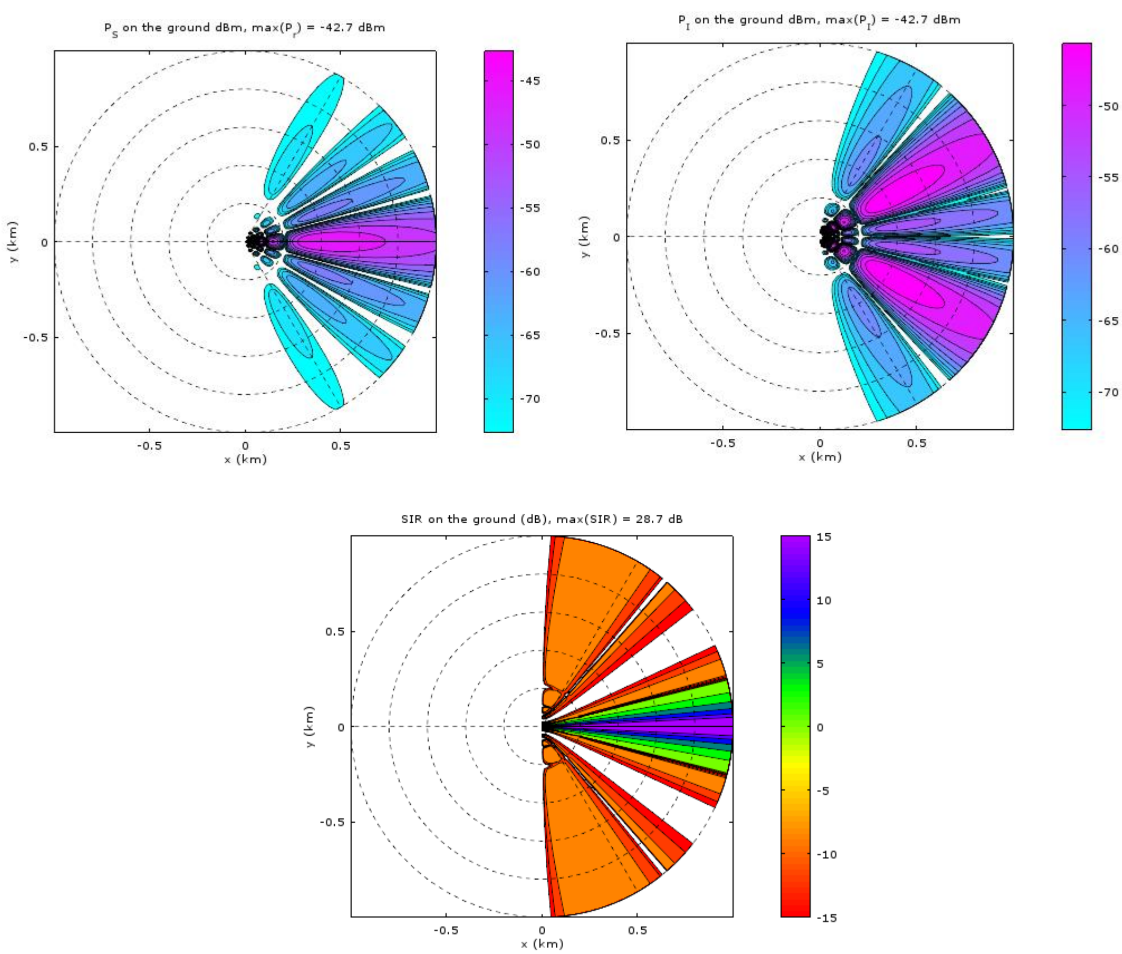


Figure 5.5. Signal Strength on the Ground in Azimuth.

Note: P_S and P_I on the ground from the desired beam at $(93°, 0°)$ and two other interference beams at $(93°, 30°)$ $(93°, -30°)$ shown in steps of 3 dB. The resulting $SIR = P_S/P_I$ is also shown.

The next example in Figure 5.6 shows beam scan in elevation with the same array as before. The desired signal is steered to -10° elevation and the interfering signal is steered to 0° elevation. The SIR is only good where the interfering beam has a null, around 250 meters (m), and drops to 0 decibels (dB) at a range of ~500 m, or 10 times the height (*h*). This example shows that we need a reasonably high tower to use elevation scan to reduce interference. Also, even if one beam is pointing to the horizon (thus increasing interference in a neighboring cell), the SIR for the other beam is good only very close to the base station. This is because the elevation beamwidth for a typical mMIMO array is fairly wide (see Figure 5.4).

Finally, the bottom right plot in Figure 5.6 shows 1/SIR for the same beams. This corresponds to the inverse case with the desired signal scanned to 0° elevation and the interference signal scanned to -10° elevation. There is virtually no area inside 1 km with SIR > 5 dB. This shows again that it is difficult to separate users in flat terrain using elevation beamforming.

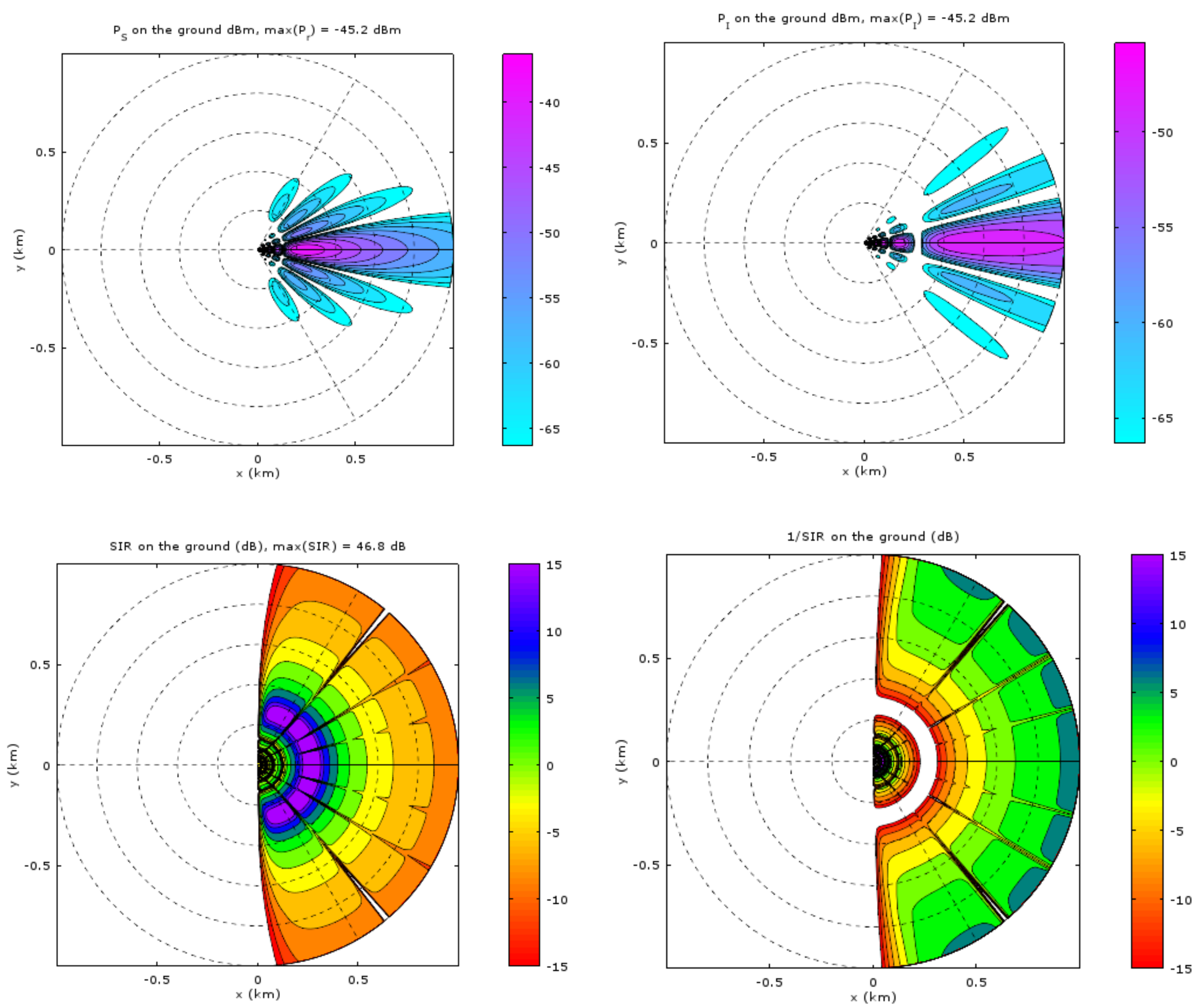


Figure 5.6. Example of Beam Scan in Elevation.

Note: The service beam is steered to $(\mathbf{100°}, \mathbf{0°})$, therefore, 10° down-tilt, and an interfering beam is steered $(\mathbf{90°}, \mathbf{0°})$, therefore, the horizon. The contours show steps of 3 dB. The resulting $\boldsymbol{SIR} = \boldsymbol{P_S}/\boldsymbol{P_I}$ and $\mathbf{1}/\boldsymbol{SIR} = \boldsymbol{P_I}/\boldsymbol{P_S}$ is also shown.

6. SPATIAL PROCESSING METHODS AND FUNCTIONALITY - ADVANCED ANTENNA SYSTEM (BF, SU-, MU-MIMO)

AASs with multielement-based linear and planar arrays have become the key enablers together with MIMO techniques to meet requirements for IMT-2020.[10] Multiple antenna transmission allows for the creation of spatial or multipath diversity in the channel, known as the MIMO channel. The spatial dimension of the multiple antennas introduces signaling degrees of freedom which is exploited by designing transmission schemes. Such AAS transmission can take advantage of uncorrelated antennas and full channel rank conditions, therefore, the ability to resolve the same number of transmission paths as the minimum degrees of freedom of the transmit and receive AAS. The three basic mechanisms that are exploited:

- *Diversity gain* – mainly realized through transmit diversity typically creating signals that are uncorrelated via antennas that are space separated or orthogonal polarized
- *Spatial multiplexing* – transmitting separate data streams in parallel using the same time/frequency resources. The receiver side also requires multiple antennas to the same level (degrees of freedom) as the number of streams or layers to spatially decorrelate, demodulate and decode. For a 2 x 2 MIMO system, spatial multiplexing can be realized using the polarization domain. For larger systems, the channel needs to be rich enough with sufficient scattering and multipath propagation
- *Array gain (Beamforming gain)* – array gain is achieved through coherent combining of the multiple antennas signals to focus a beam to a specific end user location. This coherent combining is performed by adjusting the phase and amplitude of each antenna element or subarray. This mechanism also reduces interference within the general coverage area, therefore improving spectral efficiency at large

6.1 SPATIAL PROCESSING TECHNIQUES

LTE spatial processing techniques were introduced as an integrated part of the full wireless ecosystem with defined techniques and supporting procedures. The principal of Transmission Modes (TM) was established such that each communication link is configured based on UE and base station capabilities. When switching TMs, a specific UE communication reconfiguration is required including some overhead signaling. In the previous whitepaper on antenna technology from 5G Americas,[6] an overview of the available TM's was provided based upon the latest LTE information at the time (through 3GPP Release 10), therefore, up to TM9. Later releases enhanced and evolved up to the, now ten, TMs where improvements are specifically on supporting functions and channels. For example, Channel State Information – Reference Signal (CSI-RS), is introduced to support more advanced spatial processing via more advanced feedback enabling 2D Full Dimensioning beamforming (FD-MIMO).

The spatial processing techniques for 5G NR below 6 GHz can be viewed as an enhancement on LTE Release 14 and defined with a single transmission mode like LTE TM10 with much more flexibility and enhanced supporting signals. The spatial processing in 5G NR as in LTE TMs is based on beamforming (BF), Single-User MIMO (SU-MIMO) and Multi-User MIMO (MU-MIMO).

In a simplified way, the AAS utilized in the 3GPP NR/LTE cellular system environment improved signal quality or SINR (Signal to Interference and Noise Ratio). This enables the opportunity to improve user throughput, system capacity, and system coverage, which are signal quality dependent metrics. From a DL network perspective, this can be summarized as:

- Beamforming (BF) – *concentrate* energy to the target UE and reduces interference to other UE's thereby improving coverage
- SU-MIMO – *split* the available SINR between different multiple data layers towards a target UE simultaneously where each layer is separately beamformed thereby improving peak user throughput and system capacity
- MU-MIMO – *share* the available SINR between multiple data layers towards multiple UEs simultaneously where each layer is separately beamformed thereby improving system capacity and user perceived throughput

The described methods can adapt in real time the radiation patterns in response to varying channel properties and due to UE mobility, basically updates can be performed on slot or Transmission Time Intervals (TTI).

6.1.1 MU-MIMO VERSUS SU-MIMO

Spatial multiplexing techniques, that transmit multiple data streams or layers using same time-frequency resources, can increase total throughput by virtue of maintaining varying levels of spatial isolation between the streams. Simpler mechanisms, using cyclic delay diversity to more advanced approaches requiring spatial processing to implement codebook-based beamforming or other non-discrete beamforming methods, help implement single user and multi-user MIMO schemes. Power splitting and transmitting multiple data layers simultaneously that do not interfere with each other yield higher throughput values in good channel conditions than a single layer operating under full power. Layer addition is possible until interference and power limitation reduces capacity gains.[13] Table 6.1 summarizes major aspects.

Table 6.1. Downlink SU-MIMO versus MU-MIMO.

	SU-MIMO	MU-MIMO
Description	Mechanism whereby information of a single user is transmitted simultaneously over more than one data stream using same time-frequency resources	Data streams distributed across multiple users on same time-frequency resources but dependent upon spatial separation
Key Objective	Increases user/link data rate as a function of bandwidth and power availability	Increases system capacity
Exploitation of Spatial Dimensions to Boost Capacity	Number of spatial dimensions is limited and restricted by the number of end user device capabilities and antennas	Potential to utilize all degrees of freedom at the base station when UEs are capability limited as long as the signal quality and power levels are acceptable. This is effective to resist channel rank degradation and a less rich channel environment
Performance Impact – Antenna Correlation	More susceptible	Less susceptible
Performance Impact - Source of Interference	Adjacent co-channel cells	Links supporting same cell and other MU-MIMO users, and adjacent co-channel cells

[13] Advanced antenna systems for 5G networks, Ericsson.

Performance Impact - Inter Layer dependency	Less dependent / correlated	Equally impacted with loss in spatial orthogonality
CSI/Feedback Process	Varies upon implementation, TDD or FDD and reciprocity or feedback based. Less susceptible on feedback granularity and quality	Very dependent upon CSI for channel estimation accuracy. More susceptible on feedback granularity and quality
Beamforming Dependency	Varies upon implementation TDD or FDD and reciprocity or feedback based. Less susceptible on feedback granularity and quality	Greatly assisted by appropriate beamforming mechanisms (spatial focusing) which maximizes gain towards the intended users. More susceptible on feedback granularity and quality
Power Allocation	Split between multiple layers to same user. Fixed per transmit antenna	Shared between multi-users and multiple layers. Can be allocated per MU-MIMO user based on channel condition

Figures 6.1 and 6.2 show the capacity gains from MU-MIMO operations in contrast to a dual-layer limited SU-MIMO configuration. Signals Research Group's (SRG)[14] benchmarking study of Sprint's LTE Massive MIMO technology confirms the capability of utilizing MU-MIMO aided with Massive MIMO technology. For MU-MIMO to be effective, the users need to be spatially orthogonal, therefore, at different angles relative the AAS. The improved capability for the same multi-UE distribution across the cell coverage area is relatively proportional to the number of parallel data streams that can be supported when changing from SU-MIMO to MU-MIMO.

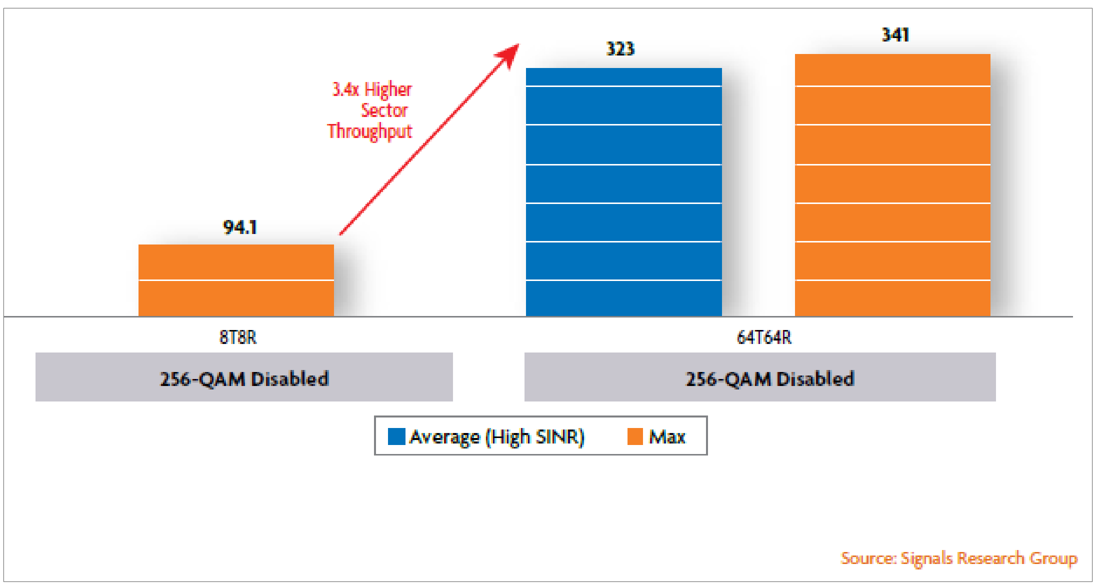


Figure 6.1. Massive MIMO Benchmarking Study- Signals Research Group.

[14] "Quantifying the Benefits of 64T64R Massive MIMO with Beamforming and Multi-User MIMO Capabilities," Signals Ahead, Part I. Vol. 14, No. 9, Nov. 29, 2018

Note: Dallas, TX - Sprint 64T6R Massive MIMO performance (Single 20 MHz carrier) with 8 layer MU-MIMO implementation on downlink, compared to 8T8R supported two layer SU-MIMO. 64T64R site SINR data for average of high values, and separately, the peak value data points.

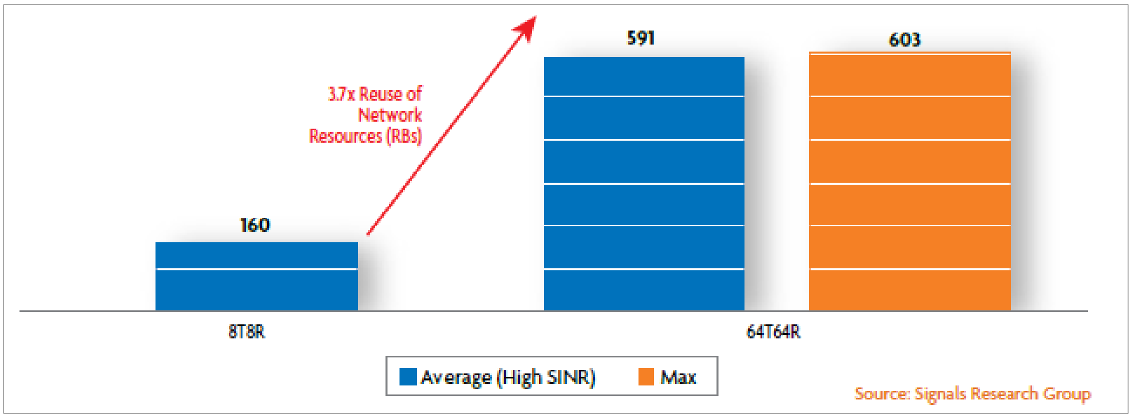


Figure 6.2. Massive MIMO Benchmarking Study - Signals Research Group.

Note: Dallas, TX - Sprint 64T6R Massive MIMO performance (Single 20 MHz carrier) evaluation. Effective gain in radio resource utilization due to Massive MIMO 64T64R 8-layer MU-MIMO implementation, compared to 8T8R supported two-layer SU-MIMO.

6.1.2 FD (FULL DIMENSIONAL) MIMO

A full-dimension FD-MIMO system has a large number of antenna elements arranged in a 2D planar array structure. This allows vertical beamforming that increases the SINR by adjusting the vertical antenna pattern specifically in the direction of an intended user. A typical use scenario is in a high rise dense urban environment. To direct the beam vertically, channel estimation and CSI availability reflecting the 2D perspective of the channel must be acquired by the base station. Utilization of CSI-RS reference signals available from LTE Advanced Release 10 and onward is one approach where end users can complete CSI measurement.

It is clear, as captured elsewhere in this document, that an appropriate number of CSI-RS ports are necessary to adequately capture the degrees of freedom of a 2D planar array. Its overuse will diminish PHY layer throughputs to a varying degree from overhead burdens on both downlink and uplink. LTE 3GPP Release 10 is limited to 8 CSI-RS ports, which is not adequate for a 64T64R massive MIMO system operating in FDD mode. This problem is not manifested in a TDD system where uplink-based SRS signals can be used instead to more adequately allow the beamformer to estimate the channel and exploit its spatial richness in forming spatial beams in both the vertical and horizontal planes.

Lastly, 3GPP Releases 13 and 14 for LTE make available 16 and 32 port CSI-RS transmission. In addition, beamformed CSI-RS transmission can also provide means for performance improvement and realization of vertical beamforming, especially for users at cell edge locations. In FDD-based mMIMO systems, a combination of SRS and CSI-RS may work together to implement 2D beamforming when the CSI-RS port count is limited to eight ports. 5G NR configurations are more flexible and are not as limited as LTE.

7. ANTENNA ARRAY STRUCTURE FOR ONE AND TWO-DIMENSIONAL BEAMFORMING

The purpose of using an antenna array, as shown in Figure 7.1-A, is to enable high gain beams and the ability 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 utilized, the higher the antenna gain in general. The 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 subarrays (groups of non-overlapping elements), as shown in Figure 7.1-C, and by applying two dedicated radio chains per subarray (one per polarization) to enable control, see Figure 7.1-D. In this way, the direction and other radiation characteristics of the antenna array beam is controlled.

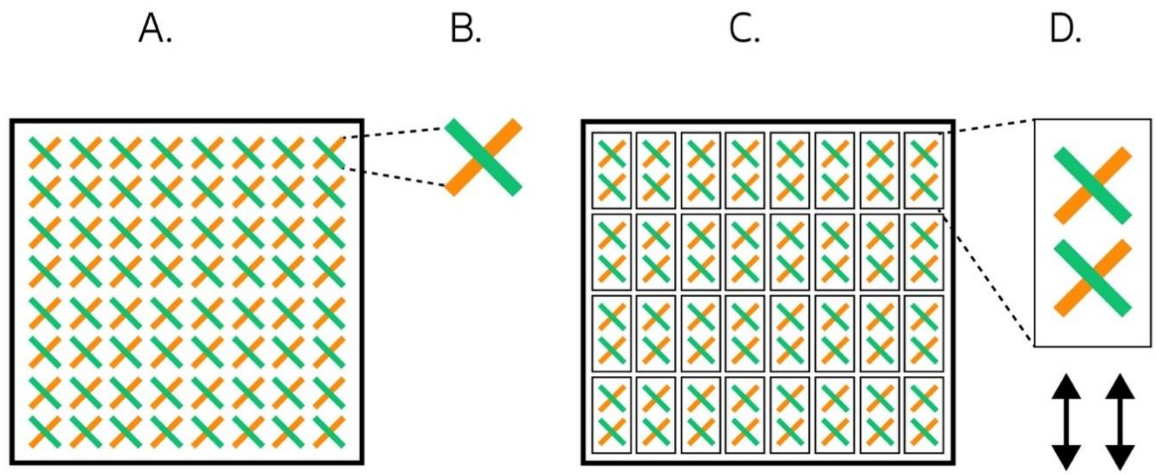


Figure 7.1. Typical Antenna Array.

Notes: 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 subarrays (C), with each subarray (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 subarrays of different sizes. For illustrative purposes, we describe only one dimension. The same principles do, however, apply to both vertical and horizontal dimensions of the antenna.

The array gain is referred to as the gain achieved when all subarray signals are added constructively (in phase). The size of the array gain relative to the gain of one subarray depends on the number of subarrays. For example, two subarrays give an array gain of 2 (therefore, 3 dB). By changing the phases of the subarray signals in a certain way, this gain can be achieved in any direction as shown in Figure 7.2-A.

Each subarray has a certain radiation pattern describing the gain in different directions. The gain and beam width depend on the size of the subarray and the properties of the individual antenna elements. There is a trade-off between subarray gain and beam width – the larger the subarray, the higher the gain and the narrower the beam width, as illustrated in Figure 7.2-B.

The total antenna gain is the product of the array gain and the subarray gain, as shown in Figure 7.2-C. The total number of elements determines the maximum gain and the subarray partitioning allows steering of high gain beams over the range of angles. Moreover, the subarray radiation pattern determines the envelope of the narrow beams (the dashed shape in Figure 7.2-C. This has an implication on how to choose antenna array structure in a real deployment scenario with specific coverage requirements.

Since each subarray is normally connected to two radio chains, one per polarization, 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.

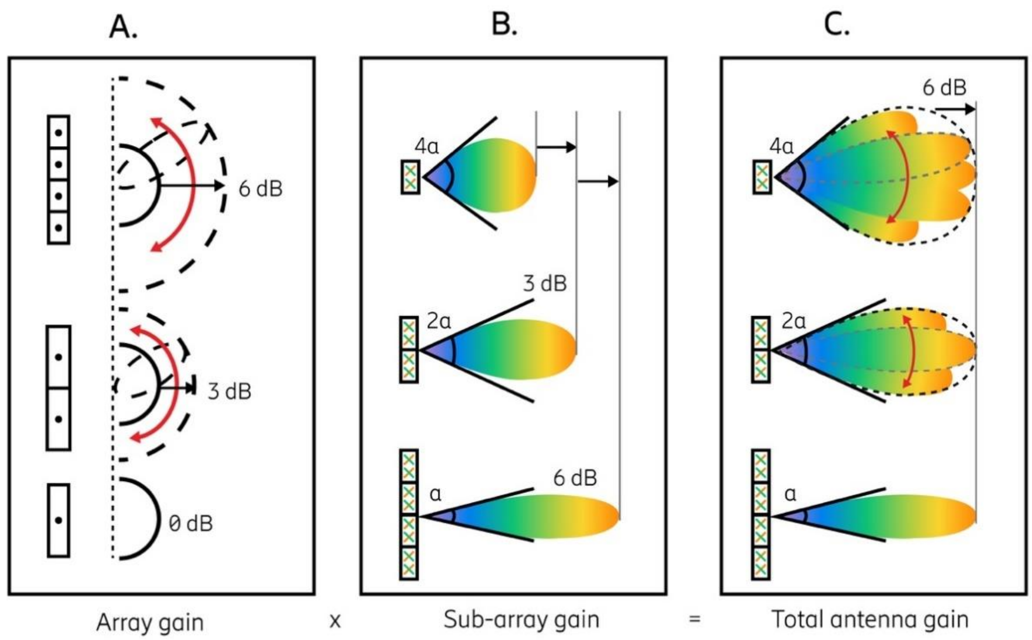


Figure 7.2. An array of subarrays supporting high total antenna gain and steerability.

8. ACTIVE ANTENNAS VERSUS PASSIVE ANTENNAS

The industry has lately seen an evolution of the site architecture to active antennas with the actual integration of the radio into the antenna and the distribution of the radio functionality across the antenna elements, when this is practical.

8.1 HOW MMIMO AND MMWAVE CAUSES THE SHIFT FROM RRH TO INTEGRATED ANTENNA

Legacy macrocell architectures had large radios in shelters at the base of the tower. Coaxial cables ran up the tower from the radio to the antenna. With the inclusion of tower mounted electronics, tower mounted amplifiers were used to simplify the RF requirements of the radio at the base of the tower with the trade-off of additional power on the tower. Further refining this technique, the Remote Radio Head (RRH) is placed on the tower that handles the RF function of the radio, thereby simplifying the equipment in the shelter, and reducing RF losses from long cable lengths. The trade-off is more complex equipment and hence more power demands on the tower. The digital portion of the radio, the Baseband Unit (BBU), is located at the base of the tower. The connection between the RRH and the BBU is optical fiber which lessens tower loading compared with the original coaxial cable runs up the tower. This separation of RF and Baseband functionally allows for a more reduced footprint on the tower and in the shelter as well as enhancing network performance.

Although simpler than past designs, there are still some shortcomings. More equipment is now placed on the top of the tower. This adds to the installation time and complexity as well as additional wind load and weight on the tower. These additional elements on the tower can also add to the tower leasing costs for the carriers.

The installation complexity comes from several sources. With MIMO, the number of ports on an antenna and the radio increase for each band. This implies that the number of cables that connect the radios to the antennas increases as well. This increase adds complexity since the radio port definition must match the proper ports on the antenna. Even though the cables are much shorter than those that ran up the tower, the losses are still significant and if one of the cables fails, the band will not operate properly.

Although more efficient than past systems, the next iteration to enhance network performance is to integrate the portions or all the RRH into the antenna thus creating an integrated or active antenna. The name integrated antenna/radio has been used in the past to describe when active electronics are designed directly into the antenna. The advantage of an integrated antenna/radio eliminates the need for multiple cables between the radio and antenna, simplifying the installation and adding reliability by reducing part counts. Now only power, baseband and control information are needed by the antenna system.

The Passive InterModulation (PIM) can be better controlled since the installer is only responsible for the ground and the mount, not intermediate cables and other equipment in the RF path from the radio to the antenna that can cause issues. Also, the PIM can be better optimized during the design process and controlled during assembly at the factory. The higher integration yields better functionality due to a more integrated design as depicted in Figure 8.1.

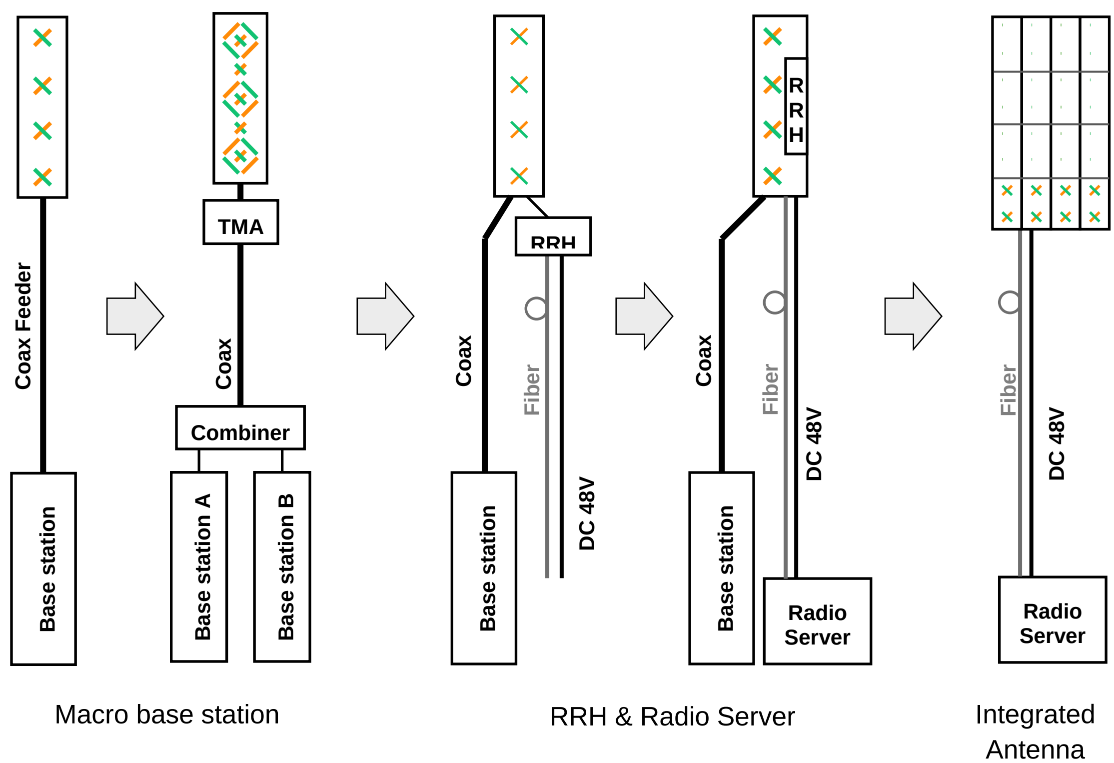


Figure 8.1. Evolution of Macro Antennas.

As higher order mMIMO systems are built, the extra layer of complexity as the order increases makes it even more important to have an integrated design, an Advanced Antenna System. Due to the larger number of active radio modules in the system, separate radios and antennas should not be considered from an installation standpoint. The design of the antenna becomes synergistic rather than creating a general specification to ensure a pair of designs work together. Functionality, weight, cost and reliability should all improve with this more integrated design.

In the mmWave band, this integration becomes even more important due to higher frequency constraints. Amplifier efficiency and RF losses are more critical over the mmWave spectrum. By integrating the hardware, the losses can be reduced through good design practices. Furthermore, mmWave equipment is more fragile due to its reduced size as compared with sub-6 GHz equipment. The need to touch the mmWave portion of the equipment is no longer necessary. With an Active Antenna System, the integrated design functionality leads to more features, therefore, enhanced beamforming.

9. DIFFERENCES BETWEEN ACTIVE AND PASSIVE ANTENNAS

9.1 STRUCTURE (HARDWARE) AND FUNCTION

The cell site antennas used in second generation (2G) wireless networks are passive and typically consist of a periodic linear array that radiates a static directional fan-beam pattern that is wider in azimuth and narrower in elevation. The array is constructed with linearly polarized radiators that are fed by a corporate feed, which typically uses some form of transmission line technology, such as coax cables or a printed circuit microstrip. The corporate feed network provides a designed amplitude/phase excitation distribution to the elements, forming a pattern that is fixed in its azimuth and elevation with static characteristics for gain, beam width, side lobes and null fill.

The passive antenna evolved to incorporate variable phase shifters in 3G networks to enable variable electrical tilt of the radiation pattern (see Figure 9.1). Some implementations have a dedicated phase shifter for every element, while others may share a phase shifter among two or more elements, with the tradeoff of cost versus performance. The fan beam is steered by varying the phase distribution along the radiators. This adjustment can be performed either locally at the antenna or remotely by integrating a Remote Electrical Tilt (RET) actuator to the antenna. The spacing of the antenna elements is generally 0.7-0.9 λ (wavelength) to reduce grading lobes as the beam is steered to the design tilt limit, typically 10° – 12° below the horizon. Since that time, base stations have accommodated this capability into their designs to allow remote tilt adjustments through the Operations Support System (OSS).

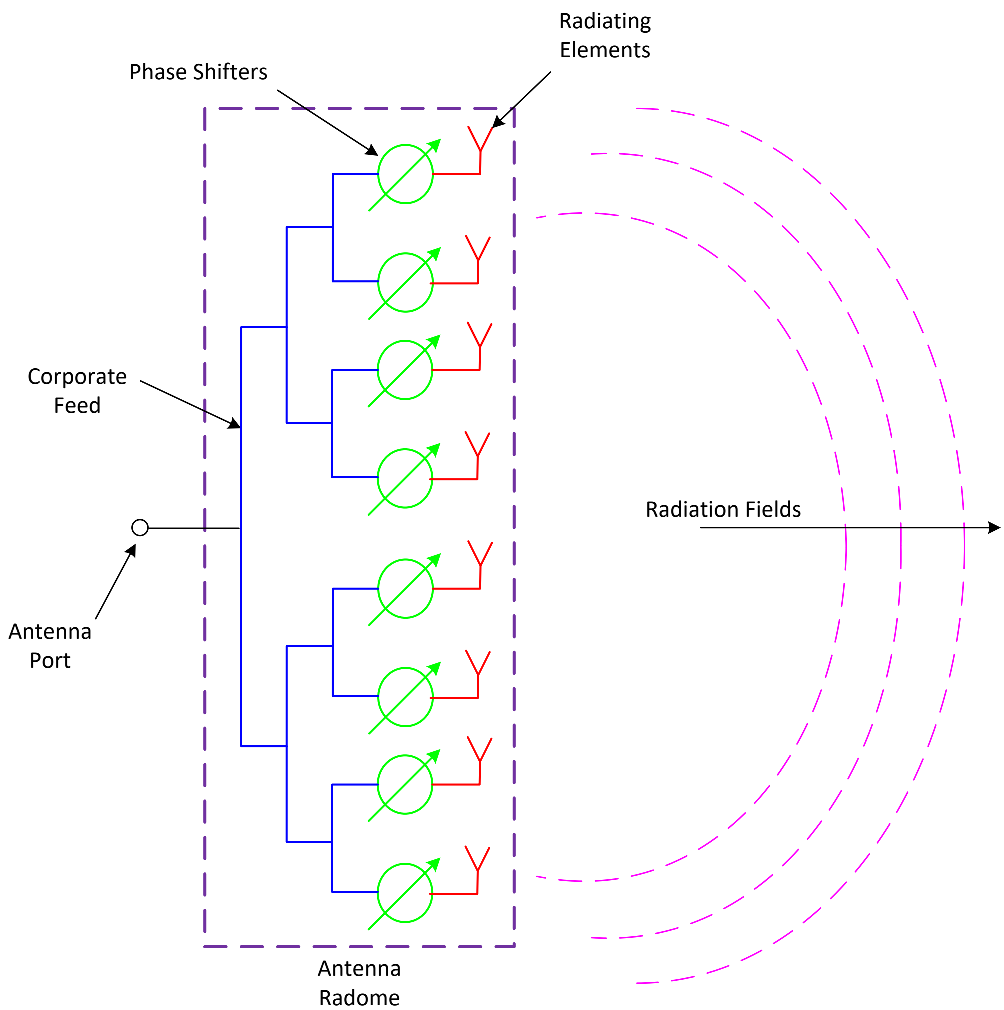


Figure 9.1. 3G Passive Macro Antenna - Single Column.

Almost all base station antennas have dual orthogonal polarized arrays which reuses the antenna aperture. Each array can be tilted independently with dedicated RET actuators, or two or more arrays are tilted together, depending on implementation. Note that these arrays are designed to operate electrically independent of each other, and so the spacing between each column should ideally be large enough to provide a minimum of 30 dB port-to-port isolation. For recent designs with 2 or even 4 side-by-side arrays, the isolation may have to be reduced to 28 or even 25 dB.

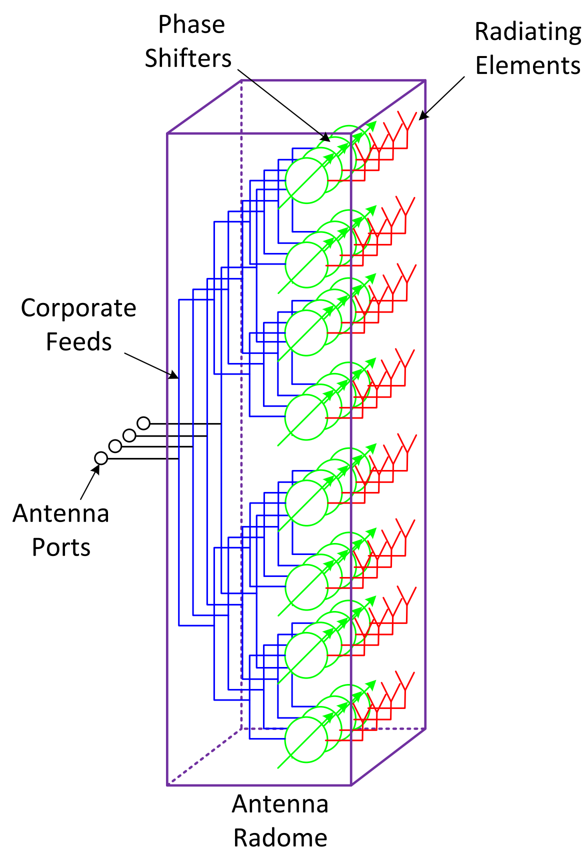


Figure 9.2. 4G Macro Antenna with Multiple Arrays and Electrical Downtilt Capabilities.

Passive antennas are applied in the radio network where prior planning and link budget predictions have been performed for deployment. Therefore, the antenna's location above terrain, azimuth direction and tilt are specified for implementation. Once installed, the antenna's electrical tilt can be remotely adjusted to optimize the desired cell edge coverage and handover boundaries.

In contrast to the passive antenna's static nature, an active antenna is designed to form varying pattern characteristics at any given instance. In LTE, needs are determined by CRS (for TM4) or CSI-RS (for TM9) measurements of the air interface with UEs, for example, a broad fan beam for broadcasting to the sector, a narrower beam traffic beam to be steered applicable over a range of azimuth and elevation angles, or a pattern with a deep null to be directed at an interferer can be activated. These adaptive modes can more optimally provide the best possible RF environment for the targeted user(s) over the static pattern of passive antennas.

For this varied beamforming ability, the element spacing of the active antenna's aperture is considered differently from its passive counterpart. The horizontal separation of the element columns will be tighter, possibly equal or less than $\lambda/2$, to avoid grading lobes when a narrow beam is steered to within ±60° in azimuth (see the *5.2 Array Theory – Grating* lobes section). Where dynamic beam forming is also implemented in tilting the beam, the vertical spacing between elements would also be closer than a passive antenna as well. Therefore, more compact elements must be used to fit within the required array spacing. The active antenna design can have a number of columns, for example, 4, 8, and etcetera, depending on the desired azimuthal spatial granularity for beamforming.

Active adjustments to the amplitude and phase distribution among all the elements for forming the desired beam pattern must be controlled by a beam former unit. In one implementation (Figure 9.3) for azimuth beamforming and steering capability (while keeping the traditional RET configuration for tilt), each column of elements has a dedicated transceiver. This design capitalizes on providing more azimuth spatial discrimination of the RF carrier for users within the beam.

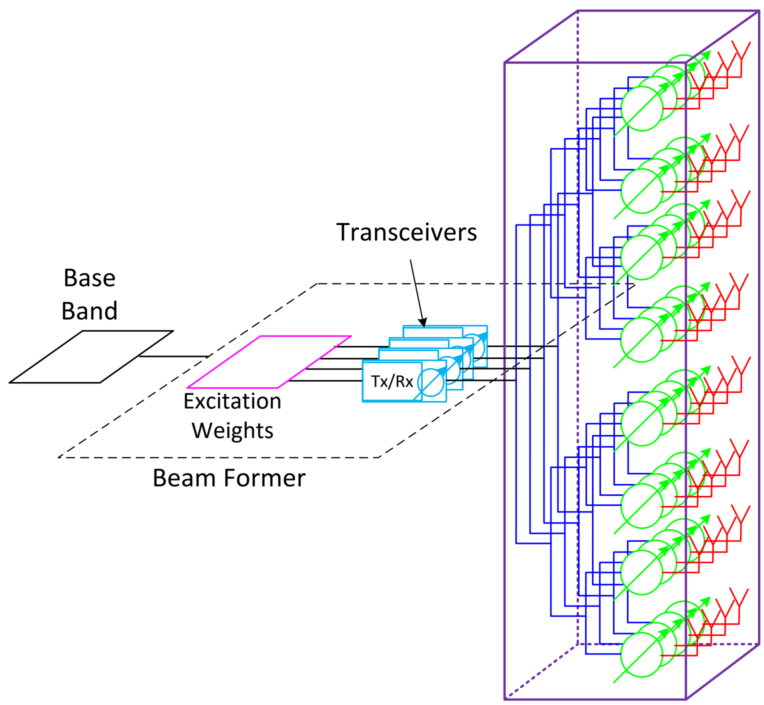


Figure 9.3. 4G Macro Antenna with Beamforming Transceiver Module.

The ultimate case is where a dedicated transceiver may be integrated directly with each antenna element for maximum amplitude/phase control of the aperture (for example, LTE TM9, 8-port massive MIMO case shown in 9.4). This gives the greatest degree of flexibility for forming the narrowest possible beam and for steering over the designed coverage. However, economic aspects, as well as manufacturability, weight, heat management, etc., must also be considered in the design. It is likely that somewhere between the two cases discussed here is the more practical design to be commercialized, i.e. transceivers are shared among two or more elements in columns and/or rows i.e. AOSA, depending on the desire to optimize certain pattern characteristics or for economics and manufacturability reasons.

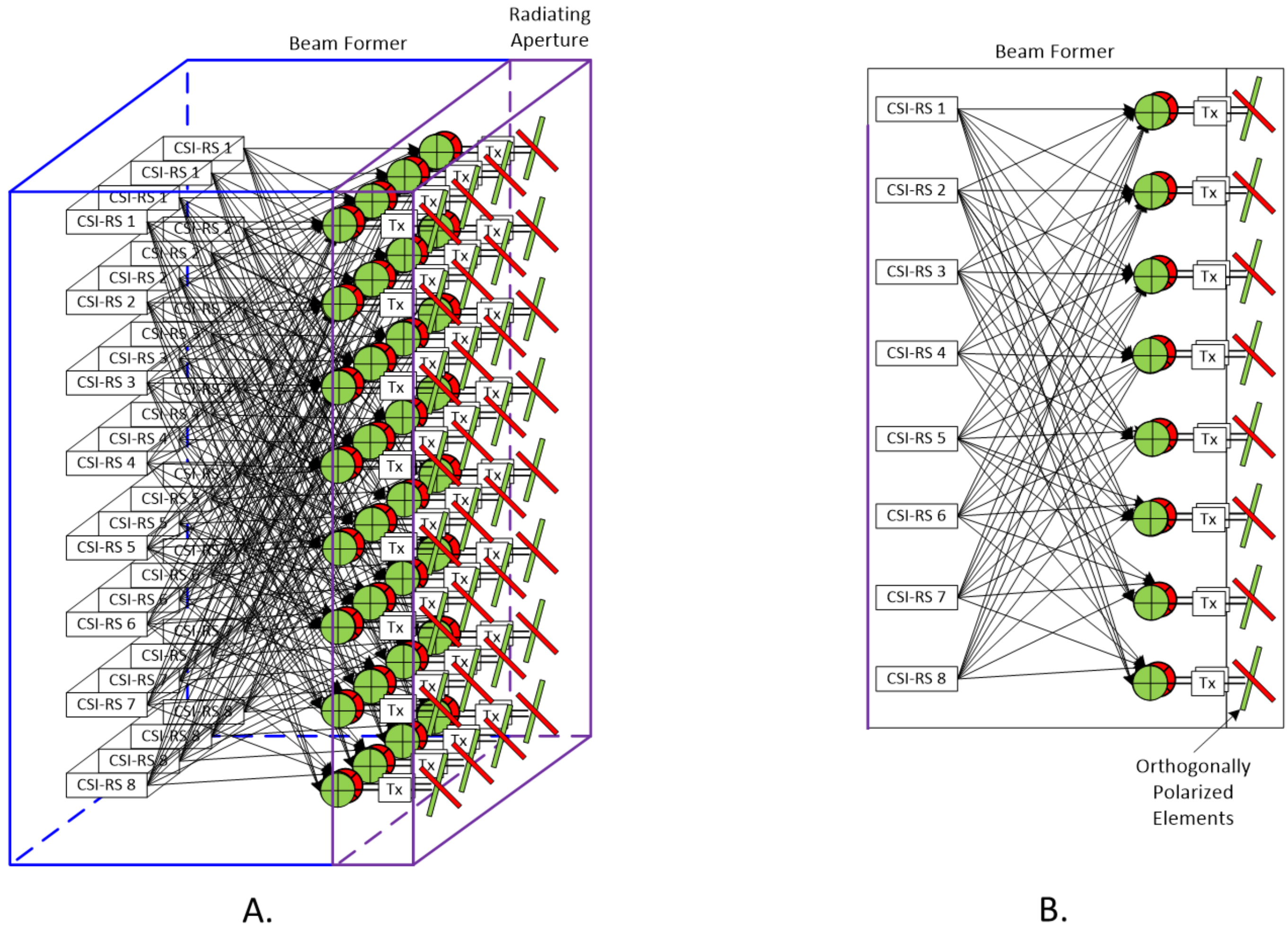


Figure 9.4. A. 3D Diagram of 8x8 MIMO Antenna B. Side view of 8x8 MIMO Antenna Diagram.

9.2 ACTIVE AND PASSIVE ANTENNAS TESTING

For radiation pattern performance assessment, the same environment needed for testing passive antennas also applies for active antennas. That is, measurements at the test range are made in the near field or far field (Figure 9.5-A). The far field distance is generally $2D^2/\lambda$ (D=max dimension of source antenna, λ=operating wavelength), with an environment as close to free space as possible, without reflected power from the surroundings. The positioner on which the antenna-under-test is mounted must be directionally precise and positioning highly repeatable.

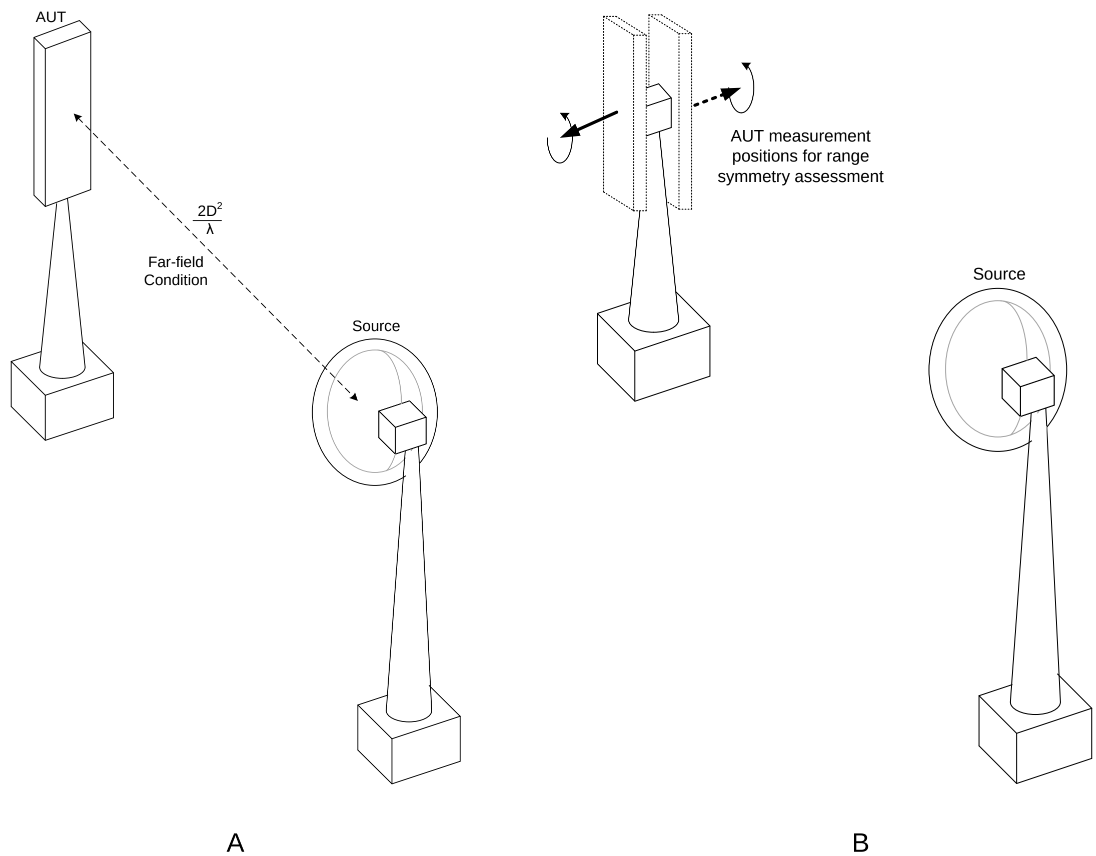


Figure 9.5. A: Sketch of Far Field Passive Antenna Measurement. B: Assessing the Range for Pattern Biasing Due to Range Characteristics.

There are volumes of texts and literature on the theory of design of antenna test ranges-- whether indoor, or outdoor, far-field, compact ranges, near-field-- typically using either planar, cylindrical, or spherical systems. For all range types, if evaluating for the first time, the accuracy of the range should be assessed. Linearity of the system is easily verified with a calibrated step attenuator in-line with the source antenna and seeing a corresponding response on the Antenna Under Test (AUT) side. This is done to ensure the receiver is not saturated due to the input power level and the gain of the antenna; otherwise, the patterns measured will become distorted. Positioner accuracy can be determined by cutting sample patterns rotating in forward, then backward, directions to see if the patterns overlay each other. Range symmetry can be characterized by recording the pattern acquired with the AUT rotated about and facing one side of the positioner, then repeating the procedure with the AUT facing the opposite side of the positioner. The patterns acquired should overlay closely unless there are unique features built into either side of the range that contributes a pattern bias (Figure 9.5-B).

Assessing the performance of passive antennas is well established. This mainly involves measuring peak gain, directivity (to determine antenna efficiency), as well as recording the principal plane cuts through the main beam in elevation and azimuth on a per port basis for each incremental tilt throughout the operating frequencies.

Methods for testing the active antenna can involve evaluating the radiating aperture, as well as with the integrated antenna with power amplifiers. The procedure will depend on the actual implementation. Some methods are:

- A number of analog beamforming circuits providing amplitude and phase excitations to the elements can be fabricated. This allows a sampling of the desired beam types and steering directions. For practical reasons, it would be difficult to perform a comprehensive test of all possible beams. Therefore, only those beams of greatest interest are likely to get tested
- Another option is to use a dedicated beamforming tester. Such "beam boxes" are available with up to 64 outputs with large variation of phase and amplitude. These can be used with any antenna test range
- Alternatively, the far-field amplitude and phase of each subarray can be measured with a common reference. Any beamforming pattern can then be analyzed by addition of said patterns multiplied by arbitrary complex weights. This is the most flexible method since no test range is needed to try out different beamforming patterns. The disadvantage is that normally this only adds patterns for the principal planes (azimuth and elevation) so the beamforming pattern cannot be studied in all directions

When adding the active electronics to the radiating aperture to form a MIMO antenna, the antenna ports are now embedded in the system. It is much more difficult to measure true gain and antenna efficiency, although pattern measurements can still be examined.

Due to the large number of antenna elements in a massive MIMO antenna and also the fact that the radiating aperture can be excited in many ways to create different narrow and broad beams in both 2D and 3D, it will be difficult to fully test and validate beam performance in terms of pattern characteristics, beam shape, beam steering, side lobe level, null location, and etcetera. Testing must be done in both the transmit case and the receive case to understand the performance of both RF chains. As discussed previously, care must be taken to ensure the pattern testing is properly performed.

The 3GPP has defined three OTA (Over the Air) test methods[15] for MIMO antennas: direct far-field method (DFF) in a far field chamber, indirect far-field method (IFF) using a Compact Range, and near-field to far-field transform (NFTF) measured in a near field chamber. The test method chosen depends on the size and type of the antenna and the measurement equipment available.

To more accurately represent real world conditions in a lab, systems can be examined using multiple sources in the range operating by using receive mode of the MIMO antenna and a channel emulator for 5G. The channel emulator will add fading, path loss, delay spread, and etcetera, to appear to the antenna as a single or multiple UEs in a given environment.

Using these OTA techniques allows for accurate, repeatable and efficient measurements to be performed on a MIMO antenna during a design or to validate performance.

10. TRADE-OFFS FOR MASSIVE MIMO ANTENNA

Massive MIMO is all about adding RF chains, while not necessarily adding more radiating elements. Massive refers to the larger number of transceivers (TRx) in the base station antenna array. The greater number of TRx the antenna is equipped with, the more degrees of freedom to modify the radiation pattern of the transmitted signal based on where the receiver is located. Another, perhaps more important feature, is having multiple RF chains so that several users can be spatially multiplexed when having multiple antennas. For this, at least as many RF inputs are needed as there are users. Each can get the full array gain and the digital precoding can be used to avoid inter-user interference. This results in higher

[15] 3GPP TR 38.810 V2.0.0 (2018-3), 3rd Generation Partnership Project; Technical Specification Group Radio Access Network, Study on test methods for New Radio, (Release 15) (https://www.3gpp.org/ftp/Specs/archive/38_series/38.810/).

beamforming granularity and the potential to utilize more degrees of freedom for more simultaneous layers and MU-MIMO as long as the signal quality and power levels are acceptable. In mMIMO, the number of degrees of freedom is usually much larger than the number of layers to be transmitted.

With large antenna arrays, conventional signal processing techniques like maximum likelihood detection become prohibitively complex. The main question is whether huge multiplexing gain can still be achieved with low complexity signal processing and low-cost hardware implementation.[16,17]

10.1 MASSIVE MIMO IN TDD

To take advantage of multipath, the spatial channel between antenna elements in the BS and UE is characterized by the Channel State Information (CSI) and must be known/measured, The CSI is used to digitally encode and decode the data. In TDD systems, where uplink and downlink channels are the same, downlink and uplink channels are said to be reciprocal. Having reciprocity means the channel needs to be measured only in one direction where the CSI can be directly retrieved from a reference signal for the purposes of channel characterization. The UL CSI can be measured on received Sounding Reference Signals (SRS) transmitted from each UE and each UEs SRS is received by all the antenna elements at the base station. In addition, all the computation intensive channel estimation and signal processing is performed at the base station. For this reason, an increase in the number of antenna ports does not lead to proportionate rise in overhead in TDD systems. It is important to note that care must be taken to ensure that the internal RF paths are properly calibrated to allow for the use of reciprocity.

In TDD, overhead associated with uplink channel estimation is proportional to the number of UEs, but independent of the number of transmit antenna RF chains, thereby making the protocol fully scalable with respect to the degrees of freedom of AAS. The overhead increases linearly with the number of active users in a cell. The derived CSI is then utilized in the downlink due to the reciprocity between downlink and uplink radio channels.

The discussion of reciprocity-based measurements is based on reception of reference signals from the UEs and is predicated on an acceptable signal quality level to perform accurate characterize the CSI. If the quality on the received sounding signals is not acceptable, the CSI can be received as feedback from respectively UE performing measurements on reference signals in the DL.

Table 10.1 shows some commercial TDD Massive MIMO systems of today and the number of transmit/receive ports versus maximum number of multiuser MIMO supported.

[16] *Massive MIMO: Fundamental and system design*, Hien Quoc Ngo, Linkoping University, Sweden Thesis, Spring 2015.
[17] *Massive MIMO: Ten Myths and One Critical Question*, Emil Björnson, Erik G. Larsson, and Thomas L. Marzetta, IEEE Commun. Magazine, vol. 54, no. 2, pp. 114 - 123, 2016.

Table 10.1. Typical Commercial TDD mMIMO Base Stations.

TxRx	Antenna elements (row x column x polarization)	TX/Rx	Maximum number of layers (Lm)
64T64R	128 (8x8x2)* 196 (12x8x2)	64	16
32T32R	64 (8x4x2)*	32	8
16T16R	32 (4x4x2)* 96 (12x4x2)**	16	8

Note (*): Every set of radiating elements makes up an antenna subarray (in this case 2 or 3) and is connected to a separate RF input signal
Note (**): In the case of 16TRX, columns can have analog phase shifters for electrical down-tilt

10.2 MASSIVE MIMO IN FDD

Most networks today in sub-6 GHz bands are operating in Frequency Division Duplex (FDD) mode, where the uplink and downlink use different frequency bands and channel reciprocity cannot be utilized. As a result, FDD mode requires additional measurement reports to estimate the CSI for both bands. Due to the additional overhead, this need for dual band CSI creates a performance penalty.

For FDD systems the downlink overhead incurred by reference signals for the CSI increases linearly with the number of transmitting base station antenna RF chains. Given overhead dependencies on both number of antenna ports and users in FDD, there are relatively more constraints and additional overhead compared to reciprocity based direct channel measurements.

A high number of downlink transmit antenna RF chains typically require a high number of orthogonal CSI-RSs in FDD. They would also require higher uplink overhead for reporting the estimated CSI from the UEs to the base station. There will be a balance of CSI-RS overhead versus user data transmission within a transmission block. This tradeoff is between reporting of more relevant channel components with higher accuracy versus reducing the number of resource elements available for data transmission; thus, limiting the maximum data throughput. Current commercial Massive MIMO systems in FDD rely on 16 or 32 TRX design.

For both FDD and TDD, the number of subarrays in architecture defines how well the mMIMO system will work in a given environment. The fifth section of the paper reviews different practical scenarios and defines where it makes sense to deploy different levels of TRx modules for a mMIMO antenna.

11. 5G SUPPORT FOR FURTHER SPATIAL PROCESSING ENHANCEMENTS

The 3GPP standard continues to include additional specifications addressing spatial processing enhancements.

11.1 CHANNEL KNOWLEDGE

For any MIMO system, Channel State Information (CSI) is critical for achieving the full potential of the system. Perfect CSI means knowing the channel response from every TX antenna to every RX antenna as a function of frequency. With perfect CSI, spatial multiplexing MIMO is in principle trivial. For example, by using Singular Value Decomposition (SVD) pre- and post-multiplication matrices are found so that channels are parallel and independent, and as many as the minimum number of TX and RX antennas are used. Furthermore, there would be no need for analog calibration networks, since any uncertainty in phase (path length) and amplitude would be accounted for as well.

Unfortunately, CSI is always limited in practice due to limited feedback, rapidly changing channel, and error in the estimation, therefore perfect CSI is in general not possible.[18] Another key aspect is FDD versus TDD operation; in the case of TDD, the same frequency is used on both UL and DL, so the channel response is the same, in theory.

It is important to understand how 5G handles limited CSI and how this affects the AAS design and specification. 5G NR support two different type of methods:

- Reciprocity based CSI – measurements on Sounding Reference Signals (SRS) transmitted by each individual UE
- Closed loop – UE feedback where the gNB transmits CSI-RS which the UEs measure and report back the Pre-Coder Matrix Index (PMI) which points out the pre-coder to use out of standardized precoding tables

A good study example is the initial access and the closed loop CSI feedback where a beam sweeping transmission procedure, using several *SS blocks* or *SSB* (up to 4, 8, or 64 depending on frequency) are transmitted including reference signals. To create these beams, it is preferable to have a phase calibrated aperture, hence a calibration network is needed in the antenna.[19]The quality of this calibration network will affect the quality of the beams, although the beam pointing direction will be fairly robust.

The UE first determines the best SSB and reports it back to the gNB. Then, more detailed information can be shared using either Type I: Normal (PMI feedback) or Type II: Enhanced (explicit or codebook based).[20] The CSI Type I codebook is targeting SU-MIMO operation that gives information about the strongest direction of the channel, while the enhanced higher resolution CSI Type II codebook is targeting MU-MIMO operation with a richer channel representation enabling MU-MIMO null-forming, as shown in Figure 11.1. After receiving the estimated CSI from the UE, the base station can select between several beams. Furthermore, since one of the objectives of using narrow beams is to reduce interference, secondary beam maxima or *grating lobes* are to be avoided. Such grating lobes can be avoided by keeping the antenna spacing near a half wavelength.

[18] For a discussion of CSI and lack thereof in TDD and FDD systems, see e.g. E. Björnson, J. Hoydis and L. Sanguinetti "Massive MIMO Networks: Spectral, Energy, and Hardware Efficiency. October 2018.
[19] *MIMO and Smart Antennas for Mobile Systems*, 4G Americas, p.32, Fig. 17. July 2013.
[20] *Understanding the 5G NR Physical Layer*, Javier Campos, Keysight Technologies. Nov. 1, 2017.

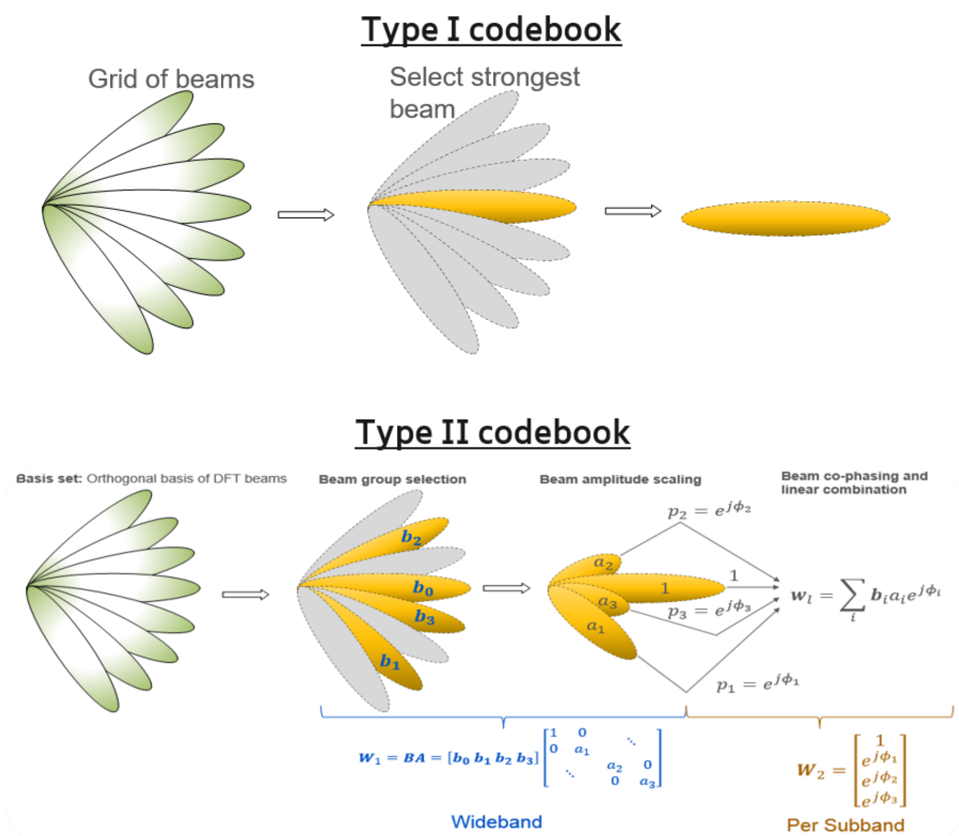


Figure 11.1. A schematic Illustration of the 5G 3GPP NR CSI Codebook Type I and Type II.

12. SPECTRUM CONSIDERATIONS

Licensed spectrum is the oxygen for the mobile wireless industry. 5G operators will use low, mid and high band spectrum to meet the diverse needs of their customers. All spectrum resources will need to be utilized efficiently by operators.

12.1 FR1, FR2 AND US SPECTRUM ALLOCATION

Initial 5G bands are part of existing International Mobile Telecommunications (IMT) spectrum as assigned by the Radio Communication sector of the International Telecommunication Union, commonly referred to as the ITU-R. Under its auspices, the World Radio communication Conferences (WRC) schedules conferences every three to four years to review radio regulations, frequency assignment and allotment plans. Allotment plans of any band may be part of existing IMT spectrum or future bands to be identified.

As such, interest around global 5G band identification first occurred during WRC-2015. New spectrum at higher frequency bands ranging between 3.3–4.99 GHz was considered appropriate to support 5G related use cases – higher data rates and massive MIMO design requirements. However, more critically, this conference also identified the need to continue evaluating the feasibility of higher frequency bands above 24 GHz, specifically for 5G mobile services. Several such bands were already assigned to mobile services, and other fixed or satellite services. Some were not yet allocated but would be put under evaluation. Bands available globally are also preferred for support of seamless roaming at an international level, and to drive economies of scale for equipment and deployment.

Interest around global 5G band identification first occurred during WRC-2015, when new spectrum at higher frequency bands ranging between 3.3–4.99 GHz was considered to support 5G related use cases involving higher data rates and massive MIMO design requirements. More importantly, this conference also identified the need to continue evaluating the feasibility of higher frequency bands above 24 GHz, specifically for 5G mobile services. Several such bands were already assigned to mobile services and other fixed or satellite services, but some were not yet allocated or yet evaluated.

Generally, spectrum bands are preferred when they are available globally, which supports seamless roaming internationally, as well as driving economies of scale with equipment and deployment. In order to standardize 5G implementation for NR development, the 3GPP divided bands into low, mid and high frequencies. Low band frequencies below 2 GHz are appealing for their large coverage attributes, while high frequency bands above 24 GHz allow for the opportunity to provide localized services with very high capacity and link throughputs. Mid band frequencies are uniquely nestled in between and are conducive towards supporting coverage, capacity, mobility and high data rates through the larger 5G bandwidth channels.

Besides application differences, the very wide range of frequencies has driven the need to identify two separate groups of sub-band ranges related to which development and deployment are driven by greatly varying RF requirements, need for different transmission technologies, implementations, antenna systems, and even the so-called numerologies. 12.1 shows this separation by Frequency Range (FR).

Table 12.1. Frequency Range Designation in 5G.[21]

Frequency Range Designation	Corresponding Frequency Range
FR1	450 MHz-6000 MHz
FR2	24250 MHz-52600 MHz

The sub-6 GHz range is called 'FR1' and the "millimeter wave" range is categorized under 'FR2'. A total of 33 NR operating bands have been defined with a mix of FDD, TDD, and supplementary uplinks or downlinks within the FR1 range.[22]

In the United States,[23] the 600 MHz band is one of the early and exclusively allocated bands for NR deployment. Other NR band ranges within the FR1 designation are created from re-farming existing LTE deployed bands, meaning that NR will begin to be deployed there during LTE to NR transition. As part of its commitment to a "forward-thinking spectrum policy" which meets the needs for a successful 5G service launch, the U.S. Federal Communications Commission (FCC) is focused on making additional spectrum bands available.

In the United States, the 5G new spectrum auction began in 2018 with the 28 GHz band, and will continue through 2019, starting with 24 GHz (March), and proceeding to 37, 39 and 47 GHz upper bands. Mid-band spectrum targeted for 5G deployment consists of 2.5, 3.5, 3.7-4.2 GHz bands that will make up to a total of 844 MHz of bandwidth. Low band channel resources will be included from 600, 800 and 900 MHz bands. And finally, unlicensed spectrum for 5G Wi-Fi will be sourced from 6 GHz[24] and above 52.6 GHz[25] bands.

[21] 3GPP TS 38.101-1 v15.5.0 Table 5.1-1, page 16.
[22] 3GPP TS 38.101-1 v15.5.0 Table 5.2-1, page 17.
[23] *The FCC's 5G FAST Plan*, FCC Initiatives.
[24] 3GPP Work Item Description RP-181551, Feasibility Study on 6 GHz for LTE and NR in Licensed and Unlicensed Operations.
[25] 3GPP Work Item Description RP-191044, Revised WID on NR-based Access to Unlicensed Spectrum.

Table 12.2 [25,26,27] is a summary of spectrum band availability and auction status, with existing significant license holder entities.

Table 12.2. 5G Spectrum & Availability.

Frequency Range	Spectrum Band	Band Range, GHz (Bandwidth)	U.S. Auction Status / Holder
FR2	n261 – 28 GHz	27.50 – 28.350	Auction completed 2019
	n258 – 24 GHz	24.25 – 24.45 24.75 – 25.25	Auction completed 2019
	n260 – upper 37 GHz	37 – 38.6 (1 GHz)	Auction – Scheduled Late 2019
	n260 – 39 GHz	38 – 40 (2 GHz)	Auction – Scheduled Late 2019.
	47 GHz	47.2 – 48.2 (1 GHz)	Auction – Scheduled Late 2019
	n257 - 26 GHz	26.5 – 29.5 (3 GHz)	Auction – Potentially Late 2020 (not scheduled)
FR1	n2 / n25 – 1900 MHz subset	UL: 1850 – 1915 MHz DL: 1930 – 1995 MHz	FCC licensed
	n5 – 850 MHz	UL: 824 – 849 MHz DL: 869 – 894 MHz	FCC licensed
	n12 – 700 MHz	UL: 699 – 716 MHz DL: 729 - 746 MHz	FCC licensed
	n14		In 3GPP Change Request
	n41-2.5 GHz	2.496 – 2.69 GHz	FCC licensed & FCC under consideration
	n30, n48		In 3GPP Change Request
	n66 - 1700 MHz	Extended AWS UL: 1710 – 1780 MHz DL: 2110 – 2200 MHz	FCC licensed
	n70 - 2000 MHz	AWS-4 UL: 1695 – 1710 MHz DL: 1995 – 2020 MHz	FCC licensed
	n71 (Low) – 600 MHz	UL: 663-698 MHz DL: 617-652 MHz	FCC licensed
	3.5 GHz [5]	3550-3700 MHz	FCC auction not yet scheduled
	n78/79 3.7 – 4.2 GHz	"C Band"	FCC proceedings on-going

[26] *Spectrum strategies for 5G: 2019 update (Analyst Angle)*, RCRWireless News. January 24, 2019.
[27] *Keeping Up A Fast Pace on Spectrum*, FCC Blog by Ajit Pai. October 1, 2018.

12.2 ANALOG, DIGITAL AND HYBRID BEAMFORMING ARCHITECTURES

The advent of analog beamforming technology dates to around the mid–twentieth century. Its application ushered in the deployment of phased array antennas or radar systems, particularly at the onset of World War 2. Early versions comprised of a single signal source with path or RF chain followed by signal splitting to more than one phase shifters (later selectable through RF switch toggle) and an equal number of antenna elements. Instead of physical movement which reoriented the direction of a fixed beam, steering was achieved by phase change at each antenna element. In effect, the fixed beam of the array was electronically steered across a wide-angle arc.

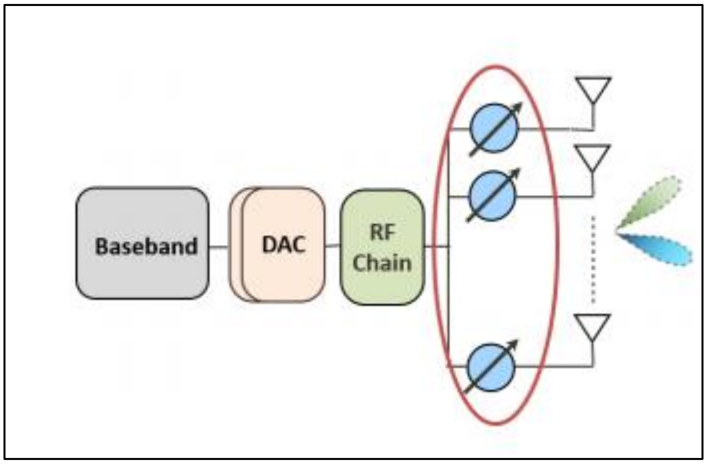


Figure 12.1. Sub-6 GHz Analog Beamforming Architecture.[28]

In analog beamforming today, the same signal is fed to each antenna and then phase-shifters are used to steer the signal emitted by the array. An array that uses analog beamforming only constitutes one antenna port per beam. It is usually called an adaptive antenna since the radiation pattern can be changed over time, but it is nevertheless a single antenna creating time domain beamforming.

In contrast, the primary objective of a digital beamformer's design entails the sending of the same information symbol off each antenna, but with appropriate adjustment to both amplitude and phase (therefore, complex valued weighting factors) of the signal at each of those antenna elements. Doing so allows the effective radiation pattern of the entire array to be shaped and directed to the intended user.

More recent digital beamforming designs adopt eigen-beamforming schemes which aim to maximize signal power at the intended user's location, based upon a pre-defined criterion. Cell coverage is therefore extended as transmission power is concentrated after determining the directions (eigen-direction of the channel) in which the RF channels provide the strongest paths. This is possible with an array of closely spaced antenna elements. The preferred choice entails pairs of cross-polarized antennas. Hence, signals from correlated antenna elements, when phased appropriately, add up constructively at that intended user's location.

[28] Robert. W. Heath Jr., Nuria Gonzalez-Prelcic, Sundeep Rangan, Wonil Roh, Akbar M. Sayeed, *An overview of signal processing techniques for millimeter wave MIMO systems*, IEEE Journal of Selected Topics in Signal Processing, vol. 10, no. 3, 2016.

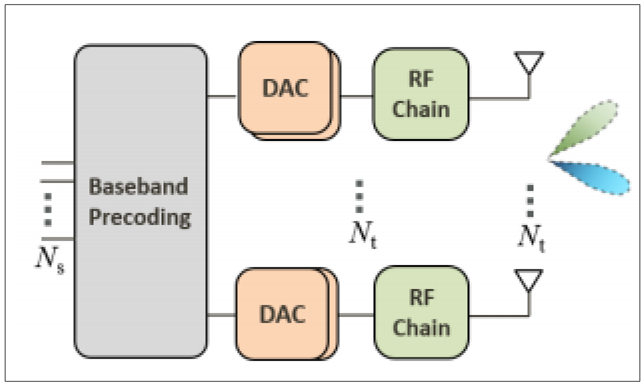


Figure 12.2. Sub-6 GHz Fully Digital Beamforming Architecture.

In digital beamforming, throughput maximization is also achieved by utilizing the multidimensional channel structure associated with multiple antennas at both transmit and receive ends. A single layer (one stream) beamformed transmission cannot simultaneously maximize the power at every receiving antenna. Hence, through precoding, multiple layers are transmitted each with their own beamformed weights associated with every antenna element. Leveraging the additional degrees of freedom in this manner maximizes the throughput of a digital beamforming system utilizing frequency domain beamforming.

Therefore, phase and amplitude settings can be applied at an antenna level by generating specific weights through baseband processing for assignment to multiple layers across the entire transmission bandwidth, as long as there are the same number of RF chains and number of antenna elements. The result is not only improved cell coverage as a function of user location, but also the ability to steer nulls in the direction of interferers and implement multiuser MIMO schemes in massive MIMO systems to achieve high spectrum efficiency.

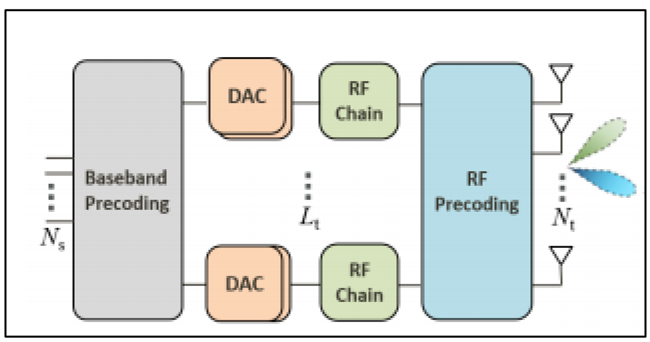


Figure 12.3. Hybrid Analog-Digital Precoding Architecture for mmWave Transmission with Ns (# of data streams) < Lt (# of RF Chains) < Nt (# of TX antennas).

Hybrid beamforming is a solution that combines the advantages of analog and digital beamforming architectures with frequency/time domain beamforming. Significant cost reduction can be achieved by reducing the number of complete RF chains. However, the number of simultaneously supported streams is lower compared to full blown digital beamforming. Hybrid beamforming is the more practical beamforming approach for mmWave in the near term.

12.2.1 BEAMFORMING ARCHITECTURE HIGHLIGHTS AND USE CASES

The key objective of digital beamforming is to have total control for optimal performance of the array by utilizing one RF chain per antenna element, which is costly both in terms of hardware, system complexity and processing requirements. The motivation for hybrid beamformers is to reduce hardware cost and processing complexity yet retain near optimal performance as that of digital designs. By using the hybrid beamformers, the packaging requirements are smaller for massive MIMO. This is ideal for rapid and space limited deployment opportunities. Reducing the RF chains also limits the number of data streams. However, per user performance can be designed to come close to a fully digital beamformer.

Hybrid beamformers are ideal for large mmWave antenna arrays to simplify the architecture, since the number of RF chains are greatly reduced for combining baseband digital and analog RF beamforming. A fully connected architecture is where each RF chain is connected to all antennas through phase shifters. This configuration has greater beamforming capabilities and gain but requires phase shifters with extremely high resolution. A partially connected architecture has each RF chain connected to a subarray through practical fixed phase shifters that simplifies hardware requirements.

Antenna array partitioning is a choice between interleaved (distributed across full array) and localized subarrays (adjacent elements) and is chosen depending on whether AoA based estimation is used.

A fundamental relationship exists between overall number of transmit antennas N_{TX}, the number of data streams N_{S}, and the number of RF chains N_{RF_Chain} for a hybrid beamformer to be competitive in performance relative to the digital variants.

$$N_S =< N_{RF\_Chain} < N_{TX}$$

The exact choice of values in design are influenced by cost, quality of hardware and precoder optimization. Precoding is performed both at a digital and analog domain. Digital precoding is implemented upon baseband frequencies while analog precoding is implemented in RF frequencies, utilizing low cost phase shifters. Precoding can be optimized to exploit the channel sparsity. In this case, the number of transmit antennas is much greater than the number of RF chains. However, the number of RF chains and data streams (or layers) are comparable in count. Thus, the dimension of the vector matrix of the digital beamformer will be considerably smaller.

The capability of beamforming algorithms implemented within the precoding structures can greatly impact hardware complexity and offset cost escalation, with limited to no impact upon desired performance. Table 12.3 summarizes the different use cases for analog, digital and hybrid beamforming architectures.

Table 12.3. Use Case Details Per Beamforming Type.

Type	Use Cases
Analog Beamforming	i. Phase array radars (Passive)
Digital Beamforming	i. Sub-6 GHz Massive MIMO - MU-MIMO w/ greater layer count ii. Sub-6GHz macro cell iii. 2D beamforming iv. AESA radars (military) v. Fixed Wireless Access (FWA solutions)
Hybrid Beamforming	i. mmWave based solutions ii. Sub-6GHz Small Cells / Hot spot coverage form factors iii. Fixed Wireless Access (FWA solutions) iv. FDD Massive MIMO Macro cells

12.3 PATH LOSS ABOVE 6 GHZ (RAIN, FOLIAGE)

FR2 operating bands fall under the mmWave range with wavelength reductions by an order of magnitude compared to today's LTE sub-6 GHz operational bands. This has a profound impact upon its signal propagation, diffraction level and solid material penetration loss. All incur higher attenuation. For these reasons alone, the importance of line-of-sight (LoS) conditions and the presence of reflecting and scattering bodies are considerably more critical in the reception of higher-powered signal.

Smaller wavelength signals (mm wavelengths) need to cover more "ground" due to their higher oscillation frequency. This make such signals lose energy more through beam spreading or absorption losses to the medium they are traversing through. They also diffract less, and hence are unable to bend around objects. Additionally, it has been determined that excessive losses occur within certain high frequency bands due to resonating oxygen and other atmospheric gas molecules.

In general, operating at higher frequencies will cause increased path loss from atmospheric effects and raised sensitivity to variation of different channel components, or small-scale fading. Moving objects is one example of the latter case.

On the other hand, weather effects such as that from rain drops comparable in size to mmWave wavelengths adversely impact from a large-scale fading/pathloss perspective.[29] Compared to lower frequencies, mmWave frequencies are impacted by 15 dB more per km under heavy rainfall. Fortunately, increase in rain attenuation tapers off beginning from 90 GHz. In contrast though, study charts indicate that sub-6 GHz band signals are impacted hardly at all by rainfall, including extremely severe downpours.

Hailstone and snowflakes, when on the order of a wavelength at mmWave frequencies, also impact propagation. Such concerns can at least partially be addressed through the usage of higher gain antennas, especially over shorter transmission ranges.

Attenuation from obstructing objects for mmWave signals exceeds that of 2 GHz range transmissions by more than 40 dB. However, as mentioned, the reflective properties of many materials provide excellent new sources of strong multipath propagation not existing with lower band transmission. Reliance upon such

[29] *Millimeter Wave Wireless Communications*, T. S Rappaport, Prentice Hall. 2015.

additional propagation paths coupled with highly direction receiver antennas that can adapt to discover the strongest signal paths will be foremost in successfully decoding mmWave links.

Table 12.4 highlights some contributors to mmWave range signal power degradation.

Table 12.4. Impact of Various Effects upon mmWave Propagation.

Contributor	Band	Loss Level
Propagation Path Loss		
Atmospheric Attenuation	60 GHz	20 dB /km in excess – oxygen molecules
	20-50 GHz	0.06 – 0.2 dB /km – oxygen
Rain Attenuation (25mm/hr. – heavy rain)	28 GHz, 39 GHz, 47 GHz, 60 GHz	6-7 dB / km – 28 GHz 8 dB / km – 39 GHz 9 dB / km – 47 GHz 10 dB / km – 60 GHz
		LOS link degradation: Severe, as alternative multipaths are created from rain reflected surfaces.
Path Depolarization Losses	60 GHz	Also due to raindrops. Adversely impacts cross polar de-correlation level between two signals
Hail Losses	38 GHz	From band specific study – 25 dB (~ 600m LOS)
Diffraction	28 – 73 GHz	• 40 dB rise in diffraction losses for building corner environment, from 28 to 73 GHz • 10 dB loss in general - hallway corners • 40 dB loss in general - around elevator shafts
Building Penetration Loss[30]		
External - Brick Wall	28 GHz	28.3 dB
External- Tinted Glass		40.1 dB
Internal – Clear Glass		3.6 – 3.9 dB
Internal - Tinted Glass		24.5 dB
Internal – Wall		6.8 dB
Other Objects		

30 *28 GHz Millimeter Wave Cellular Communication Measurements for Reflection and Penetration Loss in and around Buildings in New York City*, Hang Zhao, Rimma Mayzus, Shu Sun, Mathew Samimi, Jocelyn K. Schulz, Yaniv Azar, Kevin Wang, George N. Wong, Felix Gutierrez, Theodore S. Rappaport.

Human Body Loss [31]	20 GHz	40 dB
Foliage Loss[26]	5 versus 29 GHz	2 dB versus 10 dB
	9.6 versus 57.6 GHz	5 m distances - 40 dB difference 20 – 80 m distances - 50 – 80 dB difference
	57.5 GHz	Conifer foliage causes depolarization losses.

12.4 BEAMFORMING FOR MMWAVE ANTENNAS

Operators with spectrum limitations or other network densification needed to support many 5G use cases will alternatively explore mmWave based wireless communication systems. But such high band spectrum signals as already noted in this whitepaper, are severely limited by large propagation path loss properties. This deficiency highlights the critical need for beamforming schemes which help overcome the severe loss in signal strength. Its implementation, with dedicated digital baseband and RF chain per antenna to control both amplitude and phase of the transmitted signal across all antennas of a large array, while achieves the desirable directional gain, also becomes severely cost prohibitive. The hardware cost and power consumption levels associated with mmWave mixed signal circuits, including data converters, discourage their use in the great numbers in contrast to low/mid band digital beamforming transceiver designs.

Another characteristic inherent to the high path loss tied to mmWave propagation is the effect of scattering or low spatial selectivity. Antenna elements for mmWave systems are already closely packed with small interelement distances. From the receiving side, the latter implies that different versions of the same signal arriving at each antenna are closely correlated. Channel characteristics exhibiting low sparsity (extremely correlated channel matrices) is one reason why hybrid beamforming performance can approach that of its digital variant, despite implementing lower complexity precoding.

These two key drivers described above greatly influence the architecture development of beamformers specific to mmWave transmission and are embraced in the design of hybrid beamforming solutions with regard to hardware selection and precoding / channel estimation.

13. BEAM MANAGEMENT

Since mmWave propagation is characterized by high path loss, beamforming is essential. This means that the mmWave systems must use narrower beams than in lower frequencies and it must do so for both the broadcast and unicast data. This has many consequences. Beam Management refers to techniques and processes used to manage the logical consequences of using (relatively narrow) beams to transmit and receive data.

31 *Overview of millimeter wave communications for fifth generation (5G) wireless networks-with a focus on propagation models,* T. S. Rappaport, Y. Xing, G. R. MacCartney, A. F. Molisch, E. Mellios, and J. Zhang,, IEEE Transactions on Antennas and Propagation, vol. 65 no. 12, pp. 6213– 6230. Dec. 2017.

The first obvious consequence of using beams to transmit broadcast data is the necessity of beam sweeping. Obviously, a narrow beam can only reach a part of the coverage area at a given time and so this beam must be transmitted to different parts of the coverage area at different times to reach the entire coverage area. This is referred to as Beam Sweeping.

The user equipment (UE) that receives the beam will in general, also do a beam sweeping of its own (therefore, it will have to try out various different receive beams to isolate the one with best reception) and the best decoding results will only be obtained when the transmitting and receiving beam pair is optimal for the location of the user equipment at the time.

This means to receive broadcast data successfully, the gNB and the UE go through a simultaneous process of beam sweeping to isolate an optimal beam pair. Depending upon the number of beams that the base station and the UE used and the size of the coverage area, this process could be time consuming. To save time, it is anticipated that this process need not be immediately carried through to reach the best pair in one go. Rather, the process may initially end upon reaching a beam pair that is sufficiently good (to be able to receive the data) but not necessarily the best possible option. However, the 3GPP specification provides for a technique which can be utilized subsequently to optimize the current beam pair. This technique is called Beam Refinement.

As mentioned earlier unicast data is also handled using beams in mmWave. This raises the issue of how to handle mobility as well the possibility of beam failure due to varying conditions (even in a given fixed location). To handle mobility the UE has to keep track of the beam that is best suited for its current location, inform the base station of the current best beam and the gNB has to ensure that the transmission of unicast data is switched to the beam which is the UE’s current best beam to ensure continuous reception. This is the process of Beam Switching.

It is also possible that due to varying environmental conditions a beam that is currently in use by the UE is either degraded or is no longer available. The UE cannot, at that time, use this beam to interact with the base station to report its next best beam. This is referred to as beam failure and the process to recover from this is Beam Recovery process.

In the following sections beam management processes are discussed in some detail.

13.1 INITIAL BEAM ACQUISITION

Initial Beam Acquisition is the process by which broadcast and synchronization information is acquired by the UE just after power up. It is based on Beam Sweeping (by both the base station and the UE). The information that is acquired by the UE is the synchronization signals and Master Information Block. The synchronization signals consist of the Primary Synchronization Signals (PSS) and the Secondary Synchronization Signals (SSS) and help the UE to acquire frame, subframe and symbol timing as well as the Physical Cell Identity. The MIB (Master Information Block) contains System Frame Number and other useful system information. It is essential for the UE functioning to acquire this information accurately.

This information is sent in the form of pre-specified blocks of data called an SS/PBCH Block. The number, size, content and location of these blocks of data is fixed.[32] The following figure illustrates the characteristics SS/PBCH block vis-à-vis different subcarrier spacing.

[32] 3GPP TS 38.211 Section 7.4.3.

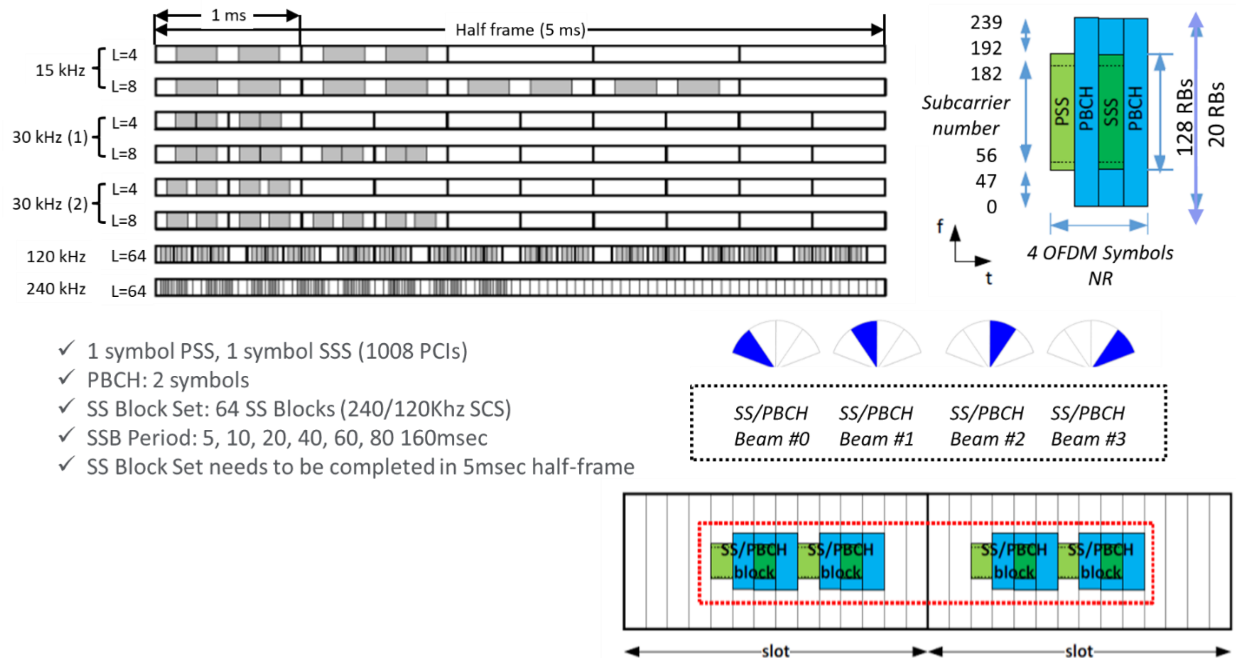


Figure 13.1. Schematic Illustration of the Characteristics SS/PBCH Block vis-à-vis Different Subcarrier Spacing.

During beam sweeping one SS/PBCH block is transmitted using one beam in one direction and then the next block is transmitted to a different direction using a different beam and so on, thus effectively sending this broadcast information to all portions of the cell.

The total number of SS Blocks and the total number of opportunities to send them are fixed by the 3GPP specification. Also, these opportunities are repeated after a certain period and this period is also fixed by the 3GPP specification to a minimum of half radio frame (5 ms). The range of periods allowed for the repetition of SS Block opportunities are 5, 10, 20, 40, 60, 80 160 msec.

The total time taken by the UE to get to an optimal beam pair is a function of the total beam sweeping time for UE receive beam sweeping and the SS Block periodicity. Therefore, any optimization of this time depends upon the same two factors.

SS Block periodicity and receive beam sweeping time depends, in turn, upon the number of beams, beam widths and the coverage area (among other things) and is thus dependent upon individual equipment manufacturers.

13.2 BEAM SWITCHING/RECOVERY

Beam Switching is the process by which the UE and base station keep track of the best beam to transmit unicast data on and to ensure that the UE switches to this best beam for successful continuous data reception.

The process of beam switching involves the following: The UE can be ordered by the base station to perform beam strength (for example, RSRP) measurements on the beams that are visible to it. These measurements are based on the SS Blocks transmitted periodically by the base station (see Beam

Acquisition section above) and are reported by the UE to the base station upon receiving a feedback request. Using this feedback, the base station may decide to order the UE to switch to a new beam (the decision of when and which beam to select for this is unto the base station). The order to switch to a new beam is sent via the Media Access Control (MAC) element and upon receiving a Hybrid Automatic Repeat Request (HARQ) acknowledgement, the base station switches the transmission to the new beam.

Figure 13.2 illustrates the beam switching process.

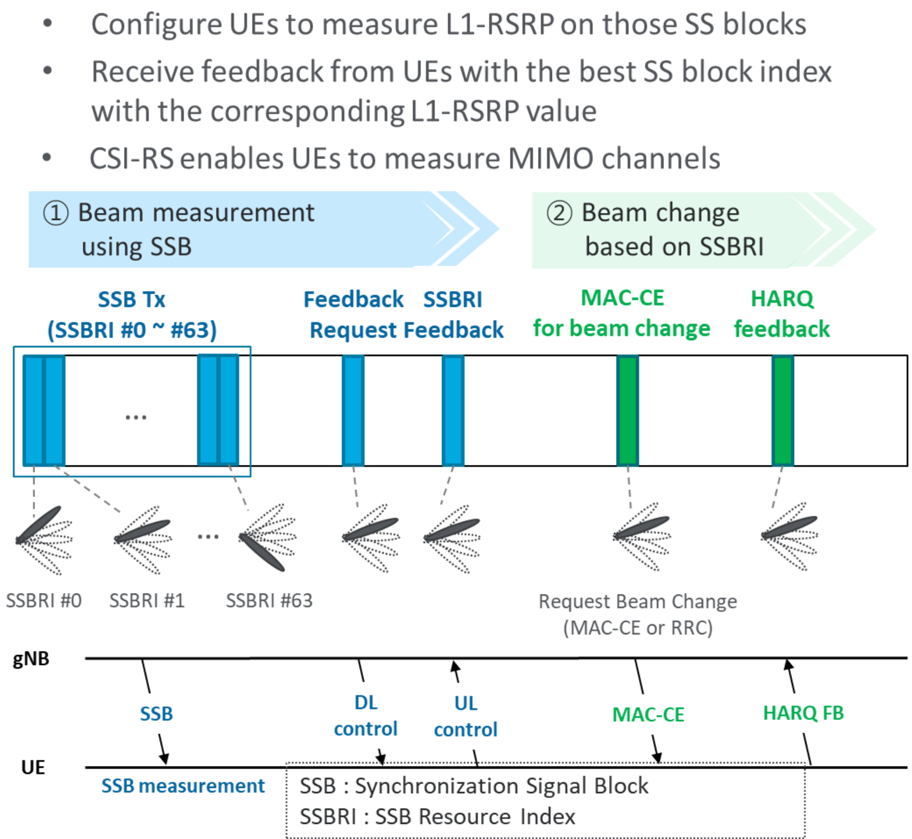


Figure 13.2. Beam Switching.

The timing and frequency of beam switching are parameters that can be optimized by individual vendors.

Beam Recovery is the process by which the UE can recover from the situation when the current serving beam falls below a threshold fast enough that beam switching cannot take place. It consists of two steps: Beam Failure detection and Recovery Request. For Failure detection, the UE monitors a quality metric of the SS block which is the reference for the Physical Downlink Control Channel (PDCCH) beam indication. If the expected quality is lower than the configured threshold for the SS block (for example, due to instant blockage as in 13.3), beam failure is detected.

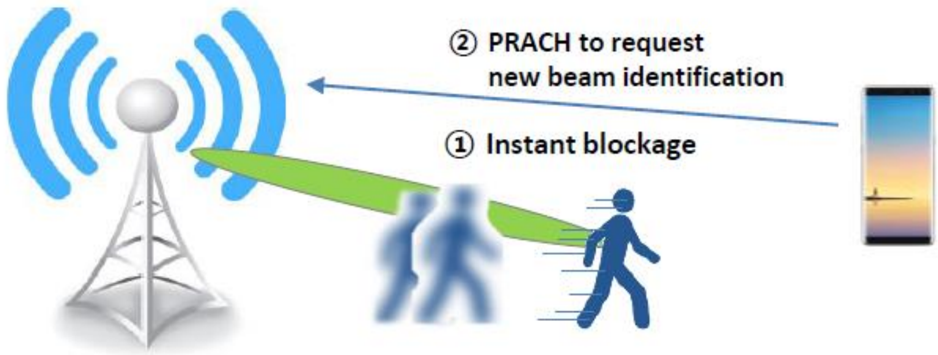


Figure 13.3. Beam Recovery.

When UE detects beam failure events, and if UE finds a new SS block having the higher quality metric than the configured threshold, UE transmits contention-based Physical Random Access Channel (PRACH) (Msg-1) whose resource is mapped to the new SS block. During the Msg-2/Msg-3 and subsequent reception/transmission, the gNB replaces the old beam with the newly identified beam

13.3 BEAM REFINEMENT

As previously discussed, the UE operates with a Tx/Rx beam pair which allows the equipment to receive and transmit data to and from the base station. The beam pair has been selected by a process of Beam Acquisition and/or Beam Tracking. This process is not guaranteed to yield the best such pairing since it is a time and resource constrained process. For example, the UE may not have had the opportunity to sweep through all Rx beams, or it may be the case that the initial Tx beam that is selected comes from a set of Tx beams which have not been fully explored. At any given time, it may become necessary for the UE to refine the Tx/Rx beam pair that it currently uses since either the Tx or the Rx beam is suboptimal. NR architecture provides for procedures wherein this beam pair refinement is done.

The refining procedure consists of the base station providing to the UE reference signals in the DL (called CSI-RS) corresponding to a set of beams, so that UE can perform further refined selection of the beam pair based on measurements performed on those signals. The set of beams for which the base station provides these signals is a matter of design and use case, but two broad cases can be discerned. One is where the purpose is to refine the Tx portion of the beam pair and the second is where the purpose is to refine the Rx portion.

In procedure P2, 13.4-A, the base station provides CSI-RS for different Tx beams and the UE then judges which of these beams is better than the existing Tx beam by using a fixed Rx beam to evaluate and select from the various Tx beams.

In procedure P3, 13.4-B, the base station provides the CSI-RS for the existing Tx beam repeatedly so that the UE can sweep through its various Rx beams in order to select the better Rx beam.

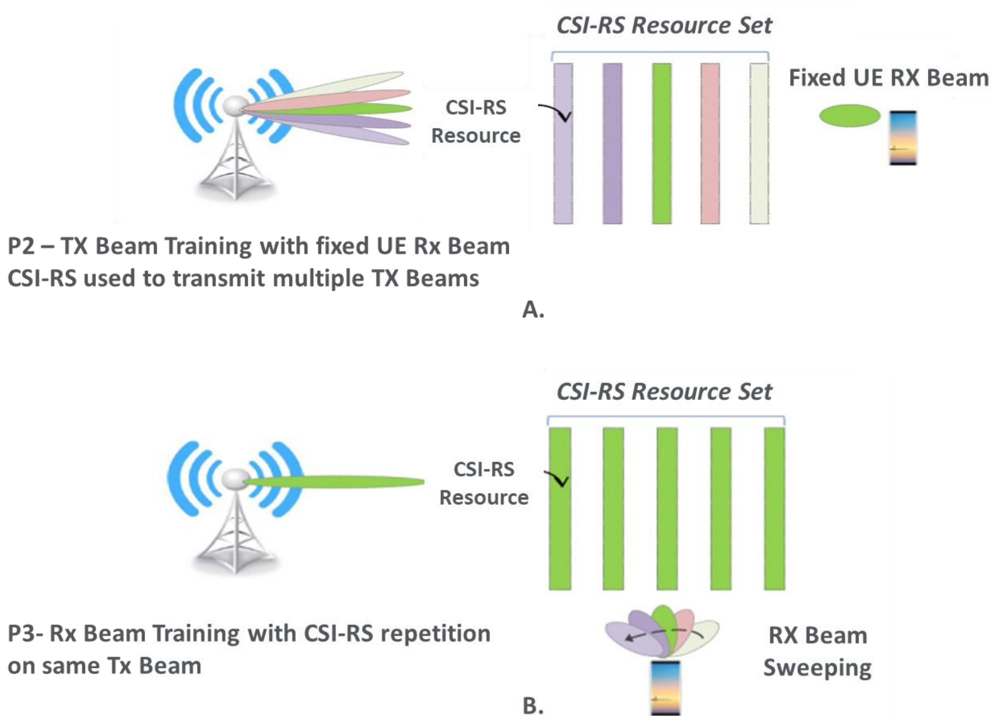


Figure 13.4. (A) The procedure for Tx Beam Refinement. (B) The Procedure for Rx Beam Refinement.

14. PERFORMANCE OF AAS FEATURES AND DEPLOYMENT SCENARIOS

The main advantage with AAS is the enabling of SINR improvement at the receiver, applicable for both DL and UL, and hence AAS improve performance in the network. These performance improvements can be manifested either as improved capacity or coverage, and/or end user throughput. The way the performance metrics improve depends on which of these performance benefits is most valued given the scenario of interest. The performance of AAS in field environment is affected by several factors, for example, antenna configuration, deployment scenario, AAS feature content, frequency range, use case and site configuration, to mention a few. There are also potential additional costs associated with AAS, for example, due to more hardware, but also to indirect costs relating to higher weight and size, and therefore potentially higher site costs. Therefore, the most suitable AAS configuration must be chosen carefully. In this section, examples will be provided for some of the cases listed previously to illustrate what can be achieved in the different scenarios and specifically how the antenna configuration will influence performance in a given scenario. The results in section 14 showcase the potential performance gains of AAS may not be always attainable in real life commercial deployments.

Performance is also affected by the choice of features, together with the selected antenna configuration type to use. Hence, there are several degrees of freedom to exploit. A couple examples of this are shown, for example, the effects on performance of different antenna configurations for SU-MIMO. The performance of MU-MIMO is also compared to SU-MIMO to show the potential additional benefits of this feature.

On high band (FR2), coverage is more challenging and solutions for coverage improvement is important. In these scenarios, AAS has a natural role to improve performance and specifically to increase coverage. AAS is almost necessary to achieve good performance in large areas. The expected site density of high band solutions does not often provide sufficient coverage solutions standalone. Deployments in high traffic areas make use of many different carriers. In such deployments, it is beneficial to manage traffic across the different frequency bands using techniques as Carrier Aggregation (CA). In such scenarios high band solutions can provide very good performance when used in combination with one or more lower bands. The resulting performance is often significantly improved compared to single band deployments. The high band solutions will then serve the users where possible and the lower band solutions will provide the service when the higher band solution is less favorable or does not have sufficient coverage. Examples on the benefits of deploying such combinations are also shown.

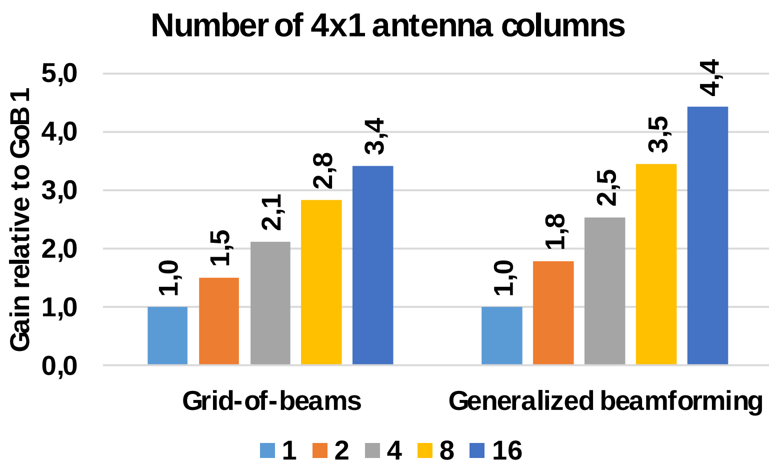
The deployment conditions influence the choice of AAS configuration and AAS features to use. Therefore, the characteristics of the different scenarios are outlined. Then suitable configuration choices in the different deployment scenarios respectively are discussed.

AAS can also be used in deployment scenarios other than mobile broadband (MBB). One example is Fxed Wireless Access (FWA) where the users are located in their homes. These users are stationary and have high bit rates requirements. Furthermore, these users often have Customer Premise Equipment (CPE) installed on the outside of the building. AAS can in these scenarios provide significant benefits.

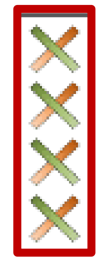
The performance examples shown and discussed in the following sections are all based on system level simulation evaluations of a radio network. The radio network is either deployed in a regular structure with 3-sector sites with a given Inter-Site Distance (ISD) as per the 3GPP defined cases or according to some emulated realistic deployment in exemplified city kernels. All users will request the same type of service with equal size of data demands (equal buffer FTP traffic). It should be understood that the performance presented is for the specific configurations and prerequisites. Thus, in reality the performance in a live network will have a large variation according to the deployment, traffic, and etcetera, and the system level simulations can be seen as examples of what can be achieved by the technology at the given specific prerequisites.

14.1 FEATURE PERFORMANCE

The feature performance depends on the antenna configuration. The beamforming capabilities and consequently the performance of beamforming and SU-MIMO depends, for example, on the ability to beamform in the dimensions where the users are distributed. In typical low-rise urban and suburban environments, the users are spread predominantly in the horizontal dimension. Therefore, gains can be obtained by increasing the horizontal beamforming capabilities. Figure 14.1 shows how performance improves when increasing the number of antenna columns in the horizontal dimension. For a basic configuration of a dual-polarized 4x1 antenna column, doubling the number of columns in four steps from 1 to 16, the performance increases up to 30-50 percent when using codebook based (grid-of-beams) beamforming and up to 40-80 percent gains when using reciprocity-based generalized beamforming. Each doubling of columns also implies a doubling of antenna aperture and a doubling of the spatial processing degrees of freedom. In a dense urban high-rise scenario, the users are likely spread in the vertical dimension as well. In this case additional gains can be achieved when performing beamforming in the vertical dimension.



a.



b.

Figure 14.1. Performance Improvement with Increasing Number of Antenna Columns in the Horizontal Dimension.

Note: The performance (a.) of SU-MIMO as a function of the number of antenna columns and (b.) system simulations according to a 3GPP UMa (Urban Macro) model environment with a ISD of 500m for TDD on 3.5 GHz with 100 MHz bandwidth using TDD ratio DL/UL 3/1 and each UE carrying equal buffer FTP traffic**.**

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Using SU-MIMO as a baseline, additional performance gains can be achieved by making use of MU-MIMO. In Figure 14.2, the relative gain of Reciprocity-Based (RB) MU-MIMO compared to Rel-14 feedback-based (FB) SU-MIMO is shown for 16T and 32T. MU-MIMO can provide gains compared to SU-MIMO in the range of 10-22 percent for the different cases, respectively. It should be noted that MU-MIMO can provide much higher relative gain in scenarios with extremely high load. Such scenarios are currently rare in reality, but they do occur in stadiums and other places with extremely high user density. It is expected that there will be more such cases in the future. Furthermore, in demonstration cases where the traffic can be controlled, for example, full-buffer traffic can be used, it is possible to show very high-performance gains with MU-MIMO. In scenarios with limited load, there may losses instead of any gains. In such scenarios, it is often better from a performance perspective not to apply MU-MIMO at all.

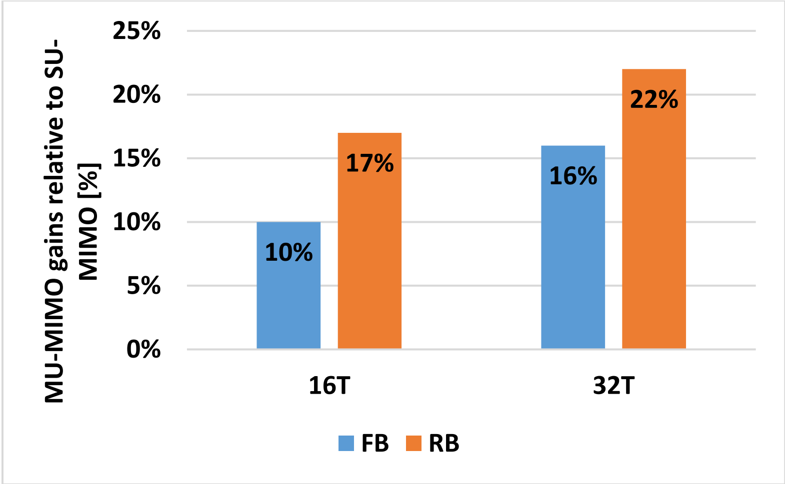

Figure 14.2. Example on Performance for MU-MIMO Compared to SU-MIMO.

Note: The comparison is made for two antenna configurations, 16T and 32T for both reciprocities based (RB) and feedback based (FB) cases. System simulations according to a 3GPP UMi (Urban Micro) model environment with an ISD of 200m for TDD on 3.5 GHz with 10 MHz bandwidth. The used TDD ratio DL/UL 3/1 and each UE carried equal buffer FTP traffic.

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AAS can also be effective in non-MBB (Mobile Broadband) use cases. For example, in FWA, the performance can be significantly improved in both DL and UL by using AAS and exploiting the benefit of beamforming. The greatest effects can be achieved if the CPE is mounted on the rooftop of the target buildings. FWA can effectively co-exist with regular MBB traffic. The graph in 14.3 shows the cell edge user throughput for the DL on 3.5 GHz with 60 MHz bandwidth. The curves represent conventional solutions with 2T2R and 4T4R and an AAS. AAS is clearly outperforming the conventional solutions. FWA deployments can also be handled by regular macrocell sites if there is spare capacity.

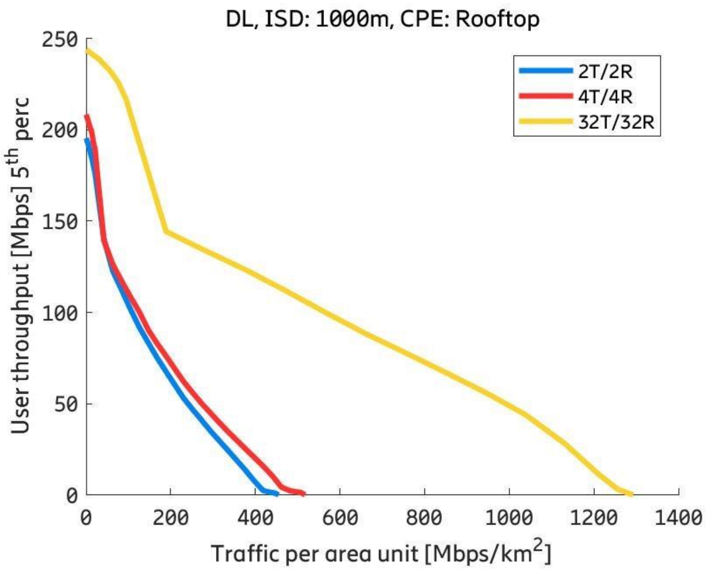
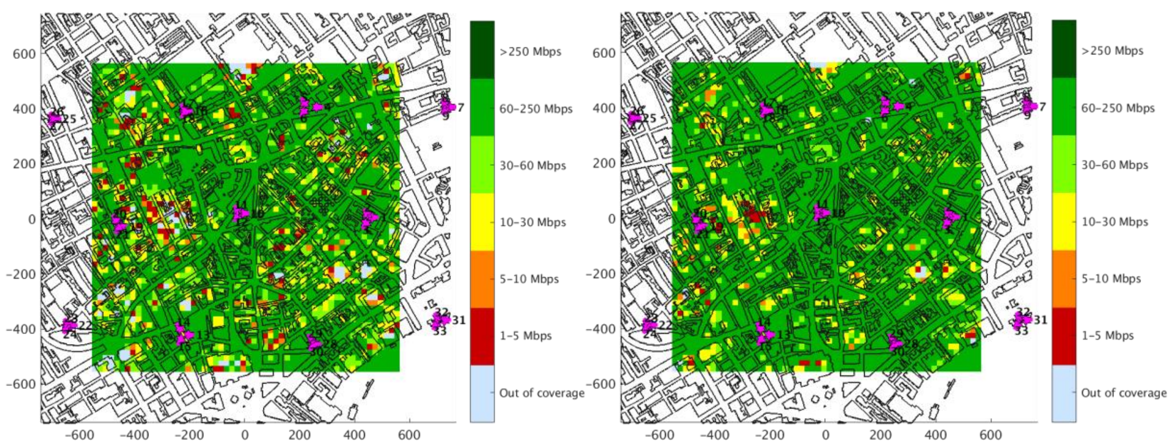


Figure 14.3. Cell Edge User Throughput for FWA deployment.

Note: FWA deployment on mid band with CPE mounted on rooftop with an ISD of 2000m in a suburban/rural environment. The graph shows user throughput for the DL on 3.5 GHz with 60 MHz bandwidth. The curves represent the 5-percentile user throughput, the cell edge users, for conventional solutions with 2T2R and 4T4R and an AAS.

14.2 MULTI-CARRIER DEPLOYMENT SCENARIO

In almost all deployments in high traffic areas, there are many technologies and frequencies deployed on the sites (a heterogenous network). Combining higher bands with lower bands in a coordinated manner can be effective, particularly on the uplink, which is commonly the limiting factor for coverage. These effects are not limited to the use of AAS, but occur also for non-AAS, and must be considered when deploying AAS on new 5G bands. In the example in Figure 14.4, it is shown that the uplink throughput for 5G users on 3.5 GHz can benefit significantly from cooperation with lower bands. For this case, the lower bands are 2.6 GHz and 800 MHz. In the example, the base station configuration on both 800 MHz and 2.6 GHz are 2T2R and the aggregated bandwidth in UL is 30 MHz. On the 3.5 GHz carrier, the bandwidth is 100 MHz and the AAS configuration is 64T64R. For the 3.5 GHz NR case, the UL user throughput can reach more than 60 Mbps for many users. A number of users do have limited performance in the range <10 Mbps. When combining the LTE and NR bands, a clear majority of the users could reach more than 60 Mbps and only a small number of users potentially would have a UL throughput less than 10 Mbps. Thus, the AAS configuration for NR 3.5 GHz performs very well standalone, but can be further improved, particularly for cell edge users, when combined with the lower LTE bands.



A **B**

Figure 14.4. Example of Uplink Throughput. A- 3.5 GHz and B- 3.5 GHz combined with 2.6 GHz and 0.8 GHz.

Another type of inter-band/inter-technology cooperation is shown in Figure 14.5, where an existing LTE low/mid-band network with limited outdoor performance is complemented with an NR 28 GHz street cell deployment. In this example, the aggregated bandwidth for LTE on low- and mid-band is 30 MHz, which is complemented at 28 GHz with 400 MHz TDD. Effectively about 300 MHz bandwidth is used for DL traffic. By adding the small cells, the end user throughput outdoors can reach up to 1 Gbps.

In this case, the existing LTE bands are combined with frequency bands in the mmWave range. The coverage of the NR high band is limited and the importance of AAS coverage improvements is essential.

The users that do get NR coverage will get very high user throughput due to the very high NR bandwidth. Gains can also be obtained when combining existing LTE bands with NR on mid-band, for example, 3.5 GHz. The NR coverage will then be improved. However, the bandwidth will be smaller over the sub-6 GHz bands and hence the user throughput will not be as high as in the present example.

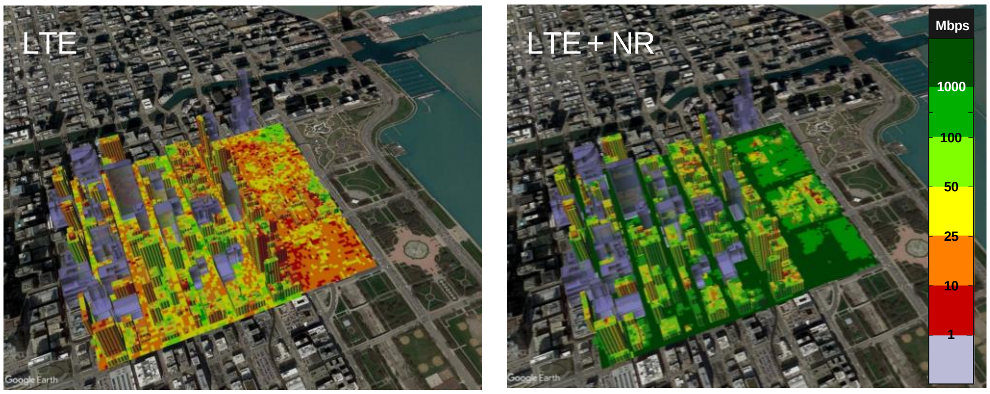


Figure 14.5. Example of 28GHz Coverage.

Note: NR on 200m ISD Street-Cell Layer.

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15. AAS IN DIFFERENT DEPLOYMENT SCENARIOS

Determining what kind of AAS configuration is most cost effective for given deployment scenarios requires a mix of knowledge about a large number of parameters, such as possible site constraints and available AAS features, and in particular the need for vertical steerability of beams, the applicability of reciprocity-based beamforming and the gain from MU-MIMO.

When deploying AASs, there are certain considerations necessary to ensure that the chosen solution meets the requirements in the type of environment where they are deployed, for example, dense urban high-rise, urban low-rise, suburban and rural. These environments are crude classifications of environments but can be useful as a starting point for understanding the different conditions considered. In practice, real city environments usually have a mix of different categories. Therefore, it is of great importance to consider the actual deployment environment. The urban (high-rise and low-rise), suburban and rural and rural/fixed wireless environment deployments are explained in subsections 15.1 to 15.4.

15.1 DEPLOYMENT SCENARIO: DENSE URBAN HIGH-RISE

In dense urban high-rise scenarios, there are different types of deployments. The rooftop base macrocell deployment, is usually the most common today. This macrocell deployment must be complemented by both indoor systems and small cell (street macro) sites.

A dense urban high-rise environment is characterized by tall buildings, high traffic density and predominantly rooftop site deployments. Due to the tall buildings, wave propagation characteristics are affected. Also, network traffic distribution will be in the vertical dimension meaning that there is a significant spread in the distribution of site height profile, since buildings' height variation may be significant. The site density is usually required to be very high to handle the amount of capacity; and the macro sites are often complemented with other site types, for example, small cells and indoor sites. Such deployments can significantly change the coverage requirements for the macrocell sites and are a vital part of deployment considerations.

15.1.1 URBAN HIGH-RISE MACROCELL

The first urban deployment considered is a pure macrocell-based scenario. The sites must cover all traffic in the area and specifically all traffic in the vertical dimension. An AAS in this scenario needs to support beamforming in the vertical dimension as well as the horizontal dimension, assuming a given antenna area, for example, of 8x8 dual-polarized antenna elements. In the vertical dimension, the users tend to be more concentrated on the ground floor and lower floors. Also, there is usually a limited vertical spread of users compared to the horizontal dimension, and the users are usually evenly distributed over the whole area in the horizontal dimension. Therefore, the need for beamforming is usually higher in the horizontal dimension, hence the granularity should be higher in the horizontal dimension, requiring high antenna gain and beamforming capabilities. As such, a wide antenna with many narrow subarrays (columns) will be preferred. As an example, a 64T64R antenna with an AOSA structure of 4x8x2 with 2x1 subarrays may be a good solution that fulfills the requirements. Array configurations with 32T32R or 16T16R, with lower degree of partitioning in the vertical dimension, may be effective in the urban and suburban scenarios. These array configurations will usually be outperformed by the 64T64R configuration which has a better capability and granularity of beamforming in the vertical dimension.

15.1.2 URBAN HIGH-RISE STREET MACRO

In the city center, particularly where the buildings are tall, it may be difficult to find good macrocell sites that have enough coverage in the area. This may result in coverage holes or areas where the capacity requirements are high and cannot be met. In these scenarios, additional sites on the street level may help to provide a good end-user service. In these scenarios, the street macros (small cells) will have requirements to cover the nearby streets as well as the lower floors in the high-rises. The street macro will thus benefit from both vertical and horizontal beamforming capabilities. The street macro deployments are usually a complement to the rooftop macrocell deployments.

15.1.3 URBAN HIGH-RISE IN-BUILDING

In city centers there are often high-rise buildings that can be characterized as ‘high profile’ in various ways, for example, important business enterprises or city administration buildings. For these buildings, the operators will very often provide dedicated indoor systems. If well built, such systems can provide enough capacity for the whole building. This means that the traffic in these buildings need not be served by the macrocell sites. If these buildings are tall, this will reduce the need for coverage in the vertical dimension. In fact, there are city centers where all central high-rises are served by dedicated indoor systems. For these cases, the coverage requirements are more like urban low-rise, since no macrocell traffic is utilized on higher building floors.

Dedicated indoor systems can be designed in many ways. For most indoor scenarios, it is advantageous to use more antennas and spread them somewhat equally throughout the indoor coverage area. AASs may have some advantages in certain scenarios. In almost all indoor scenarios, only horizontal beamforming is required. Therefore, many subarrays in the horizontal dimension will be needed. The requirements on output power are usually quite low.

15.2 DEPLOYMENT SCENARIO – URBAN LOW-RISE

Urban low-rise environments are characterized by lower and more evenly distributed building heights, about four to six floors. The site heights are normally rooftop-based and hence the traffic density is very high, however the spread in the vertical dimension is somewhat low. The average site-to-site distance is larger than in the dense, urban high-rise scenario. Since the need for vertical beamforming is lower, the number of subarrays in the vertical dimension can be limited to two, for example, and the subarrays can be tall in the vertical dimension to retain aperture size and total antenna gain. For example, a 32T32R with AOSA structure 2x8x2 of 4x1 subarrays would be adequate.

15.3 DEPLOYMENT SCENARIO – SUBURBAN AND RURAL

The dominant application is to increase both capacity and coverage depth within an existing macrocell footprint. The suburban environment is, like the urban low-rise scenario, characterized by lower and rather evenly distributed building heights. The building heights and traffic density are generally lower than the urban scenarios. Therefore, the site-to-site distances are greater and the traffic distribution in the vertical dimension is even lower. Consequently, it is reasonable to assume that there is only need for beamforming capabilities in the horizontal dimension. The subarrays can be tall to compensate for the longer site distances with an array structure of 16T16R and an AOSA structure of 1x8x2 of 8x1 subarrays. Higher beamforming capabilities in the vertical dimension, therefore, a subarray partitioning with higher granularity, will add cost, but not significantly improve performance, as shown in Figure 15.1.

15.4 DEPLOYMENT SCENARIO – RURAL AND FWA

Cost effective Rural MBB coverage has relied on sparse deployment of tall sites operating on low bands for maximum range, with selective densification at population centers. Large antenna apertures support new FWA services, thereby leveraging new mid- or high-band spectrum to satisfy the unmet demand for fast household internet particularly in more suburban and rural areas.

FWA is a big driver for AAS antenna demand in outer suburban and rural environments, often in Time Division Duplex (TDD) spectrum between 2.5 and 3.5 GHz. Low and clustered user/household distributions present different RF planning challenges to those in urban environments, such as:

- Need for maximum coverage range while achieving high UE UL throughput requirements
- Maximum DL capacity over the extended UL coverage footprint for best Return on Investment (ROI) per site
- Limits on Transmitter (TX) Equivalent Isotropically Radiated Power (EIRP) if shared or un-licensed spectrum is used
- Leverage MU-MIMO for UEs closer to the cell that can operate with DL power sharing

To better understand tradeoffs between coverage and capacity density, FWA system simulations were conducted in a sparse open rural environment with traffic at known household concentrations. The values in Figure 15.1 show maximum cell spectral efficiency and resulting capacity density/(sq km) for a 20 MHz 3.5 GHz TDD carrier. The 64 Transmitter/Receiver (T/R) antenna is 8 columns x 4 cross polarized subarrays. CPE directional antenna gain is 10 dBi. Note that the spectral efficiency is constrained by thermal noise limited SINR. Much higher values are possible if all users are close to the site.

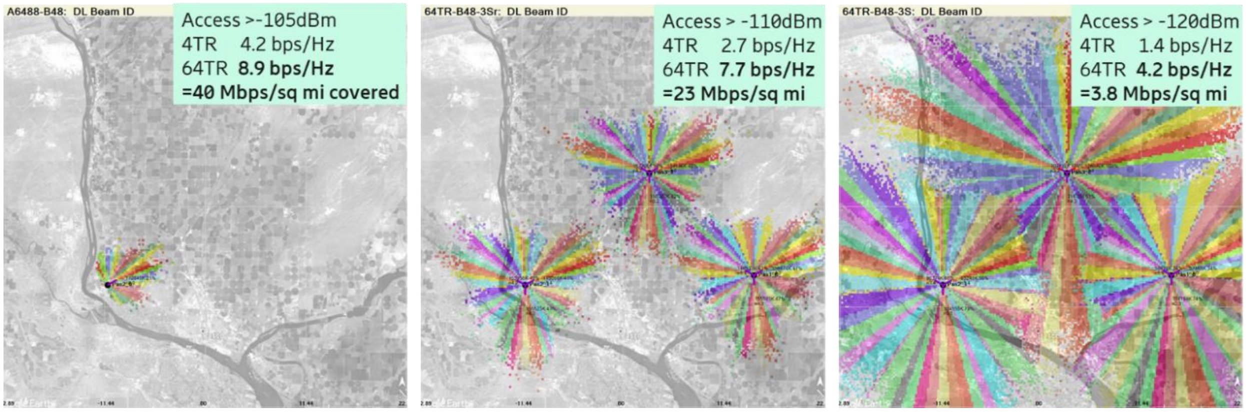

Figure 15.1. Maximum Cell Spectral Efficiency and Resulting Capacity Density/ sq km for a 20 MHZ 3.5 GHz TDD Carrier.

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Interference to and from surrounding cells is highly variable and when combined with cell range limiting can greatly affect the achievable capacity per sq. km. This tradeoff can be optimized per environment by choice of antenna alignment and access thresholds to contain the footprint.

Network spectral efficiency and coverage are further improved by use of outdoor elevated fixed directional antennas at the household CPE. These antennas are usually small fixed panels or Yagi antennas but could also be an adaptive array in higher mmWave bands. Directional antennas may reduce Rank 3+ SU-MIMO transmission and peak throughput due to more restricted angle of reception, thereby limiting multipath arrivals CPE antenna. However, this results in better network spectral capacity gain. This problem does not occur with MU-MIMO normally using RANK 1/2 per user due to channel estimation from a single/dual CPE TX.

Arrays most suited to open rural areas tend to be as large as is practically deployable for maximum aperture and gain. Wider arrays with more columns create narrower horizontal beams to reduce overlap which helps MU-MIMO if the CPEs are clustered together. Array height is also important for gain and tilt control of interference. Vertical beam steering is less critical, so fixed or Remote Electrical Tilt (RET) is adequate.

A big advantage of Adaptive Array Antennas in sparse environments is the ability to flexibly beamform to move capacity as traffic hotspot locations move around, focusing on commercial locations during the day and residential areas during the evenings. This would require capacity over dimensioning if the alternative of a static small cell coverage footprint were used.

Operators with both TDD and lower band FDD spectrum have the option of multi-band operation, using the lower band to fill cell edge coverage gaps. This requires agile Inter-Frequency Handover (IFHO) or Carrier Aggregation (CA) to leverage the more robust FDD coverage where needed while keeping traffic on TDD where there is coverage. This also drives the need for AAS beamforming in the lower bands to improve cell edge capacity density and balance TDD inner capacity/coverage balance with the FDD-only outer ring. Inadequate cell edge FDD capacity would cause underutilization of inner TDD capacity as shown in Figure 15.2.

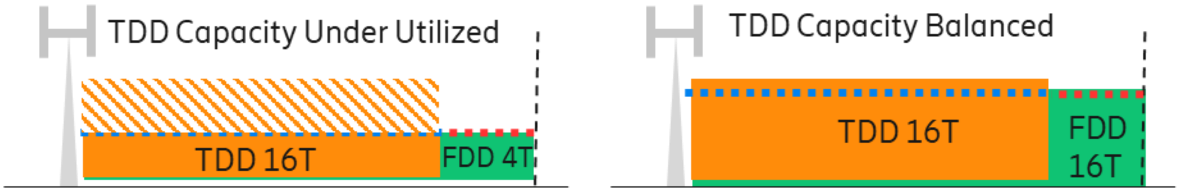

Figure 15.2. Illustration of Outer and Inner Cell Capacity Balance.

This multi-band operation creates a network capacity multiplier effect for FDD AAS gain, for example, increasing FDD capacity by 80 percent allows higher cell edge traffic density and enables 80 percent higher TDD capacity utilization over a larger area. This effect is most evident if traffic is randomly but evenly distributed over the area causing high resource utilization in the cell edge areas that can leverage beamforming.

15.5 AAS DEPLOYMENT CONFIGURATION CHOICES

Potential antenna array structures are outlined in Figure 15.3. As a basis for comparison, the array containing 8x8=64 dual-polarized antenna elements is used. The array is chosen as a basis to keep the antenna area constant and only vary the partitioning with different scenarios. As shown in Figure 15.3, the partitions, therefore, the subarray configurations of this array structure, which both meet the performance requirements and are most cost efficient in the scenarios, EW respectively different, depending on how the users are spread in the scenarios. The deployments chosen for consideration are rooftop macrocell deployments, in dense urban high-rise, urban low-rise and suburban environments, which have characteristics according to Figure 15.3. The scenarios, including relevant characteristics are described with a suitable AAS configurations, and are in Figure 15.3.

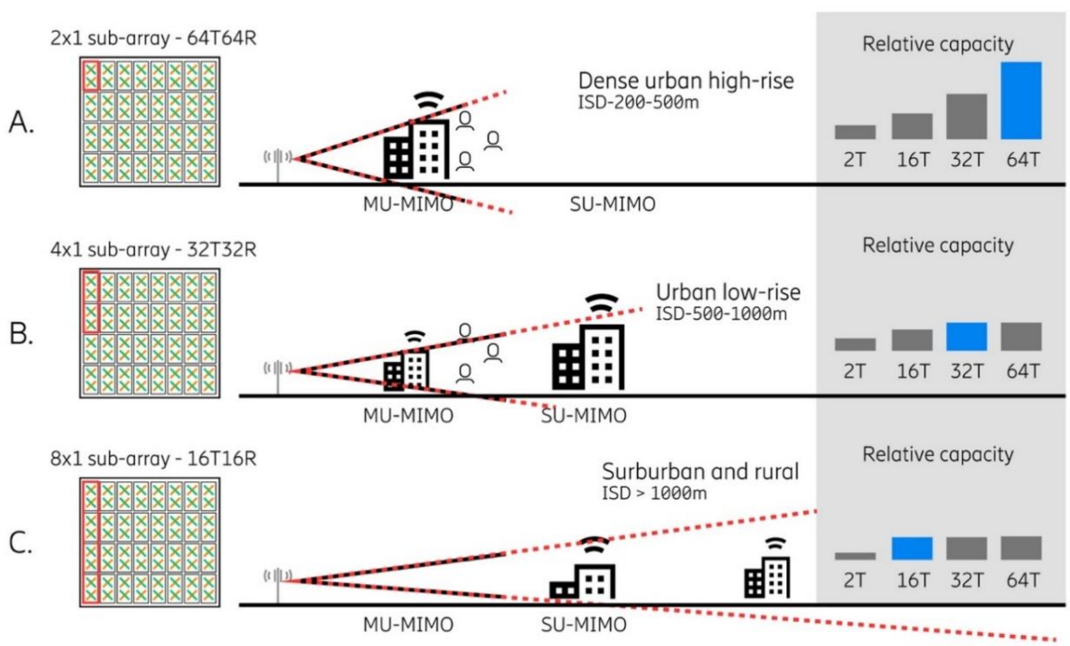

Figure 15.3. Schematic Illustration of Suitable AAS Configurations in Different Deployment Scenarios.

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16. SUMMARY AND CONCLUSIONS

Whether for 4G networks and now in 5G networks, operators continue to enhance the user experience through better coverage and capacity in the network.

- Using 4G spectrum makes a leap in network performance challenging, however, leveraging new 5G spectrum both below 6 GHz (FR1) and in the mmWave range (FR2) aids in making these improvements possible
- Todays' technology development of AAS systems via beamforming, beam management and massive MIMO (mMIMO) allows for another significant increase in capacity. This new AAS technology also makes mmWave mobile and fixed wireless communications possible
- AASs for FR1 and FR2 are complex and operate much differently than a passive antenna. Measurement methodology has been defined in 3GPP Release 15 and the simulations and measurements in this 5G Americas white paper show the potential improvements when deploying AAS
- There are a variety of use cases involving different deployment scenarios including urban, suburban and rural with FWA for both passive antennas and AAS

3GPP Release 15 was published in early 2019;[7] the coming years will see further advances with both mMIMO and mmWave.

APPENDIX

A. DEFINITIONS AND ACRONYMS

Term	Definition	Units
2D	Two Dimensional	
3D	Three Dimensional	
3GPP	The 3rd Generation Partnership Project (3GPP) is a global standards organization for mobile telephony made up of seven regional telecommunication associations as primary members and other organizations as associate members	
3rd Order PIM (Passive Intermodulation)	3rd order intermodulation products using two 20W (2 x 43dBm) carriers; 3rd order product defined at frequencies of (F1 +/- 2*F2) and (F2 +/- 2*F1) falling within the receive band when transmit frequencies F1 and F2 are used as the input carriers. The output is typically specified to be -150dBc or better	dBc
5G	5th Generation mobile networks or 5th Generation wireless systems is the next major upgrade of the mobile telecommunications standards beyond the current 4G standards	
λ	Free space wavelength	
(θ_0, ϕ_0)	Pointing angle in spherical coordinates where θ_0 represents the polar angle and ϕ_0 represents the azimuth angle	
AOSA	Array of Subarrays	
AAS	Advanced Antenna System – composed of an antenna array, radio chains and parts of the baseband, all tightly integrated to facilitate feature such as beamforming and MIMO	
AISG	Antenna Interface Standards Group - specified interface control signals for RET as well as power	
AoA	Angle of Arrival	
AUT	Antenna Under Test	
BBU	Base Band Unit	
BF	Beamforming	
BS	Base Station	
DL	Downlink	
CA	Carrier Aggregation	
CPE	Customer Premise Equipment	
CRS	Cell Reference Signal	
CSI	Channel State Information	
CSI-RS	Channel State Information Reference Signal	
DL	Downlink	
EIRP	Equivalent Isotropically Radiated Power is the product of transmitter power and the antenna gain in a given direction relative to an isotropic antenna of a radio transmitter	dBi, or decibels over isotropic
Elevation Beamwidth	Typically stated as 3dB beamwidth (unless otherwise specified); defined as the angular width of the elevation (vertical) pattern, including beam maximum, between points 3dB down from beam max level	degrees
FD	Full Dimensional	
FDD	Frequency Division Duplexing	
Frequency Range	Operating frequency band the antenna will perform to spec over	MHz
FWA	Fixed Wireless Access	
Gain	Measured antenna gain using a Swept Frequency Gain-by-Comparison method (standard procedure) involving a Standard Gain Antenna with Published Absolute Gain	dBi
gNB	Gigabit NodeB	
HARQ	Hybrid Automatic Repeat Request	

HPBW	Half-Power Beamwidth, same as 3 dB beamwidth - measure of the angle between the half-power points of the main beam in the azimuth or elevation pattern	
IFHO	Inter-Frequency Handover	
Integrated Antenna/Radio	Active Antenna – with power amplifier, LNA, filter and CPRI connection integrated into one radome. This is a special case of the more capable AAS antenna array insofar as it only controls the horizontal directions of the beams/MIMO parameters	
MBB	Mobile Broadband	
MIB	Master Information Block	
MIMO	Multiple Input Multiple Output is a method for multiplying the capacity of a radio link using multiple transmission and receiving antennas to exploit multipath propagation. MIMO has become an essential element of wireless communication standards including IEEE 802.11n (Wi-Fi), IEEE 802.11ac (Wi-Fi), HSPA+ (3G), WiMAX (4G), and Long Term Evolution (4G LTE)	
mMIMO	Massive MIMO	
MU-MIMO	MultiUser MIMO	
NR	New Radio	
NSA	Non-Stand Alone	
OSS	Operations Support System	
OTA	Over the Air	
PBCH	Physical Broadcast Channel	
PDCCH	Physical Downlink Control Channel	
PIM	Passive Intermodulation (se 3rd Order PIM)	
Polarization	Definition of antenna port(s) polarization: +/- 45° Slant, Hor, Vert, Hor/Vert, LHCP, RHCP	degrees
Port-to-Port Isolation (In-band / Intra-band / Intra-system)	Isolation between 2 antenna ports within the same frequency band	dB
Port-to-Port Isolation (X-band / Inter-band / Inter-system)	Isolation between 2 antenna ports in a multiple band system across separate frequency bands (co-pol & x-pol port configurations)	dB
PRACH	Physical Random-Access Channel and is used by UEs to request an uplink allocation from the base station	
PRB	Physical Resource Block	
PSS	Primary Synchronization Signal	
RE	Resource Element	
RET	Remote Electrical Tilt	° downtilt (positive down)
Return Loss	Listed Spec; Production Spec = Listed Spec + 0.5dB margin safety factor	dB
RF	Radio Frequency	
ROI	Return on Investment	
RRH	Remote Radio Head	
RSRP	Reference Signal Received Power	
SA	Stand Alone	
SINR	Signal-to-Interference+Noise Ratio	
SIR	Signal-to-Interference Ratio	
SS	Synchronization Signals	
SSB	5G NR Synchronization Signal Block consists of SS (therefore, PSS and SSS) and PBCH channels	
SRS	Sounding Reference Signal	
SSS	Secondary Synchronization Signal	
SU-MIMO	Single User-MIMO	
SVD	Singular-Value Decomposition (SVD) is a factorization of a real or complex matrix	
TDD	Time Division Duplexing	
TM	Transmission Mode	

TTI	Transmission Time Intervals	
TR	Transmitter/Receiver or Transceiver	
Tx	Transmitter	
UE	User Equipment	
UL	Uplink	
ZF	Zero Forcing	

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The mission of 5G Americas is to advocate for and facilitate the advancement of 5G and the transformation of LTE networks throughout the Americas region. 5G Americas is invested in developing a connected wireless community for the many economic and social benefits this will bring to all those living in the region.

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