STRATEGY ANALYTICS
Research, Experts, and Analytics

Networks & Service Platforms

4x4 MIMO Boosts 4G and Gives Consumers a Taste of the Gigabit Experience

Networks & Service Platforms (NSP)

MIMO is an essential feature to improve spectral efficiency. Recentfield test results in live commercial networks have proven that 4x4 MIMO can effectively improve network performance and user experience. With 4Rx becoming a mainstream configuration of flagship smartphones in 2H 2017, 4x4 MIMO will gain momentum in global market to help operators meet growing data demands and prepare for 5G.

Service Providers

November 2017

Guang Yang and Christopher Taylor
Tel: +44 1908 423662
Email: gyang@strategyanalytics.com

Contents

Exhibits

1. Executive Summary

Global mobile date use continues to grow rapidly as smartphones and mobile video increasingly dominate the traffic landscape. Today 4G dominates as the bearer of global cellular data traffic, but 5G will emerge starting in 2019. Even as 5G reaches the market, 4G/4.5G will still carry more than 93 percent of global cellular data traffic in 2022. Meanwhile, the performance of 4G networks will be important for the success of 5G rollout, because 5G coverage will be limited in its early phase. A nationwide, high performance 4G network must not only meet the growing traffic demand, but also should provide a solid foundation for 5G deployment.

Wireless communication theory indicates multiple dimensions to improve cellular network performance. Carrier aggregation (CA) is used to extend system bandwidth through combining multiple component carriers (CCs). But spectrum availability limits the performance potential of carrier aggregation in live deployments. Network densification is another efficient way to improve network capacity and coverage. But the most effective way to reduce total cost of ownership (TCO) is to decrease the number of sites.

MIMO is an essential feature to improve spectral efficiency in 4G. MIMO features first defined in LTE Release 8 can be found in today's commercial LTE networks. Transmission Mode 9 (TM9) in LTE Release 10 has been implemented by major infrastructure vendors. Devices with four antennas and receiver chains are emerging in global market. These enable operators to deploy 4x4 downlink MIMO, and even massive MIMO with additional base station transmit antennas, in their networks.

Field test results in live commercial networks have proven that 4T4R in the base station can effectively improve network performance and user experience; 4x4 MIMO can improve user throughput by 40 - 75 percent according to tests by MTN South Africa. Similarly, True Corp's results show great improvement in cell throughput with today's commercial two-antenna receiver devices. Currently all major infrastructure vendors offer 4T4R features in their 4G base station products. And, the number of 4Rx devices is growing quickly. Therefore, we expect to see 4Rx becoming the mainstream configuration of flagship smartphones in 2H 2017.

Massive MIMO can further improve network capacity to meet high traffic demand, particularly in hot-spot scenarios. The experience of deploying and operating massive MIMO in live networks can help vendors and operators to prepare for the rollout of 5G networks, where massive MIMO will be an iconic technology. Transmission Mode 9 will be required to fully exploit massive MIMO's performance benefits.

With the growth of traffic demand and availability of user devices and base station equipment equipped for MIMO, it's time for operators to roll out advanced MIMO features:

- Deploy 4T4R on a large scale to improve capacity and coverage across the network.
- Introduce 4Rx devices regardless of whether network the network has been upgraded to 4T4R.
- Deploy massive MIMO in hot-spots to meet high traffic demand and gather experience for 5G.

2. Growing Market Demand Requires 4G Network Evolution

2.1 Data Use Continues to Grow Rapidly

Global cellular data traffic has grown rapidly, and growth will continue over the next five to ten years. The Wireless Operator Strategies service of Strategy Analytics predicts that global cellular data traffic will grow from 66 exabytes in 2016 to 323 exabytes in 2022 (see Exhibit 1), as smartphones and mobile video increasingly dominate the traffic landscape:

- Active data subscriptions on user-linked[1] cellular devices will increase from 4.1 billion in 2016 to 6.0 billion in 2022.
- Smartphones will increase from 2.9 billion active (non-SMS) data connections in 2016 to 5.1 billion in 2022.
- Smartphones accounted for 81 percent of all traffic in 2016 and will grow to 92 percent of all traffic in 2022.
- Average use per active smartphone connection will increase from 1.6 GB/month in 2016, to 5.0 GB/month in 2022.

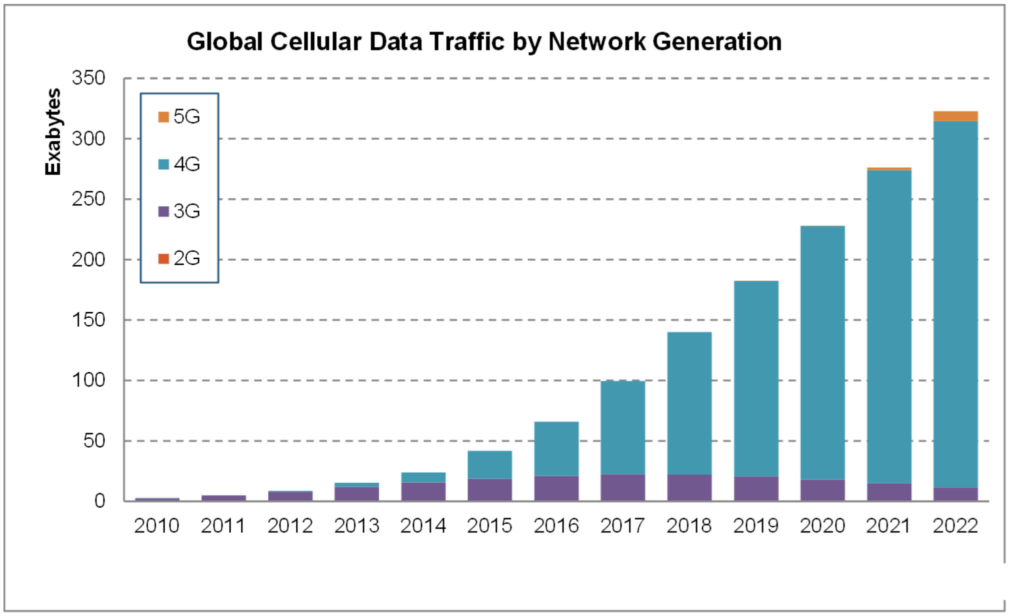
Video already accounts for a significant share of traffic on mobile network operators' networks, and this will increase:

- According to Strategy Analytics' forecast, video will account for close to 60 percent of all mobile data traffic in 2021, up from 48 percent in 2016.
- In advanced markets such as North America or West Europe, the percentage will be over or approaching 70 percent by 2021

Growth in live video streaming, 4K UHD and 360 video will place further demands on the mobile network from a latency and throughput perspective.

[1] User-linked cellular devices consist of phones, PC & modems, tablets, and user-managed connected devices such as e-book readers, portable games consoles & media players, digital cameras, navigation devices, consumer wearables, and connected cars.

Exhibit 1: Global Cellular Data Traffic Growth



Source: Strategy Analytics

As shown in Exhibit 1, 4G is the dominant bearer of global cellular data traffic today; 4G networks accounted for over two-thirds of cellular data traffic in 2016. Active 4G data connections will overtake 3G in 2017 and will account for 80 percent of the global total in 2022. Even though 5G will emerge in the market in 2019, 4G/4.5G will still carry more than 93 percent of global cellular data traffic through 2022.

2.2 Enhanced 4G as a Foundation for Future 5G Deployment

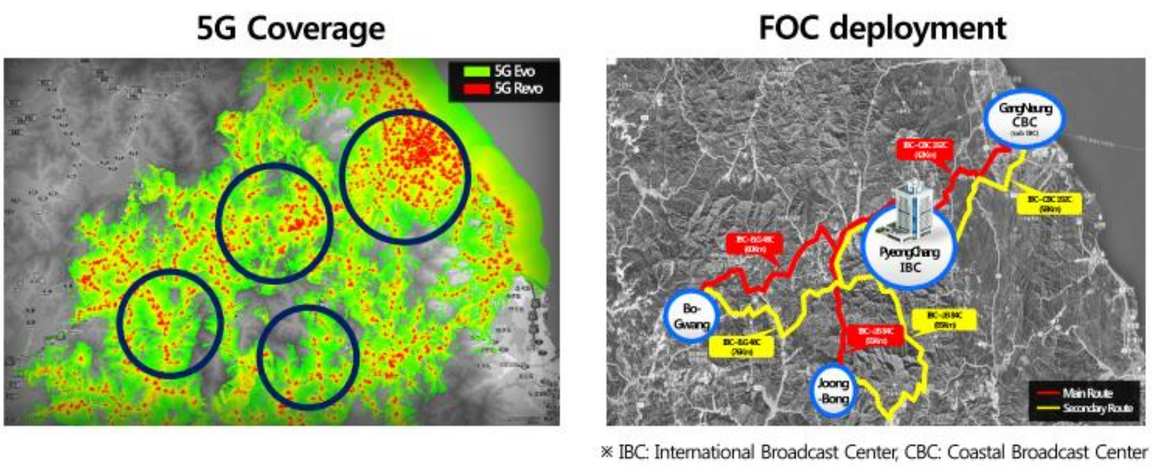
5G networks will be deployed in diverse frequency bands, ranging from sub-1 GHz bands to millimetre wave (mm-Wave) bands. Even though T-Mobile US has announced a plan to use 600 MHz and 700 MHz spectrum for 5G, LTE high / very high band and millimetre wave spectrum – such as 3.5 GHz and 28 GHz – will be major frequency bands for initial 5G deployments to support a significant enhanced mobile broadband experience. US operators Verizon and AT&T are targeting the deployment of 5G at 28 GHz and 39 GHz. South Korean 5G networks will use 28 GHz as well. 5G networks in China and Japan will likely deploy 5G in the C-Band, 3300 – 4200 MHz and 4400 – 4990 MHz.

5G using mm-Wave spectrum will provide a 10 Gbps peak downlink data rate. In the C-Band, the average throughput of a 5G system is also much higher than today's 4G networks.

However, the higher frequency, mm-Wave bands suffer from poor propagation characteristics, which restrict system coverage. The exhibit below shows the coverage plan for a 5G pilot service at the PyeongChang Olympics in South Korea. The red dots in Exhibit 2 indicate the planned coverage of a 5G pilot system using 28 GHz, referred to as

"***5G Revolution.***" We can see that the coverage is quite limited due to atmospheric absorption and regulatory power limits. To provide seamless coverage for the Olympics, a "***5G Evolution***" system (green part) that is actually an enhanced LTE system will be used. This is the expected Korean operators' 5G overlay deployment approach for both the Olympics and beyond.

Exhibit 2: 5G Coverage for PyeongChang Olympics



Source: KT

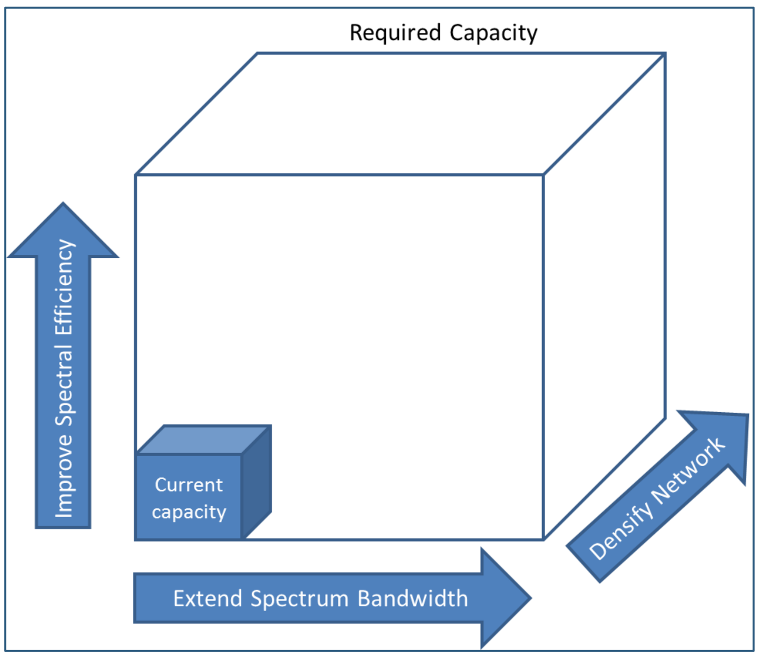
Even if an operator deploys a 5G system in the C-Band, the operator probably cannot provide nationwide coverage in the short term. Customers' seamless mobile broadband experience will still rely on the underlaying 4G network. If the data rate in the 4G network is not high enough, customers will see a large drop in performance when they move out of 5G coverage. Therefore, the performance of the underlay 4G network will be important for the success of early 5G deployment. A nationwide high performance 4G network must not only meet fast growing traffic demands, but also it must become a solid foundation for 5G deployment. Later, after successfully deploying 5G, an operator can take 4G spectrum and begin migrating users of this to sub-6 GHz 5G using new mobile devices.

3. The Importance of MIMO for Improving Network Performance

3.1 Ways of Improving Mobile Network Performance

According to the analysis in Section 2, the industry needs to continuously improve the performance of 4G networks to meet growing traffic demand and to build the foundation for future 5G rollout. Wireless communication theory indicates that there are multiple dimensions to improving cellular network performance as illustrated in Exhibit 3.

Exhibit 3: Dimensions of Improving Cellular Network Performance



Source: NTT DoCoMo, Strategy Analytics

3.1.1 Bandwidth

Wider system bandwidth can improve user data rates and increase cell capacity. In LTE-Advanced systems, carrier aggregation (CA) is used to extend system bandwidth by combining multiple component carriers (CCs). In LTE Release 10, CA enables combining of up to five LTE Release 8 compatible carriers, each with up to 20 MHz of channel bandwidth, for a total aggregate bandwidth of as much as 100 MHz for any user. Under Release 13, the 3GPP has enhanced carrier aggregation to enable up to 32 component carriers including carriers within unlicensed spectrum.

According to the GSA, 195 LTE-Advanced networks had been launched worldwide as of March 2017. Carrier aggregation is the main feature of these networks. However, spectrum availability has limited the performance potential of carrier aggregation in most live deployments. In particular, fragmented spectrum allocation is a key factor both encouraging operator adoption of carrier aggregation and limiting its usefulness:

- An operator wants to have at least 100 MHz of available LTE downlink spectrum spread across no more than five LTE bands, ideally. This amount of spectrum supports a peak downlink data rate of up to 450 Mbps (64 QAM with no MIMO), along with improvements in capacity at lower data rates.
- According to a Strategy Analytics' study, only 34 percent of LTE operators owned more than one contiguous 20 MHz block of downlink spectrum at the end of 2017, and almost half of LTE operators had 40 MHz or less for LTE downlink.
- The GSA has indicated that more than 80 percent of commercial CA deployments were operated in aggregate bandwidth of less than 50 MHz as of the end March 2017. Therefore, operators have to seek other ways to further improve network performance.

3.1.2 Densification

Network densification is an efficient way to improve network capacity and coverage. With growing traffic demand, cellular networks have to be deployed in higher frequency bands, which will require smaller cells and denser networks as well, thanks to propagation characteristics at higher frequencies. However, the CAPEX and OPEX related to cell sites are always a large part of the overall total cost of ownership (TCO) of a cellular network. According to China Mobile, the cost of major wireless equipment makes up only 35 percent of radio access network CAPEX. In the OPEX part of costs, cell site rental fees and electricity together account for more than 70 percent of total expenditures. The cost of site acquisition, civil works, and equipment installation is more than 50 percent of the total cost. China Mobile concluded that '*the most effective way to reduce TCO is to decrease the number of sites.*' Therefore, operators need to carefully adjust the tradeoff between performance gain and the cost of denser network construction. This is one of the main challenges of higher frequencies such as mm-wave for 5G.

3.1.3 Spectral Efficiency

Improving spectrum efficiency becomes the most efficient method of improving network performance given typical bandwidth limitations and site density limitations. Multiple Input Multiple Output (MIMO) techniques have been essential to improving spectral efficiency in the 4G era, and this can be extended to 5G as well.

A MIMO system means multiple transmit antennas are equipped at the transmitter and receiver end of a radio linkthese can be denoted by m and n, respectively. Depending on the channel state information (CSI), several data stream can be transmitted from the transmit antenna array. The maximum number of streams, denoted by M, is limited by the smaller of the number of antennas at the transmitter or the receiver. The channel capacity of a MIMO system can be improved M times compared to a Single Input Single Output (SISO) system – single antennas at transmitter and receiver, as shown in the exhibit below.

Exhibit 4: Channel Capacity of MIMO vs. SISO

MIMO	vs.	SISO
$C = M B \log_2 \left(1 + \frac{S}{N}\right)$		$C = B \log_2 \left(1 + \frac{S}{N}\right)$
Shannon-Hartley theorem for MIMO		Shannon-Hartley theorem for SISO

Source: Strategy Analytics

If a single multi-antenna transmitter communicates with a single multi-antenna receiver, it's called Single User (SU) MIMO. If a multi-antenna transmitter can communicate with multiple receivers at the same time, this is called Multi User (MU) MIMO. With MU-MIMO, multiple devices on the same base station are coordinated to simultaneously share spectrum "spatially" via unique antenna beamforming. All the devices provide their channel state information to their associated base station to facilitate coordination of the shared spectrum. This greatly improves multipoint access capacity and spectral efficiency and reduces latency. MU-MIMO can further improve the spectral efficiency when the number of transmit antennas greatly exceeds the number of receiver antennas.

3.2 MIMO Evolution in the LTE Standards

MIMO technology was introduced to the first LTE version, Release 8, and has been enhanced continuously in Release 9 to Release 14. The 3GPP designates the type and complexity of MIMO by using the term "Transmission Mode." The different transmission modes differ in terms of:

- Number of layers (streams, or rank).
- Antennas (or independent antenna ports) used.
- Type of reference signal, Cell-specific Reference Signal (CRS) or Demodulation Reference Signal (DM-RS).
- Precoding type.
- And corresponding signalling.

In Release 8, the 3GPP specified 2x2 MIMO in the downlink, four-antenna downlink transmission (4x2 MIMO), and 4 or 8 antenna uplink reception. There are various scenarios that LTE Basestation and user equipment communicate through multiple antennas. Each scenario is defined as a Transmission Mode (TM). In the downlink, seven transmission modes (TM1 to TM7) were defined in Release 8, each specifying different versions of MIMO based on number of antennas and streams. Later 3GPP releases introduced additional transmission modes:

- Release 9 introduced TM8, and Release 10 introduced TM9; Release 10 was frozen in June 2011.

- In the uplink (UL), the 3GPP defined TM1 and TM2, where TM1, the default, was introduced in Release 8 and TM2 was introduced in Release 10.

- TM9 supports 8x8 MIMO in the DL, and TM2 UL 4x4 MIMO UL.

Exhibit 5 summarizes the DL MIMO transmission modes in Release 8 to Release 11. TM9 and TM10 are continually enhanced in later releases. In Release 12, a new 4-transmit antenna downlink codebook was defined to improve performance further. The channel state information reporting mechanism was also enhanced to make channel state information more accurate. Accurate channel state information can improve the MIMO performance particularly in LTE FDD systems.

As indicated by Exhibit 4, increasing the number of transceivers is the key to unlocking higher spectral efficiency. So in Release 13, up to 16 transceivers at the base station are allowed. The larger antenna arrays in base stations can support three-dimensional (3D) beamforming, which is also called full dimensional MIMO (FD-MIMO), a.k.a. massive MIMO. To support MU-MIMO, channel state information reference signals (CSI-RS) were defined, and the CSI reporting mechanism and demodulation reference signal structure were also enhanced.

In Release 14, the maximum number of antenna ports at the base station will be increased to 32. The reporting efficiency and accuracy of channel state information will be further enhanced to enable more efficient MU spatial multiplexing and improve performance in high speed mobility.

Exhibit 5: LTE Downlink MIMO Transmission Modes

LTE Release	TM	Description	Comments
8	1	Single antenna port aka SIMO	Applicable to cells configured w/ one CRS port, fairly uncommon across deployments
8	2	Transmit diversity	Used for DL control
8	3	Open loop spatial multiplexing	Large delay CDD
8	4	Closed loop spatial multiplexing	Closed loop pre-coding
8	5	Multi-User MIMO	Not used in practice
8	6	Closed loop rank 1 precoding	Not seen in practical deployments
8	7	Single stream beamforming	Mainly driven by 8Tx TD-LTE deployments to support reciprocity based beamforming
9	8	Dual stream beamforming	Extension of TM7 to two spatial streams
10	9	UE-RS based SU/MU-MIMO	Provisions for DEMOD & CSF w/ increased number of Tx antennas, up to 8 layers, introduction of dedicated RS for feedback (CSI-RS)
11	10	TM9 enhancements to support inter-cell coordination (CoMP)	Concepts of interference measurement set and CSI processes, notions of RS co-location to handle timing / frequency and long term channel parameters

Source: Qualcomm

MIMO features in LTE Release 8 can be found in today's commercial LTE networks. Mobile and portable devices with four antenna receivers are emerging in the global market, for example the Netgear Nighthawk M1 mobile LTE router, the China-US version of the Samsung Galaxy S8, and the Huawei P10 Plus. These user devices take advantage of operator deployments of 4x4 DL MIMO in their networks, allowing users to experience peak downlink rates up to 1 Gbps. Meanwhile, TM9 in LTE Release 10 has been implemented by major infrastructure vendors. Leading operators have started testing massive MIMO technology. In the next section, we will review the test results in recent deployments.

4. Live Deployments: Examples of Advanced MIMO

4.1 Four Antenna Transceiver (4T4R) in Base Stations Boosts Network Performance Significantly

Operators have already deployed more than 80 4T4R networks across the globe, according to announcements by vendors and operators. Test results from these networks show significant performance gains compared to legacy 2T2R per sector systems.

China Telecom trialed 4x4 DL MIMO in its commercial LTE FDD network in early 2017. The trial was done in Shenzhen, China. The LTE FDD network used the 1800 MHz band with 2x15 MHz system bandwidth. Transmission Mode 4 (TM4) was used in the test. China Telecom compared the performance of 2x2, 4x2 and 4x4 DL MIMO in terms of throughput in stationary and driving scenarios, as well as cell coverage.

The stationary test was done in near, medium and far points. In near point conditions, theoretic peak data rates were achieved as shown in the exhibit below. 4x4 MIMO can provide about 94 percent throughput gain compared to 2x2 MIMO. But the gain of 4x2 MIMO is negative in the near point due to higher pilot overhead in 4x2 MIMO than 2x2 MIMO.

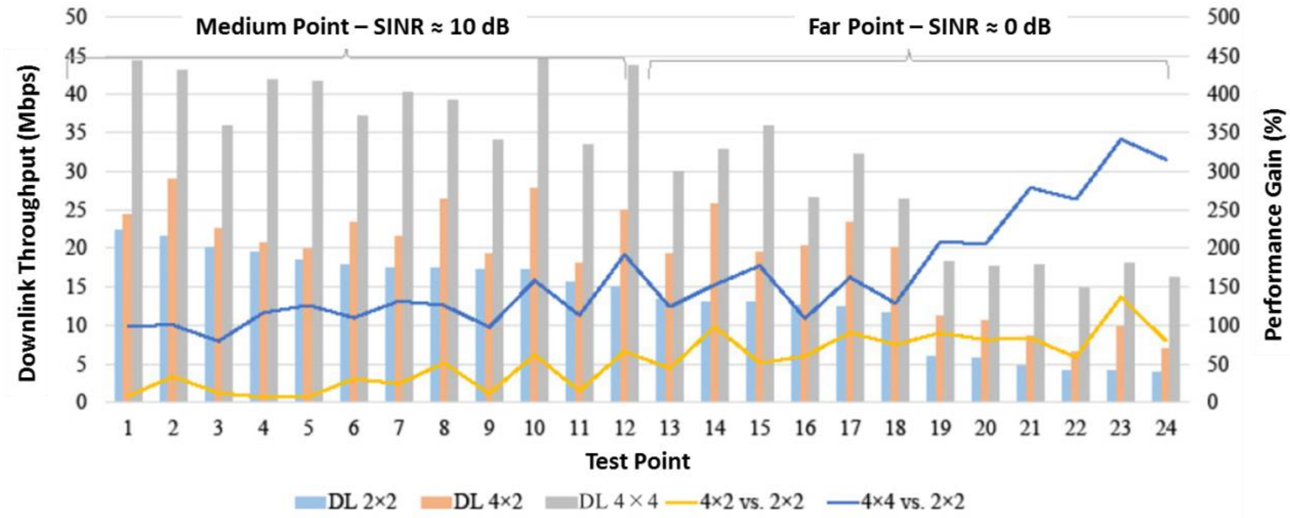
Exhibit 6: Near Point Throughput Results in China Telecom Tests

Test scenario	Near Point with Ideal Channel Conditions		
Average Throughput (Mbps)	2x2 MIMO	4x2 MIMO	4x4 MIMO
	107.7	104.6	208.8
Throughput Gain vs. 2x2 MIMO	-	-2.9%	93.9%

Source: China Telecom, May 2017

In medium point conditions, 4x4 MIMO and 4x2 MIMO can provide 100-150 percent and 10-50 percent throughput gain, respectively, compared with 2x2 MIMO. In far point conditions, the gain of 4x4 MIMO and 4x2 MIMO are 150-350 percent and 100-150 percent respectively. The exhibit below illustrates the test results in medium and far points.

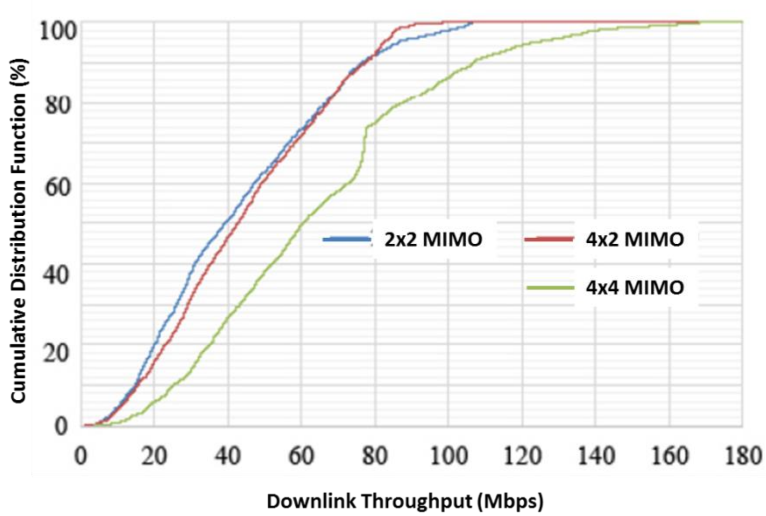
Exhibit 7: Medium Point and Far Point Throughput Results in China Telecom Tests



Source: China Telecom, May 2017

In general, 4x4 MIMO can provide significant throughput gain compared to 2x2 MIMO – particularly in the far point scenario, which has the worst channel conditions. In drive tests, significant performance gains were observed also. The exhibit below shows the Cumulative Distribution Function (CDF) curve for downlink throughput in the drive tests.

Exhibit 8: CDF of Downlink Throughput in Drive Tests of China Telecom



Source: China Telecom, May 2017

The data rates of 2x2, 4x2 and 4x4 MIMO at 50 percent CDF are summarized in the exhibit below.

Exhibit 9: Downlink Throughput at 50 Percent CDF in Drive Tests

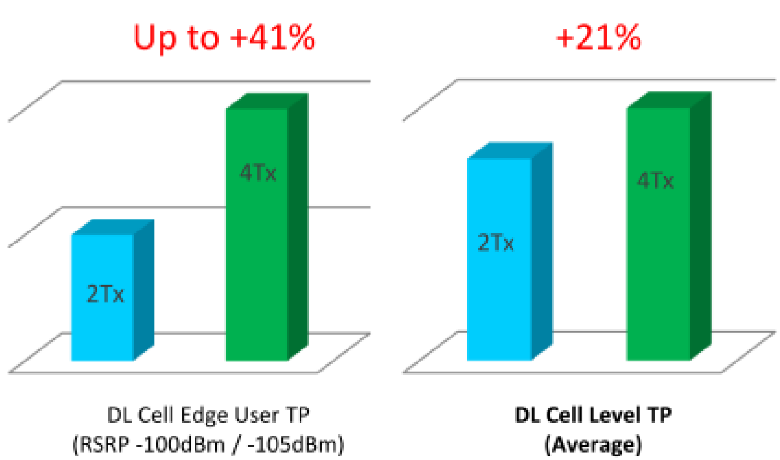
Test scenario	Drive Test		
Throughput at CDF=50% (Mbps)	2x2 MIMO	4x2 MIMO	4x4 MIMO
	39.0	42.5	60.1
Throughput Gain to 2x2 MIMO	-	9%	54%

Source: China Telecom, May 2017

Both stationary tests and drive tests indicate significant throughput gain from 4x4 MIMO. But in today's markets, the majority of devices are still equipped with two antenna receivers (2-Rx). Therefore, the performance gain of 4x2 MIMO is the most important for operators; China Telecom's tests indicate that 4x2 DL MIMO can also provide modest performance gains, particularly in cell edge areas.

Commercial deployments have also proven the performance gains of 4x2 DL MIMO. A South East Asian operator deployed 4T4R base stations in its commercial LTE network in 2016. A clear performance gain was observed in the commercial network (see the exhibit below).

Exhibit 10: True Corp Downlink Performance with Commercial Devices – 4x2 DL MIMO vs. 2x2 DL MIMO

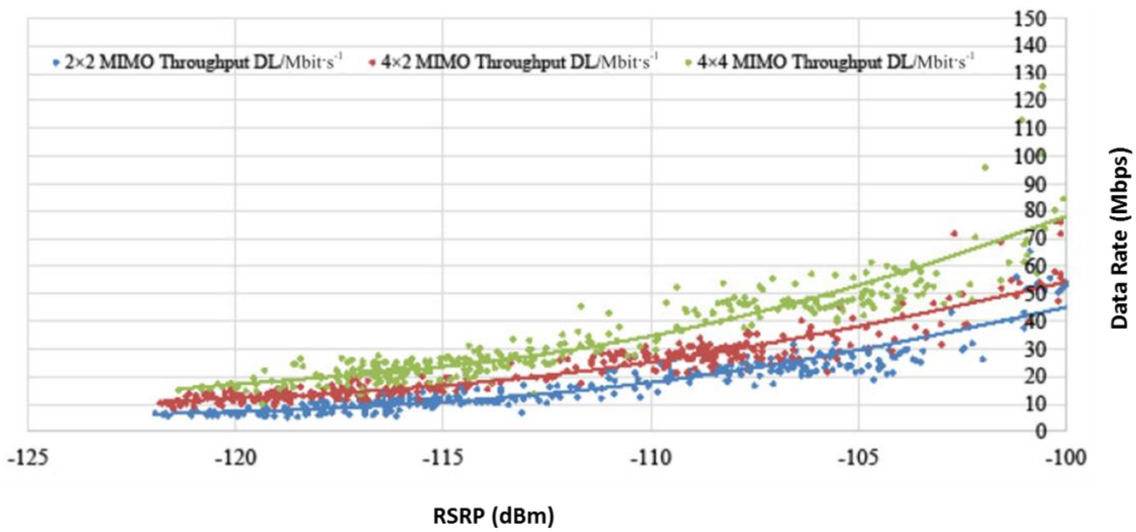


Source: True Corp

4.2 Four Antenna Transceiver (4T4R) Also Extends Cell Coverage

4T4R in the base station not only boosts downlink throughput, but it also improves cell coverage. China Telecom's 4x4 MIMO indicates significant coverage extension thanks to 4Tx transmission in the base station. The exhibit below illustrates the result of single cell coverage tests by China Telecom.

Exhibit 11: Single Cell Coverage Test



Source: China Telecom, May 2017

In the single cell coverage tests, significant throughput gains at the cell edge were observed (see the exhibit below). The cell edge throughput gain can be translated to link budget gain. If 10 Mbps is set as the target data rate at the cell edge, 4x2 DL MIMO can provide 7 dB of link budget gain compared to 2x2 MIMO. 4x4 MIMO's gain is even higher.

Exhibit 12: Cell Edge Throughput Gain

Test scenario	Cell Edge Throughput at -120 dBm RSRP		
Average Throughput (Mbps)	2x2 MIMO	4x2 MIMO	4x4 MIMO
	7	12	18
Throughput Gain to 2x2 MIMO	-	71%	157%

Source: China Telecom, May 2017

4T4R in the base station also brings higher receiver diversity gain in the uplink. Compared with legacy 2T2R base stations, 4T4R will generate around 3 dB of diversity gain according to wireless communication theory. Tests in Turkcell's commercial network prove this gain.

In April 2016, Turkcell launched 4.5G (LTE-Advanced) service in 81 city centers in Turkey. An uplink coverage test for LTE VoLTE and GSM voice was done by Huawei and Turkcell jointly, where LTE was deployed in the 1800 MHz band and GSM in the 900 MHz band. When VoLTE's MOS[2] (Mean Opinion Score) reaches 3, the inflexion path loss in an LTE network with a four antenna receiver is up to 149 dB. That is aligned with 148 dB in a GSM network when MOS reaches 2.5 there. This means that with 4Rx in the base station, LTE in the 1800 MHz band can reuse GSM900's cell sites to provide seamless VoLTE coverage, even though propagation and range characteristics differ for the two bands. This indicates that 4T4R can help accelerate LTE rollout and lower deployment costs.

The UL performance gain brought by 4T4R base station also reminds us that MIMO – as a multi-antenna technology – not only provides the benefits of spatial multiplexing and beamforming, but also brings Rx diversity gains that increase with the number of receive antennas. Higher order Rx diversity can not only be deployed in base stations but also be applied to user equipment to improve downlink performance.

4.3 Massive MIMO will Further Improve Network Performance

The above sections show the significant performance gains provided by 4x4 MIMO. LTE operators and vendors are advancing to massive MIMO to seek the higher performance gains available with more antennas.

Unlike FDD – that uses different frequencies for the UL and DL – TDD massive MIMO benefits from channel reciprocity (same DL/UL channel). TDD operators are actively leveraging massive MIMO to improve network performance:

- Softbank launched massive MIMO with 128 antenna elements in its TD-LTE network in November 2016. Massive MIMO will also be a key part of Softbank's 5G project. The operator looks to deploy a few thousand massive MIMO sites across Japan in 2017.

- Sprint in the US has deployed 8T8R base stations in its TD-LTE network. The operator has achieved gigabit per second data rates in its TD-LTE network using 8T8R, CA and high order modulation. For more details see the Strategy Analytics' analysis *Sprint's Gigabit LTE: What it Means for Sprint, China, and 5G*.

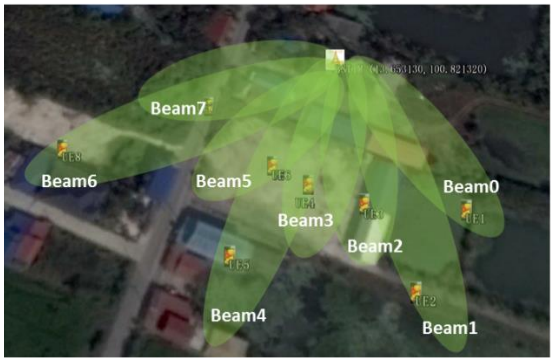
In LTE FDD systems, Transmission Mode 9 (TM9)-capable devices will be required to fully exploit the benefit of massive MIMO. TM9-capable devices can feed back more accurate CSI information to the base station, which helps the base station to form user dedicated beams. With these dedicated beams the signal strength is enhanced and the interference among simultaneously active users is reduced. This can improve the data rate to single devices and enable more efficient multiplexing of spectrum resource in a cell. Therefore, massive MIMO in base stations and TM9-capable user equipment together can provide significant capacity gains to LTE networks.

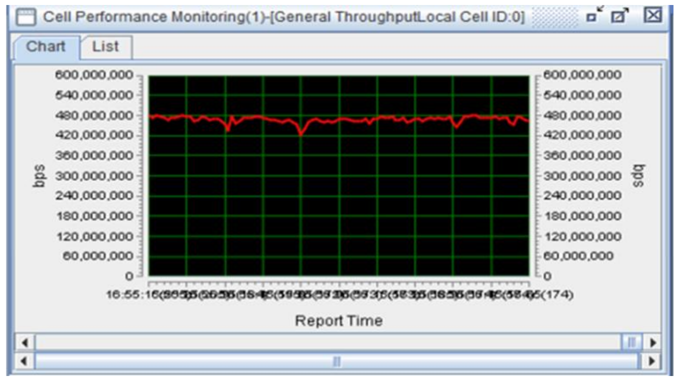
In January 2017, Huawei collaborated with a South East Asian operator for tests of 32T32R massive MIMO in a LTE FDD system. The network used the 1800 MHz band with 15 MHz of channel bandwidth. Eight TM9-capable commercial smart phones were used in the tests. The tests assessed MU-MIMO and 3D beam forming using 32T32R Massive MIMO with different types of data applications during high traffic conditions.

[2] Mean Opinion Score (MOS) is a standard numeric value used to measure and report on voice quality. MOS scores range from 1 for unacceptable to 5 for excellent.

Test phones were uniformly placed in the test sector to determine the best place for MU-MIMO with beamforming. During the tests, the average data rates that eight phones experienced ranged between 50 Mbps and 63 Mbps, and the overall cell throughput reached 460 Mbps to 480 Mbps. That is five to eight times that of current 4G technology with the same bandwidth.

Exhibit 13: Test Scenario and Results – 32T32R Massive MIMO





Source: Huawei

It can be seen in the results that the multi-user scheduling algorithm is a key factor that affects Massive MIMO performance. For multi-user beamforming, a base station needs to choose a set of user devices from a large pool of candidates to serve simultaneously. A good scheduling algorithm can take advantage of spatial multiplexing and manage co-channel interference.

Meanwhile, the software algorithm should be tightly integrated with Active Antenna System (AAS) hardware. In an active antenna system, the active components such as power amplifiers (PAs) and low noise amplifier (LNAs) are attached to each antenna element. AAS can dynamically control the gain and phase of each antenna element to manage the radio waves in both the vertical (elevation) and horizontal (azimuth) directions. This is a hardware enabler for 3D beamforming.

The performance of massive MIMO system significantly depends on vendor's R&D capability for AAS hardware and scheduling algorithm as well as the integration of the hardware and the software. As described in Section 3, Release 13 and 14 standardized enhanced features to further improve the performance of massive MIMO systems.

Based on the early results with 4G, massive MIMO will be an iconic technology of future 5G systems. Introducing massive MIMO into current 4G networks will help operators to narrow the performance gap between 4G and 5G, while giving them experience deploying and operating massive MIMO in live networks. All this will build a solid foundation for the roll out of 5G. At the same time, 4G networks with advanced MIMO will give consumers their first experience with higher data rates, (typically well above 50 Mbps DL, and higher capacity networks for less congestion during peak load times.

5. The Ecosystem Is Ready for Advanced MIMO Deployment

5.1 Infrastructure Development

4x4 DL MIMO is gaining momentum in global markets. According to the GSA, there were already more than 80 4x4 MIMO trials and commercial networks underway as of October 2017. Huawei announced they had provisioned 50 commercial 4x4 MIMO networks as of the end of May, 2017. Huawei predicts that the number of 4x4 MIMO-capable commercial LTE FDD networks will exceed 100 at the end of 2017.

Developed 4G markets lead in commercial deployment of 4x4 MIMO. For example:

- **Verizon** in the US started deploying 4x4 MIMO in 2015. This has pushed its US competitors to roll out 4x4 MIMO as well. Verizon announced, in August 2017, that it would roll out gigabit LTE with four-component carrier aggregation (4x DL CA) and DL 4x4 MIMO, claiming this would provide the fastest LTE service in the US. In a demonstration in Boca Raton, Verizon used LTE-LAA for one of the four carriers.

- **AT&T** announced it would launch '5G Evolution' in more than 20 metropolitan regions in the US by the end of 2017; this is actually a gigabit LTE system that uses carrier aggregation, 4x4 MIMO and 256-QAM in the downlink. As part of "5G Evolution," AT&T said it would deploy LAA at some small cell sites by the end of the year.

- **T-Mobile** is also moving quickly. It launched 4x4 MIMO in 319 US cities in September 2016, and offered its first gigabit LTE-capable phones with DL 4x4 MIMO and 256-QAM in March, 2017. T-Mobile has said it would also deploy LTE-U/LAA.

- **Sprint** started to roll out its "LTE Plus" with 8T8R base stations in September 2015, and announced gigabit LTE with 3x DL CA in March, 2017. Sprint has said it would move to 64T64R base stations later in 2017.

The 4G spectrum of US operators is quite fragmented and limited in some parts of the country, and 4x4 MIMO can help US operators to boost network performance with limited bandwidth. In addition to 4x4 MIMO, operators can exploit LAA using 5.8 GHz unlicensed spectrum for CA, but this requires numerous small cells for nationwide coverage.

The APAC region is another advanced 4G market moving quickly to 4x4 MIMO:

- **Telstra** in Australia is a pioneer for high performance 4G. In January 2017, Telstra launched the world's first commercial gigabit LTE network. This uses 4x4 MIMO, an important feature to enable the gigabit experience.

- Japanese, South Korean and Chinese operators are also rolling out 4x4 MIMO in commercial networks**. NTT DoCoMo** and **SK Telecom** are deploying 4x4 MIMO to meet growing demand on 4G network capacity. They started to provide commercial 4x4 MIMO service in 1H 2017.

- **China Telecom** and **China Unicom** also launched 4x4 MIMO in multiple Chinese cities. China Unicom's LTE FDD has been able to provide Gigabit experience through combining 3-carrier aggregation, 4x4 MIMO and 256-QAM.

Besides developed markets, some developing markets are also driving the adoption of 4x4 MIMO in Asia. **AIS** and **TrueMove** in Thailand, **XL Axiata** and **Telkomsel** in Indonesia, **Celcom** in Malaysia, and others have deployed commercial 4x4 MIMO in their LTE FDD networks:

- Thanks to late-mover advantage, these operators were able to use the latest technology with their greenfield 4G networks. The growth of mobile data traffic also drives operators in developing countries to adopt new technologies.

- In Thailand, the average data use of AIS customers reached 4 GB/month in Q1 2017. Considering the high population density in South East Asian countries, operators in the region have strong motivation to increase network capacity using 4x4 MIMO and other advanced network features.

More than 37 countries have cellular infrastructure in place for gigabit LTE. Among these:

- **EE** (United Kingdom) demonstrated gigabit LTE with 4x4 MIMO in July, 2017, and claimed it would be the first operator in Europe to offer services using the technology.

- **Megafon** (Russia) announced gigabit LTE with 4x4 MIMO in August, 2017, making it the first gigabit LTE operator in Eastern Europe.

- **Elisa** (Finland) announced that it has established a true gigabit LTE network in October 2017.

Beyond 4x4 MIMO, massive MIMO can further improve the performance of 4G networks, at the same time helping the industry to prepare for the rollout of 5G.

As discussed above, Massive MIMO requires new hardware and software. Its performance significantly depends on vendor's R&D capability. Only through live deployments can vendors and operators get enough experience for development and optimization of massive MIMO. Therefore, deploying massive MIMO in 4G networks, particularly in traffic hot-spots, can not only improve network performance but also create an opportunity for the industry to prepare for future 5G deployment.

Besides TD-LTE operators mentioned in section 4.3, some leading FDD LTE operators – such as AT&T, China Unicom, China Telecom, etc. – have trialed Massive MIMO in their 4G networks as well. We expect to see more operators in major markets launch massive MIMO in 4G networks before 5G goes to large scale deployment.

5.2 Chipset and User Equipment Development

Devices that support DL 4x4 MIMO, which is to say user devices that have four independent receive antennas, include the following 15 phones, with more models arriving every month:

- **Samsung Galaxy S8, S8+, S8 Active**. T-Mobile US is among the first to offer the US-China versions with Qualcomm Snapdragon 835, but other operators in North America and in China are following. The international versions use the Samsung Exynos 8895.
- **Samsung Galaxy Note 8**, due in mid-September 2017, will be offered by all four major US carriers, in China, and across most of the world
- **Sony Xperia XZ Premium smartphone**. This phones reached retail shelves in the US and Western Europe in June 2017, with distribution expected well beyond gigabit LTE-capable networks. Sony announced the similar
- **Sony Xperia XZ1**. Sony announced this phone in August 2017. Like the XZ Premium, the XZ1 supports LTE Cat 16 / gigabit LTE with DL 4×4 MIMO.
- **ASUS Zenfone 4 Pro.** The flagship smartphone from ASUS features 802.11ad / WiGig, noise cancellation using three microphones, and dual main cameras for autofocus, zoom, and low-light sensitivity.
- **HTC U11**. This is “The first smartphone with hands-free Amazon Alexa.”
- **Huawei Mate 9** and **Huawei P10 Plus,** based on the Kirin 960.
- **Huawei Mate 10 Pro**, based on the Kirin 970.
- **LG V30**. This flagship phablet phone features a 6.0-inch, QHD+ OLED display and DL 4x4 MIMO.
- **Motorola Z^2 Force Edition,** based on Qualcomm’s Snapdragon 835, to be offered by all top 4 US carriers and US Cellular.
- **Sharp Aquos R.** This top-of-the-line smartphone features a 22 megapixel camera with wide angle lens and Qualcomm Snapgdragon 835 cellular platform with DL 4x4 MIMO.
- **ZTE Nubia Z17**. ZTE showed a prototype at Mobile World Congress in February 2017, and started shipping this gigabit LTE phone in the summer of 2017.

The high data rates available with DL 4x4 MIMO make it attractive for LTE routers and mobile Wi-Fi / LTE routers. At least four models are now available:

- **Netgear Nighthawk M1 Gigabit LTE Route**r. Telstra (Australia) was the first to publicly launch gigabit LTE services in January, 2017, and made this LTE router available to subscribers of its gigabit LTE high-speed service.
- **Wi-Fi Station N-10J**. This mobile Wi-Fi / LTE router, offered by DoCoMo in Japan, supports carrier aggregation using 3.5 GHz spectrum, 256 QAM, and DL 4x4 MIMO for peak downlink data rates of 788 Mbps, marketed by DoCoMo as “Premium 4G.”
- **Speed Wi-Fi Next W04**. Available through UQ and KDDI in Japan, this mobile router uses DL 4x4 to attain up to 440 Mbps of LTE downlink speed.
- **Pocket Wi-Fi 603HW.** This mobile router, made by Huawei, is available through Softbank in Japan. The device supports 802.11ac Wi-Fi to link other devices to the internet using LTE with 4x4 MIMO at 612 Mbps, or can use 3G or AXGP.

Most of the above phones and mobile routers support gigabit LTE, which requires the following features in the device with support from the network:

- 4x4 downlink MIMO, usually on the high bands, where antenna independence is greatest.
- 256-QAM downlink.
- 5x downlink carrier aggregation.
- 2x uplink carrier aggregation.
- 64-QAM uplink.
- Together these features support 12 downlink layers for 1 Gbps DL, and two uplink layers for 150 Mbps UL.

In reality, some of the networks claiming “gigabit LTE” come close but do not quite reach 1 Gbps DL peak rates, usually a consequence of spectrum and number of component carriers, but they all support DL 4x4 MIMO.

Qualcomm was the first to support gigabit LTE, and many of today’s shipping phones use Qualcomm chipsets, however, the company’s competitors have announced competing platforms to support gigabit LTE with DL 4x4 MIMO (see Exhibit 14). This is good news for OEMs, who want multiple, secure sources of supply, and the benefits on prices and features that competition can bestow.

Exhibit 14: Announced UE Chipsets That Support 4x4 MIMO

Company	Chipset / Platform	LTE Capabilities	CPU core	GPU Core	Process Node
Qualcomm	SD835 (MSM8998) with baseband-integrated apps processor	Cat. 16 / 13 (Up to 1 Gbps DL / 150 Mbps UL)	Quad Kryo 280 + Quad Kryo 280	Adreno 540	10 nm FinFET
Qualcomm	X16 Modem (baseband and transceiver chipset)	Cat. 16 / 13 (Up to 1 Gbps DL / 150 Mbps UL)	Quad Kryo 280 + Quad Kryo 280	?	10 nm FinFET
Qualcomm	X20	1.2 Gbps DL	TBD	TBD	10 nm FinFET
Samsung LSI	Exynos 8895	Cat. 16 / 13 (Up to 1Gbps DL / 150 Mbps UL)	Quad Custom M1 + Quad A53	Mali-G71 MP-20	10 nm FinFET
Samsung LSI	Cat. 18 Modem	Cat. 18 / 12 (up to 1.2 Gbps DL / 150 Mbps UL)	TBD	TBD	7 nm FinFET?
HiSilicon	Kirin 960	Cat. 12 / Cat. 13 (Up to 600 Mbps DL, 150 Mbps UL). 8 streams: 4xCA 2x2 MIMO or 2xCA with 4x4 MIMO	Quad A73 @ 2.36 GHz, Quad A53 @ 1.84 GHz	Mali-G71 MP8 @ 1.04 GHz	16 nm FinFET
HiSilicon	Kirin 970	Cat. 18 / 13 (Up to 1.2 Gbps DL / 150 Mbps UL)	Quad A73 @ 2.4 GHz + Quad A53 @ 1.8 GHz	Mali-G72 MP12	10 nm FinFET
Intel	XMM 7560	Cat. 16 / 15 (Up to 1 Gbps DL / 225 Mbps UL)	X86?	NA	14 nm 3D (?)

Source: Strategy Analytics RF & Wireless Components

Most of the processors in the line-up of gigabit LTE chipsets use 10 nm FinFET process technology from Samsung LSI or TSMC. Intel has said that they will use their own in-house production process for the XMM 7560. In addition to Samsung, TSMC and Intel, Global Foundries will have a fully-depleted silicon-on sapphire (FD-SOI) process at 12 nm said to compete with today's FinFET processes available for cellular chipsets. One advantage of this process, according to GF, is that it is suitable for the RF transceiver, not just the digital processor. Another claimed advantage is that fewer metal layers are needed in the production compared to FinFET processes, and this is said to offset any additional costs associated with the SOI starting substrate. If GF can meet all requirements for producing gigabit LTE chipsets, this will benefit the entire ecosystem by providing another supply source and potentially reducing production costs to the fabless semiconductor and design firms.

Starting in 2018, leading-edge CMOS will move to the 7 nm node, and by 2020, probably to 5 nm. By this time, we believe that gigabit LTE will have moved from the premium tier to the mid-tier of smartphones, and should reach very high volume status. What is clear is that gigabit OEMS will have more choices in LTE chips for gigabit LTE and 4x4 DL MIMO devices, which will help gigabit LTE reach mainstream status.

Gigabit LTE is at the leading edge today, but soon the market will move to multi-mode **5G NR** modems, **LAA / LTE-U, Cat. M1, NB-IoT, and millimeter wave 5G**. The rapid evolution of cellular communications technology – and the depth and breadth of cellular chipset capabilities needed – will put pressure on some vendors, mainly the lower-share suppliers not shown in Exhibit 14.

6. Conclusion and Recommendations

Test results in live networks have proven that 4T4R in the base station can effectively improve network performance and user experience. 4x4 MIMO can improve user throughput by 40 percent to 75 percent according to tests by MTN South Africa. True Corp's results also show great improvement of cell throughput with today's commercial two-antenna receiver user devices.

For operators in developed markets, 4T4R can help them keep competitive in the 4G network speed contest. The improvements in performance can also **guarantee positive user experience leading up to 5G**, because 5G coverage will be limited in its early phase. For operators in developing markets, the latest technology can help them to meet the demands of growing data traffic, while avoiding frequent network upgrades.

Currently all major infrastructure vendors offer 4T4R in their 4G base station products. Devices with four-antenna receiver are emerging in the market. We expect to see 4Rx becoming a mainstream configuration of flagship smartphones in 2H 2017. Test results have shown that 4Rx diversity in devices can effectively improve network coverage, capacity and user experience, even with 2T2R network. Before upgrading to 4T4R, operators can firs introduce 4Rx devices to improve network performance. 4Rx ready device will enable consumers to enjoy 4x4 MIMO experience immediately after operator upgrades network to 4T4R.

Massive MIMO can further improve network capacity to meet higher traffic demand, particularly in hot-spots. The experience of deploying and operating massive MIMO in live networks can help vendors and operators to prepare the rollout of 5G network where massive MIMO will be an iconic technology. Transmission Mode 9 will be required to fully exploit massive MIMO's performance benefits.

With the growth of traffic demand and maturity of advanced MIMO ecosystem, it's time for operators to roll out advanced MIMO features:

- Deploy 4T4R on a large scale to improve capacity and coverage across the network.
- Introduce 4Rx devices regardless of whether the network has yet upgraded to 4T4R.
- Deploy massive MIMO in hot-spot scenarios to meet high traffic demand and realize the data rate, coverage and capacity advantages of 4x4 MIMO.

Gigabit LTE and 4x4 DL MIMO are at the leading edge today for chipset suppliers, but soon more suppliers will enter the market with modems that support 4x4 DL MIMO and also support advanced carrier aggregation with five CCs, LAA / LTE-U and eventually millimeter wave 5G. This will benefit the entire ecosystem from operators to consumers with more availability, lower prices, and new services.

7. Acronyms

Term	Short For
4T4R	Four Transmitter Four Receiver [system]
AAS	Active Antenna System
BLER	Block Error Rate
CC	Component Carrier
CDD	Cyclic Delay Diversity
CAPEX	Capital Expenditures
CoMP	Coordinated Multi-Point transmission
CRS	Cell specific Reference Signal
CSF	Channel State Feedback
DL	Downlink
DM-RS	Demodulation Reference Signal
FD-MIMO	Full Dimensional MIMO
LAA	Licensed Assisted Access
LTE-U	LTE Unlicensed
MIMO	Multi Input Multi Output
MOS	Mean Opinion Score
MU-MIMO	Multi-User MIMO
OPEX	Operating Expenditures
RSRP	Reference Signal Received Power
Rx	Receiver
SISO	Single Input Single Output
SU-MIMO	Single User MIMO
TCO	Total Cost of Ownership
TM	Transmission Mode
Tx	Transmitter
UL	Uplink

8. How Can We Help You?

Strategy Analytics provides strategic and tactical support to global clients through a range of customized solutions:

- Multi-Country primary research assignments using leading edge tools and techniques
- User Experience Design and Innovation engagements
- Real Time Mobile Consumer On-Device Tracking projects
- B2B Consulting Projects and Whitepapers

Please contact us at Custom@strategyanalytics.com with any questions and for further details and solutions on how we can work with you on creating a custom solution to address your specific needs.