Goldman Sachs

5G: How 100x faster wireless can shape the future

Equity Research

5G will enable ultra-high speeds and a massive IoT ecosystem

The What, When, and Why of 5G

What – 5G is the next generation wireless technology after 4G/LTE. The exact standards and specifications of 5G will likely be finalized over the next 2-3 years, but compared to 4G we expect it to be 100x faster (reaching 1Gbps speeds – similar to Google Fiber), have 50x lower latency (reaching 1 millisecond), and scale to 100x more devices (Internet of Things, or IoT).

When – Full 5G mobile services are not expected until 2020. However, we expect pre-standard 5G commercial deployments to begin in the US in 2017, when AT&T and Verizon plan to be first in the world to roll out fixed wireless 5G broadband to the home, followed by pre-standard 5G mobile networks in Korea in time for the 2018 Olympics.

Why – 5G will likely be evolutionary *and* revolutionary. It will be *evolutionary* in enabling mobile devices to handle more data, as the rise of video use requires more bandwidth. It will be *revolutionary* in enabling a massive IoT ecosystem, requiring larger scale, lower latency and greater reliability.

Where could the landscape shift?

5G will provide the network infrastructure for a wave of new products and services over the next decade, including IoT, autonomous driving, virtual reality, and robotics – which are beyond the scope of this report but have been addressed in our other publications. 5G will also shift the landscape for the network ecosystem vendors in ways that we detail in this report: we should see more small cells, fiber, RF content, servers, and software; and fewer base stations, specialized telecom equipment, and carrier WiFi.

Companies that could benefit from 5G

We see 5G as an opportunity for **Broadcom** and **Murata** (increased RF content), **Cisco** (insertion point in wireless networks), **Qualcomm** (widening competitive lead), **Intel** (increased server demand), **Crown Castle** (rising small cell deployment) and **Zayo** (increasing dark fiber use to connect cell sites to cloud RAN).

Companies that could get challenged by 5G

We see 5G as a potential headwind to **Adtran** (5G as competition for wired broadband), **Mediatek** (likely lagging Qualcomm in the transition), **Ruckus** (5G cannibalizing carrier WiFi), **cable operators and regional telcos** (fixed 5G wireless services as potential competition for residential broadband).

Simona Jankowski, CFA
(415) 249-7437 simona.jankowski@gs.com
Goldman, Sachs & Co.

Brett Feldman
(212) 902-8156 brett.feldman@gs.com
Goldman, Sachs & Co.

Alexander Duval
+44(20)7552-2995 alexander.duval@gs.com
Goldman Sachs International

Daiki Takayama
+81(3)6437-9870 daiki.takayama@gs.com
Goldman Sachs Japan Co., Ltd.

Toshiya Hari
(646) 446-1759 toshiya.hari@gs.com
Goldman, Sachs & Co.

Donald Lu, Ph.D
+86(10)6627-3123 donald.lu@ghsl.cn
Beijing Gao Hua Securities Company Limited

Ikuo Matsuhashi, CMA
+81(3)6437-9860 ikuo.matsuhashi@gs.com
Goldman Sachs Japan Co., Ltd.

Marcus Shin
+82(2)3788-1154 marcus.shin@gs.com
Goldman Sachs (Asia) L.L.C., Seoul Branch

Doug Clark, CFA
(415) 249-7453 doug.clark@gs.com
Goldman, Sachs & Co.

Mark Delaney, CFA
(212) 357-0535 mark.delaney@gs.com
Goldman, Sachs & Co.

In Young Chung
+852-2978-1171 inyoung.chung@gs.com
Goldman Sachs (Asia) L.L.C.

Tina Hou
+86(21)2401-8694 tina.hou@ghsl.cn
Beijing Gao Hua Securities Company Limited

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We would like to thank Balaji Krishnamurthy, CFA, for his contribution to this report.

Did you know…?

Exhibit 1: 5G by the numbers

25 Gbps	Throughput achieved by Ericsson 5G Radio prototypes	**2500x** faster than average LTE download speeds in the US
11,000 MHz	Amount of millimeter wave spectrum that the FCC is looking to make available for 5G	**16x** the amount of spectrum currently licensed for mobile networks in the US
50 billion	Number of global IoT devices that Cisco estimates by 2020	**7x** the global population
1ms	Targeted latency of 5G network	**1/50th** of a 4G network
6 seconds	Amount of time it will take to download an HD movie over 5G	**70x** faster than downloading the same movie over 4G
10 years	Targeted battery life of an IoT device on a 5G network	**4,900x** longer than the battery life of an Apple Watch when fully charged

Source: Cisco, Ericsson, Huawei, Nokia, Goldman Sachs Global Investment Research.

Portfolio Manager summary

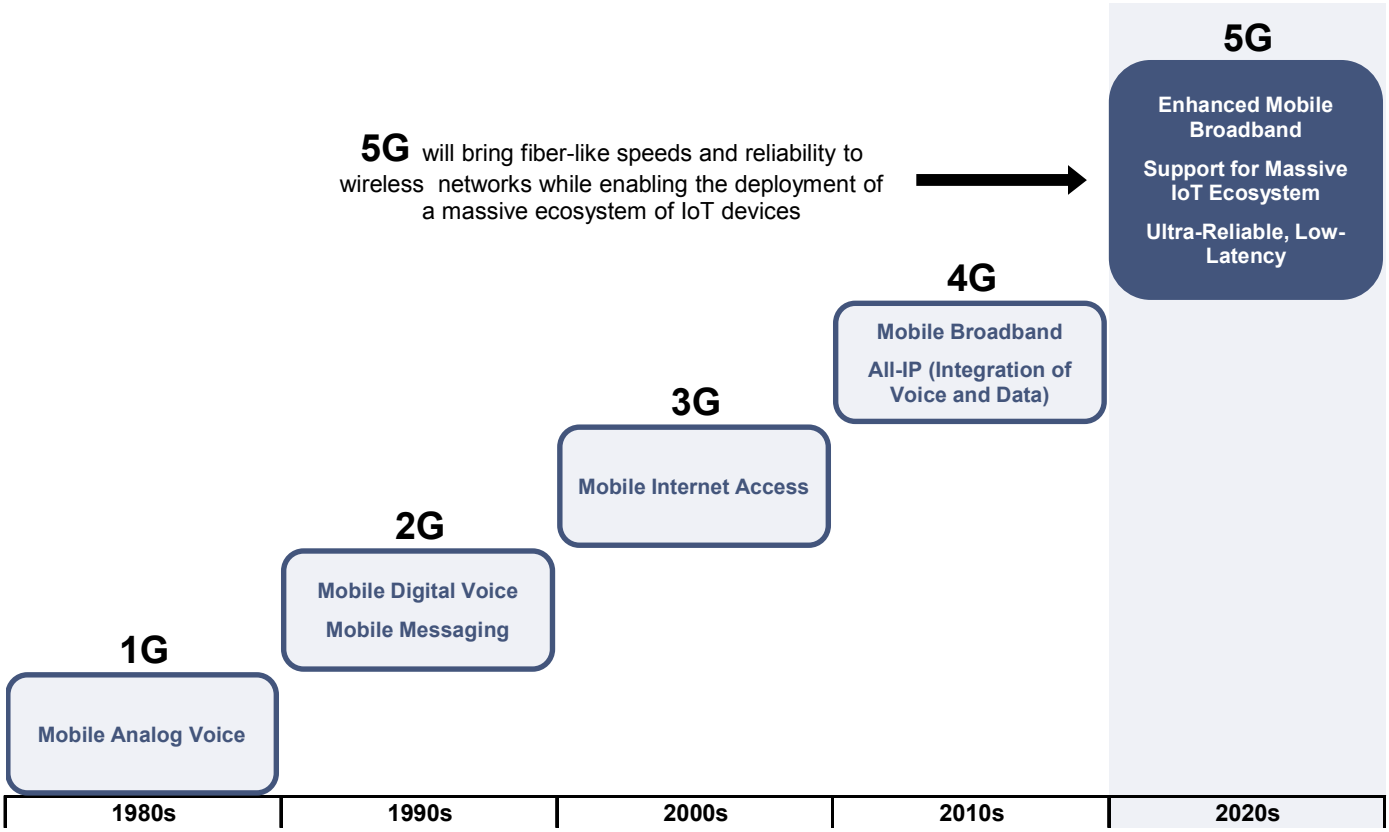
Approximately once per decade, the wireless sector undergoes a 'generational' evolution in its underlying technology. As shown in Exhibit 2, the last four decades have seen mobile networks evolve from supporting analog voice services (1G) to all-IP mobile broadband services (4G). 5G is the next step in this evolution.

Based on the objectives established by 3GPP, the industry's primary standards setting body, 5G will improve wireless networks by supporting three high level use cases:

1. **Enhanced mobile broadband.** This means 5G will be able to handle substantially higher levels of capacity on mobile networks in order to support services such as streaming 4K video.
2. **Massive machine type communications.** This means that 5G will be able to handle an ecosystem of IoT devices that Cisco estimates at 50 billion globally by 2020.
3. **Ultra-reliable, low latency communications.** This means that 5G will be able to support services that require immediate and uninterrupted connectivity, such as autonomous cars.

In this report, we provide a summary of the key technological advances of 5G and examples of real-world use cases that we expect 5G to enable.

Exhibit 2: Wireless technology evolves approximately once per decade
Generations of wireless technology



Source: Goldman Sachs Global Investment Research

Top 5 takeaways

1. **Potential shift of wireless center of gravity to Asia** – Europe led the 3G transition, with industry giants such as Ericsson and Nokia leading the way. With 4G, the baton passed to the US, driven by a new group of industry leaders such as Qualcomm and Apple. With China, Korea and Japan targeting 5G rollouts on par with or ahead of their Western counterparts, it bears watching whether the wireless industry's center of gravity shifts west once again.
2. **New competition for residential broadband** – Fixed wireless broadband access will likely be the first application of 5G, with Verizon planning to deploy it commercially as early as 2017. As such, deployments of fixed wireless broadband services based on 5G could potentially disrupt the market for residential broadband by presenting households with a 2nd or 3rd option in addition to their local cable or telco provider.
3. **Enabling mission critical and massive sensor IoT** – In addition to having 100x the bandwidth of 4G, 5G will have two other critical aspects that will enable new products, services and businesses to grow. First, it will have low latency (50x lower than 4G), enabling mission critical applications such as autonomous driving, robotics, or virtual reality healthcare. Second, it will be designed to handle massive scale (up to 100x the human population), giving rise to massive sensor networks such as in precision agriculture or connected cities.
4. **Small cells with a cloud back end** – Unlike the traditional wireless network built by base stations on towers, 5G will leverage a dense patchwork of small cells with a distributed network of data centers for the signal processing, connected by fiber. This will drive a shift from specialized telecom equipment to industry standard hardware (servers) running network function virtualized software (NFV).
5. **Higher frequency bands and unlicensed spectrum** – 5G will use much higher frequency bands, including millimeter wave (>24GHz) and unlicensed spectrum (e.g. 3.5GHz and 5GHz). This will dramatically increase the RF content and chip complexity in mobile devices. It will also likely cap the use of WiFi by carriers, given they can leverage unlicensed spectrum as part of their cellular network.

Companies that could benefit from 5G

Broadcom (AVGO, Buy) and Murata (6981.T, Buy): RF vendors likely to benefit as network complexity increases

We expect 5G to lead to an overall increase in network complexity, particularly in relation to RF transmissions and see increasing RF complexity as one of the long term drivers of the RF market. We see Broadcom and Murata as the key beneficiaries. Broadcom primarily caters to the high performance portion of the RF market and we believe the company is well positioned to benefit from increased RF complexity as more higher-frequency spectrum is utilized. In the smartphone space, Murata should be able to leverage its strengths both in SAW filters as well as ceramic filters required for high-frequency bands.

Cisco (CSCO, Buy): 5G provides an insertion point into wireless networks

We expect 5G to create an insertion point into wireless for Cisco. In the past, Cisco's wireless exposure has been limited outside of Wi-Fi, as it has lacked a basestation/RAN solution. While we do not expect Cisco to enter the radio market, it will be able to intercept a portion of the 5G TAM through the move to cloud-RAN, by delivering data center infrastructure (servers, routers, switches) and virtualized networking software. Further, its recently announced strategic partnership with Ericsson allows Cisco an improved go-to-

market channel to wireless opportunities, and joint development for 5G. Lastly, we view Cisco's market leading position in IoT as a strategic differentiator, given that 5G will likely be closely coupled with IoT. Cisco's recent acquisition of Jasper gives it a SaaS platform for the delivery of IoT services such as connectivity management, security, and data analytics.

Qualcomm (QCOM, Buy): Likely to widen competitive advantage in 5G
We expect Qualcomm to benefit significantly from the industry's shift to 5G. We expect Qualcomm to be at the forefront of the industry transition, much like it has been in previous generation upgrades. Empirically, Qualcomm has shown successful execution in the early years of a new technology cycle, as it can differentiate its products to drive both market share gains as well as premium pricing (see Exhibit 23, page 41). As 4G matures and competitive pressures increase, the transition to 5G can provide Qualcomm opportunities to once again take the lead with differentiated products and benefit from market share gains and premium pricing. Furthermore, we think it's likely that Qualcomm's TAM outside of smartphones will expand, as 5G will enable the proliferation of IoT.

Intel (INTC, Neutral): Increased data traffic drives demand for more processing power
We expect Intel's server and networking business to benefit from increased data traffic and greater demand for compute-intensive data analytics. Intel addresses both of these segments with its server processors and FPGA offerings.

Crown Castle (CCI, CL-Buy) and Zayo (ZAYO, Buy): Small cell operators and dark fiber providers well positioned as carriers increase site density ahead of 5G
A key aspect of 5G networks is that they will be able to utilize much higher frequency spectrum bands, which offer much wider channels and therefore enable much higher speeds. However, in order to realize these speeds while overcoming high frequency spectrum's limited propagation, 5G networks will need to be built on a dense configuration of fiber-fed small cells. As the largest operator of small cell networks in the US and one of the largest pure-play providers of dark fiber in large metros respectively, Crown Castle and Zayo look well positioned for this long-term investment cycle. In addition, we expect 5G networks to be based on a cloud RAN architecture, which will aggregate up to hundreds of remote radio heads or cell sites to a centralized baseband data center. This will require dark fiber connection from cell sites to the data centers where these network functions are centralized. Owing to its deep and expanding fiber footprint, Zayo looks well positioned to win this business across many major US markets.

Companies that could get challenged by 5G

Adtran (ADTN, Sell): Fixed Wireless over 5G poses threat to wireline Broadband Access business
Our research suggests fixed wireless services will be the initial application of 5G networks, with AT&T and Verizon targeting rollouts beginning in 2017. We see this as a critical risk to wireline (copper or fiber) broadband access equipment vendors. Today, consumers receive their broadband connections via a physical cable that connects to each home and is aggregated by access equipment (supplied by companies like Adtran, Nokia, and Calix), the final connection between a service provider's network infrastructure and a consumer. Fixed wireless can allow carriers to deliver high capacity broadband connections to businesses and residences, otherwise known as the last mile connection. And by leveraging high frequency spectrum (28GHz/60GHz), carriers can achieve broadband speeds of 10Gbps, which far exceed copper speeds up to 1Gbps. One of the principal benefits of fixed wireless

Please see Doug Clark's companion report *"Adtran: Down to Sell given premium valuation, margin risks and 5G"* for further detail.

connections vs. copper/fiber wireline connections is ease and cost of deployment, specifically eliminating the complication of underground cabling.

Adtran derives over 60% of sales from broadband access equipment. We see two potential risks for Adtran and the wired broadband access equipment market. First, fixed wireless could be an alternative architecture that cannibalizes some of the $9.1bn traditional broadband access equipment market. Second, and more likely, the evolution of 5G technology could cause carriers (even outside of AT&T and Verizon) to pause or adjust edge network upgrades as they consider 5G technologies. Near term, we expect a pick-up in discussions around 5G fixed wireless to adversely impact valuations of traditional broadband access equipment vendors.

Adtran's largest customers include US tier 2 operators like CenturyLink, Windstream, and Frontier, and it also supplies equipment to AT&T and Verizon. Adtran currently trades at a premium to other telecom equipment peers (at 22X 2016E P/E vs. peers at 14X), despite potential industry pressures from 5G applications.

Mediatek (2454.TW, Neutral): May lag in early days of 5G and face margin pressure

For some historical perspective, Mediatek did not launch its 4G mobile chipset when China Mobile launched its 4G service in major cities in 1Q13. Rather, Mediatek's first 4G chipset was on the market in 4Q14 when China Mobile already had 14mn 4G subscribers. In contrast, Qualcomm led in the 4G market by 3 years. As we look into 5G, Qualcomm has been doing a lot of development already and is influencing the standards; as a result, we expect it to be an early leader, similar to 4G. By comparison, Mediatek has not disclosed its 5G roadmap given the global 5G standard is not yet fully finalized. We believe that Mediatek may still lag behind Qualcomm in 5G while it aims to narrow the gap to below 3 years. Further, if Chinese competitor Spreadtrum narrows the gap with Mediatek in 4G/5G with strong government subsidies over the next four years, Mediatek may face intense price competition and margin pressure in the 5G chipset market in China.

Ruckus Wireless (RKUS, Neutral): May see some cannibalization of its carrier WiFi business

Ruckus is the leading Service Provider WiFi vendor with 35% share in 2015, followed by Cisco at 27% and Ericsson at 11%. Service Provider WiFi drives about a third of its revenues. Ruckus supplies over 250 service provider customers globally, including major US cable operators like Time Warner Cable. We see 5G as potentially cannibalistic to WiFi deployments by mobile operators, such as AT&T. Note, however, that it is likely not cannibalistic to the vast majority of Ruckus' business – enterprise WiFi and cable WiFi – as those operators don't own spectrum. In aggregate, we still expect Ruckus to grow its service provider WiFi business driven by cable operators and its expansion into small cells on 3.5GHz unlicensed spectrum, while facing headwinds in the mobile operator portion. Note that on 4/4/16 Brocade announced its intention to acquire Ruckus. If the transaction closes, it remains to be seen how Brocade can leverage Ruckus' core competencies in managing RF interference, including beamforming, for gaining a larger presence in 5G.

Cable operators and regional telcos: Fixed 5G wireless services present a potential source of competition in the market for residential broadband

In most markets, residential customers have only one or two options for broadband: the local cable company and/or the local telco, with cable typically offering the highest speed service in duopoly markets. As such, deployments of fixed wireless broadband services based on 5G technology could potentially disrupt the market for residential broadband by presenting households with a 2nd or 3rd option.

With AT&T and Verizon the primary wireless carriers with fixed wireless 5G business plans, we would expect them to focus on markets where they are not the incumbent wireline

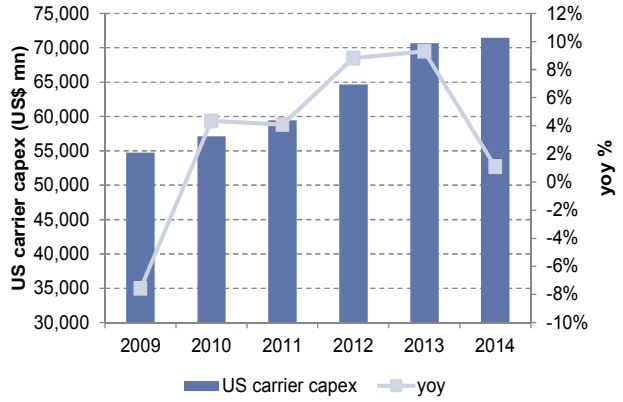
telcos. This implies that they will likely focus on markets where broadband share is dominated by cable operators and/or regional wireline operators such as CenturyLink and Frontier. At a more granular level, the risk is likely highest in metro markets as this is where the wireless carriers are best able to deploy dense configurations of fiber-fed small cells that are in close proximity to customer locations and therefore capable of utilizing very high frequency spectrum. However, we view this is a longer-term risk as none of the major wireless carriers have sufficient site density, or access to very high frequency spectrum, to target a substantial number of markets (or even wide swaths of individual markets) with 5G fixed wireless services any time soon.

What is 5G?

5G will enable IoT, much like 4G enabled smartphones

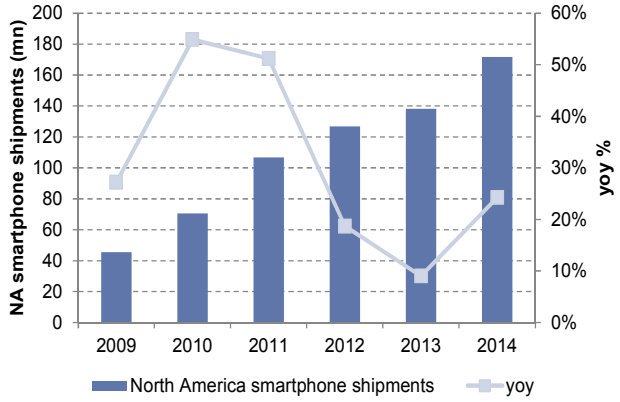
We expect 5G to drive the proliferation of Internet of Things (IoT), similar to what 4G did for the smartphone ecosystem. While the prior generations of cellular technology have focused on voice (2G), data (3G), and mobile broadband (4G), we expect 5G to deliver **ultra-fast speeds** (100X more than 4G), **low latency** (50X lower than 4G), **and massive scalability** (for connecting up to 100X more devices than there are people on the planet).

Exhibit 3: Carriers made big investments into LTE…
US carrier capex (US$ mn)



Source: Company data, Goldman Sachs Global Investment Research.

Exhibit 4: …that drove the adoption of smartphones
North America smartphone shipments (mn)



Source: Gartner.

With the Internet of Things, devices will likely outnumber the human population by many orders of magnitude (Cisco forecasts 50bn IoT devices by 2020, compared with the human population of ~7.5bn today). To ensure that future networks are able to support this scale of devices, the network would need to be pervasive, scalable, and cost effective. For context, IoT would require connectivity for deployment scenarios as diverse as smart connected devices in a dense residential environment, to a connected car on the freeway, to an offshore oil rig. At the same time, networks would need to be capable of supporting devices that transmit a few kilobytes of data per day (such as parking meters) to those transmitting hundreds of gigabytes per day (oil rigs, connected cars etc.).

Today's networks built on 4G technology are unlikely to deliver on these requirements due to a few issues:

1) **Scale** - The massive scale of IoT requires cost efficient coverage and low cost sensors. Currently, each basestation handles thousands of mobile devices. However, with IoT,

each basestation would handle hundreds of thousands of devices. This will require a re-architecting of the network with cloud-like technologies such as virtualization that enable it to scale by orders of magnitude without escalating costs.

2) **Latency** - In mission critical deployments (e.g. a factory floor, autonomous cars or augmented reality), reliability, availability and latency would be the key considerations. The typical latency on 4G networks is 50 milliseconds; while that is plenty fast, it is not fast enough for applications such as autonomous driving or augmented reality. 5G promises to deliver latencies as low as 1 millisecond.

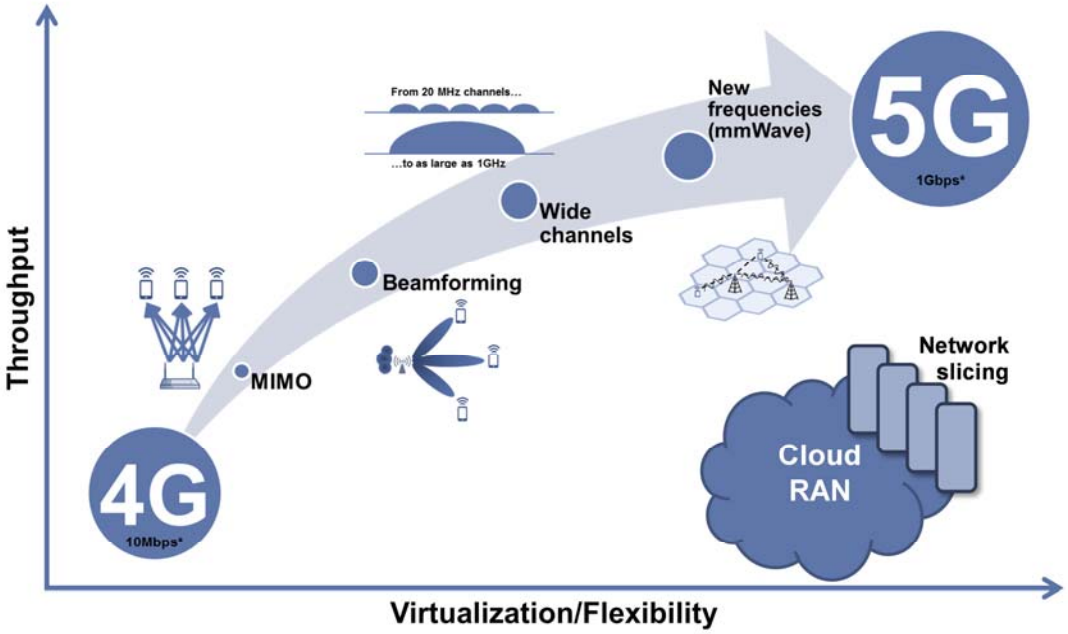
3) **Control** – Because of its wide range of use cases (e.g. from massive sensor networks to mission critical applications to bandwidth hungry video consumption), IoT requires a much larger "control plane" in the network, as opposed to today's networks which are built to service fewer devices with large data consumption (e.g. video) and thus have a larger "data plane". 5G will separate the control plane from the data plane and scale them separately in order to meet the requirements of IoT.

5G architecture - We believe 5G will be able to overcome the above limitations through a host of technologies, including leveraging unlicensed spectrum, deploying massive MIMO (multiple-input multiple-output) communications, adopting beam forming technologies, shifting to a cloud-like virtualized architecture, adding a large number of small cells, and utilizing high frequency millimeter wave spectrum. We discuss these technologies in more detail in the rest of the report. Note that unlike the move from 2G to 3G and 3G to 4G, 5G does not involve a new air interface standard – it still uses OFDMA (orthogonal frequency-division multiple access), the technology underlying 4G/LTE. This is because from an underlying physics perspective, there aren't any further significant gains to be obtained from improvements in modulation. Since most of the 5G throughput gains will be delivered by small cells using high frequency spectrum waves, which don't travel far, the LTE network will need to serve as the canopy that unifies the patchwork of underlying high frequency small cells.

In Exhibit 5, we illustrate the two key dimensions along which 5G will deliver order of magnitude improvements over 4G.

- **100X throughput improvement** – First, on the vertical axis, we show 100X improvement in throughput (from 10Mbps to 1Gbps in typical speeds – though the maximums are much higher). The technologies that will enable these throughput improvements – MIMO, beamforming, and wide channels on higher frequency spectrum – will be delivered via a large number of distributed 5G small cells.
- **Network virtualization and flexibility** – On the horizontal axis, while difficult to quantify, we show a dramatic increase in the network's virtualization and flexibility in 5G compared to 4G. As discussed in more detail in the network slicing section below, a key benefit of 5G networks will be the ability to offer slices of virtualized networks to various customers for various use cases (e.g. medical device monitoring vs. connected cars vs. utility sensors). This will require a cloud-like architecture for hosting these virtualized network services and performing data analytics. The cloud RAN (radio access network), which are data centers that will centralize the baseband processing functions in 5G, will likely emerge as a key location for hosting these virtualized services.

Exhibit 5: 5G still uses LTE, but achieves 100X faster speeds than 4G through additional spectrum and new technologies



**Typical speeds; 4G can reach a theoretical maximum speed of 1Gbps, and 5G can reach upwards of 10Gbps.*
Source: Goldman Sachs Global Investment Research.

Use cases: High quality wireless video, mission critical IoT, and massive sensor IoT

While 5G technology is still in an evolutionary pre-standards phase, and we expect multiple different applications to emerge, our industry conversations have pointed to three core use cases, each with specific attributes: **1)** Fixed wireless (i.e. massive capacity for high quality video to homes, **2)** Mission critical IoT (e.g. applications such as industrial automation and autonomous driving that require very low latency), and **3)** Massive sensor IoT. Carriers such as AT&T and Verizon, equipment vendors such as Ericsson and Nokia, and supply chain participants such as Qualcomm are already directing their efforts along these lines.

We explain below the attributes of each of these use cases, along with some of the enabling technologies.

1) High quality wireless video

A key use case of 5G technology is its utilization as an alternative to fiber in the delivery of high definition video to the home. This will be especially relevant for the ~1bn households globally for whom rolling out fiber is not economically viable (e.g. due to topological restrictions). As such, rather than a configuration involving fiber connected to WiFi, 5G wireless connectivity would essentially replace the last mile access (but with WiFi still retained in the building). In addition, 5G could enable high speed video delivery to the ~1-2bn trains/cars which cannot be connected to fiber (given they are in motion).

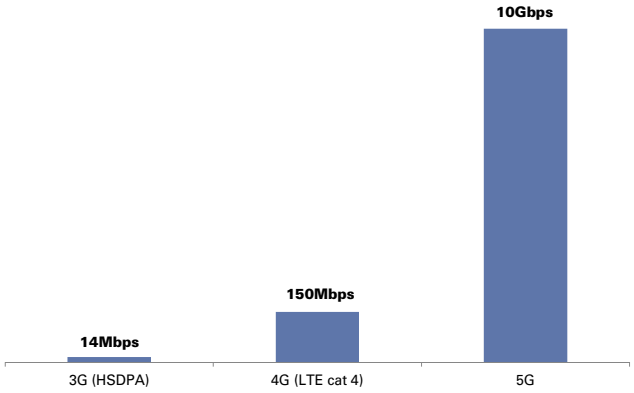
To enable this, 5G equipment and networks will need to deliver far higher throughput than 4G, i.e. roughly 100x higher speed (1Gbps 5G vs. 10Mbps 4G in typical speeds, and much higher theoretically). In other words, **5G speeds will be equivalent to those offered today by Google Fiber**. Given that the network will need to deliver on-demand streaming of high quality videos rather than simply web surfing, payloads will be significantly higher:

whereas a 4K video may have a payload of 15Mbps, higher quality media such as 8K or beyond will tend to require delivery of 100Mbps. Thus, while an 8GB HD movie would typically take 70 minutes to download on 3G or 7 minutes on 4G, on 5G it would take 6 seconds.

Video on demand streaming will likely require the system to deliver above 50Gbps per square kilometer in dense metropolitan areas. Infrastructure vendors have already started to demonstrate progress in this area. At the Mobile World Congress (MWC) in Barcelona in February 2015, Nokia demonstrated a massive capacity implementation of 5G on pre-standard hardware with delivery of peak data rates of 30Gbps. **Ericsson's 5G radio prototypes are already achieving over 25Gbps mobile throughput**, according to a joint Ericsson - T-Mobile USA press release from MWC in February 2016. Similarly, Huawei at MWC in Shanghai has this year demonstrated 10Gbps peak data rates on 5G vs. 4G peak rates, which are currently 150Mbps.

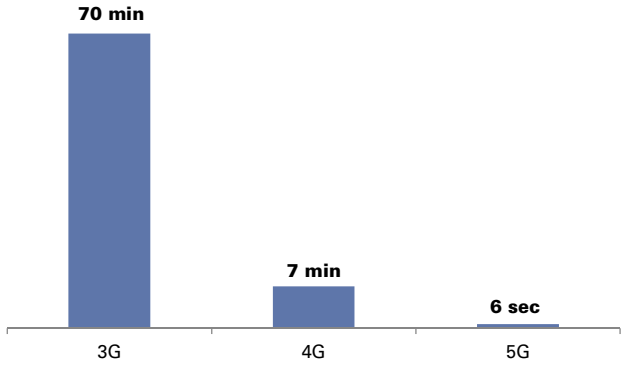
The other key vector where vendors will likely focus their attention will be cost of delivery, as the system will need to be affordable. Cost per connected house will clearly be in focus, and it seems likely the yearly TCO will need to be below $10 for global scalability, i.e., beyond the highest ARPU telco markets.

Exhibit 6: Peak data speeds for different generations of cellular technologies
Peak data rates for 3Gvs. 4G vs. 5G



Source: Huawei, Goldman Sachs Global Investment Research.

Exhibit 7: Time required for download of a 8GB video on various technologies
Download time on 3G vs. 4G vs. 5G



Source: Huawei, Goldman Sachs Global Investment Research.

Key enabling technologies for high quality wireless video

The key parameters overall for delivering high quality video streaming over 5G will be cost per gigabit per square km and cost per gigabit delivered end to end. Given that more advanced video is 15x as information rich, the challenge is to provide this to hundreds of households in the same cell without a step function change in terms of hardware densification (or macro layer). In other words, the telco will need to provide 50-60 Gbps per sq. km with economics that allow TCO per subscriber to remain at $10 per year.

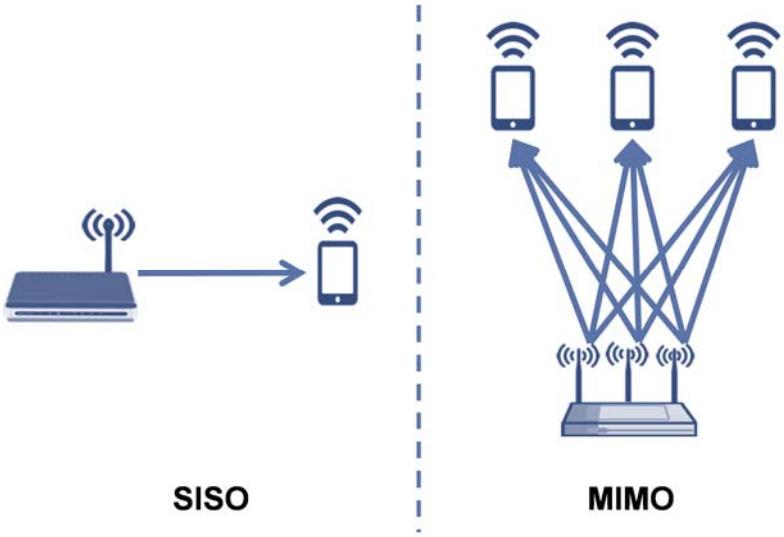
In the sections below, we detail three of the key technologies that will enable the order of magnitude improvements in throughput that 5G promises to deliver over 4G: **1)** massive MIMO (multiple input multiple output), **2)** autonomous beam forming, and **3)** significantly wider channels.

The first of these two technologies (massive MIMO and beam forming) will be facilitated by an architectural shift in 5G toward the use of wide arrays of antennas. Rather than the current setup with antenna integrated radios which have 2 or 3 power amplifiers emitting 20 watts, 5G will see hundreds of one watt or lower power antennas which work together in coordinated fashion to create a 100W radio. For example, Ericsson

in November 2015 announced its work with NTT DoCoMo to trial its advanced antenna design incorporating 128 antenna elements and 64 radio chains in each Ericsson 5G Radio Prototype in an outdoor radio design.

1) Massive MIMO: Massive MIMO will be possible in a 5G world given a broad antenna array. Our industry conversations suggest that massive MIMO can **lead to a 10x system gain**, or higher throughput all else being equal. Massive MIMO effectively means that rather than having one transmitting/receiving channel per household, there will be 10s or even 100s of channels per household. This will mean that it will be possible to send many bits in parallel, delivering higher capacity per square kilometer at a lower TCO.

Exhibit 8: MIMO could enable a 10X system gain
MIMO allows antennas to communicate with multiple devices simultaneously



Source: Goldman Sachs Global Investment Research.
Note: SISO: Single Input Single Output; MIMO: Multiple Input Multiple Output

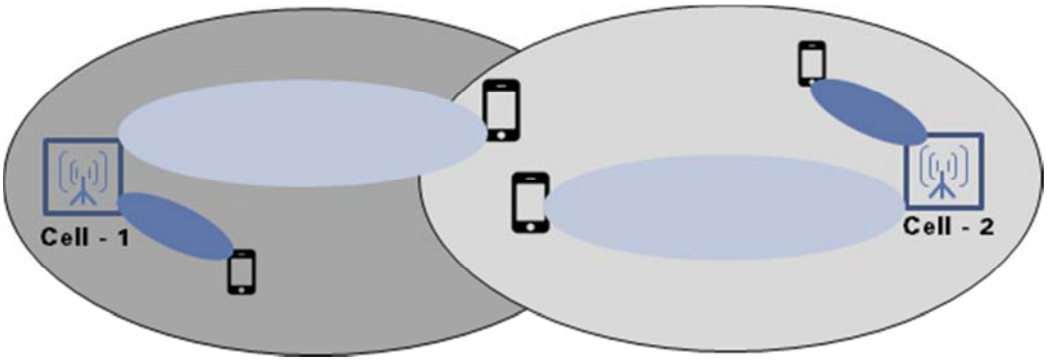
2) Autonomous beamforming: Autonomous beamforming will also hinge on having broad arrays of multiple antennas, and is expected to lead to **a further 10x system gain**. In basic terms, beamforming involves the transmitter and receiver tracking one another to improve energy transfer. Beamforming enables a setup where, for example, 100 households (on a given frequency) can be delivered different content without interference. Typically today 1Mbps requires 1MHz of spectrum, but with this approach it will be possible to get over 10Mbps per 1MHz.

From a technical perspective, beamforming limits interference to small fractions of the entire space around a transmitter and reduces the impact of interference on a receiver. Specifically, the base station tracks the user's phone and tries to point the antenna beam in the direction that gives the user's phone the best possible signal quality. This can be achieved either by the base station processing directional information for the signal from the phone to the base station or by the phone providing measurement data to the base station that it can use to determine where to point the beam. The phone actually has no ability to point its beam in a predetermined direction. It can have multiple antennas in order to better process the signals but beamforming is not realistic in the phone.

At MWC in February 2016, Ericsson in a joint press release with KT Corp. and NTT DoCoMo announced operator field trials of its 5G pre-standard radio prototypes that delivered downlink throughput of 25Gbps and over 12Gbps mobile experience per user by leveraging massive MIMO and beamforming. The radio prototypes tracked the position

and movements of a given device and pointed one or more beams in the best direction for that device in real time, to ensure reliable connections (such beams can come from multiple transmission points).

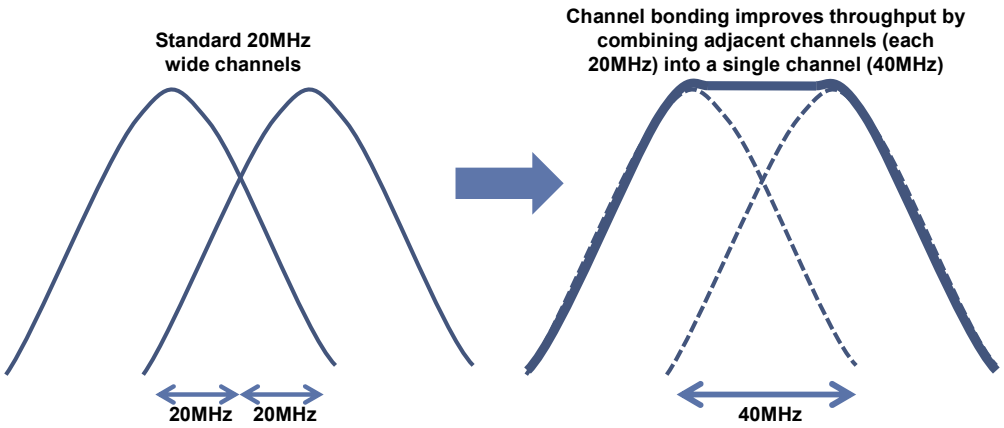
Exhibit 9: Intelligent beamforming can lead to a 10x system gain
Illustration of a beam forming implementation for 5G



Source: Goldman Sachs Global Investment Research.

3) Wider channels: The third key technology for enabling ultra-high speeds on 5G is wider channels. Whereas on GSM one would use 0.2MHz for 8 simultaneous voice calls on 10Kbps, on 3G one had a 5MHz for 2Mbps cell capacity. On 4G one might have multiple 20MHz carriers adding up to 100MHz of spectrum for 1Gbps. In contrast; 5G will allow that instead of each carrier / "channel" being 20MHz wide, there can be carriers 100MHz-1GHz wide. For example, Ericsson demonstrated 800MHz wide carriers at MWC in 2016. Note that these channels can be so wide due to the addition of much higher frequency bands of spectrum – e.g. 28GHz or even 60GHz (more on that below).

Exhibit 10: Wider channels would be a key component of 5G
Channel bonding is used to create wider channels currently



Source: Goldman Sachs Global Investment Research.

2) Mission critical IoT – requiring lower latency and high reliability

The industry is also focused on mission critical IoT as a key area where 5G can be a crucial enabling technology, opening up opportunities for carriers to monetize incremental revenue streams from new users. In short, this area involves wirelessly connecting devices

remotely to the network for the purpose of carrying out sensitive tasks in a more cost effective or safe manner. In such cases applications typically will not work properly if network delays are too high or reliability too low, and a new network architecture is therefore required.

Multiple applications could fall under this category where the evolution of the wireless network to 5G capabilities (rather than current 4G capabilities) will be required. Important applications include **1)** Remote robotics, **2)** Industrial automation, **3)** Autonomous cars, **4)** Healthcare, **5)** Augmented reality and public safety.

1) Remote robotics: Controlling heavy machinery remotely using robots can help lower risks in hazardous environments such as factories, mines, bomb disposal. Nokia has stated that systems used in such contexts will need to be extremely reliable with a BLER (block error rate) up to 10^{-9} with end-to-end latency of less than 1 ms. The latter will allow a configuration that supports haptic feedback (i.e. tactile sensations between the user's finger and a screen). Thus 5G networks could, for example, work with a configuration combining haptic interaction, 360 degree cameras with live video feeds and a VR device. At MWC in February 2016, Nokia and China Mobile demonstrated an ultra-low latency system used as a communication platform connecting robots to a central server, resulting in fast and synchronized collaboration (the robots worked together to reposition/balance an object).

2) Industrial automation: Industrial automation over 5G offers the potential to optimize processes, gain flexibility and reduce costs (e.g. by reducing the need for wiring and humans). In such a context machine-to-machine connectivity requires ultra-reliable connectivity (Nokia states less than 10^{-9} packet error rate), given that system failure could lead to loss of production or equipment. Given also that machines can receive, process and execute workloads faster than humans, industrial automation will likely need lower than 1ms latency. Another reason for low latency being needed is to facilitate rapid optimization of processes based on real time monitoring of sensors and systems.

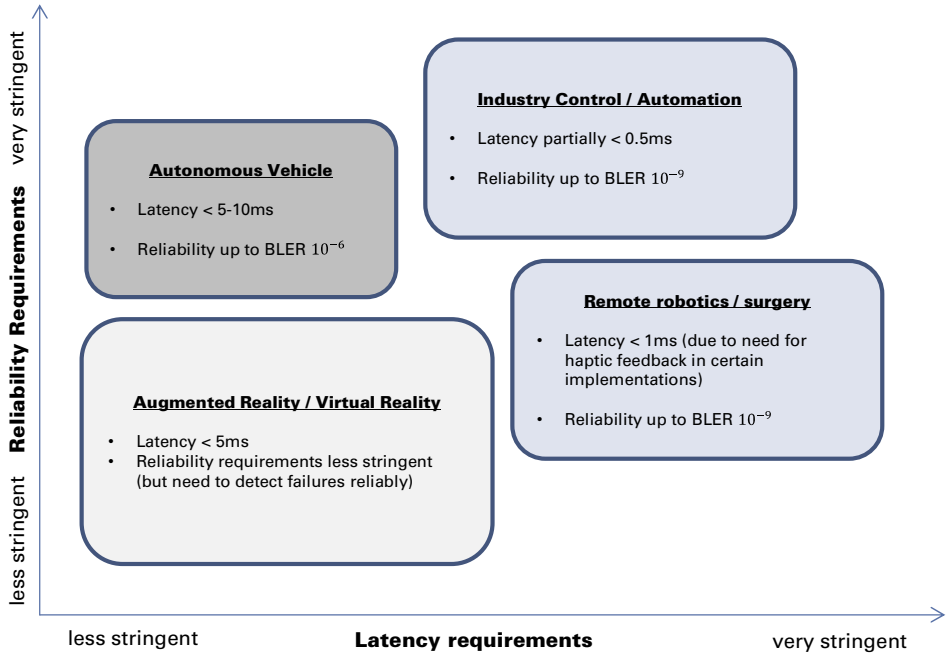
3) Autonomous cars: Autonomous vehicles will be a clear reality in the mid to long term, as addressed in our piece *"Monetizing the rise of Autonomous Vehicles"* (published on September 17, 2015), and the US Secretary of Transportation has stated driverless cars will be in use globally by 2025. We see clear benefits to leveraging 5G networks in this context. While semi-autonomous vehicles in production today largely rely on sensors within the vehicle, we have argued that wireless connectivity will be an important element of technology underpinning fully autonomous vehicles. For example, transportation companies will be able to utilize fleets in a more effective manner by "platooning" vehicles that can talk to each other. This will likely rest upon an extremely reliable communication system given that human safety is involved and due to the exacting failure rate requirements of automotive grade technology. As such, Nokia sees end-to-end latency requirements in this context as being as low as 5-10ms.

4) Healthcare: Connected healthcare can help increase efficiency and reduce costs and will also be enabled by an advanced 5G network. Remote robotic surgeries could be conducted over a 5G network as if a surgeon were physically present in theatre. Moreover, over time augmented reality is likely to play a larger role in certain medical procedures in the future, allowing doctors access to key medical data while performing procedures and thus necessitating extreme reliability.

5) Augmented reality and public safety: Augmented reality refers to technology which enhances a user's real world view with additional graphics representing real time information, e.g. by wearing glasses or a headset. The relevant information can change dynamically depending on user location and/or vision. Examples of AR in a 5G world include use in emergency scenarios. For examples, firefighters could use AR to see a building's layout, temperature data and/or hazardous areas. Police officers could use AR in

combination with facial recognition technology to identify suspects. Latency will have to be sub 5ms or it could lead to sickness for the user. At MWC in February 2016, Nokia demonstrated collaboration of two mobile virtual reality users, with pre-standard 5G technology on its Nokia AirScale Base Station, set up to deliver 1ms latency and high throughput. The system utilized 8x8 MIMO and >20 Gbps speeds.

Exhibit 11: Latency and reliability requirements for various use cases
5G Use cases requiring low latency and/or high reliability



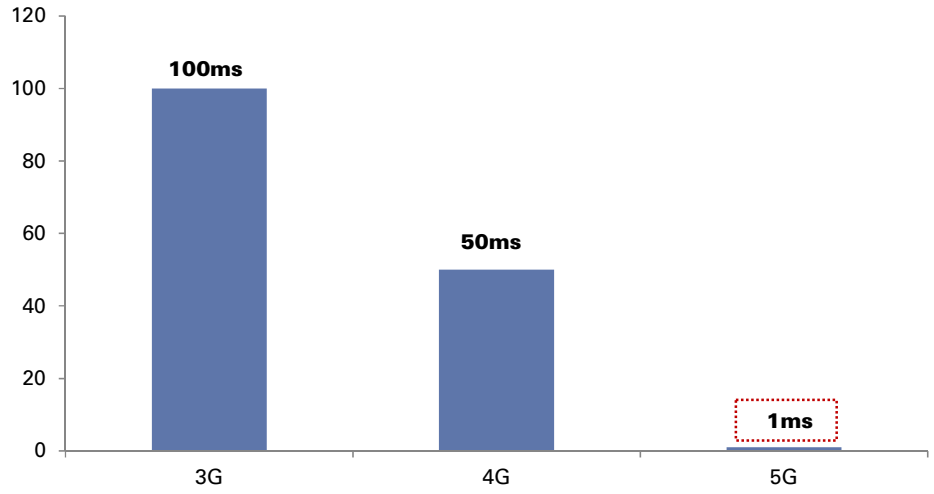
Source: Nokia, Goldman Sachs Global Investment Research.

Key enabling technologies for mission critical IoT

To deliver mission critical IoT, key aspects of the radio access network that will be required on 5G include:

1) **Extremely high radio access reliability** (with potentially built in functions to estimate and report on this).
2) **High node/service availability** (of at least 99.999%).
3) **Ultra-low latency** (Huawei sees 1ms on 5G, roughly 1/50th of that exhibited by 4G networks).

Exhibit 12: Latency for different generations of cellular technologies
Latency time for 3G vs. 4G vs. 5G



Source: Huawei, Goldman Sachs Global Investment Research.

3) Massive sensor IoT

A third key use case for 5G will be deployment of massively scaled IoT sensors. Some examples include the **monitoring and automation of buildings/infrastructure** (e.g. monitoring pipes or parking meters), **smart agriculture** (e.g. monitoring acidity levels of soil), and **logistics and tracking** (e.g. fleet management). These types of applications are in some ways the opposite of the prior two use cases. Unlike the wireless video use case, they may not require significant bandwidth; in fact, monitoring certain assets such as parking meters requires very low data rates. And unlike the mission control IoT use case, they may not require high reliability or low latency. What they have in common, however, is the requirement for massive scale and low cost. This requirement puts a lot more strain on the control plane of the network (i.e. managing thousands of communications sessions and signals), while requiring less from the data plane (i.e. less bandwidth use).

Key enabling technologies of massive sensor IoT

While bandwidth and latency will be less important in this area, cost efficient coverage will be paramount. Devices will need to be able to run on battery power for many years. Given they may be positioned in hard to reach locations, they may require **battery lives of up to 10 years**. Long transmission ranges will be needed where remote locations are involved. Devices must use a low complexity transmission mode with low cost sensors. Networks have to be scalable such that they can connect a very large number of devices (and handle associated signaling workload).

Cost effective authentication of the device onto the network would be critical; given a higher number of connected devices in an M2M world vs. a smartphone world, there will be more sensitivity to the cost of authentication modules (e.g. SIMs). Finally, security of connected devices will be important; for example, the hacking of one connected lightbulb could lead to issues with the building it is part of. Technology such as ARM's mBed Server and Sansa Security acquisition address some of these issues.

A more distributed, cloud-like architecture

The move to 5G will see networks become more "cloud like" vs. the 4G world. In particular, there is scope to **separate the radio and the baseband**, and also for **non-real time functionality (e.g. subscriber management) to run in cloud RAN** (radio access network), i.e. a virtualized data center. These developments will likely bring certain cost and efficiency advantages, as we discuss in more detail below.

Splitting the radio and the baseband

5G will offer scope to separate the radio (for transmitting/receiving) and the baseband (for signal processing), and connect the two with fiber, whereas hitherto these two tended to be within the same radio unit. By separating these two elements, it is possible to centralize the signal processing. The benefit of such an approach is that one is able to have one location where all the intelligence on the network is located, and processing can be directed to the parts of the network where it is most needed, thus allowing more efficient utilization of equipment. A further advantage is that this allows for better spectral efficiency as different cells will be able to talk to each other (such a plug and play self-organizing network is sometimes referred to as "tight coordination"). One derivative effect of such a setup will be an **increased requirement for dark fiber** due to the fact that latency between the radio and the baseband will need to be very low. Indeed, Verizon's pending deal to acquire XO Communications and plans to expand its FiOS footprint in Boston are likely precursors of this architectural shift in 5G.

Cloud RAN

Another key architectural change will be the advent of Cloud RAN (C-RAN), a data center aggregating traffic from the radios, where non real time functionality will be virtualized and run on commercial off the shelf servers. Clearly, there are certain functions that cannot be migrated to the cloud easily in this way. For example, radio scheduling (which involves knowing exactly when to burst energy in different directions in a radio network) should take place close to the radio and needs to be purpose built, to avoid energy efficiency issues. In contrast, certain functions do not need to take place in real time and can work on a slower cadence. Examples of functions that can be virtualized and centralized in this way include mobility management, subscriber management, and other layer 4-7 network services. As such, some of the radio functionality will be software defined and migrate to a server. By contrast, those functions that are real time critical will tend to take place on purpose built high performance hardware.

Spectrum for 5G

5G will extend the range of frequencies used for cellular communication, in order to be able to handle increased traffic capacity and enable bandwidths required for very high data rates involved in use cases such as high quality video streaming. High frequency spectrum has not played a major role in wireless networks in the past because the shorter wavelengths do not travel over long distances and in many cases cannot penetrate walls or other obstacles. 5G technology does not fundamentally resolve these challenges. However, because we expect 5G to be deployed as carriers densify their networks, we believe that higher frequency spectrum will become increasingly useful because signals will not need to travel as far from cell sites to reach customers. For this reason, 5G standards are expected to include features that help address the propagation challenges of high frequency spectrum. These include MIMO, beamforming and beam tracking, which we discussed earlier.

Spectrum relevant for 5G cellular is likely to range from below 1GHz up to approximately 100GHz. The specific spectrum that will be used in higher frequency bands is yet to be decided upon by entities such as the ITU-R or individual regulatory bodies. The entire frequency range up to 100GHz is under consideration at this stage. While the lower part of the range, i.e., <30GHz will tend to have better propagation properties, Ericsson has explained that very large quantities of spectrum and the possibility of wide transmission frequency bands (1Ghz or more) are more achievable at >30GHz.

Exhibit 13: Spectrum range relevant for 5G wireless access

Source: Ericsson, Goldman Sachs Global Investment Research.

Very high frequency spectrum (over 24 GHz), also called millimeter wave (mmW) spectrum, is likely to play a role in 5G, though initial use cases will likely be limited to fixed wireless broadband services. This is because a primary technique for overcoming these bands' propagation challenges is transmitting at a higher power level. This is easy for fixed devices, which can typically access power through the electrical grid, but remains a challenge for mobile devices owing to the limits of portable battery technology. We therefore do not expect millimeter wave spectrum to be utilized for mobile 5G any time soon. However, as we discuss next, the Federal Communications Commission (FCC) in the US is nonetheless looking to repurpose a substantial amount of this spectrum for both fixed and mobile 5G services.

As of April 2016, the World Radio Conference (WRC)-15 discussions resulted in an agreement on a set of frequency bands that will be studied for 5G. Ericsson has noted that a significant number of such bands are in the millimeter wave subset and include:

- 24.25Ghz-27.5GHz, 37.0GHz-40.5GHz, 42.5GHz-43.5GHz, 45.5GHz-47.0GHz, 47.2GHz-50.2Ghz, 50.4GHz-52.6GHz, 66.0GHz-76.0GHz and 81.0GHz-86.0GHz
- 31.8GHz-33.4GHz, 40.5GHz-42.5GHz and 47.0GHz-47.2GHz.

While the telco industry will likely seek to gain access to spectrum in the frequency range 6GHz-20GHz, certain policy directions being followed by various regulators seem to be focused on frequency bands above 30GHz. The US FCC issued two Notices of Public Rule Making on bands above 24Ghz. Ofcom in the UK stated it prefers bands above 30GHz within the mobile industry.

Nokia has noted that lower frequency bands being made available for 5G have good penetration characteristics that provide coverage to support applications with high mobility and reliability. Effective use of sub 6 GHz spectrum will require different carrier bandwidths and flexible spectrum aggregation techniques. Within this range, carrier bandwidths of 40-100MHz and efficient spectrum aggregation techniques will be needed for sub 3GHz FDD deployments. For 3-6GHz spectrum, support for high contiguous carrier bandwidths of over 100MHz will be particularly relevant.

It is also possible that operators may decide to use complementary solutions to obtain additional spectrum. This may include sharing spectrum with other incumbents through Licensed Share Access (LSAs). Further, unlicensed bands such as 5GHz, and in the future 60GHz, offer additional offload options for less critical applications (where potentially quality of service guarantees do not need to be as strong).

US regulators are looking to make 11 GHz of mmW spectrum available for 5G

The FCC is currently conducting a rulemaking process to define millimeter wave spectrum bands above 24 GHz that appear suitable for terrestrial 5G mobile services. It issued a notice of proposed rulemaking (NPRM) in October 2015, and the public comment period ended in February. We expect the FCC to announce final rules later this year. In its proposal, the FCC considered four key criteria for each proposed band:

1. The availability of at least 500 MHz minimum of contiguous spectrum per band to accommodate mobile use.
2. To the extent possible, these bands should also be under international consideration for mmW mobile service.
3. The ability to use these bands for mobile services in a manner that is compatible with existing incumbent licenses and uses.
4. License rules that that provide maximum flexibility for a wide variety of uses.

In its NPRM, the FCC has proposed to allocate a total of approximately 11 GHz for 5G mobility across four bands. To put this in context, this is 16x the amount of spectrum currently licensed for terrestrial mobile services (675 MHz) in the US. Below is a discussion of each proposed band that ultimately may or may not be used for 5G mobile services.

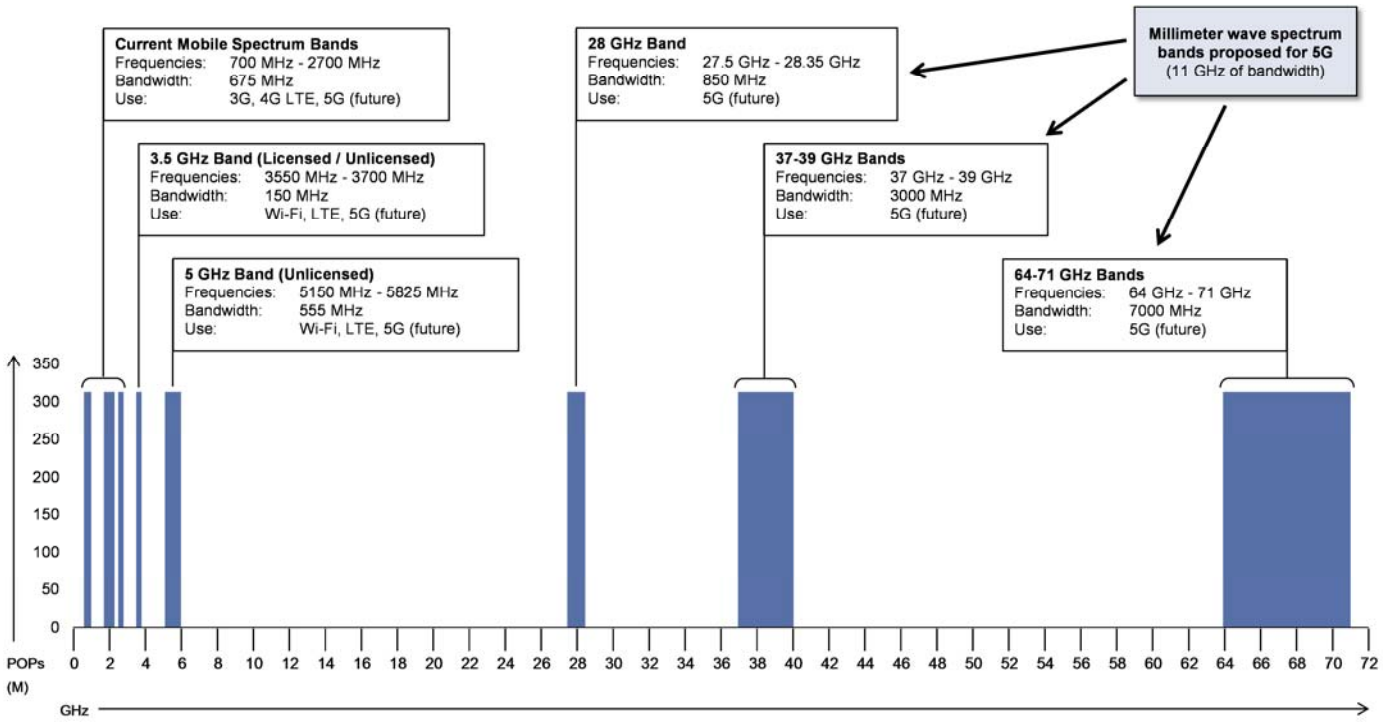
- **28 GHz band** - The FCC has proposed licensing the 27.5-28.35 GHz band configured as one 850 MHz contiguous block licensed in traditional geographic areas. In this band, the FCC has proposed to expand its current authorization for fixed service to include mobile. There are no federal government allocations, but earth-to-space fixed satellite services have a secondary allocation and are currently in use. The FCC has proposed examining opportunities for sharing the frequencies with satellite service providers.
- **39 GHz band** - The FCC has proposed licensing the 38.6-40 GHz band (1.4 GHz total) configured as 14 paired blocks of 50x50 MHz channels licensed in traditional geographic areas. The band is currently allocated to both fixed and mobile services. Although there are no government allocations in 38.6-39.5 GHz, there is a military satellite allocation for 39.5-40 GHz that is subject to power limits to accommodate fixed services. There are no commercial operations currently in these bands, but there are government operations.

  For both the 28 and 39 GHz bands, the FCC has proposed that active fixed licensees would be reassigned for rights including fixed and mobile. In the 28 GHz band, 42% of designated licenses are active, and in the 39 GHz band, 35% are active. The inactive licenses would be made available by competitive bidding. Both bands have worldwide mobile allocations.
- **37 GHz band** - The FCC has proposed licensing the 37-38.6 GHz band (1.6 GHz total) configured in either 3 blocks of 533.3 MHz each or 4 blocks of 400 MHz. These bands are currently allocated for both (1) terrestrial fixed and mobile service for government users, and (2) non-government satellite services. The FCC has proposed to work with the NTIA to protect federal space research service facilities in the 37-38 GHz band. The FCC would also consider options for mobile operators to share the spectrum with satellite operators. These proposed bands are contiguous to the 39 GHz band, so the FCC is considering potentially aggregating up to 3 GHz of bandwidth.

  As for the licensing mechanism, the FCC has proposed a hybrid indoor/outdoor scheme to facilitate the deployment of advanced enterprise and industrial applications not suited to unlicensed spectrum or public network services, while also providing additional spectrum for more traditional cellular deployments. The FCC is vague on how it would award the indoor, "local area" licenses but has suggested competitive bidding for the outdoor "wide area" licenses. The 37 GHz band also has a worldwide mobile allocation.

- **64-71 GHz band** - The FCC has proposed authorizing short-range unlicensed operations in the 64-71 GHz band (7 GHz total) for Wi-Fi-like "WiGig" operations. The spectrum is allocated for mobile use but is also authorized for links to the International Space Station. However, the FCC believes that signals at the power levels contemplated would not be able to reach satellites using ISS links. Further, the FCC believes that unlicensed mobile operations in this band could be used in conjunction with the existing 57-64 GHz band to double the spectrum available for the next generation of unlicensed wireless broadband technologies.

Exhibit 14: Spectrum band plan in the US including bands potentially available for licensed and unlicensed 5G use



Source: The Federal Communications Commission, Goldman Sachs Global Investment Research

Unlicensed high-frequency spectrum more likely to support Wi-Fi and LTE than 5G in the near-to-medium term

All of the mmW bands discussed above are being considered for licensed operations. The FCC has also taken steps to make other high frequency bands available for unlicensed use. These include the 5 GHz band and the 3.5 GHz band. We provide details below, but the key takeaway is that we see these bands as being initially used for Wi-Fi and unlicensed LTE operation with potential 5G use after mobile standards have been adopted.

- **5 GHz band** - In April 2014, the FCC increased the utility of 555 MHz in the 5 GHz band already available for unlicensed operations, including Wi-Fi, while protecting incumbent users from harmful interference. Since then, Verizon, AT&T and T-Mobile have discussed trials and/or potential commercial deployments of unlicensed LTE (either LTE-U or License Assisted Access) in the 5 GHz band. However, the standards development process has been delayed by recent claims by the Wi-Fi Alliance (with its 600+ members) and by the national cable association that LTE transmission using the 5 GHz band degrades Wi-Fi performance. Since then, the carriers and their equipment partners have been conducting trials aiming to prove that unlicensed LTE and Wi-Fi can successfully coexist.

- **3.5 GHz band** – There will also be potential for the unlicensed 3.5GHz band to be used in 5G. In the US, in April 2015, the FCC adopted rules for commercial use of 150 MHz in the range of 3550-3700 MHz. In this shared-use band, the FCC intends commercial carriers to deploy small cells within up to 80 MHz with "general authorized access." This is the lowest access priority relative to (1) incumbent government and satellite users, and (2) other high priority licensees, such as hospitals, utilities, and public safety entities. The higher tier users are all permitted to cause interference to the carriers' operations. The exact amount of 3.5 GHz spectrum available to carriers is dynamic, so the carriers can deploy spectrum on an unlicensed basis where they need additional capacity but also have an opportunity to pay for license protection in targeted locations where they need interference protection. US wireless carriers have not yet committed to using the 3.5 GHz band, likely owing to the uncertain amount of available spectrum and interference concerns. There will also be scope for part of the 3.5GHz band to be used in Japan. Additionally, 3.5GHz will become available in Europe, although its use will depend on capacity needs.

Timeline and standards

Fixed wireless broadband: The first use case for 5G, coming to a market near you (maybe) in 2017

We see fixed wireless broadband as the first commercial 'use case' of 5G. Based on public statements by Verizon and AT&T, commercial deployments by these operators are targeted for 2017, although we expect them to be initially limited to only a handful of markets. While the wireless industry has attempted multiple iterations of fixed wireless as replacement for wireline connections, 5G is the first technology that can provide similar speeds to wireline broadband services. For example, Verizon is seeing speeds well over 1 Gbps, and sometimes over 10 Gbps, during 5G trials at its headquarters in Basking Ridge, NJ.

In September 2015, Verizon detailed its 5G roadmap, with field tests starting in 2016. Verizon announced that it would be partnering with Alcatel-Lucent, Cisco, Ericsson, Intel, Nokia, Qualcomm, and Samsung as part of its "5G Technology Forum". Further, Verizon is partnering with SK Telecom, KT, and NTT Docomo to form a service provider alliance for testing 5G standards. Separately, in February 2016, AT&T introduced its 5G roadmap, with trials also scheduled for 2016. AT&T named Ericsson and Intel as partners for the lab testing of 5G solutions. Please see pages 32 and 43 for more details on AT&T and Verizon's 5G strategies.

Standards – first specification in 2018, final by 2020

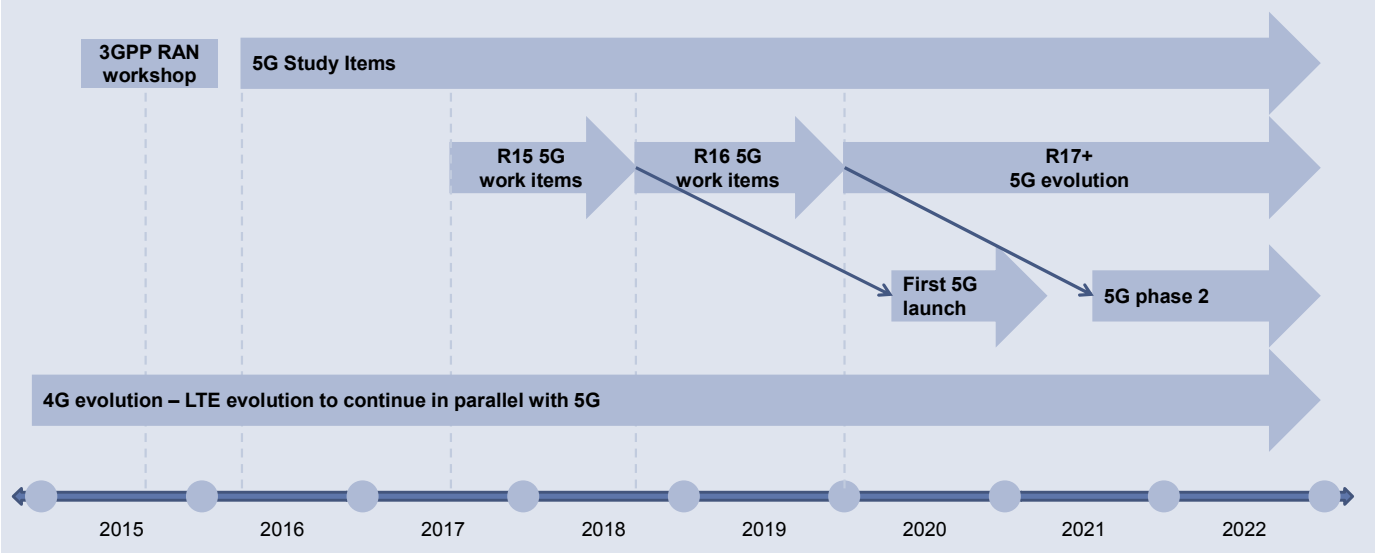
In June 2015, the International Telecommunication Union (ITU) outlined its vision and overall roadmap for 5G defined as 'IMT-2020'. (IMT stands for International Mobile Telecommunication; IMT-2000 was defined for 3G and IMT-Advanced for 4G). 5G technology will need new standards to offer new capabilities discussed above. 3GPP is an industry collaboration which will define the 5G standards. In September 2015, 3GPP started a standardization process to define the 5G standards. It also marked official kickoff of 5G through a 3GPP RAN workshop and 5G study items have already started. This is expected to cumulate into Release 15 work, likely to be confirmed around 2018. 3GPP will continue with the 5G study items to come up with Release 16 after that to address additional aspects. Industry expects the 5G standards will be in 2 phases; phase 1 would focus on fixed

wireless, and phase 2 on mobile phones, voice, and fully inter-operable communications standards.

The Release 15 work items will form the basis for launch of first phase of 5G in 2020, while Release 16 will form the basis for phase 2 of 5G launch in around 2022. Similar to initial 4G launch being followed by 'Long Term Evolution' (LTE), 5G evolution is expected to continue long after initial phases. Meanwhile, industry participants still see a long road ahead for nearly 10 more years, for 4G/LTE evolution globally, in parallel with 5G research and development.

Several industry participants are calling Verizon's accelerated 5G plans for 2017 launch as 'pre-standards' 5G, likely for specific use cases.

Exhibit 15: Proposed 5G standardization for 2020 launch



Source: Qualcomm

2018 Korea Winter Olympic may showcase the commercial application of 5G

With 4G maturing with 72% penetration in 2015, South Korean telecom operators regard 5G as the next growth opportunity, and are engaging with local and global partners to achieve the leadership in 5G commercialization. Korea telcos expect the commercial launch of 5G in 2020, if 5G standards are confirmed by then.

SK Telecom, the no. 1 mobile operator in Korea, is actively partnering with local/global manufacturers and operators to play a role in 5G standardization. In February 2016, SK Telecom and Ericsson signed an MOU for 5G pilot network. In March 2016, SKT tested its 5G system on mmWave (28Ghz) in outdoor settings with Samsung Electronics, before the launch of its pilot 5G network in 2H16. It also signed a partnership with Deutsche Telecom in MWC 2016, to cooperate in 5G standard projects.

KT Corp., the telecom sponsor of 2018 Pyeong Chang Winter Olympic in 2018, plans to showcase 5G technology in broadcasting and data-service. KT plans to run 5G on 28GHz for the event. Some of the broadcasting technologies include: a 5G-connected mobile camera that transmits live action of athletes, as well as VR/hologram-based live streaming services to provide live stadium experiences for external audiences.

The key challenge appears to be the timing mismatch between the Winter Olympic (February 2018) and the first specification of 5G (e.g., Release 15 is expected in 2018). To resolve this issue, KT plans to establish its proprietary 5G specification by June 2016, and begin pilot-operation in 2017. The Vice President of KT's Network Division stated the proprietary 5G specification will incorporate the key requirements of 5G, currently known to the industry, such as massive capacity (greater than 20Gbps throughput), ultra-low latency (less than 1ms) and massive connectivity.

Where the landscape could shift

From Europe (3G) to US (4G) to Asia (5G)

We believe that Asia may lead the transition to 5G, similar to what Europe and US did with 3G and 4G, respectively. We view countries such as China, South Korea and Japan as most likely markets to carry out 5G trials and large scale deployments for telecom operators as well as communications equipment vendors. China Mobile, being the world's largest wireless carrier by number of subscribers and following the success of its home-grown TD-LTE technology, is actively collaborating with industry participants. Telecom operators in South Korea and Japan have set the earliest targets for their mobile 5G commercial applications – the 2018 Winter Olympics and 2020 Summer Olympics, respectively. We believe their compact geography and leadership in 4G also make them suitable markets for a fast upgrade to 5G.

China: In terms of technology advancement, we believe China is becoming more important on a global scale. From its home grown 3G technology TD-SCDMA which is only adopted by China Mobile, to its next generation 4G technology TD-LTE which has been adopted by 71 telecom operators globally as of January 2016 including Bharti Airtel, SoftBank, Vodafone etc., China has also been active in the development of 5G technology. China Mobile plans to start 5G commercial trials in 2018 and plans a commercial launch in 2020. This would put it on par with Verizon, in contrast to 4G where it was more than 2 years behind. CM has established a 5G Joint Innovation Lab (JIL) with 11 partners, including Ericsson, Huawei, Nokia, Qualcomm, ZTE, Datang, Intel, Keysight Technologies, Haier, Hisense, and Beijing Shougang Automation Information Technology. The JIL will build a central lab in Beijing, and regional labs in the China Mobile International Information Port, Qingdao, Chongqing and other places. China's CommTech industry has come a long way over the past three to four decades, from completely depending on foreign vendors and technologies to now having some of the biggest telecom operators and CommTech equipment vendors in the world. In October 2015, Huawei and NTT DoCoMo demonstrated mobile internet speeds of 3.6Gbps on a sub-6GHz frequency band outdoors across the city of Chengdu in Sichuan Province, China. At the MWC in Barcelona in February 2016, ZTE and China Mobile jointly unveiled a 5G high-frequency prototype which operates on a 15GHz carrier with a bandwidth of 500 megabits and boasts a hardware structure of a large-capacity baseband unit and an intelligent remote radio unit.

South Korea: Korea telecom operators plan to launch 5G in 2020 if 5G standards are confirmed by then. Before the commercial launch, Korea may also showcase the commercial application of 5G during the 2018 Winter Olympic in Korea. South Korea's Ministry of Science, ICT and Future Planning announced in 2014 that it was committing $1.5 billion to its "5G Creative Mobile Strategy." As arguably the most wired country in the world, when it comes to network upgrades, Korea's compact geography and existing wireless infrastructure mean that upgrades can happen faster and cheaper, and will reach more of the population than in geographically spread-out countries like the United States.

Samsung Electronics started developing 5G technology in 2011 and succeeded in demonstrating 1.2 Gbps data transmission using ultrahigh frequency for the first time in the world in 2013. In October 2014, Samsung set the first record by achieving a wireless speed of 7.5Gbps in tests at its DMC R&D Centre over a 4.35km outdoor race track and using a 28GHz network. During the Mobile World Congress (MWC) in February 2016, Samsung unveiled the world's first handover technology connecting 5G base stations. At a recent 3GPP meeting in Busan (April 2016), Samsung said it will lead the global standardization of 5G network technologies for the 3GPP RAN1. As a member of the 3GPP, Samsung will announce its plans for integrating diverse IoT services to the 5G network and securing compatibility with future 5G technologies that will be further improved by June 2017. Based on this research, the company said it will complete the first standardization phase of the 5G network in June 2018.

Japan: Japan's largest wireless carrier, NTT DoCoMo, plans to launch 5G in time for the 2020 Olympics. The company plans to deliver the technology through a variety of "massive MIMO" and 128 polarization elements within the antenna arrays, along with narrow-beam transmission to each user. In October 2015, NTT DoCoMo conducted its first real-world tests of its upcoming 5G network technology, a 5G data transmission test at a commercial complex in Tokyo, in partnership with Nokia. The test produced 5G speeds in excess of 2Gbps. The trial used millimeter-wave signals at 70GHz. In February 2016, researchers from Hiroshima University, Panasonic and Japan's National Institute of Information and Communications Technology have developed a radio transmitter operating in the sub-millimeter terahertz frequency range that is able to carry high speed (100Gbps) data connections over multiple channels.

5G as competition for wireline broadband

Fixed wireless broadband access will likely be the first application of 5G, with Verizon planning to deploy it commercially as early as 2017. There are three reasons that we believe 5G may find commercial traction as a fixed wireless broadband service:

1. **Improved antenna technology.** Recent innovations in antenna technology enable wireless operators to provide 5G services using very high frequency millimeter wave spectrum, which has typically been difficult to use for point-to-multipoint services. These innovations, which we discussed earlier, included MIMO, beamforming and beam tracking.

   Together, these advancements enable 5G antennas to deliver high capacity and high quality signals to fixed customer locations through very high frequency spectrum. This is significant because spectrum licenses for very high frequency spectrum typically come in very wide channels (e.g., 100-1000 MHz vs. 5-20 MHz for cellular), which means they can technically enable very high-speed transmissions if their propagation challenges can be overcome.

   The same technologies can eventually be used for mobile 5G, but in order to do this over millimeter wave spectrum there will need to be material advances in mobile devices, which are not currently powerful enough to use these capabilities.

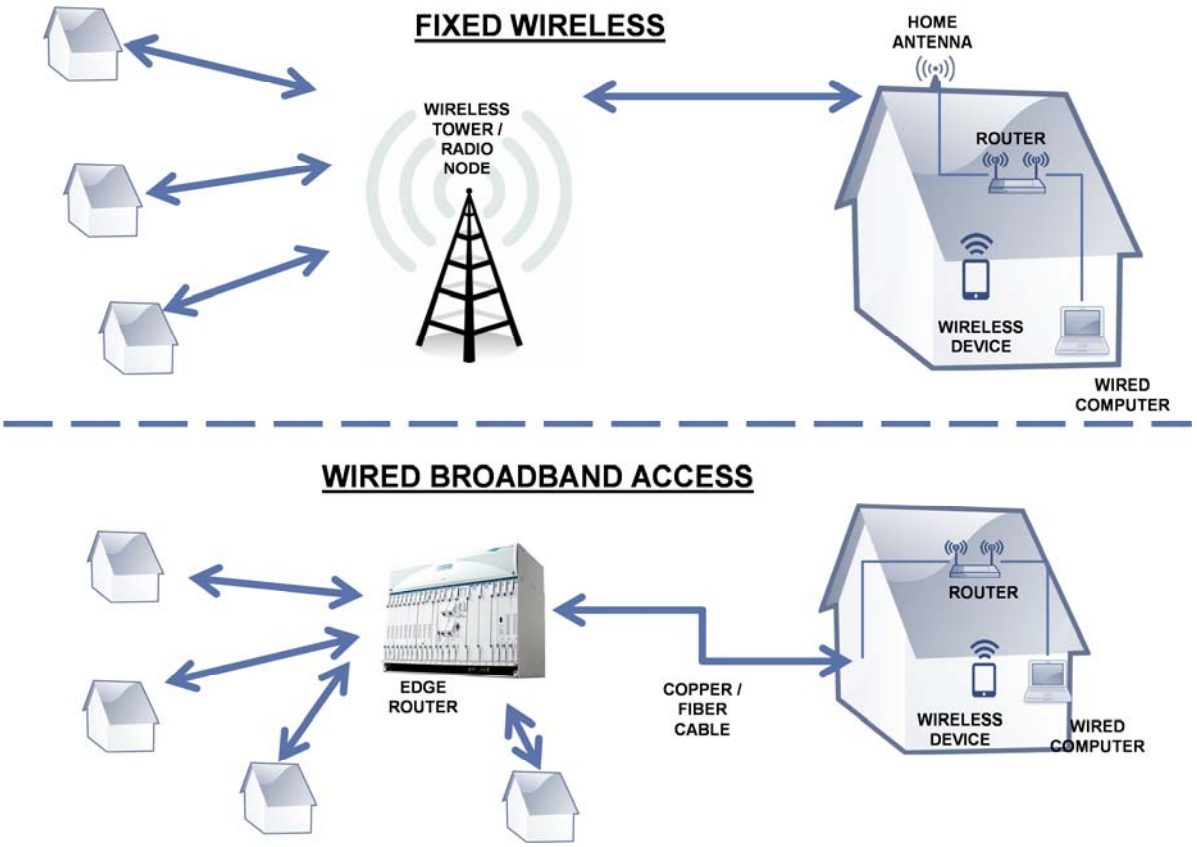
2. **Fiber densification to support LTE small cells.** 5G can be easily deployed as an overlay to the small cell grids that the major wireless carriers are deploying to support their mobile 4G networks. In other words, as operators deploy fiber in dense metro areas to support LTE small cells, they can also attach fixed 5G antennas to these fiber-fed LTE nodes. This will provide the dual benefit of getting these 5G antennas close to potential residential customers while providing the high capacity backhaul necessary for a fixed broadband service.

3. **Availability of millimeter wave spectrum.** The FCC is looking to make 11 GHz of millimeter spectrum available for use in 5G applications in the US. As noted above, the wide channels available at these frequencies enable much higher throughput than we have seen in mobile technologies, which have typically been the basis for past attempts at providing fixed wireless services. With access to much wider channels for fixed services, 5G networks should be able to deliver speeds that are competitive with fiber- and coax-based broadband networks.

Initially, the addressable market for fixed 5G services may be limited. This is a result of fragmented spectrum holdings in millimeter wave frequencies, a need for more fiber density (because the technology works best if the network antennas are within short range of customer locations) and limited availability of commercial equipment. Indeed, because full 5G standards will not be established until 2019-2020, initial fixed wireless applications will be based on pre-standard 5G network gear and devices.

5G is not the only emerging technology that can be used for high-speed fixed wireless broadband. For example, Starry, a private company, is also looking to deploy gigabit speed wireless broadband over millimeter wave spectrum using advanced 802.11ac technology (i.e. Wi-Fi). The key advantage of Starry's model is that the cost of 802.11-based network gear is much lower than cellular gear owing to the large market for consumer Wi-Fi routers. Facebook is building a similar fixed wireless system called Terragraph, which also utilized millimeter wave spectrum, but is based on the open WiGig standard. So, the market for fixed wireless broadband could become crowded quickly.

Exhibit 16: Fixed Wireless connections in a 5G architecture could present an alternative technology vs. traditional wired broadband access
Fixed Wireless vs. wired broadband access



Source: Goldman Sachs Global Investment Research.

From macro cells to small cells; coexisting with WiFi

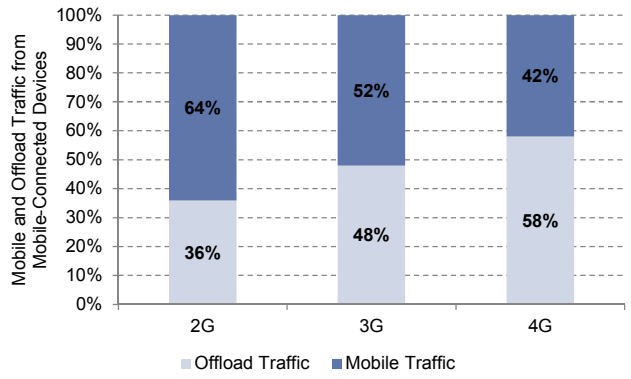
5G network architecture would likely be characterized by the deployment of small cells, as opposed to the macro cell based architecture in place in today's networks. While 5G architecture is still fluid, as standardization efforts are underway, it is quite likely that small cells would be critical. A part of the reason for this is necessity (such as for densification), and part of it is due to technological requirements (propagation constraints of high frequency spectrum). Even in fully deployed 4G networks, such as those in the US (AT&T, Verizon, T-Mobile), operators have shifted focus towards deploying small cells for densification of the networks.

A key difference between 5G networks and 4G networks would be the use of higher frequency spectrum (including millimeter wave). In contrast to the crowded low frequency bands, operators would be able to benefit from larger chunks of spectrum in high frequency bands. However, millimeter wave frequencies have poorer propagation characteristics – the higher the frequency of radio waves, the lower the transmission range. This would imply that operators would need to split macro cells into much smaller cells, enabled by the use of small cell equipment. **We expect this shift to move a larger portion of the revenue pool from RAN/basestation equipment to small cells**.

5G small cells can emerge as a competitive technology to WiFi, given they will have comparable speeds and compete for similar physical space. WiFi offers consumers uncapped internet connectivity (for the most part), in contrast to consumption based cellular services. We would not expect 5G networks to impact the $4.5bn Enterprise WiFi market, as enterprises like to have control over their networks, and as WiFi is the cheaper solution given it leverages their existing wired networks. However, **the $300mn Service Provider WiFi market could be partially cannibalized by 5G small cells**, in particular the mobile operator portion (as opposed to the cable portion).

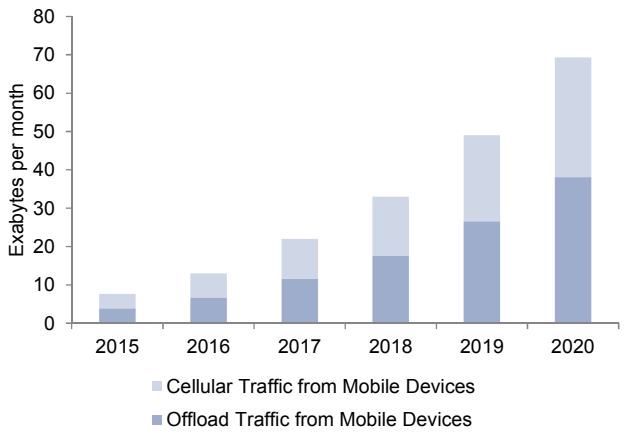
One key debate pertaining to WiFi is if 5G networks (more specifically the aggregation of licensed and unlicensed spectrum) will impact the performance of WiFi networks. For example, LTE-U (LTE unlicensed) and LAA (License Assisted Access) would enable LTE connections in the unlicensed 5GHz spectrum band, which is currently used for WiFi networks. Industry participants such as Qualcomm and Ruckus believe that the rules behind LTE-U and LAA can allow them co-exist with WiFi because of "listen-before-talk" protocols that manage interference.

Exhibit 17: Traffic offloaded from cellular networks is higher on next-gen networks
Cellular traffic vs. offloaded traffic by cellular technology



Source: Cisco VNI, 2016.

Exhibit 18: A majority of mobile traffic is expected to be offloaded from cellular networks
Cellular traffic vs. offloaded traffic



Source: Cisco VNI, 2016.

We believe the 5G vs. WIFi decision will be based primarily on whether an operator owns licensed spectrum. For example, wireless operators AT&T and Verizon have not been adopters of outdoor WiFi technology and instead rely on licensed spectrum. We would expect this to continue following advances in 5G. This contrasts with US cable operators, which have deployed millions of WiFi access points. WiFi remains a suitable solution for cable operators and fixed line operators since it enables wireless connectivity offerings without needing licensed spectrum. **We would expect WiFi to remain the dominant wireless connectivity technology for companies without licensed spectrum.**

To combat any threat presented by 5G networks, WiFi vendors are pursuing technology advances for WiFi. One example is the WiFi Alliance's HotSpot 2.0, which enhances the onboarding, security, roaming, and handoff features of WiFi connections, in an effort to create an experience more akin to a cellular service. **WiFi standards are also evolving for higher capacity connections (Wave 2 802.11ac) and offer a roadmap towards a broader range of IoT applications** (like .11ah for high frequency, high capacity, short range connections and .11ad in low frequency, low capacity, long range connections).

More fiber links from the cell sites to the data centers

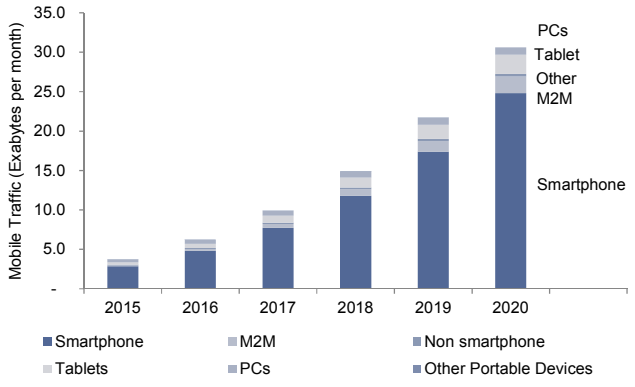
Whether it's high speed cellular connections, fixed line wireless, or disparate IoT endpoints, 5G networks will drive more traffic (and likely complexity) on wired and backhaul networks. This will require high capacity and large fiber connections. Therefore, in general, we see 5G connections driving continued investments in fiber network upgrades, particularly around next generation technologies like 100G, 200G, 400G, 1Tb optics. This should prove positive for both optical system vendors (like Ciena, Cisco, and Infinera) as well as optical component suppliers (Lumentum, Finisar). Ciena estimates 5G networks could ultimately drive up to 1000X increase in bandwidth per unit area, based on 100X more connected devices and up to 10Gbps connection rates to mobile devices.

Exhibit 19: Next-gen cellular networks enable high bandwidth connections, adding to network traffic
Mobile network technology upload/download rates

Wireless Standard		Upload Rate	Download Rate
2.5G	GPRS	20 Kbps	114 Kbps
2.75G	EDGE	60 Kbps	384 Kbps
3G	UMTS	64 Kbps	384 Kbps
	W-CDMA	153 Kbps	2 Mbps
	HSPA-3.6	384 Kbps	3.6 Mbps
	HSPA-7.2	2 Mbps	7.2 Mbps
Pre 4G	HSPA14	5.7 Mbps	14 Mbps
	HSPA+	22 Mbps	56 Mbps
	LTE	50 Mbps	100 Mbps
4G	WiMAX 2	500 Mbps	1 Gbps
	LTE Advanced	500 Mbps	1 Gbps

Source: Ciena.

Exhibit 20: Mobile traffic is expected to grow at a 53% CAGR from 2015-2020
Global Mobile Traffic by device type



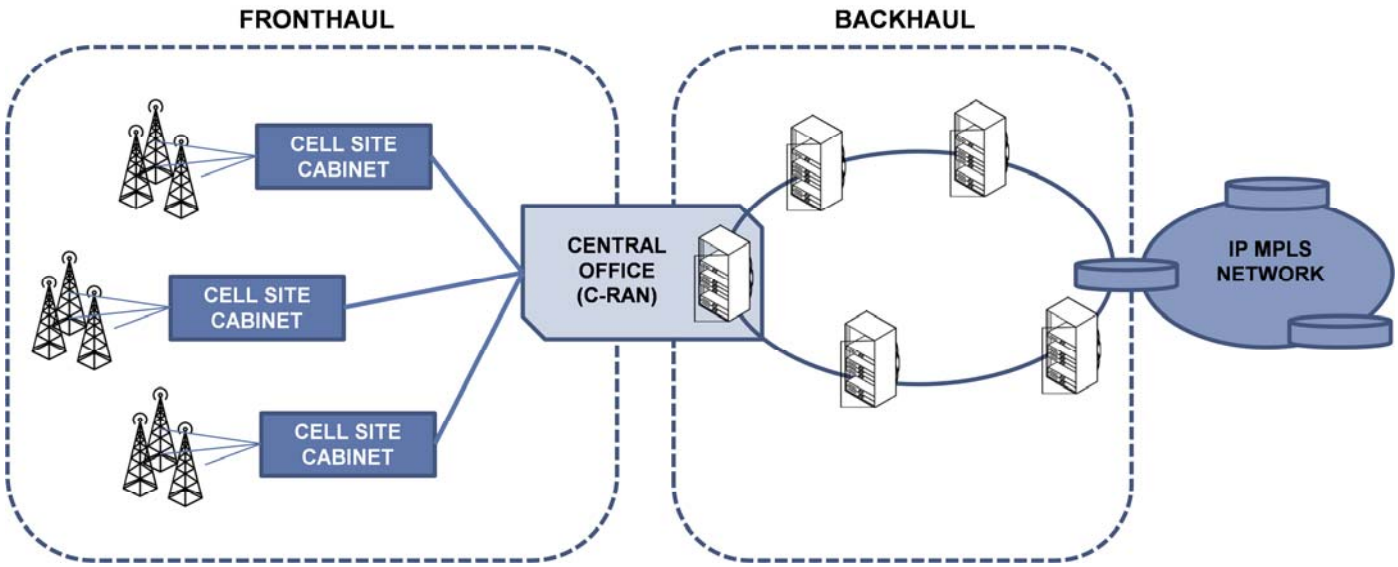
Source: Cisco VNI, 2016.

In addition to elevating the capacity of core networks, mobile traffic has a direct impact on backhaul and fronthaul solutions. These are essentially the connections between the radio tower or cell site and the fixed wireline network.

C-RAN creating a market for mobile fronthaul equipment. Fronthaul pertains to the emerging architecture known as Cloud RAN or Centralized RAN (C-RAN), as discussed on page 17. C-RAN architecture can aggregate up to hundreds of remote radio heads (RRH) or cell sites to a centralized baseband data center. This allows operators to take advantage of

cloud and NFV implementations, creating a more dynamic and efficient network. The optical links that connect the remote radio head and centralized baseband data center is known as fronthaul. Infinera (via its acquisition of Transmode in 2015) estimates the mobile fronthaul equipment market is around $350mn and should ramp in 2017/18. In a C-RAN architecture, the higher wireless network traffic will require expanded capacity between these central office 'data centers' and the rest of the core network, requiring more data center interconnect solutions.

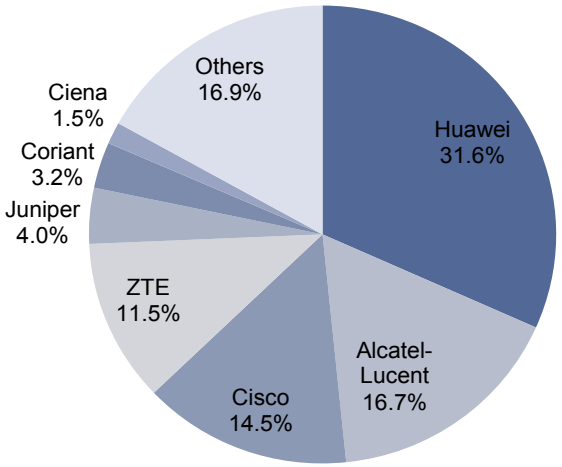
Exhibit 21: 5G networks will drive upgrades in both mobile fronthaul and backhaul wired networks



Source: Company data, Goldman Sachs Global Investment Research.

Mobile Backhaul connects a mobile network (e.g. tower) to the wired network. Fiber-based backhaul offers higher potential bandwidth capacity relative to HFC (hybrid-fiber coaxial), copper, and wireless. According to IHS, the global Ethernet macrocell mobile backhaul equipment market was $3.8bn in 2015, up 1% yoy, led by Huawei, Alcatel, and Cisco (note, including microwave backhaul, the TAM is about $8.4bn).

Exhibit 22: Ethernet macrocell mobile backhaul market share
2015



Source: Infonetics.

From specialized telecom equipment to servers + software

As detailed in page 17 above, in the radio access portion of 5G networks, service providers would be able to separate the radio and the baseband, with only the radio deployed in physical basestations. The baseband (for signal processing) can be deployed in a data center location (cloud RAN or C-RAN) that aggregates traffic from several basestations. In addition, the C-RAN will host other non-real time functions (subscriber management etc.) that can be virtualized and deployed on servers. This means that with 5G we will see a **shift in content away from basestations and other specialized equipment and toward standard servers with NFV**.

NFV (network function virtualization) refers to the delivery of networking functions via virtualized software instances on commodity hardware, as opposed to the traditional delivery via specialized telecom equipment (e.g. mobile packet core, session border controllers, application delivery controllers). A lot of the NFV transformation would already be in place ahead of 5G commercialization. For instance, AT&T has set formal targets around virtualization: it intends to virtualize 75% of its network using cloud infrastructure by 2020. Before it began its virtualization journey, AT&T deployed 300 distinct types of telecom equipment in its network. Among the early use cases for virtualization, AT&T targeted GPON optical line terminal (OLT) equipment, and customer premise equipment (CPE). Other service providers who are actively trialing NFV technologies include Verizon, SK Telecom (Korea), NTT, and Telstra.

The ability of equipment vendors to transition from specialized equipment to NFV will be critical in their ability to maintain relevance in 5G. So far, vendors such as Cisco, Ericsson, Nokia, Brocade, F5 and others have been aggressively moving in that direction. Still, they face a risk that NFV will be net deflationary to their revenues given the higher utilization enabled by virtualized software on commodity hardware. The silver lining is that NFV has higher margins than telecom equipment, given its software-centric nature.

On the flip side, we **expect demand for servers to increase structurally with 5G** as they handle tasks previously addressed with specialized telecom equipment, and as 5G/IoT services proliferate. This will be positive for server vendors, such as Cisco and HP Enterprise,

which haven't historically had much presence in mobile networks. However, these vendors might not benefit if carriers were to adopt white box servers instead, similar to what the major cloud providers have done. In either case, **Intel would be a primary beneficiary**, given its leadership position in the server processor space, where it has 95%+ market share. We also see 5G and the shift to a more software centric network as an important insertion point for chips based on ARM architecture, both for servers and for networking, given its flexible architecture, clear investment roadmap and low power approach.

While it is clear that holistically speaking 5G networks will develop in a more software centric way, with NFV forming the platform for 5G protocols and being relevant not only to base stations but also routing and other "layer 4-7" functions, it is as yet unclear whether the RAN part of the network will be less hardware intensive (vs. software centric) than in 4G. While some vendors expect upgrades to 5G to be enabled to a significant degree by software, others believe that hardware will still retain as prominent a role in the system.

One possible scenario, however, is that although 5G RAN may still be significantly hardware intensive, **the phasing of rollout may be slightly different vs. earlier cycles**. In particular, it is possible that 5G-capable base stations (i.e., capable of running the relevant algorithms and computation for 5G) may be rolled out well ahead of the timeline for mass deployment, with potential for software to upgrade the hardware as appropriate once standards have been fully defined and precise specifications determined. This is analogous to what was seen with the 4G transition from 3G.

Nokia already launched at MWC this year a next generation platform that will be 5G capable in this way. This may have implications for the gross margin trajectory of wireless infrastructure players given that the phasing of software upgrades is a key determinant of profitability.

Network slicing: Now you can have your own network, too

A number of industry participants, ranging from Cisco to Ericsson to Qualcomm, are architecting solutions to enable "network slicing" as a key capability of 5G networks. A network slice is a virtualized network that can be defined according to a set of requirements, for example by geography, latency, reliability, duration, security, capacity, and/or speed. For example, a carrier such as Verizon that runs a nationwide network can sell various slices of that network to various users, parameterized to fit their requirements: e.g. a utility (for managing smart meters and fault sensors), a healthcare company (for medical device monitoring) and a police department (for mission critical first responder situations).

The enabling technologies for network slicing are cloud and NFV (discussed above). Legacy wireless networks were designed in a more inflexible, vertically integrated way – which made sense given that they largely served one use case (cellphone users) with a relatively predictable growth curve and usage pattern. For next-gen 5G networks, key networking functions will be delivered as virtualized software running in the data center or C-RAN, and thus can be configured in various logical network slices that all share the same underlying physical infrastructure.

Increased RF content and complexity from the shift to higher frequency spectrum

We are constructive on the RF market and believe that RF-related companies stand to benefit as wireless operators begin to utilize higher frequencies of spectrum in an effort to increase data speeds and bandwidth. Network operators seeking to enhance their services can achieve this in two ways: 1) by using *more* spectrum, and/or 2) by utilizing *existing* spectrum more efficiently. Given the high cost of spectrum we believe that there is more incentive in the near term for operators to increase the efficiency of their existing networks

by implementing technologies such as carrier aggregation, which allows them to aggregate existing frequency bands into various combinations in order to build a larger data pipe. We expect network capacity on 5G to be greater than that of 4G, which will allow more devices to join the network.

Longer term, we expect operators will need to use more spectrum in order to provide more bandwidth, increasing the number of frequency bands that devices can transmit and receive data on. However, radio interference increases as the number of activated frequency bands increases, requiring additional RF content to filter out unwanted signals. The problem of frequency interference becomes even more acute as operators extend coverage into higher frequencies, which not only increases the overall number of frequency bands, but also the number of possible combinations. Higher frequencies have shorter wavelengths, which require specially manufactured RF filters to isolate transmission signals. We expect an increase in RF complexity to coincide with use of higher frequency spectrum and would therefore favor companies with product portfolios that are strongly positioned in the high performance segment of the RF market. We discuss this further later in our report.

Company overviews

ARM (ARM.L, CL-Buy): Architecture gaining increasing traction with 5G

Covered by: Alexander Duval, European CommTech

ARM is a leader in processor architecture design for chip manufacturers, which it monetizes via its royalty model. While ARM has a dominant market position in the handset vertical, we expect rapid growth in royalties from non-mobile, including in areas such as Networking, Server and IoT/embedded, to drive roughly 50% of incremental royalty revenue growth out to 2020. ARM's licensing and royalty model is extremely scalable with 95% incremental EBIT margins, and we see the licensing base as a key platform for continued market share dominance in mobile alongside progressive share gains in non-mobile. We estimate a path towards 60% underlying operating margins by 2020 (vs. 50% in 2016) and a five year EPS CAGR of c. 20%.

5G strategy

Given that 5G will be crucial in facilitating important use cases for IoT, ranging from mission critical safety applications to autonomous driving to industrial automation, we see ARM as a key beneficiary of the rollout, with its low power and flexible chip architecture set to play a key role in connected end devices. In particular we see its Cortex-M designs gaining increasing traction within areas spanning micro controllers, embedded connectivity, connectivity hubs and wearables. We also see ARM solutions to provide security for embedded devices as a key differentiator in the context of IoT use cases that will be seen in a 5G world. In particular, reliability and robustness will be especially important given the economic risks of hacking/tampering with connected devices in such contexts.

In addition, however, we see 5G and the shift to a more programmable and flexible software centric networks as a key insertion point for chips based on ARM architectures, both for servers and for networking. On the networking side in particular, we note ARM's increasing momentum in gaining wins with key OEMs in light of its flexible architecture, clear investment roadmap and low power approach, all of which are highly suited to 5G, NFV and SDN. We continue to argue that the move toward more open source software entails a need for standardization, with ARM set to become one of the key architectures (gaining share from legacy architectures where investment has been lower e.g. MIPS,

PowerPC). ARM reached 15% share in Networking in 2015 (from 10%) in 2014 and targets 45% by 2020.

AT&T (T, Neutral): Ready for 5G when 5G is ready

Covered by: Brett Feldman, US Telecom Services

AT&T is the second largest wireless carrier in the US based on its 88.7 million retail wireless customers as of the end of 2015. The company generated wireless revenue of $73.7 billion in 2015 representing 50% of consolidated revenue.

5G strategy

AT&T expects that it will be fully prepared to for 5G deployments as soon as the standards-setting body, 3GPP, releases the standards. It expects 3GPP to complete the first phase of that process in 2018 followed by standards for full mobility and interoperability in 2019. Based on this timeline, AT&T plans to implement 5G in two phases: (1) fixed wireless in 2017, followed by (2) fully interoperable mobility, including voice, in 2019-20. However, AT&T is prepared for the standards to be pulled forward, depending on progress within 3GPP, and can accelerate its timelines if appropriate.

In February, AT&T announced plans to collaborate with Ericsson and Intel to work on 5G solutions in AT&T's labs beginning in 2H16, including outdoor tests and trials over the summer. AT&T expects field trials of 5G technologies to provide wireless connectivity to fixed locations in Austin, TX, before YE16. The trials will help guide AT&T's 5G standards contributions and set the stage for widespread commercial and mobile availability once technology standards for 5G are established. AT&T expects 5G to deliver speeds that are 10x to 100x faster than average LTE connections, and it expects 5G latency to range from 1 to 5 milliseconds.

AT&T's current network strategy is macro-centric owing to its large macro-site grid relative to Verizon (66,000 macro-sites at AT&T vs. 53,000 at Verizon). For this reason, it is less immediately focused than Verizon on adding outdoor small cell locations. However, as part of AT&T's accelerated capex program beginning around 2010 (owing to its initial iPhone exclusivity), the company has been deploying a substantial number of in-building systems. The carrier recognizes that small cells will ultimately play an important role in 5G and believes it will have an advantage since it can leverage its existing fiber builds (e.g., U-verse and GigaPower, including business locations), for its small-cell build-out. Further, AT&T expects to leverage its global leadership in SDN to support rapid growth in mobile video consumption. For example, AT&T plans to virtualize 75% of its network by 2020. It completed 5.7% in 2015 and is accelerating to 30% in 2016.

We believe AT&T does not currently own any mmW spectrum licenses, so it would need to acquire or lease them through new transactions, including potential FCC auctions. For AT&T's 5G trials, the company in February applied to the FCC for three-year experimental licenses in the frequency bands of 3.5GHz, 15 GHz and 28 GHz.

Broadcom (AVGO, Buy): Well Positioned to Capitalize on Growth in Wired and Wireless Markets

Covered by: Toshiya Hari, US Semiconductors

Avago addresses both the wireless and wired portions of the 5G network. The company manufactures RF products for mobile devices (est. 15-20% of sales in 2016) as well as products for wired infrastructure applications, including ASIC switches for networking (est. 40-50% of sales in 2016), and optical components. Within the RF market AVGO is most well-known for its FBAR products, which are primarily used for high-end RF applications where there are stringent performance requirements, such as in high frequency filtering for smartphones. AVGO recently disclosed that it had entered into a 3-year pricing contract

with Apple to supply RF content, which we view as a positive for AVGO and the RF industry more broadly as it highlights the importance of RF components within the handset supply chain. With its recent acquisition of Broadcom, we believe that AVGO is also well positioned to benefit from the higher density deployment of small cells, which it addresses with its switching and routing portfolios. Finally, we see continued investments in fiber network upgrades as positive for AVGO's optical business.

5G Strategy

On the wireless side we believe that the importance of the RF industry to mobile communications will only continue to grow with the emergence of 5G networks given the higher performance requirements. AVGO primarily caters to the high performance portion of the RF market and we believe the company is well positioned to benefit from increased RF complexity as more higher-frequency spectrum is utilized. The company has a sizeable competitive moat because RF complexity continues to increase, forcing new entrants to design toward a moving roadmap. Additionally, yields and performance on RF chips improve with time and incumbents have significant patents and trade secrets around the manufacture and integration of RF chips. Within the wired segment we expect AVGO to capitalize on the shift from proprietary ASIC switches to merchant silicon offerings, such as AVGO's Trident/Tomahawk/Jericho chipsets. Merchant silicon vendors offer faster development cycles as they keep pace with Moore's Law, which enables vendors to refocus R&D investments on things such as software differentiation.

China Mobile (0941.HK, CL-Buy): Targeting 5G commercial launch in 2020

Covered by: Donald Lu, Asia Pacific Telecom, Internet and Media

China Mobile is the largest mobile telecommunications operator worldwide, with 826mn subscribers as of 2015. It also provides fixed broadband services with 55mn subscribers as of 2015 after the acquisition of China Railcom. CM is the domestic 4G leader with 312mn 4G subscribers and over 1mn base stations. Going forward, its strategy is to provide bundled mobile-fixed line services to create customer stickiness.

5G Strategy

China Mobile plans to start 5G commercial trials in 2018 and commercial launch in 2020. CM has established a 5G Joint Innovation Lab (JIL) with 11 partners, including Ericsson, Huawei, Nokia, Qualcomm, ZTE, Datang, Intel, Keysight Technologies, Haier, Hisense, and Beijing Shougang Automation Information Technology. The JIL will build a central lab in Beijing, and regional labs in the China Mobile International Information Port, Qingdao, Chongqing and other places. The joint innovation will start with a focus on IoT and industrial internet, including environmental monitoring, flexible manufacturing, smart meters, and smart home etc. For future deployment of 5G, China Mobile hopes to decouple RAN and core network in order to provide more flexible access, more intelligent control, and more open networks.

Cisco (CSCO, Buy): 5G provides a long sought insertion point into wireless networks

Covered by: Simona Jankowski, US Hardware & Communications Technology

Cisco is a leading global provider of networking technology, including systems, software and services, with $49.6bn in revenues in CY15. The company has been a long-standing leader in the $24bn switching industry, with about 62% market share, and switching products drove 30% of total company revenues in CY15. Its second biggest segment, routing, drove 15% of total revenues, as Cisco has about 40% share in the $10bn service provider routing market and 75% share in the near $3.2bn enterprise routing market. In addition to its core switching and routing revenues, Cisco has a leading position in a

number of other categories, including service provider video, which includes video infrastructure and software ($3.4bn in CY15 sales), collaboration ($4.2bn in CY15 sales), Wi-Fi ($2.6bn), servers ($3.4 bn), and security ($1.8bn). Cisco's services business, which was $11.5bn last year, accounted for the remaining 23% of CY15 revenues.

5G strategy

Cisco announced a strategic partnership with Ericsson in November 2015 that includes joint development for 5G, cloud and IoT, and a reseller relationship (Ericsson reselling Cisco equipment). We expect the partnership to strengthen Cisco's position in wireless networks, where Cisco has had limited direct exposure outside WiFi. Cisco's routing, switching, server and networking software products are complementary to Ericsson's radios and can be integrated in a broader 5G solution that leverages the cloud RAN. Recall from the discussion above that the cloud RAN will host the baseband processing in 5G (currently done in the basestation) and as such it represents an insertion point for Cisco. In addition, we expect many services that enable network slicing (also discussed above) to reside in the cloud RAN. We see Cisco participating in the cloud RAN, both as a vendor of data center infrastructure and virtualized network functions, as well as potentially as a managed service provider. In the latter scenario, Cisco would own and operate the data centers and offer IoT services to customers, transforming that portion of its business away from hardware sales and towards a software and services model.

Cisco is a key partner for Verizon in its 5G Technology Forum (alongside Alcatel-Lucent, Ericsson, Intel, Nokia, Qualcomm and Samsung). This would not only allow Cisco to participate closely with Verizon on its 5G commercialization, but also field test its products well ahead of larger scale deployments by other operators. Importantly, Verizon has also formed an alliance with KT and SK Telecom (both operators in South Korea), and NTT DoCoMo (Japan) to collaborate on standardization. This implies that Cisco has an opportunity to expand into those operators' 5G tests as well. Note that SK Telecom is currently working with Ericsson on its 5G pilot network, which could further support Cisco's prospects at the carriers. Cisco also introduced its first 5G router at Mobile World Congress 2016.

Given that IoT would be tightly coupled with 5G, we view Cisco's strong market leading position with IoT technologies as a differentiator. Exiting 2014, IoT was a $2.5bn business for Cisco, growing at 40% yoy. Cisco acquired Jasper in February 2016 for $1.4bn. Jasper is a cloud-based IoT service platform that allows both enterprises and service providers to automate management of IoT services and drive monetization on a global scale. In particular, Jasper offers a SaaS platform for device connectivity management, security, and data analytics, which Cisco can expand to additional services. Jasper has over 3,500 enterprise customers (including Ford, GM, Garmin, Heineken, and Starbucks) and 27 service provider partners in over 100 countries (including AT&T, China Unicom, Telefonica and Telenor).

CommScope (COMM, Neutral): Development of small cell technologies key in 5G

Covered by: Mark Delaney, US IT Supply Chain, Semiconductors

CommScope provides antennas, small cell systems, cables, and connectors for the wireless infrastructure, broadband, and enterprise end markets. Wireless accounts for 40-45% of CommScope's total revenue, and the company's geographic footprint is tied to North America, EMEA and Asia (but with limited presence in China). Its key competitors in wireless include Kathrein, Amphenol, and Huawei (in countries outside the USA), and broader communications and fiber competitors include Corning. CommScope has strong share in multimode antennas and DAS systems.

5G strategy

For 5G, we expect numerous small cell deployments operating at high frequencies to augment the current 4G backbone. In such an environment, individual antennas would be smaller but sold in higher volumes. CommScope's DAS business and recent Airvana acquisition give the company a presence in small cells, and we believe CommScope will need to focus on new technology developments such as beamforming.

Crown Castle (CCI, CL-Buy): The #1 provider of small cells looks best positioned among tower operators for 5G

Covered by:
Brett Feldman,
US Telecom Services

We view Crown Castle as the US tower operator best positioned for 5G; not because of its tower business, but because of its small cell business. As of 4Q15, Crown's small cell business represented 12% of its site rental revenues and was growing over 30% annually. The operator's small cell business is primarily focused on building and leasing outdoor distributed antennas systems (DAS). These are typically dense configurations of fiber-fed wireless nodes that Crown deploys on public rights of way (e.g., light poles) in large markets. As discussed throughout this report, we expect wireless carriers' 5G networks to be based primarily on this type of infrastructure, which will enable them to take advantage of higher frequency spectrum.

While American Tower and SBA Communications do not have a large presence in outdoor DAS, both build and lease indoor systems. We do not anticipate meaningful indoor deployments of 5G in the near- to- medium-term as these systems would most likely leverage millimeter wave spectrum that is not yet licensed for this use. So, this looks like a bigger opportunity beyond 2020. However, we do expect both operators to capture nearer-term demand for indoor systems as carriers densify their LTE networks, especially as higher frequency (3.5 and 5 GHz) spectrum becomes available for LTE operations.

Over time, the major carriers expect to deploy mobile 5G technology across their networks. This will likely require new antennas, and to the extent the carriers are able to utilize higher frequency spectrum in their macro networks, potentially more tower-based cell sites. So, we do anticipate that 5G will create new leasing revenues for tower operators, but this opportunity may not become meaningful until 2020+.

Ericsson (ERICb.ST, Sell): Early mover in efforts to cloudify the RAN

Covered by:
Alexander Duval,
European CommTech

Ericsson is the largest global player in wireless networking infrastructure, i.e. base stations, with a market share of 30%. While this represented 44% of revenues in 2015, we note that 44% of revenues are associated with Services both for installing and maintaining networks. It also offers capabilities around OSS/BSS. The company has a highly global footprint, spanning Europe, Asia and the US (alongside frontier markets).

5G Strategy

Given Ericsson's leadership status in wireless infrastructure and broad regional reach, we expect it to be a significant participant in multiple earlier implementations of 5G, i.e. those in Japan, Korea, China and the US. At Mobile World Congress in February this year, Ericsson stated it had signed 20 MoUs with its customers, and had run 15 industry pilots with 20 companies in different industry segments. As examples, we note Ericsson's engagements with AT&T, Verizon, NTT DoCoMo, SK Telecom and China Mobile.

We note Ericsson's significant yearly R&D budget of EUR 3.5bn, as well as its early mover status in efforts to industrialize implementations utilizing multiple antenna arrays for techniques such as massive MIMO and beamforming. We expect another differentiating factor for Ericsson to be its efforts in splitting the radio and the baseband, as well as work to hive off to the cloud non real time functionality such as subscriber management. We

also see Ericsson as one of the leading players in cellular small cells, which we believe will be important in 5G networks. We also expect Ericsson to seek to leverage its strong capabilities in terms of network rollout, services, planning and integration as a key component of its strategy for 5G.

We note that Ericsson also recently partnered with Cisco, which we see as aimed at reinforcing its ability to work with IP routing technology, which in our view may see increased importance in 5G networks (due to a more distributed network architecture where small cells proliferate).

Intel (INTC, Neutral): Data Traffic Drives Demand for Processing Power

Covered by: Toshiya Hari, US Semiconductors

Intel is the market share leader in desktop, notebook, and server processors and also manufactures products for mobile devices, networking equipment, and memory applications. The company has significant (i.e. 95%+) market share in server processors, the building blocks of datacenters through which worldwide data traffic flows. Intel generates approximately 60% of its revenue from notebook, desktop, and mobile products and 30% from server products. While server processors contribute less on a revenue basis, they contribute about the same amount of operating profit to Intel as PC products (about 48% each).

With the notebook and desktop markets in secular decline, Intel's focus on its more profitable data center business has become more pronounced, in our view. In 2015 Intel acquired Altera in an effort to integrate Field Programmable Gate Arrays (FPGAs) with its processors. FPGAs are devices that can be programmed by the customer "in the field" i.e. customers can reprogram circuits as they wish to execute various tasks. FPGAs are used in a number of applications such as communications infrastructure (base stations) and computing acceleration (where FPGAs compete with GPUs). In the coming years we expect Intel to offer both discrete and on-die FPGA solutions, which should enable the company to benefit from 5G network build outs as well as strengthen its datacenter product portfolio.

5G Strategy

Intel's 5G strategy is three-pronged, in our view: 1) enable devices that generate and consume data, 2) provide products that route data, and 3) provide products that analyze and process data (in ascending order of profitability, compute intensity, and market share).

Intel's product portfolio spans the entire chain of network-connected devices from:

- embedded IoT sensors and smartphones (data generators and consumers, where Intel has low share);
- to base stations (data routers, where there is essentially a duopoly between Altera and Xilinx); and
- to server processors (data analyzers, where Intel has a near monopoly).

In our view though, the primary focus of Intel's strategy is to facilitate as much consumption and transmission of data as possible in order to drive demand for its data center and networking products. Processors for servers can cost $9,000+ and carry significantly higher margins relative to embedded and smartphone chips, which can range in price from $1-$15. Intel's Altera acquisition also provides it with the ability to integrate on-die FPGAs, which are used to accelerate CPUs in compute-intensive workloads such as genomic sequencing, autonomous driving, and big data analytics. We believe these applications will grow as 5G enables the "sensification of things" and more data becomes available for analysis. All of this data will need to be transmitted over a communications network, which Intel also addresses with its FPGAs for base stations.

MACOM (MTSI, Buy): 5G an opportunity to grow in base stations

Covered by:
Mark Delaney,
US IT Supply Chain,
Semiconductors

MACOM is an analog and photonic semiconductor company with about 70% of revenue derived from the communications end market. MACOM's revenue has historically been tied to applications in long-haul optical, CATV, and PON. However, the company is targeting new growth opportunities in base stations, metro, and datacenters.

5G opportunity

MACOM offers GaN on silicon power amplifier chips, and hopes to be able to gain share in the roughly $1 bn annual base station PA end market. We believe that while MACOM has the potential to penetrate this market in late 2016 or 2017 with its GaN on silicon technology for LTE (as MACOM's approach to GaN can be done at competitive costs), we believe that the higher frequencies used in 5G will require the performance of GaN semiconductors that companies such as MACOM offer. MACOM also has analog semis with high gain that could be used in 5G antennas, and we believe the company would also benefit from increased demand for fiber connections.

Mediatek (2454.TW, Neutral): Determined to narrow the gap with Qualcomm in 5G

Covered by:
Donald Lu,
Asia Pacific Telecom,
Internet and Media

Mediatek is a fabless semiconductor company based in Taiwan that provides system-on-chip (SOC) solutions for wireless communications, HDTV, DVD and Blu-ray. In 2015, Mediatek shipped about 400mn smartphone chips including 150mn 4G chips, which represented roughly 35% of China 4G SOC market share, making it No.2 closely behind Qualcomm at 52% market share. In 2016, we expect Mediatek to benefit from the improving EM demand and China demand for 6-mode 4G smartphone. But Mediatek's margin remains a sore spot as a result of ongoing price war with Qualcomm and Spreadtrum, and risk of substitution as the top six system houses including Xiaomi, Lenovo, and ZTE are developing in-house SOCs. Mediatek's announced 1Q16 revenue was 2% below GS estimate, but we expect 2Q16 revenue guidance could surpass GS estimate of 1% qoq growth due to improving China smartphone demand. We see downside risk to our GPM estimates of 39.0% and 38.4% in 1Q16 and 2Q16, respectively, unless non-smartphone margin improves.

5G strategy

Mediatek did not launch its 4G SOC when China Mobile launched its 4G service in major cities in 1Q13. Mediatek's first 4G smartphone (with its SOC) was on the market in 4Q14 when CM already had 14mn 4G subscribers. In 5G, Mediatek has plans to move faster than 4G. Mediatek has progressively participated in 5G standard setting discussions. In February 2015, Mediatek also announced a partnership with NTT DOCOMO on 5G.

Mediatek has not disclosed its 5G SoC schedule given the global 5G standard is not yet fully finalized. Mediatek plans to start its development as early as possible once the standard is set. Mediatek targets to close the technology gap with competitors and support China Mobile and other operators in a timely manner. We note Mediatek has also been more aggressive on process technology at 16nm and potentially 10nm. We expect Mediatek SOC enabled 5G smartphone to hit the market before China Mobile launches its 5G commercial service in 2020.

The profitability in 5G depends on the progress of Qualcomm and Spreadtrum. If Qualcomm continues to collect hefty royalty and use the royalty to subsidize its chipset business, Mediatek and Qualcomm would likely continue to fight it out in mid-tier to high-end SOC. Spreadtrum seems to making good progress in 4G in light of its in-house developed CAT7 SOC, introduced at MWC in February 2015. If Spreadtrum narrows the gap

with Mediatek in 4G and 5G, we expect low margins in all low-end SOC markets. Overall, we are cautious on 5G SOC margins in China.

Murata Mfg. (6981.T, Buy): Major beneficiary of 5G among Japan tech names

Covered by: Daiki Takayama, Japan Electronic Components

Established in Kyoto in 1944, Murata Mfg. today has global market shares of around 45% for multi-layer ceramic capacitors (MLCCs) and 50-60% for surface acoustic wave (SAW) filters. Murata is focusing their strategy on modules combining various components including power amplifiers. The company cemented a dominant position in the global market for passive components as it benefited from the global penetration of set products and rode on technological change with the shift to lighter, thinner/more compact /higher-frequency components. Murata's products are widely employed in wireless communications. We believe the company is poised to sustain growth as the number of installed components rises and applications broaden with the evolution of communications technology from LTE to advanced LTE and on to 5G.

5G Strategy

We see potential for 5G proliferation to significantly hasten Murata's growth. We regard Murata as the key beneficiary of 5G among Japan tech names. Whereas 4G is synonymous with growth for smartphones and an associated increase in Murata's installed components, we expect 5G to stimulate substantial demand for high- to low-end components across a much wider range of applications (smartphones, wearables, autos, energy, healthcare, and robots, for instance). The company's strategy will be critical to determining how it will capture this market.

In the smartphone space, Murata should be able to leverage its strengths in SAW filters as well as ceramic filters required for high-frequency bands. We believe the company has in place the basic technologies necessary for 5G devices, and we expect it to further enhance its product qualities via its module and miniaturization strategies. 5G trials in Japan have supported the solidity of Murata's technology roadmap.

Murata places importance on creating value from information within the various business opportunities presented by IoT. The company provides not only wireless technology but also solutions that integrate sensors and software. Its strategy is to capture the maximum demand for components possible while adding value across the breadth of applications, from those that require high-priced components to those requiring low prices but high volume. We think the company has already made sufficient preparations, and based on management comments, we believe it is ready to consider other strategic options including M&A if its technologies in sensors and software need further strengthening.

Nokia (NOKIA.HE, Neutral): Alcatel deal enhances ability to invest in 5G, fixed line position

Covered by: Alexander Duval, European CommTech

Nokia is one of the three largest global players in wireless networking infrastructure (base stations), with a market share of 25%, following its completed acquisition of Alcatel Lucent, which significantly strengthened its position in the important N. American market. While wireless infrastructure represented 44% of pro forma Network segment revenues in 2015, associated Services are 23% of Network segment revenues. However, by acquiring Alcatel Lucent, Nokia now has significant assets on the fixed-line side. In particular, it now has a solid IP routing asset (25% market share in Edge routing and 7% market share in Core routing in 2015), which represents 27% of Networks segment revenues.

5G Strategy

Following the acquisition of Alcatel Lucent, we now estimate that Nokia will spend c. EUR 4.0bn on Networks R&D in 2016 (vs. Ericsson at EUR 3.5bn), which in our view enhances its ability to invest for the 5G technological transition. Further, prior to the transaction, Nokia's leadership in 4G was largely focused on Japan and Korea, as far as more advanced wireless markets are concerned. However, with the acquisition of Alcatel Lucent, Nokia has strengthened its position in both N. America (where ALU was strongly positioned with Verizon and AT&T) and in China (while we expect some market share reallocation in China following the deal, we continue to see Nokia as one of the best positioned foreign vendors). We note Nokia's announced 5G engagements with Verizon, T-Mobile USA, DoCoMo, SK Telecom and China Mobile.

Moreover, we believe that certain technological bricks brought to Nokia by its acquisition of Alcatel could help it differentiate in a 5G world. In particular, the increased emphasis on small cells in a more distributed network may lead to even greater prominence in the network of IP routing, a capability brought to Nokia by the ALU deal. Moreover, given the rise of SDN/NFV, i.e. increasing requirement for network programmability and flexibility for a plethora of use cases, we see Nuage as a further potential differentiator vs. other wireless infrastructure players.

At the Mobile World Congress in February 2015, Nokia demonstrated multiple 5G use cases including autonomous vehicles, industrial networking of connected robots (with ultra-low latency and high reliability), interactive virtual reality (with 1ms latency) and massive capacity (with delivery of peak data rates of 30Gbps).

NTT DoCoMo (9437.T, Buy): Expected to roll out 5G in 2020

Covered by: Ikuo Matsuhashi, Japan Telecom Services

NTT DoCoMo is the largest communications service provider in Japan, with over 67mn subscribers. DoCoMo has nearly 44% share of subscribers in Japan. The company launched its 4G/LTE services in 2010, and expects to introduce 5G services in 2020.

5G Strategy

NTT DoCoMo is aggressively developing 5G technology and promoting its standardization. However, it is more selective about the full-fledged development of commercial applications than it was before. NTT aims to start 5G services in 2020 to coincide with the Tokyo Olympics. However, considering factors like progress toward standardization, we believe 5G services will be limited to a few areas, mainly central Tokyo, in 2020. For example, we expect 5G technology to be used to stream Olympic events. Based on the progress of Release 16, we do not expect 5G services to expand in earnest until 2023.

Based on our 5G usage assumptions, we do not expect an increase in related capex before 2020. Instead, we believe LTE will be improved to respond to traffic growth. Specifically, we expect the use of 3.5GHz bandwidth, carrier aggregation expansion, 4x4 MIMO, and modulation to achieve 1Gbps LTE. It will be necessary to maintain investment in networks because the antenna, amplifiers, and baseband will be different to those used for existing LTE. NTT DoCoMo aims to achieve a 3.5GHz population coverage rate of 50% by 2019.The definition used for the population coverage rate target has been changed to a more realistic one (coverage in prefectural capitals). Specifically, the 50% coverage target is based on a nationwide grid of 500 meter units.

For Japanese communications carriers, including NTT DoCoMo, we believe the main priority in developing 5G is realizing larger network capacity. European and US carriers, on the other hand, are focusing on IoT.

Qualcomm (QCOM, Buy): 5G could help Qualcomm widen its competitive advantage, similar to 4G

Covered by: Simona Jankowski, US Hardware & Communications Technology

Qualcomm is a pioneer in wireless communications technology. It is a leading chipmaker and sells mobile chipsets (System-on-Chips) and modems to smartphone OEMs. This segment, Qualcomm CDMA Technologies, constitutes about 2/3rd of its revenues and 1/3rd of its profits. The other segment, Qualcomm Technology Licensing, involves licensing its patents to smartphone manufacturers and constitutes about 1/3rd of its revenues and 2/3rd of its profits. Theoretically, Qualcomm gets revenue from every smartphone sold in the world, through chipset sales or through royalty fees.

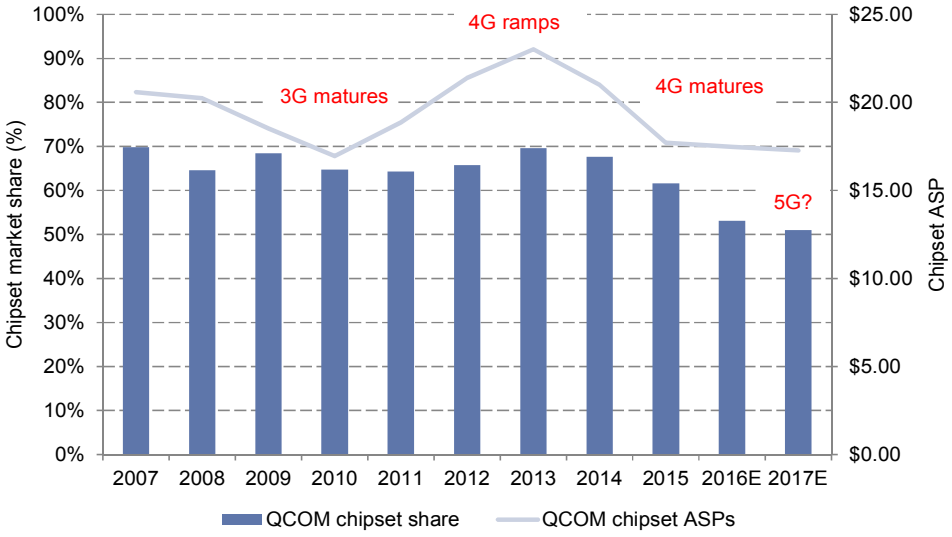
5G Strategy

Qualcomm is heavily involved in 5G standards setting and is working with Verizon for its trials. Its partners include China Mobile, T-Mobile, Ericsson, etc. The company has already invested a substantial amount in R&D for 5G. However, the company still sees a long road ahead, nearly 10 more years, for 4G/LTE evolution globally. Therefore it is committed to LTE evolution, while working in parallel on 5G development. It expects devices will need to be multi-mode (backward compatible with 3G/4G) as 5G will not be available everywhere in early years of the deployment.

Near term, LTE-U and LTE-LAA are opportunities Qualcomm is pursuing. The company is working on demonstrating fair co-existence of LTE-U/LTE-LAA with WiFi. In February 2016, Qualcomm successfully completed the world's first trial of LTE-LAA technology in Germany, along with Deutsche Telekom. Furthermore, the FCC announced in late January that it has granted Verizon and Qualcomm permission to conduct LTE-LAA trials in the US. Qualcomm has also developed MulteFire, which enables LTE connections over unlicensed spectrum. At Mobile World Congress 2016, Qualcomm announced the Snapdragon X16 LTE modem, which is the world's first modem capable of supporting download speeds of 1Gbps, providing fiber-like (wired broadband) speeds over LTE (wireless). Additionally, it supports LTE Licensed Assisted Access (LAA), which indicates Qualcomm's progress in implementing LTE-U and is another step towards the transition to 5G. It also demonstrated mmWave technology at MWC. We think Qualcomm's technology expertise in 4G-LTE, LTE-Advanced Pro, LTE-U, LTE-LAA, and MulteFire will lead the way for it to take early lead in 5G.

We view Qualcomm as one of the primary beneficiaries of the industry's shift to 5G and expect that 5G could propel the company back on the high-growth trajectory. We expect Qualcomm to be at the forefront of the industry transition, much like it has been in previous generation upgrades. Empirically, Qualcomm has shown successful execution in the early years of a new technology cycle, as it can differentiate its products to drive both market share gains as well as premium pricing (Exhibit 23). For example, towards the end of the 3G adoption cycle in 2008-09, 3G chipsets were becoming relatively commoditized, and Qualcomm faced significant pricing pressure from competitors at the time, such as STMicro and Infineon. However, with the ramp of 4G in 2010, Qualcomm commanded near 100% market share in the first couple of years, helping generate double-digit chipset ASP increases in 2011-12. Similarly, we see Qualcomm's chipset business exposed to increasing pricing pressure and market share loss from Mediatek and in-house AP designing in 2015-16 as 4G matures. The transition provides Qualcomm with more opportunities to once again take the lead with differentiated products. Qualcomm could begin benefiting from higher market share and ASPs as commercial deployment of 5G nears. Furthermore, we think it's likely that Qualcomm's TAM outside of smartphones would increase rapidly, as 5G will be a critical enabler for IoT to become mainstream, just like 4G helped wide adoption of smartphones over the last 6 years. However, while large scale commercial 5G deployments will not occur until 2020, in the intertwining years, we believe Qualcomm will develop a new portfolio of patents to enrich its licensing business for the next decade.

Exhibit 23: Qualcomm's chipset market share and pricing tends to benefit at the beginning of new technology cycles
Qualcomm's chipset market share and ASPs relative to key technology cycles; calendar years



Source: Company data, Goldman Sachs Global Investment Research.

Samsung Electronics (005930.KS, Neutral): 5G an opportunity to expand network business

Covered by: Marcus Shin, Asia Pacific Technology

Samsung Electronics (SEC) is one of the largest technology companies in the world, having businesses ranging from hardware products such as smartphones, tablet PCs, and TVs to components such as semiconductors and display panels. Its network business, which sells network equipment, is in the IT & Mobile division, and with revenue of about W3tn, it accounted for around 2% of the company's total sales in 2015.

While the network equipment business sales have been only an insignificant portion of the company's overall sales, SEC has recently denied that it plans to sell the business and showed confidence in its capability to become one of the leading players in the transition to 5G.

5G Strategy

SEC's main strategy in network equipment business in the past has been focusing on sales to domestic players such as SK Telecom, KT Corp., and LG Uplus. For 5G, however, the company has said that it will expand its global business and compete with the global leaders such as Nokia and Ericsson. SEC announced the "5G rainbow" in 2014, which identifies the seven core technical pillars of the 5G technology: peak data rates, cell spectral efficiency, speed of mobility, cell edge data rate, the number of simultaneous connections, latency, and cost efficiency. At the MWC 2016, SEC introduced the world's first mobile handover test using the mmWave radio system which is one of the core technologies in telecommunications. As such, SEC is showing progress in technology development in the 5G space. As the company has shown relatively small presence in the 3G and 4G space, it is actively trying to become one of the leading companies in the transition to 5G, and it is aiming to do so by leveraging its global R&D capabilities and working with global telcos such as Verizon and Deutsche Telecom to speed up the commercialization process.

T-Mobile (TMUS, CL-Buy): Near-term focus is expanding LTE network foundation…5G is later

Covered by:
Brett Feldman,
US Telecom Services

T-Mobile is the third largest wireless carrier in the US based on its 49.3 million retail wireless customers as of the end of 2015. T-Mobile is also the fastest-growing US carrier, having captured more than 100% of industry growth in postpaid phone subscribers in each of the past two years. The company generated revenue of $32.1 billion in 2015.

5G Strategy

T-Mobile believes that LTE is the foundation of everything from a mobility perspective and is mainly focused on improving the breadth and depth of its urban-centric LTE network. This includes repurposing spectrum used for GSM and HSPA+ as fast as possible to free up spectrum for LTE, which could increase its current capacity by 3x, as well as expanding its geographic network presence by deploying LTE in its low-band 700 MHz licenses.

While T-Mobile is not planning pre-standard fixed wireless 5G commercial deployments like AT&T and Verizon, it is preparing for its own 5G trials. In February, T-Mobile announced 5G lab and field trials in 2H16 with current LTE partners Nokia and Ericsson using 28 GHz band spectrum to trial pre-standard 5G components and accompanying use cases that support massive bandwidth capacity and ultra-low latency.

In March, T-Mobile proposed to the FCC to conduct 5G trials using 28 and 38 GHz spectrum over two years, in both inside and outside facilities at its Bellevue headquarters. T-Mobile said the outdoor tests will use mobile end-user equipment operating within 2 km of the fixed devices to gain information on signal propagation between buildings. In each case, T-Mobile will test signal strength, transmission and reception characteristics and other parameters that will be useful as it contemplates how it might include mmW spectrum in its network to support 5G operations. For 5G, T-Mobile owns 200 MHz of 28 GHz spectrum across a large part of the US including in large cities like New York, Miami and Dallas.

T-Mobile expects the initial 5G standards work to conclude in June 2018 followed by a second round in December 2019, and product launches 12-20 months later. T-Mobile expects 5G phones using new chipsets and higher frequency bands to go mainstream in early 2020s. It is currently working with vendors to establish the economics. T-Mobile does not see fixed wireless as a compelling consumer solution today but rather a reasonable starting point that could result in some suburban 5G deployments by 2018-19 which would likely be less focused on mobility.

In T-Mobile's view, the industry should consider new 5G applications when the antenna and radio development solve the macro deployment issues for high-frequency spectrum. For example, T-Mobile is currently working on LTE-A using 4x4 MIMO antennas, up from 4x2 currently deployed. T-Mobile may have 4x4 handsets ready by late 2016 or early 2017. However, 5G requires 64x64 MIMO or 128x128 to achieve economical beamforming. Ultimately, T-Mobile believes that it will take a lot of effort and standardizing to get this technology down to the size of a phone for commercial mobility solutions.

Verizon (VZ, Neutral): Laying 5G groundwork with urban small-cell densification

Covered by:
Brett Feldman,
US Telecom Services

Verizon is the largest wireless carrier in the US based on its 112.1 million retail wireless customers as of the end of 2015. The company generated wireless revenue of $91.7 billion in 2015 representing 70% of consolidated revenue.

5G Strategy

Following its first-to-market global launch of 4G-LTE service in 2010, Verizon has said that it is committed to being the first to deploy and deliver 5G service in the US. Verizon

envisions 5G as a way to satisfy demand in areas of its mobile network where traffic is most dense. As such, it sees LTE remaining at the core of its mobile network for the foreseeable future with an initial 5G overlay in areas where it deploys small cells.

Verizon has a two-phase timeline for 5G trials. In phase-one, Verizon is conducting trials for engineering and commercial needs for end-to-end connections including CPE form factors and line of sight issues. Verizon is performing most of its testing using a minimum channel width of 100 MHz but sees 200 MHz+ as a sweet spot.

In February, Verizon and its 5G technology forum partners announced they have completed tests in which fixed wireless and mobile 5G systems were connected to Verizon's network backbone, and signals were transferred between outdoor and indoor environments in real-world scenarios at its Basking Ridge (NJ) facility, achieving millisecond-range latency and speeds in the range of 3 Gbps using one node. Verizon and Nokia also jointly announced a successful 4K video trial using 5G technology using 73 GHz and 28 GHz providing a fixed wireless broadband services environment. Separately, Verizon and Ericsson announced that (1) radio prototypes applying beamforming and beam tracking delivered speeds above 10 GHz, and (2) outdoor-mounted radio prototypes delivered HD video streaming to devices located indoors, emulating a residential customer environment.

In phase-two, Verizon will conduct trials using the 28 GHz and 39 GHz spectrum it will lease and potentially buy, pursuant to its planned acquisition of XO Communications. Verizon is considering locations for testing based on optimal form factors, local demographics and overall economics. Currently, for example, Verizon expects that deployments in suburban areas would likely have more favorable economics than rural areas.

Commercial 5G deployments will begin with fixed services in 2017. Verizon is planning limited commercial fixed wireless broadband in 2017 using existing assets, followed by a nationwide roll-out in 2018. Verizon recently announced an expanded FiOS deployment in Boston where it will use the fiber to support small-cell densification and as a 5G backbone network.

Verizon does not yet know its 5G mobility timeline, and this is where the standards will play an important role to enable full-mobility smartphones. The carrier sees progress in its 5G forum and is also working with NTT DoCoMo and SK Telecom. In the meantime, Verizon sees two key areas where it needs to continue evolving its network in order to prepare for 5G. These are (1) a centralized RAN design, and (2) fiber density.

Zayo (ZAYO, Buy): The #1 pure-play provider of dark fiber in the US

Covered by:
Brett Feldman,
US Telecom Services

As the largest pure-play provider of dark fiber in large metro markets in the US, we believe Zayo is also well positioned to benefit from 5G in two key ways. The first is site densification to support 5G deployments. While small cell leasing is a small part of Zayo's business today, the operator has indicated that it is seeing increased demand from wireless carriers to attach small cells to fiber that Zayo has deployed to support enterprises and other network operators. This implies that as the operator wins increasingly larger fiber deployments from carriers and enterprise customers, its inventory of metro fiber that can support small cells will expand, which may increase its ability to win small cell business and potentially Zayo's strategic value as the 5G ecosystem develops.

The second is the increasing dark fiber use to connect 5G cell sites to cloud RAN. C-RAN architecture can aggregate up to hundreds of remote radio heads or cell sites to a centralized baseband data center. This allows operators to take advantage of cloud and NFV implementations, creating a more dynamic and efficient network. However, in order for this architecture to work, cell sites need dark fiber connections to the data centers where these network functions are centralized. Owing to its deep and expanding fiber footprint, Zayo looks well positioned to win this business across many major US markets.

ZTE (0763.HK, Rating Suspended): Expect 5G capex cycle to reaccelerate growth

Covered by: Tina Hou, China Technology

ZTE is the second largest telecom equipment vendor in China and the fourth largest globally. It provides both wireless network equipment such as base stations and fixed line network equipment such as OTN, PTN, PON etc. It also has a handset business which generates about 70% of revenue from the US, making ZTE No.4 in the US. The company generates about half its revenues from overseas markets, such as Asia, Europe, and Africa.

5G Strategy

5G will be a fundamental pillar of the "M-ICT" era envisioned by ZTE. In February 2016, ZTE and China Mobile jointly announced their latest 5G high-frequency prototype and demonstrated 10 Gbps+ high bitrate, beam-tracking, and other key 5G technologies. This prototype operates on a 15GHz carrier with a bandwidth of 500MB and has a hardware structure of a large-capacity BBU and an intelligent RRU. In April 2016, ZTE signed a strategic cooperation agreement with China Telecom Beijing Research Institute to develop a number of technologies including SDN/NFV, 4G+/5G, and IoT. Three themes will be central to the 5G landscape: service ubiquity, vast meshes of interconnections, and a more energy efficient future. ZTE believes in the transition towards 5G, network architecture will more closely resemble the cloud structure, which will coordinate heterogeneous types of network resources, managing inter-RAT, inter-frequency and inter-site radio access and interference cancellation to deliver improved network performance at the cell edge.

Together with Chinese telcos' peak capex spending in 2015 on 4G network deployment, we believe ZTE's revenue growth also peaked in 2015 at 23% yoy. The three Chinese telcos' combined capex guidance for 2016 declines by 19% yoy, and we believe ZTE's revenue will be negatively impacted due to its high exposure. The start of telcos' (especially China Mobile) 5G capex cycle should drive the next revenue growth acceleration for ZTE.

Valuation and Key Risks

Exhibit 24: Summary of ratings, price target, valuation methodology and risks

Company Name	Ticker	Current Price	Rating	12-month Price Target	Target Methodology	Risks
ADTRAN Inc.	ADTN	$	Sell	$ 17	19X 2017E EPS	Share gains, CAF stimulus projects, capital returns
American Tower Corp.	AMT	$	Neutral	$ 105	67% 2016E AFFO (19.5X), 17% 2015E EV/EBITDA (17X), 17% DCF (WACC: 7.8%, TGR: 2%)	Downside: Slowing investment in network projects, cell site decommissioning, credit market volatility, and FX exposure Upside: Stronger leasing trends, favorable tower acquisitions or buybacks
ARM Holdings	ARM.L	£	Buy	£ 1400	Royalty DCF	Slower growth in Server/Networking, market share in Mobile
AT&T Inc.	T	$	Neutral	$ 38	1/3 EV/EBITDA (6.8X), 1/3 P/E (13.5X), 1/3 DCF (6.8% WACC, 0.5% TGR)	Downside: Competition, merger integration, the economy, regulation Upside: Revenue/cost synergies, improved core trends, low interest rates
Broadcom Ltd.	AVGO	$	Buy	$ 175	14X normalized EPS of $12.48	Trajectory of the semi cycle, supply/demand in wireless, M&A execution
CenturyLink Inc.	CTL	$	Sell	$ 22	1/3 2016E EV/EBITDA (5.25X), 1/3 Dividend Yield (10.0%), 1/3 DCF (WACC: 6.9%, TGR: 0%)	Improved operating trends, accretive M&A, tax relief/reforms, sustained low interest rates, CAF II support, and use of a REIT structure
China Mobile (HK)	0941.HK	HK$ 90	Buy	HK$ 110	DCF-SOTP	Additional regulatory pressure on data tariff and capex in 2016
Cisco Systems Inc.	CSCO	$	Buy	$ 32	14X CY16E non-GAAP EPS	Macro, service provider capex, commoditization, competition, and execution around the recent executive transitions
CommScope Holding	COMM	$	Neutral	$ 27	12X normalized EPS of $2.25	Key risks relate to revenue, margins, BNS integration, and debt levels
Crown Castle International Corp.	CCI	$	Buy	$ 101	Dividend Yield (3.5%)	Delayed network projects, site decommissioning, credit market volatility, competing technologies, limited land ownership
Ericsson	ERICb.ST	Skr	Sell	Skr 80	7X 2017E EBITDA	Patent negotiations, higher wireless capex and effective cost cutting
Frontier Communications Corp.	FTR	$	Neutral	$ 5.5	1/3 2016E EV/EBITDA (6.1X), 1/3 Dividend Yield (8.0%), 1/3 DCF (WACC: 6.3%, TGR: -0.5%)	Downside: integration risk, competitive pressures, higher interest rates Upside: upside to M&A synergies, improved demand, low cash taxes
Intel Corp.	INTC	$	Neutral	$ 34	SOTP; implied P/E of 12X CY2017 EPS	Consumer PC demand, enterprise and cloud spending, gross margins, and technology transitions
M/A-COM Technology Solutions Holding	MTSI	$	Buy	$ 47	Fundamental (75%): 18X normalized EPS of $2.20 M&A (30%): 22X normalized EBITDA	Key risks relate to product ramps, margins, M&A, laser lead times, and silicon photonics
Mediatek	2454.TW	NT$ 234.5	Neutral	NT$ 235	15X NTM P/B-ROE	Upside: a competitive X20; Downside: FX fluctuation
Murata Mfg.	6981.T	¥ 13395	Buy	¥ 17200	FY3/17E EV/GCI vs. CROCI.WACC; implied P/E of 17.4X	Greater-than-expected yen appreciation, smartphone output adjustments
Nokia	NOKIA.HE	€	Neutral	€ 6.5	SOTP (Networks: 8X 2017E EV/EBITDA and Patents: DCF)	Upside: Better than expected wireless capex, upside to synergy targets, upside to routing market share Downside: Macro impacts in EMs
NTT DoCoMo	9437.T	¥ 2668.5	Buy	¥ 2880	P/B of about 1.9X FY3/17-FY3/18E midpoint BPS	Across-the-board tariff cuts in response to the outcome of Ministry of Internal Affairs and Communications panel discussions
Qualcomm Inc.	QCOM	$	Buy	$ 56	13X CY16E non-GAAP EPS	End demand, competition, execution, M&A, and legal/regulatory actions
Ruckus Wireless Inc.	RKUS	$	Neutral	$ 14	Fundamental (50%): 20X 2016E P/E, M&A (50%): 2.8X 2016E EV/S	Competition, product cycles, higher opex, E-rate seasonality, tech alternatives such as LTE-U, execution
Samsung Electronics	005930.KS	W 1299000	Neutral	W 1300000	P/B-ROE	Better-/weaker-than-expected smartphone margins, component demand
SBA Communications Corp.	SBAC	$	Neutral	$ 110	2/3 2015E AFFO (19.0X), 1/6 2015E EBITDA (17.0X), 1/6 DCF (WACC: 7.4%, TGR: 2%)	Downside: Delayed network projects, cell site decommissioning, growing exposure to emerging markets, credit market volatility, competing technologies Upside: Stronger leasing trends, tower M&A, buybacks
T-Mobile US Inc.	TMUS	$	Buy	$ 47	Standalone (85%): 50% EV/2016E EBITDA (7.6X), 50% DCF (7.3% WACC, 2.2% TGR) M&A (15%): 8.0X EV/2016E EBITDA	Intensifying wireless competition, a need to acquire more low-band spectrum which may require financing, a high debt load
Verizon Communications	VZ	$	Neutral	$ 50	1/3 EV/EBITDA (6.5X), 1/3 P/E (12.0X), 1/3 DCF (6.8% WACC, 0.5% TGR)	Downside: Increased competitive intensity, rising interest rates, economic weakness, regulatory reforms Upside: Rapid LTE smartphone and tablet adoption, new differentiated product launches
Zayo Group	ZAYO	$	Buy	$ 28	10.3X 2016E EBITDA; SOTP (Network Connectivity: 9X, Dark fiber/colocation: 12X, Allstream: 4.7X)	Pricing pressure, customer concentration, M&A integration, low float
ZTE Corp. (H)	0763.HK	HK$ 12.3	Rating Suspended	NA	NA	Not Applicable

Note: China mobile (HK), ARM Holdings, CCI, TMUS are on the regional Conviction Lists.

Source: FactSet, Goldman Sachs Global Investment Research.

Disclosure Appendix

Reg AC

We, Simona Jankowski, CFA, Brett Feldman, Alexander Duval, Daiki Takayama, Toshiya Hari, Donald Lu, Ph.D, Ikuo Matsuhashi, CMA, Marcus Shin, Doug Clark, CFA, Mark Delaney, CFA, In Young Chung and Tina Hou, hereby certify that all of the views expressed in this report accurately reflect our personal views about the subject company or companies and its or their securities. We also certify that no part of our compensation was, is or will be, directly or indirectly, related to the specific recommendations or views expressed in this report.

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