4G and 5G Capacity solutions - comparative study

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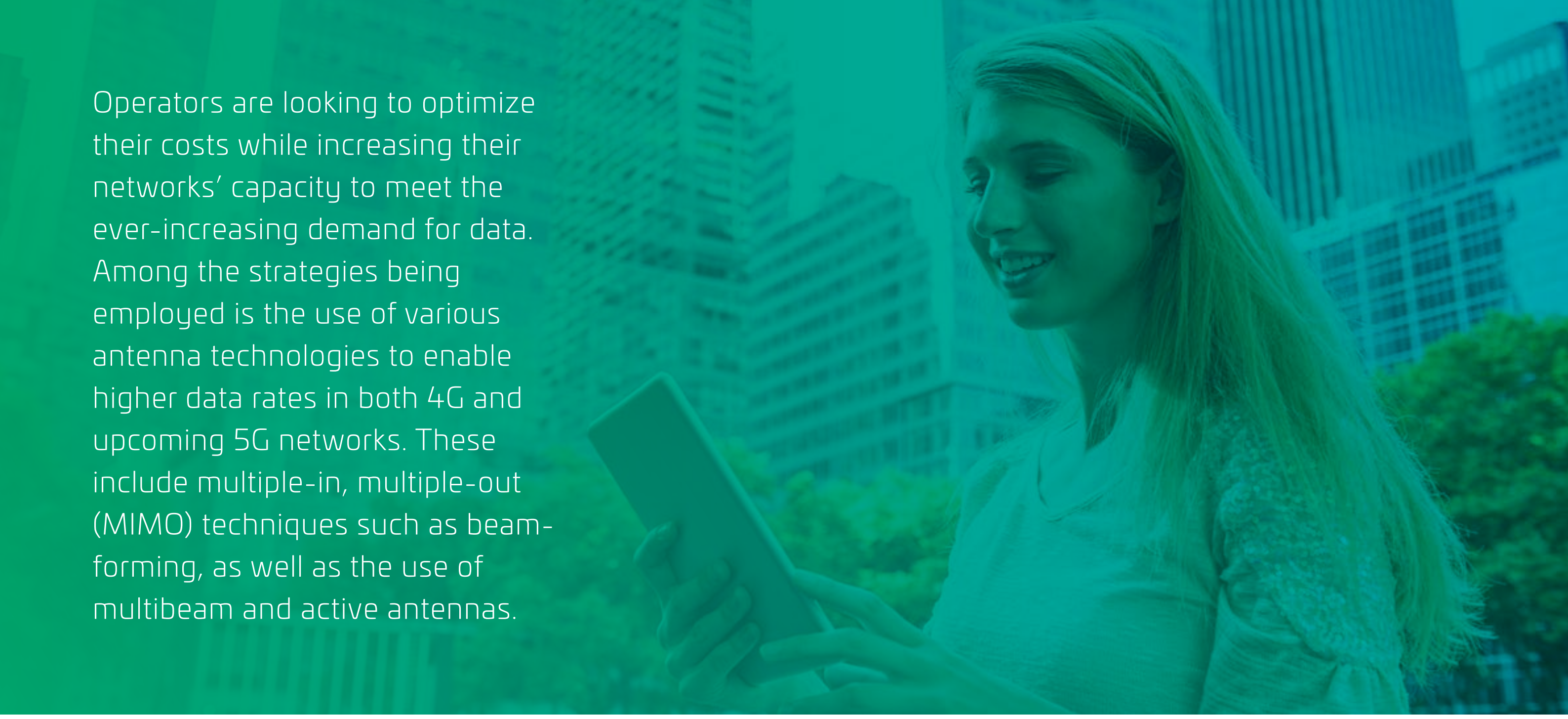


Operators are looking to optimize their costs while increasing their networks' capacity to meet the ever-increasing demand for data. Among the strategies being employed is the use of various antenna technologies to enable higher data rates in both 4G and upcoming 5G networks. These include multiple-in, multiple-out (MIMO) techniques such as beam-forming, as well as the use of multibeam and active antennas.

This paper evaluates the degree to which these various techniques increase capacity and their application to various network scenarios. To provide more context, we will consider these techniques in light of specific constraints like cost, ecosystem support, frequency division duplex and time division duplex (FDD/TDD), and channel bandwidth. As our purpose is to evaluate and compare, this paper does not discuss the basic working details of these techniques.

Antenna solutions for capacity

Antenna tradeoffs for spatial multiplexing (MIMO) and beamforming

With passive antennas, LTE networks can usually be implemented with one, two, four, or eight transmit antennas at the base station and two, four, or eight receive antennas in the user equipment (UE). These are designated as: 1x2, 1x4, 1x8, 2x2, 2x4, 2x8, 4x2, 4x4, 4x8, and 8x2, 8x4, and 8x8 MIMO or spatial multiplexing, where the first digit is the number of antennas per sector in the transmitter and the second number is the number of antennas in the receiver.

A conventional base station antenna is made up of multiple cross-polarized elements arranged in a column. The arrangement of columns differs for configurations optimized for MIMO as compared to configurations optimized for beamforming applications.

MIMO requires un-correlated channels with a typical column spacing of around 0.7 times wavelength or above. On the other hand, beamforming works better with closely spaced arrays, and the recommended distance between the columns is 0.5 times wavelength.

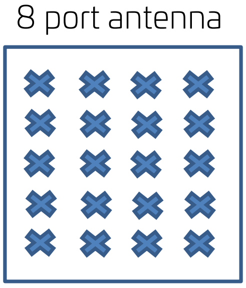


Figure 1:
Column spacing: 0.5λ for Beamforming and ≥ 0.7λ for MIMO

MIMO can work with as few as two antenna ports (for example, a single dual-polarized column array) where the cross-polarized elements of a column form a two-layer MIMO channel. On the other hand, beamforming uses elements of same polarization on multiple columns and generally requires four or more array columns to form a beam in the horizontal plane. Beamforming requires a minimum of two array columns, but most implementations use at least four columns (eight ports).

So, the eight-port antenna in Figure 1 can work best as up to eight-layer MIMO (with ≥ 0.7 wavelength column spacing), or as two-layer MIMO with 0.5 wavelength spacing through beamforming. In the latter scenario, all +45-degree elements form one MIMO layer and the -45-degree elements form the other MIMO layer. Even though each of the beamformed layers uses four physical antenna ports, UE sees it as a single layer from a single antenna port (virtual port).

A MIMO configuration can be deployed in single- or multi-user modes. Single-user MIMO allows only one user per time-frequency resource. This mode is good for improving individual user throughput, regardless of the network load. In multi-user MIMO, multiple users share the same time-frequency resource. This mode can be used to increase overall cell capacity, but at the expense of individual user throughput. In multi-user mode, the greater the network load, the higher the increase in cell capacity.

The following table provides an overview of different variations of MIMO and beamforming, as per the standards:

TM	Antenna type	Antenna port	Description
2	Two or four antennas	Ports 0 to 3	Open loop transmit diversity, Rank 1; same information is transmitted through multiple antennas with different coding/frequency resources
3	Two or four antennas	Ports 0 to 3	Open loop SU-MIMO, Rank 2 to 4; no precoding matrix information (PMI) is sent; only rank indicator (RI) and CQI is sent by UE; used for fast-moving UEs
4	Two or four antennas	Ports 0 to 3	Closed-loop SU-MIMO, rank 2 to 4; UE estimates the channel information from the CRS signal sent by eNodeB and responds with PMI, RI and CQI; used for stationary or slow-moving UEs
5	Two or four antennas	Ports 0 to 3	Similar to TM4 but used for multi-user MIMO, rank 2 to 4
6	Two or four antennas	Ports 0 to 3	Same as TM4, uses PMI feedback but used only with one layer as closed-loop MIMO, Rank 1
7	Data and an additional demodulation reference signal (DMRS) are transmitted with the same UE specific weights, forming a virtual antenna pattern (port 5) that uses several physical antenna ports. UEs see this signal as if it is from a single antenna port.	Port 5 (virtual port)	Single-layer beamforming; mandatory for TDD and optional for FDD
8	Same as TM7 but for dual layers. eNodeB weights two separate layers at the antenna so beamforming can be combined with spatial multiplexing for one or more UEs	Ports 7 and 8 (virtual ports)	Dual-layer beamforming, SU-MIMO or MU-MIMO; mandatory for TDD; optional for FDD
9	Eight antennas	Virtual ports 7 to 14	Eight-layer SU/MU-MIMO; most suitable TM for MU-MIMO, both for FDD and TDD systems
10	Eight antennas	Virtual ports 7 to 14	Enhancement to TM9 to support CoMP with eight-layer transmission; both for FDD and TDD systems

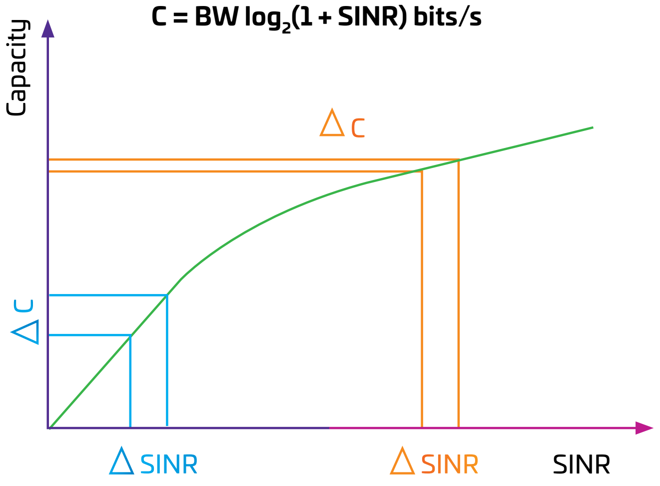
Beamforming antennas can be used as coverage or capacity strategy. The array gain from the beamforming process provides higher downlink gain in the service beam, and enables higher order receive diversity in the uplink. This helps improve cell-edge throughput or extend cell-edge coverage for the minimum desired user throughput.

One way to evaluate the applicability of MIMO and beamforming is through Shannon's Capacity Theorem. Capacity is a logarithmic curve, which is linear at low signal-to-interference-plus-noise ratio (SINR) and flattens out at high SINR.

In high-SINR conditions, the capacity increase per unit increase in SINR is relatively low. In such environments, beamforming—which further improves the signal-to-noise ratio—will be less effective than MIMO, which uses multiple layers in either single- or multiple-user modes, and is more effective.

At low-SINR conditions, the relation between SINR and capacity is linear. Beamforming techniques, due to their higher signal gain, prove very effective in such scenarios. Beamforming that uses direction of arrival (DoA) information is more effective in low-scattering and low-SINR environments. However, beamforming accuracy can be further improved with the use of channel state information (CSI) feedback from UE, which enables the beamforming technique to be effective in all types of clutter.

$$C = BW \log_2(1 + SINR) \text{ bits/s}$$

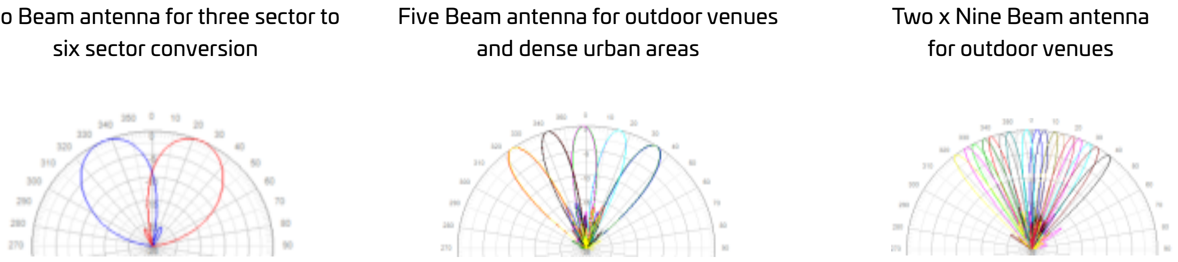


In general, a low-SINR region will benefit from **beamforming** techniques by improving SINR through higher antenna gain

A high-SINR region will benefit from spatial multiplexing or MIMO (closed loop, open loop, SU MIMO, MU MIMO) with multiple layers/users

Multibeam antennas

The multibeam antennas are equivalent to several narrow-beam antennas in one radome, enabling operators to save space, reduce installation errors, and accelerate deployment. Functionally, multibeam antennas reuse spectrum over multiple beams to boost (densify) existing capacity. This antenna solution is ideal to address high-traffic areas and is well suited for sector splitting and outdoor venue applications. These solutions help improve ROI. For example, by using twin-beam antennas, operators can nearly double the capacity in existing cells. This optimizes site cost and provides a workaround where new site builds are not allowed.


Two Beam antenna for three sector to six sector conversion

Five Beam antenna for outdoor venues and dense urban areas

Two x Nine Beam antenna for outdoor venues

Figure 2: Radiation patterns for various multibeam antennas

Figure 3 compares the radiation pattern of a twin-beam antenna with a traditional 65-degree antenna. Clearly visible is the improved containment and improved roll-off of the twin-beam antenna, which reduce the interference between cells. The enhanced footprint also creates a 2-3 dB gain at boresight, increasing coverage. The overlap between the twin beams should be such that it minimizes inter-cell interference but doesn't impact coverage around the 0-degree azimuth. Usually an overlap of nearly 8 to 10 dB is preferred.

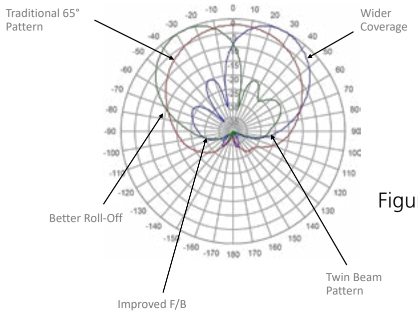


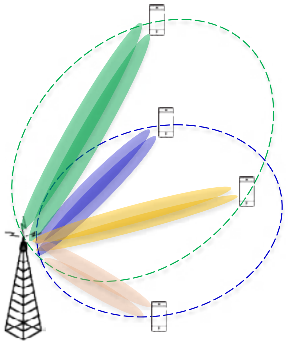
Figure 3: Sample twin-beam pattern comparison

Active antennas for capacity

Carriers are now deploying active antennas and massive MIMO antennas, which employ a far larger number of steerable antenna elements at the base station. Antennas with 192 elements or more are being deployed for current bands like 2.3 GHz TDD, 2.5 GHz TDD, 3.5 GHz TDD; and 256 elements or more for mm Wave bands. They feature externally- or internally-integrated radio units. Some active antennas are also capable of beamforming in both the horizontal and vertical planes—also referred to as "full dimension MIMO."

Active antenna beamforming can be accomplished digitally, or in the analog domain. Digital beamforming is a baseband function that occurs in the frequency domain by applying beamforming weights. This, though, comes at the expense of larger computational complexity and power consumption. Analog beamforming, on the other hand, applies the weights in the time domain at the antenna. The advantage of analog beamforming is reduced bit rate requirements on the fronthaul interface. Hybrid beamforming combines both techniques to create multiple time domain beams within each sub-frame.

Using active antennas can provide very high capacity benefits, particularly in dense urban deployments. Systems operating at higher frequency bands will have an advantage, as the antenna arrays will be much smaller due to smaller wavelengths.



Massive MIMO Antennas:

- Multiple transmission layers
- Dynamically steerable beams
- Beam tracking of users instead of broadcasting

Capacity comparison

In comparing the capacity potential of a 4G site, we will look at five different configurations:

1. Transmit and receive diversity
2. MIMO
3. Beamforming
4. Twin beam
5. Massive MIMO (64T64R)

Specifically, we will consider how these configurations affect capacity when using TDD and FDD. The average values listed in this section are taken from field trials and industry reports published by various sources. They should be considered as ball-park numbers only, as actual values will depend on several variables, including OEM radio features, RF environment and terminals.

TDD

Most operators deploy 4T4R as their default radio configuration for LTE TDD networks (for example, Band 40 and Band 41). Therefore, capacity for this configuration is considered the baseline against which other configurations are to be measured.

In developing capacity estimates, we have made a few assumptions:

- TDD will use 70 percent of radio resources in the downlink.
- Estimates for 4x4 MIMO assume 100 percent penetration of user equipment (UE) with 4Rx.
- The interference rejection combining (IRC) feature at the receiver is enabled.
- The results are based on industry averages for simulations per 3GPP 3D-urban macro (UMa) models.

Table 1 compares the various configurations as measured against the 4x4 MIMO baseline for DL capacity using TDD transmission (UMa). Figure 4 illustrates the normalized site capacity for each configuration.

TDD site configuration	Normalized site capacity DL	% increase over baseline
4T4R using 4x4 MIMO (baseline)	1.0	
8T8R beamforming (planar array)	1.2	20%
4T4R twin-beam using 4x4 MIMO	1.8	80%
Massive MIMO (16T16R)	2.0	100%
Massive MIMO (32T32R)	2.3	130%
Massive MIMO (64T64R)	3.0	200%

Table 1

The values shown in this table are generally representative of the feature-rich antennas currently deployed in the industry. The actual values may change with specific deployment scenarios. The purpose is to understand the broad comparison between the various options.

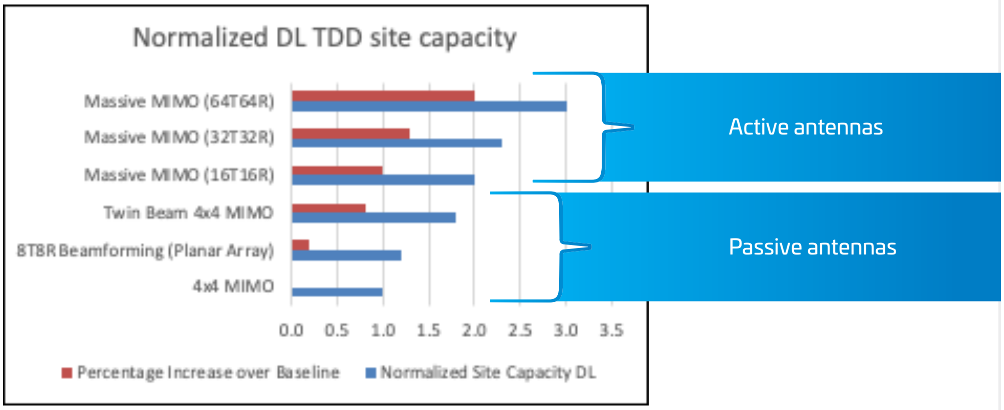


Figure 5:

Based on this evaluation, passive antennas using a multibeam 4x4 MIMO approach will provide the best capacity option. The 8T8R beamforming option works very well when the traffic demand originates more from the cell edge or from inside a building, where RF conditions may not be good. In these hard-to-cover areas, beamforming will improve the network SINR and provide better relief than 4x4 MIMO. Some studies (as well as results in commercial networks) have shown that 8T8R beamforming can improve downlink throughput at the cell edge by 150 percent and boost uplink throughput at the cell edge by 100 percent. This is due to the 8 Rx diversity. Beamforming can also be used as a coverage strategy, as compared to traditional 4T4R radio configuration, to address coverage in areas where site acquisition is difficult.

With active antennas, the incremental benefit from 4T4R to 16T16R vs 4T4R to 32T32R is much higher. As a result, the 16T16R configuration provides more capacity value per TRX (for upgrades) compared to 32T32R. 64T64R provides the best absolute capacity overall but is also the most expensive option. To get the maximum benefit of 64T64R, operators should consider deploying this configuration mostly in heavy-traffic areas—such as high-rise buildings—that require good spatial distribution in the vertical plane.

Operators should consider the following issues before making a decision on active antenna configurations:

1. Capacity forecast for the site
2. Cost benefit analysis of various active antenna configurations, including total cost of ownership
3. Feasibility of having a single active-passive antenna strategy
4. Infrastructure issues of space/weight/power requirements for each option

It is interesting that 16T16R could also be the most feasible configuration for a single active-passive antenna strategy at frequencies below 6 GHz. This is true for both TDD and FDD bands. A larger active-passive configuration, with 32T32R or 64T64R active antenna arrays, may prove difficult to justify, given the increased physical size and tower loading.

For applications requiring a single active antenna—for either 4G or 5G using sub-6 GHz bands—operators may consider two potentially effective strategies. The first involves using two antennas per cell/sector: one passive and one active antenna, typically 64T64R for 3.5 GHz. The second good option involves a single active 16T16R array integrated with passive arrays. An example would be a four-port, low-band passive array and 4/8-port mid-band array to accommodate the remaining popular 4G bands—700-900 MHz and 1700-2700 MHz.

FDD

For FDD systems, the default radio configuration is 2T2R for most operators; hence, 2x2 MIMO is considered a baseline capacity here. Currently, there is a trend in many markets to upgrade to 2T4R or 4T4R for FDD. This is due to several reasons:

- The additional capacity benefit of 4x2 MIMO on the downlink, with 4T delivering around 20 percent capacity increase
- Diversity of 4 Rx in the uplink can provide a 50 percent uplink capacity gain over 2 Rx diversity
- The improved downlink coverage that results from a 2+ dB beamforming gain in TM4

Operators should also consider that the support for massive MIMO in FDD requires R14 terminals in the network. This means capacity benefits with massive MIMO in FDD will improve over time, as the penetration of these mobiles improves.

Table 2 below compares the various configurations against the 4x4 MIMO baseline for DL capacity using FDD transmission (UMa). The following assumptions have been made

- Estimates for 4x4 MIMO assume 100 percent penetration of user equipment (UE) with 4Rx.
- The interference rejection combining (IRC) feature at the receiver is enabled.
- The results are based on industry averages for simulations per 3GPP 3D-urban macro (UMa) models.

Figure 6 illustrates the normalized site capacity for each configuration.

FDD site configuration	Normalized site capacity DL (ball-park)
2T2R using 2x2 MIMO	1.0
4T4R using 4x2 MIMO	1.2
4T4R using 4x4 MIMO	1.7
2T2R twin-beam using 2x2 MIMO	1.8
4T4R twin-beam using 4x2 MIMO	2.2
4T4R twin-beam using 4x4 MIMO	3.1
Massive MIMO (16T16R)	3.4
Massive MIMO (32T32R)	3.9

Table 2

The values shown in this table are generally representative of the feature-rich antennas currently being deployed in the industry. The actual values may change with specific deployment scenarios. The purpose is to understand the broad comparison between the various options.

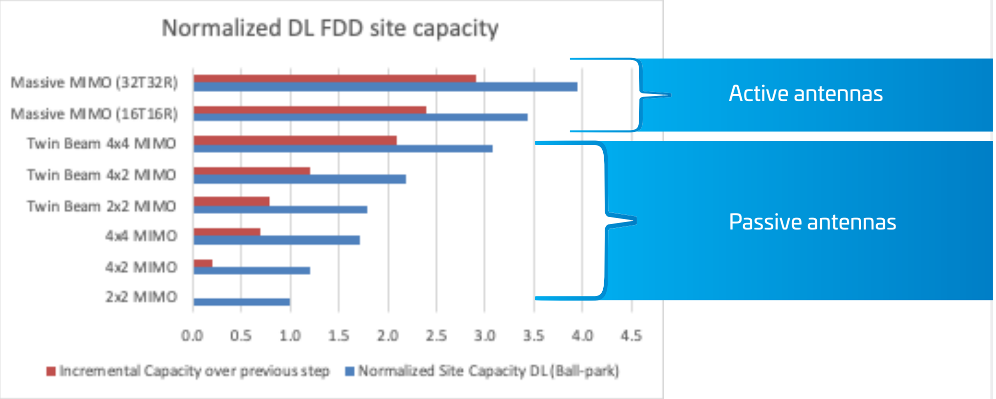


Figure 6: Comparative graph for FDD site capacities

The capacity of 4x4 MIMO depends on penetration mobile devices that are Category 6 or above. Therefore, in markets where penetration of mobiles with four receive chains is limited, a twin-beam 2x2 MIMO antenna configuration can be a very effective capacity option, compared to 4x4 MIMO.

For active antennas, operators appear to be waiting on more eco-system support for terminals before investing. Some operators are looking at using radios that are blind mated to the antenna. This has the benefits of better space management on towers, lower cable/connector losses, and internal diplexing within antennas for two bands.

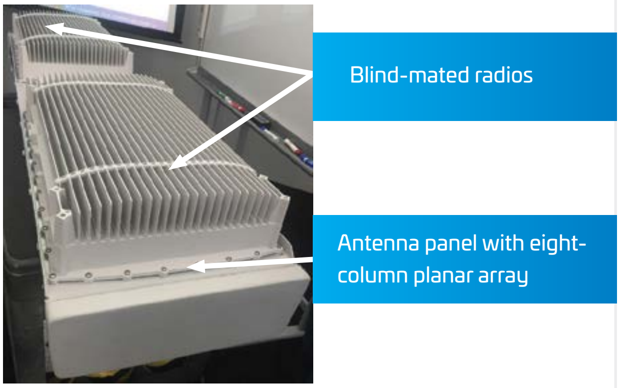


Figure 7:

Applicability to network traffic scenarios

Now that we've evaluated the various antenna configurations for TDD and FDD performance, let's look at how they can be expected to perform in different network traffic scenarios. Figure 8 illustrates the network traffic distribution across sectors/sites during peak hours for a typical network.

Notice that very few cells are highly loaded during peak hour, but there is a large tail of very lightly loaded cells. The graph shows the trend continuing as the network traffic increases over time.

It is prudent to use the capacity solution that best matches the capacity demand forecast for high-, medium- and low-traffic sites. For example, investing in an expensive capacity solution to serve a medium- or low-traffic area would result in a sub-optimal cost benefit analysis.

Very high-capacity solutions, like massive MIMO, are most suitable for very dense traffic areas (typically less than 10 percent of the sites). Other solutions—like 4x4 MIMO, beamforming, and multibeam antennas—can provide more cost-effective and feasible solutions for most of the sites.

As noted earlier, a 4x4 MIMO solution requires good SINR (>17 dB) and high levels of UE penetration to be effective. Typically, SINR conditions are best in areas near the site where the signal dominance of the serving cell is strongest. Hence, MIMO performance improves with better optimization of the networks.

Also noted earlier, beamforming is very effective for improving performance at the cell edge and can increase the cell edge throughput as much as 150 percent. This is important to remember during network planning, as operators look to increase cell coverage. Some OEMs recommend using a beamforming antenna in conjunction with soft splitting an eight-port radio to approximate the performance of a twin-beam 2x2 MIMO configuration. Twin-beam antennas, on the other hand, can be alternatives to massive MIMO in many high-capacity locations. As mentioned earlier, this can provide both better coverage and almost 1.8 times the capacity of the original single cell.

Higher beam solutions—such as five-beam and 18-beam—can be good choices for outdoor venues like stadiums that require localized high capacity to meet the wireless traffic demands of a large crowd in a small area.

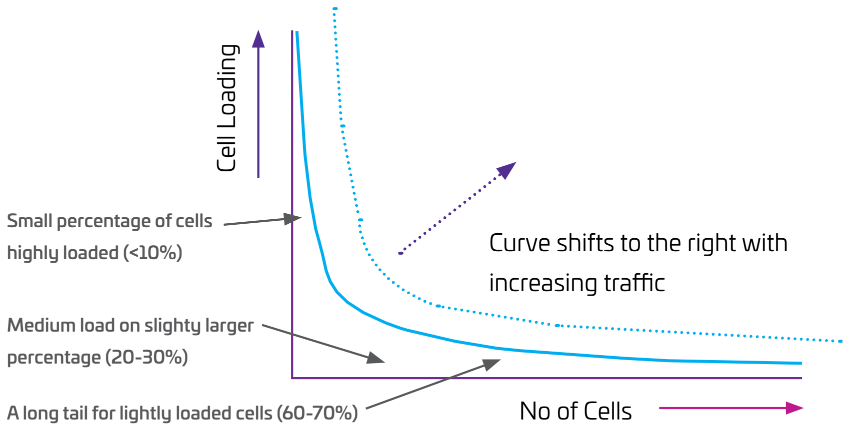


Figure 8:

Bandwidth and devices

Apart from the radio and antenna configurations, capacity benefits depend on two additional critical factors—the amount of bandwidth available in the band of interest and the device penetration in that band. Table 3 includes the popular bands and their bandwidth, as well as technology options and device availability. Operators may hold sub-sets of these bands depending on their license conditions/allocations.

As highlighted in green in Table 3, bands B1, B3 and B7 score high in most categories, while bands B40 and B41 are excellent choices where bandwidth is important. B40 and B41, the two TDD bands, also provide legacy device support for TDD beamforming and massive MIMO. B2 and B4 are popular U.S. bands along the same lines.

Band	Bandwidth (MHz)	Total devices (GSA, Nov 2018)
B7 (2600)	**2 x 70**	**7938**
B41 (2600 TDD)	**194**	3300
B40 (2300 TDD)	**100**	4449
B1 (2100)	**2 x 60**	**7285**
B3 (1800)	**2 x 75**	**8877**
B8 (900)	2 x 35	4216
B5 (850)	2 x 25	4597
B28 (700)	2 x 45	1450
AWS Band 4	2 x 45	3594
B20 (800)	2 x 30	5211
B2 (1900)	2 x 60	3472

Table 3: Some popular frequency bands with their total BW and available devices

It should be noted that 4x4 MIMO is quite prevalent in most TDD networks—the exception being TDD-based fixed wireless access (FWA) networks where 4x4 MIMO may be less effective. However, a 2T4R configuration for FWA can substantially improve uplink throughput and can be used where uplink link budget and capacity are limiting factors.

The traditional practice has been to deploy 2T2R radios in FDD bands. Recently, however, operators have been upgrading to 4T4R radios in many networks. This yields higher-layer MIMO benefits in the downlink, improves coverage with beamforming, and also provides 1x4 Rx diversity benefits in the uplink. Many uplink-limited scenarios can hugely benefit by upgrading to 4T4R/2T4R radios.

For high-capacity applications that involve external diplexing of multiple bands (such as 1800/2100 or 2300/2600), using multibeam antennas that support wide bands from 1700 MHz to 2300 MHz (or 2300 MHz to 2700 MHz) can be very effective. Another specialized capacity solution combines MIMO and multibeam configurations in the same panel, creating a hybrid antenna that can reduce the number of physical antennas at a site and provide a single-antenna capacity solution for all bands.

Costs comparison

Table 4 compares the capacity and cost of each of the above solutions. The cost inputs are based on market research and may vary in different geographies and customers.

As seen in Table 4 and Figure 9, the relationship between the cost to operators and capacity of passive antennas is nearly linear, whereas the same relationship for massive MIMO has cost rising at a much higher rate (the cost of massive MIMO to operators may improve with volumes over time). Massive MIMO solutions also require a significant investment in infrastructure, including tower space, sway resistance and the provisioning of large amounts of power to the tower top. For operators looking to deploy massive MIMO, these added costs and considerations pose major obstacles—particularly when deploying at the sub-6 GHz bands.

For now, the capacity benefits of massive MIMO are still theoretical and are based on simulated results, field trials, and very few commercial deployments. The industry will have to wait to see if hard field numbers from large-scale deployments can back up the promised results.

TDD site configuration	Normalized site capacity DL (≈)	Normalized weighted cost	Power for antenna (W)*
4x4 MIMO	1.0	1.00	NA
8T8R beamforming (planar array)	1.2	1.19	NA
Twin-beam 4x4 MIMO	1.8	2.02	NA
Massive MIMO (16T16R)	2.0	3.21	500
Massive MIMO (64T64R)	3.0	8.56	800

Table 4

**Power for passive antennas is not applicable, but power feed will be required for external radio units with power consumption of approximately 400 watts per 4T4R radio*

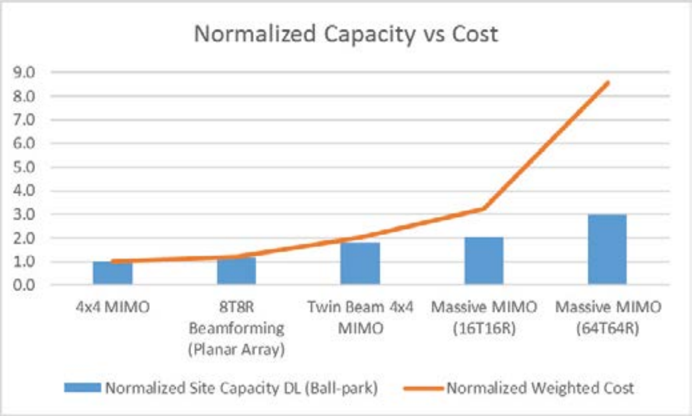


Figure 9:

Benefits and challenges

Capacity solution	Benefits	Challenges
2x2 MIMO	Baseline scenario	
4x4 MIMO	1. Easy to implement 2. Requires very good SINR to be effective 3. Uplink Rx diversity improves uplink coverage/capacity 4. Typical configuration for TDD due to UE support	1. UE penetration in FDD, limits capacity 2. Capacity benefits depend on geographical traffic distribution (i.e., traffic originating only from good RF locations will benefit)
8T8R beamforming (planar array)	1. Improves cell edge performance 2. Improves SINR at bad RF locations 3. Works with legacy UEs 4. Improved uplink Rx diversity helps with uplink coverage/capacity 5. Can be used as coverage solution, reducing number of sites for greenfield applications	1. Eight-port radio required 2. Capacity benefits depend on geographical traffic distribution (i.e., traffic originating from bad RF locations will improve) 3. May require RF optimization of the cluster for optimum results
Twin-beam 2x2 MIMO	1. Excellent capacity for FDD (typically deployed with 2x2 MIMO radios) 2. No new site costs	1. Additional radio required 2. May require RF optimization of the cluster for optimum results
Twin-beam 4x4 MIMO	1. Excellent capacity for TDD (typically deployed with 4x4 MIMO radios) 2. Uplink Rx diversity improves uplink coverage and capacity 3. No new site cost	1. Additional radio required 2. May require RF optimization of the area for optimum results 3. UE penetration in FDD may limit capacity 4. Tower loading
Massive MIMO (16T16R)	1. Better beamforming in horizontal plane than 8T8R 2. Better incremental capacity gains versus 32T32R, so could be preferred active-antenna configuration where 64T64R is not feasible or cost competitive 3. Can be combined with passive arrays for a hybrid active-passive antenna which can save space and cost	1. Capacity benefits in vertical plane are limited 2. Could be costly from $/bit perspective as compared to traditional passive solutions 3. Requires power to the antenna at tower top 4. Infrastructure issues (sub 6 GHz)
Massive MIMO (64T64R)	1. Maximum capacity benefit potential 2. Improved coverage 3. Works with legacy UEs 4. Suitable for dense urban areas with very high capacity demand	1. Infrastructure issues—space/power/weight (Sub 6 GHz) 2. Seen as very costly, impacting ROI

Summary

As data traffic increases and operating margins continue to grow razor thin, operators must look for new ways to add network capacity while at the same time decreasing their costs. Each site is unique in terms of its RF environment, indoor/outdoor traffic patterns, coverage needs and the spectrum assets they've deployed. The best-fit radio and antenna solution considers all these factors in addition to the additional capacity required and the cost of achieving it.

In this paper, we have considered several antenna-based solutions that can provide network operators the necessary added capacity without having to acquire more spectrum or invest in building new sites. Massive MIMO appears to have strong potential to help to meet the capacity challenge in some cases. At the same time, the use of beamforming, multibeam and active antennas can provide immediate and effective solutions with a good cost/benefit analysis in several network scenarios, whether LTE or 5G.

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