EQUITY RESEARCH GLOBAL

Telecom Services
The Geopolitics of 5G and IoT

Key Takeaway

Behind the complicated technology lie significant geopolitical forces that drive the current development of 5G and IoT standards, as well as selection of 5G spectrum. China wants to be a leader; the US thinks it is ahead in mmWave, Japan and Korea lean toward supporting the US, and Europe is more relaxed but practical. A deeper look at the tech explains the geopolitical landscape, and supports our view that China will roll out 5G fast and big.

5G an opportunity of the century to China. China did not have any say in 2G, developed a China-only standard in 3G, and finally had some participation in 4G (TD-LTE). 5G will be a single, global new standard, and thus gives China a brand new opportunity to be a significant player. 5G is very different from 4G since it is not only about much faster data for humans, but more about massive machine connections and low-latency services. To protect legacy 4G investments, the 3GPP/ITU will develop a Phase 1, which is much more similar to 4G, and Phase 2, which is more revolutionary. For Phase 2, the waveform, modulation, multiple access, and channel coding could all be different.

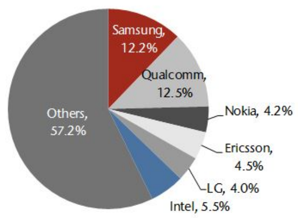
IPRs are up for grabs. IPRs for cellular tech have always been controversial since there are a large number of tech components that together make it work. What is "standard-essential" is sometimes a court's decision. China has never been a player in this game. Even the home-grown TD-SCDMA standard did not give China any edge since it was built upon Qualcomm's CDMA platform. Now there is a new game, and China can almost have a fresh start. However, strong incumbent players will not give way easily. On Aug 28, the 3GPP decided to adopt OFDM as the waveform for 5G Phase 1, basically the same as 4G LTE. At least Huawei's Polar code has been accepted as the coding method for the control channel. But, as we all know, Phase 1 is for protecting the incumbents. Phase 2 is the new game, and it will be finalized by mid-2018. We await eagerly the decisions on the various components, which Chinese players have made plenty of proposals for.

Why some operators say 5G will cost less than 4G? Mainly because we always tend to look for simple answers even for a complicated question like this. First, operators who decide to migrate to Phase 1 only, and only in high-density urban areas, will give you this answer. Second, capex always depends heavily on the ultimate coverage and capacity. Without stating these two assumptions, the answer may not be fair. Third, we believe China is mainly interested in Phase 2, and wants wide coverage to support its IoT and big data initiatives. That is why we believe 5G in China will cost more than 4G.

High frequencies vs low frequencies? We believe this is the major source of geopolitical tension. Practically, low frequencies (<6GHz) are congested but provide much better wide-area coverage. High frequencies (> 24GHz), also called mmWave, can offer much wider, cleaner bandwidth but has tech challenges such as rain fade, tree blockage and short transmission distance. China clearly preferred low frequencies for coverage (that's one reason we believe China wants to build nationwide coverage), which is supported by Europe. However, the US is pushing for mmWave since it may have a tech edge, and lots of its 3-6GHz is being used (including military). KT in Korea and DoCoMo in Japan tend to support mmWave and are keen to roll out 5G in 2018/9. Therefore, we believe China wants a first-mover advantage by rolling out 5G at low frequencies fast to scale up the supply chain and lower equipment cost for the rest of the world. This is to pre-empt mmWave from gaining scale ahead and become the tech of choice by other markets.

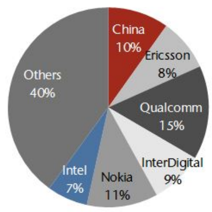
The ITU/3GPP a major political arena. These are UN organizations and 3GPP uses a consensus building approach to agree on tech specs. China (mainly Huawei and China Mobile) has aggressively sought leadership positions in both to raise its influence, which has irritated the US and other incumbents. But we believe China's influence will continue to rise.

Chart A: Distribution for Seminal Patents for 4G-LTE



Source: iRunway 2012

Chart B: Shares of 5G-Essential Patents



Source: LexInnova

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^Prior trading day's closing price unless otherwise noted.

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Executive Summary

5G is the opportunity of the century to China

China owns few IPRs in mobile tech despite being the largest market in the world

China is transitioning from a technology adopter to a technology innovator across many industries. Telecom is a big area where China tried before (in 3G) but failed. Qualcomm, Nokia, Ericsson, Samsung and LG continue to dominate the IPR chart of mobile tech, even though China is the world's largest mobile market by subscriber and network size.

5G will be a game where China can re-set its position

But 5G will create a brand new opportunity for China since the technology needs to be totally redesigned to address the three use cases: 100Mbps minimum data speed for consumers, massive machine connections and super low latency and reliable services. China can participate in the design process from day one, and it has.

5G tech standard is divided into Phase 1 and 2

5G technology standard will be divided into two phases. Phase 1, which is backward compatible with 4G LTE to protect legacy investments, will be finalized by the end of this year. Owing to the backward compatibility constraint, Phase 1 can satisfy mainly the high-speed consumer use case only. Phase 2 will be based on an all-new design that can address all three use cases, and will be finalized in mid-2018.

Table 1: Key Technologies in the Physical Layer of Radio Access

Standard	Waveform	Modulation	Duplex	Channel Coding
GSM	FDMA/TDMA	Gaussian Frequency Shift Keying (GFSK)	FDD	Turbo
CDMA	CDMA with a carrier spacing of 1.23 MHz (direct sequence, spread spectrum)	quadrature-phase shift keying (QPSK)	FDD	Turbo
WCDMA	CDMA with a carrier spacing of 5 MHz (direct sequence, spread spectrum)	mainly based on Phase Shift Keying (PSK)	FDD	Turbo
CDMA2000	CDMA with a carrier spacing of 1.25 MHz (direct sequence, spread spectrum)	QPSK, 8PSK and 16QAM as possible modulation schemes depending on the handset's RF environment	FDD	Turbo
TD-SCDMA	TDMA/CDMA with a carrier spacing of 1.6 MHz	QPSK/8PSK/16QAM	TDD	Turbo
4G LTE	OFDM (downlink) and SC-FDMA (uplink), with a carrier spacing of 180KHz. Channel width scalable at 1.4, 3, 5, 10, 15 or 20MHz	QPSK/16QAM/64QAM	FDD or TDD	Turbo
5G Phase 1	OFDM (downlink) and SC-FDMA (uplink)	Downlink: QPSK, 16QAM, 64QAM, 256QAM Uplink: Pine/2-BPSK, QPSK, 16QAM, 64QAM and 256QAM	FDD or TDD	Quasi-cyclic LDPC codes for transport blocks, Polar codes for PBCH & Control information

Source: ITU and 3GPP

The Phase 1 radio access set up is similar to LTE, except channel coding

On August 28, 3GPP announced that it decided to adopt OFDM (downlink) and SC-FDMA (uplink) as the waveform for 5G Phase 1 radio access, supporting both FD and TD duplexing. That is exactly the same setup as in 4G LTE. However, the channel coding methodology has changed. It dropped Turbo Coding in favour of 1) LDPC for data channel, and 2) Polar Coding for control channel. It is important to note that Polar Coding is a solution proposed by Huawei based on its R&D.

Physical layer of radio access is regarded as the crown jewel

Radio access has attracted the most R&D competition, and is split in three layers: physical, medium access control (MAC) and radio resource control (RRC). Since the shapes and properties of electrical connectors, the frequencies to broadcast on, the modulation scheme to use and other basic parameters are all specified in the physical layer, it is considered the most high-profile part of a cellular technology standard.

The following are the key technologies of 5G (all radio access related except the last one):

These are the key 5G technologies being developed and proposed

Waveform – there are several candidates, including FB-OFDM (ZTE), F-OFDM (Huawei), UF-OFDM (Nokia), NOMA (DoCoMo) and CP-OFDM (Ericsson). Note that these are mostly variants of OFDM except for NOMA. CP-OFDM is in fact the same as what is currently used in 4G LTE.

Duplex – either half-duplex supporting both FD and TD, or full-duplex (no more splitting of channels)

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Channel coding – LDPC for data channel and Polar Coding for control channel have been chosen for Phase 1. The same coding methods will likely be adopted for Phase 2.

Massive MIMO - It deploys a large number of 2-dimensional arrays of active antennas at the base station in order to increase signal strength and deliver more focused beams that achieve mass machine connections and increase transmission distance. The larger number of antenna elements allow the base station to focus its energy only where it is needed, thus reducing both interference and total radiated power.

Massive beamforming – At higher frequencies, the antennas become smaller, making it possible to pack more elements into them. With more elements, the beams can be steered to focus its transmission toward the targeted receiver. But it will require powerful computational capabilities and a complicated algorithm at the baseband.

C-RAN - A large number of remote radio units (RRU) will be controlled by a software-driven baseband unit (BBU). The centralized BBU will be based on open platform with virtualization capability, and can easily and dynamically allocate radio resources among the RRHs based on real-time usage patterns. The RRUs can also communicate with one another with high bandwidth and low latency.

Service based architecture is already adopted for the 5G core network

Service-based core network architecture - 3GPP has already adopted the concept of service-based architecture for the 5G core network, which consists of 1) network slicing, 2) mobile edge computing and 3) the separation of user plane and control plane. Network slicing means the network is flexible enough to dedicate parts of the entire network for different types of services (eg, eMBB, m-MTC and URLLC), by allocating network resources, bandwidth and capacity to properly deliver the required services.

Who owns the cellular technology?

Cellular IPR situation has always been controversial

The IPR situation for the cellular industry has always been murky. A cellular network is composed of a large number of technology components, which were developed by a diverse set of companies. Over time, the incumbents and new players can also contribute new IPRs by improving the existing technology.

Do note that IPR shares in different sources could differ

The analysis of IPR shares among major players is complicated by the fact that it is very difficult to judge which IPRs are really "standard essential." Therefore, IPR share estimates done by different organizations are rarely similar. In summary, China does not own any IPRs in 2G and 3G (except for TD-SCDMA but the details are unknown). In 4G, Chinese firms started appearing. A proprietary analysis done by Jefferies in 2011 showed ZTE with 6% and Huawei only 1%. But ZTE and Huawei do not show up as one of the top 4G IPR owner according to a survey done by iRunway in 2012.

China has aggressively engaged in 5G R&D work

Ever since the ITU started the "IMT-2020 and Beyond" initiative in 2012, various Chinese entities have actively engaged in R&D work in 5G. With its bad experience in 3G, China is determined to be a major player in 5G, with a meaningful IPR share. That is also in sync with China's other strategic objectives in its 13th five-year plan (2016-2020): becoming a leading digital country; aggressively adopting IoT, big data and cloud across all industries; developing its leadership position in ICT technology.

LexInnova reported that China owns about 10% of 5G-essential IPRs

Based on LexInnova's estimate in early 2017, China in total owned about 10% of "5G-essential" IPRs. It divided 5G technology into three areas: radio access (e.g., multiplexing, channel coding and data rate enhancements), modulation (mainly at the physical layer) and core networking. China was estimated to have the highest IPR share in radio access (13.3%), likely due to China's early adoption of TD duplexing.

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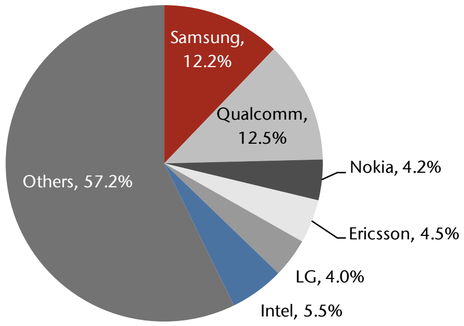
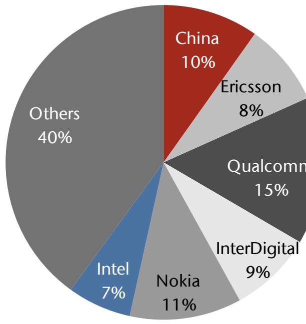


Source: iRunway 2012

Chart 2: Shares of 5G-Essential Patents



Source: LexInnova

Spectrum a major source of geopolitical tension

Global spectrum coordination is done at World Radio Conferences, which are held every 3-4 years. The next one will be held in Oct 2019

Global spectrum coordination is done at the World Radio Conference (WRC), which is managed by the ITU. WRCs are held every three to four years. The last WRC was held in 2015. The next one will be held in October 2019, and 130 member countries are expected to participate. In WRC-19, the main agenda would be to: 1) study further spectrum allocation for international mobile services, and 2) study coordination issues of previously allocated spectrum (in 2015) for 5G to ensure there will be no interference with incumbent users.

One 5G requirement on the spectrum allocation is a minimum of 100MHz contiguous spectrum to provide a high data speed and capacity

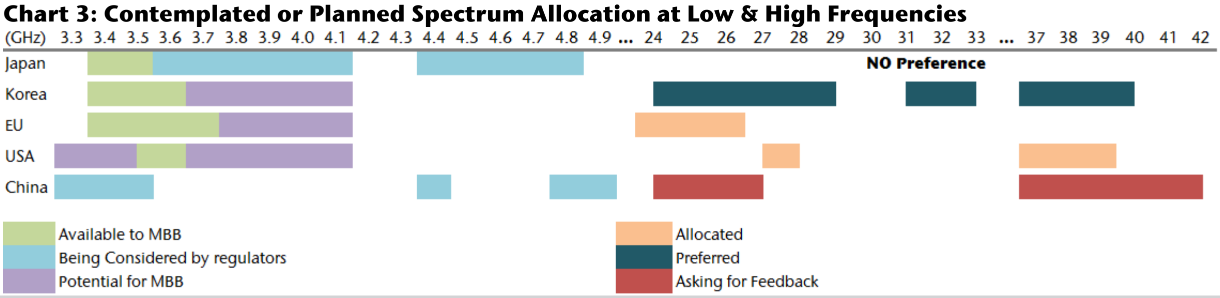
One important 5G requirement to enable much higher data speed and capacity is the availability of much more radio spectrum. The 3GPP has established the specification that, in order to provide proper 5G services, a cellular network will, ideally, need minimum contiguous spectrum of 100MHz. In WRC-15, the following spectrum was identified to be candidates for 5G services globally.

Table 2: Spectrum Identification for 5G at WRC-15

Low Frequencies (GHz)	High Frequencies (GHz)	High Frequencies (GHz)
3.4 -4.2	24.25 - 27.5	50.4 - 52.6
	31.8 - 33.4	66 - 76
	37 - 43.5	81 - 86
	45.5 - 50.2	

Source: WRC-15

Chart 3: Contemplated or Planned Spectrum Allocation at Low & High Frequencies



Source: GSA, FCC, MIIT, EU and MSIP

China treats low frequencies as the core while the US treats high frequencies as the core

These are our observations of the global 5G spectrum issues

- **China treats low frequencies as the core**, and high frequencies as a supplement
- **The US treats high frequencies as the core**, and low frequencies as a supplement, likely because most of its low frequencies are being occupied, and some by military uses.

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- **Some US academia (eg, NYU, UT at Austin and U of Wisconsin at Madison) claimed they have achieved breakthrough at mmWave technology,** making it not only a viable but attractive wireless spectrum.
- **Some US operators seem to be keen to build 5G early at 28GHz, but this frequency is not included in the WRC-15 identification list**.
- **Korea seems to support US choice of high frequencies**. KT is launching limited 5G services during the Winter Olympics in 2018 at 28GHz.
- **The MIC of Japan seems to be neutral on spectrum choice**. However, DoCoMo supports high frequencies while Softbank is keen on low frequencies.

EU has made allocation at both low and high frequencies

- **The EU is practical** and has made allocation at both low and high frequencies.
- **The 3GPP technical specification work so far is focused on utilizing low frequencies**.

As long as 5G usesTDD, the different sub-bands adopted within the proposed low frequency range will not be an issue for equipment harmonization

- **As long as the multiplexing is based on TDD, national decisions to pick a smaller frequency range will not affect handset equipment harmonization**. A TDD device would work in different sub-ranges within the wider band, without emitting signals outside of those country-specific ranges.
- **Softbank in Japan and China's leading wireless experts disputed the commercial readiness of mmWave**.
- The US just auctioned about 70MHz of spectrum at 600MHz, having raised US$20bn mainly from T-Mobile, Comcast and Dish.

China needs FIRST MOVER ADVANTAGE:

Once 5G at low frequencies is in scale, lower handset and network costs will create a virtuous circle

It will be in China's interest to make a first move in building 5G at below 6GHz in scale as soon as the technology is available. We believe the technology will then be visibly proven to all those operators who have not yet built 5G, the equipment cost (both network and devices) will fall, and handset selections will become plentiful. We expect it to significantly reduce the chance that mmWave will become the dominant mobile technology.

This will also support China's goal to introduce IoT, big data and cloud aggressively

In addition to satisfying China's goal to become a leader in the next-generation ICT technology, building 5G fast and in scale would also help China implement ambitious initiatives in industrial IoTs, big data and cloud to help upgrade all major industries and sustain healthy economic growth.

The ITU and 3GPP is a political arena

ITU and 3GPP are UN organizations

These are UN organizations that are in charge of coordinating among member countries on telecom issues, including spectrum, standards and satellite orbital slots. For the first time, a China representative was elected to become the Secretary-General in 2015.

3GPP is an engineering taskforce that uses a consensus-building approach to develop acceptable tech specs

In 3GPP, where the cellular tech specifications are developed, there are 19 groups each focusing on one part of the technology, and 57 leadership positions (chairman or vice chairman). In the latest election this year, China's representatives occupied 10 of these 57 positions, up from 8 in 2015 (5 from Huawei, 3 from China Mobile, one from ZTE and one from CATT). The number of China Mobile's reps has risen from one to 3 since 2015, implying that the government has high expectations on China Mobile's role in 5G development. But in this year's election, Qualcomm's rep beat Huawei's rep to win the chairmanship at the RAN1 sub-group, which is in charge of developing specs for the physical layer of the radio access network. No Chinese rep has ever been elected into a leadership role in RAN1.

China's aggressive participation in ITU/3GPP irritated some member countries such as the US

China's rising influence in the ITU/3GPP has drawn criticism of other countries, especially the US. One FCC Commissioner recently made the following comments on the ITU/3GPP in an open occasion: "…***there has been a concerted effort by some countries to manipulate these multi-stakeholder bodies. I have heard several reports that some authoritarian governments are now focusing their attention on leadership positions at these organizations so that they can promote their agendas and dictate the future design of not only wireless networks, but also the Internet."*** Regardless of the US comments, we believe China's rising influence at the ITU/3GPP will continue, which is in line with the backdrop of China's growing importance in the world stage.

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The Geopolitics of 5G & IoT

The development of 5G not only involves complicated technologies, but also geopolitical forces

Our view that China will be aggressive in 5G and IoT build-out is positive for ZTE, and negative for CM

Behind the complicated technology of cellular communication lie significant geopolitical forces that drive the current development of 5G and IoT standards, as well as global coordination of 5G spectrum allocation. China desperately wants to be a leader; the US thinks it is ahead in high frequency technology; Europe is more relaxed but practical; Japan and Korea lean toward supporting the US. A deeper look at the underlying technology, which then explains the political landscape, supports our view that China will be motivated to build 5G and IoT as fast and as large scale as possible. Negative for China Mobile and positive for ZTE Corp.

5G: Opportunity of a Century for China

In 2G we followed; in 3G we caught up; in 4G we ran head to head; in 5G we will lead

Cellular technology migration in a China context

The 2G and 3G technologies are mainly controlled by Ericsson, Nokia and Qualcomm

The above is the most popular slogan we have heard and seen in China as far as 5G development goes. In 2G cellular technology (1st generation of digital technology), there were three standards: GSM, TDMA and CDMA, with the first two mostly controlled by Ericsson and Nokia and CDMA owned by Qualcomm. When we moved to 3G in 2008, TDMA converged with GSM into WCDMA (still majority controlled by Ericsson and Nokia), and CDMA migrated to CDMA2000 (still majority owned by Qualcomm).

China developed its own 3G standard: TD-SCDMA

During that time, China (China Academy of Telecommunications Technology in collaboration with Datang Telecom and Siemens) developed its 3G standard: TD-SCDMA. TD-SCDMA combines time division multiple access (TDMA) with an adaptive, synchronous-mode code division multiple access (CDMA) component. Time division (TD) is a duplexing technology (ie, the way multiple analog or digital signals are combined into a single carrier), versus frequency division (FD) for WCDMA and CDMA2000. The advantage of the TD technology is in its high efficiency of handling data traffic. Since the TD duplex scheme is able to utilize the entire spectrum allocated (eg, 20MHz or 50MHz) to transmit data traffic, and data traffic is almost always asymmetric (ie, much more download then upload), it can transmit more data at a higher speed than FD given the same spectrum. The FD duplex scheme, on the other hand, requires an allocation of identical bandwidth for both upload and download, regardless of the traffic's asymmetric patterns. That is why TD does not require paired spectrum, while FD does.

Technical note: TD and FD Duplex Schemes

In order for radio communications systems to be able to communicate in both directions it is necessary to have what is termed a duplex scheme. A duplex scheme provides a way of organizing the transmitter and receiver so that they can transmit and receive. There are several methods that can be adopted. For applications including wireless and cellular telecommunications, where it is required that the transmitter and receiver are able to operate simultaneously, two schemes are in use. One known as FDD or frequency division duplex uses two channels, one for transmit and the other for receive. Another scheme known as TDD, time division duplex uses one frequency, but allocates different time slots for transmission and reception.

Source: www.radio-electronics.com

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Table 3: Chronology of China's Cellular Technology Adoption

Time	Standard	Foreign/Local	Equipment
Before 1994	Analog	Foreign	Buy foreign
1994-2002	CM-GSM	Foreign	Buy foreign
	Unicom-GSM, CDMA	Foreign	Buy foreign
2002-2008	CM-GSM	Foreign	Buy local, reduce foreign
	Unicom-GSM, CDMA	Foreign	Buy local, reduce foreign
2008-2014	CM - TD-SCDMA	Local	Buy local
	Unicom - WCDMA	Foreign	Buy mostly local
	CT - CDMA2000	Foreign	Buy mostly local
2014-now	CM - TD-LTE 4G	Local	Buy mostly local
	Unicom - FD-LTE 4G	Foreign	Buy mostly local
	CT - FD-LTE 4G	Foreign	Buy mostly local
2019 & Beyond	5G	Global	Buy mostly local

Source: Jefferies estimates

The Chinese 3G standard was accepted by 3GPP but the global adoption rate was low due to commercial reasons

TD-SCDMA was accepted by the ITU's 3rd Generation Partnership Project (3GPP) as one of the three 3G standards (the other two are WCDMA and CDMA2000). However, mere acceptance by the ITU does not mean that any countries will have any obligation to adopt the standard. Adoption was driven mainly by commercial considerations of the operators. These considerations are mainly:

1) How easy and costly it is for the operator to upgrade from the current technology standard to the new standard. All GSM and CDMA networks use FD multiplexing technology.

2) Will handsets of a technology standard be widely available at affordable prices and with a large range of models. TD-SCDMA was at a big disadvantage here because a low adoption rate by operators globally would translate into a vicious circle of small scale, high chipset and component prices and high handset prices and a small selection.

3) Will there be many network equipment vendors (or an operator's existing network vendor) that are able to supply equipment of that standard at competitive prices. Given TD-SCDMA was not developed by the traditional western vendors, they were less enthusiastic and it would be less profitable (since they would need to pay royalties to China) to make TD-SCDMA equipment.

The Chinese Government's bet to ask CM to build a TD-SCDMA to draw global adoption was overly optimistic, in our view

In order to kickstart the adoption of TD-SCDMA, China decided to ask China Mobile to build a TD-SCDMA network in its migration from GSM to 3G, while allowing China Unicom and China Telecom to migrate their GSM and CDMA network to WCDMA and CDMA2000, respectively. The Chinese government believed that China Mobile's large scale of subscriber base (500m at that time) and strong balance sheet would be able to develop the supply chain of the Chinese standard into scale. However, that proved to be overly optimistic. Most importantly, handset makers and chipset makers (eg, Ericsson, Nokia, Qualcomm and Samsung) were not interested in producing TD-SCDMA chipsets.

Qualcomm had a disagreement with China on TD-SCDMA's IPR ownership

While China claimed that TD-SCDMA was its own technology, Qualcomm disagreed. Qualcomm argued that a large part of the TD-SCDMA standard was built upon Qualcomm's CDMA radio modulation technology at the physical layer of the mobile network. Therefore, Qualcomm still owns a majority of the intellectual property rights (IPRs) of TD-SCDMA. We believe Qualcomm and the Chinese government finally reached a private and confidential agreement on the patent share on TD-SCDMA.

The migration from 3G to 4G involves a number of significant but subtle changes in the technology:

- As 3GPP (the organization in charge of designing the WCDMA standard) and 3GPP2 (the organization in charge of designing the CDMA2000 standard) merged, they decided to move to a new, single modulation technology, which

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would be more efficient for data transmission. Eventually OFDM was chosen to replace CDMA.

- The core network converged to become 100% IP-based and could support both FD-based and TD-based wireless transmission.

There are only 2 standards for 4G: FD-LTE and TD-LTE

- Therefore, the number of standards narrowed from three to two: FD-LTE and TD-LTE. In fact, an operator can deploy a mix of FD-LTE and TD-LTE technology if it has been allocated both FD and TD spectrum (i.e., FD still requires paired spectrum, TD does not).

The changes in technology have brought about several important changes:

Over 39% LTE devices support the TD-LTE standard

- Handset and chipset makers started to be willing to make dual-mode handsets that work on both FD-LTE and TD-LTE networks. By mid-2017, over 39% of LTE devices support the TD-LTE mode, including 2,156 smartphone models. (***This has dramatically helped China Mobile recover market share in China***)

TD has an edge over FD in handling data transmission

- The superiority of TD technology's ability in handling data transmission, and the rising importance of data traffic in 4G, have increased the adoption of TD-LTE networks globally. According to the Global Mobile Supplier Association (GSA), there were 97 TD-LTE operators in 56 different countries by May 2017. However, the number of TD-LTE operators probably overstated the popularity of TD-LTE, since the majority of these are either small operators, or focus on wireless broadband, or operate a hybrid mobile network with only a small portion in TD-LTE (e.g., China Unicom and China Telecom).

The global popularity of TD-LTE is still limited by:

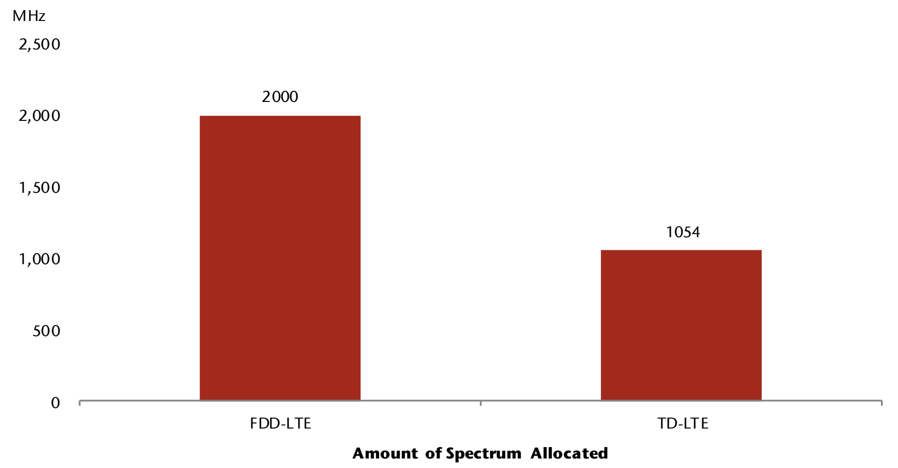
Migrating from WCDMA or CDMA2000 to TD-LTE is costly

1) The unwillingness of operators that adopted WCDMA or CDMA2000 3G networks to migrate to TD-LTE owing to higher costs

2) The much smaller amount of spectrum allocation that has been made for TD-LTE vs FDD-LTE technology.

TD-LTE has a much smaller spectrum allocation compared with FDD-LTE

Chart 4: Global Spectrum Allocation for FDD-LTE vs TD-LTE



Source: ITU

China Mobile is the largest TD-LTE 4G operator globally

Therefore, China Mobile currently remains by far the largest TD-LTE 4G operator in the world (it is in fact the largest mobile operator in the world by subscriber number and base station number, among all standards). Outside of China, one significant investor saw the benefit of the TD technology and decided to adopt it in its networks: Masayoshi Son of Softbank. Mr. Son's Softbank bought Vodafone Japan in 2006, upgraded its network to 3G using WCDMA technology in 2008. In 2013, it upgraded its 3G network to 4G using

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TD-LTE technology. In 2012, Softbank bought a 70% stake in Sprint-Nextel in the US, and subsequently raised its stake to 80%. Sprint also adopted TD-LTE in its 4G network. Therefore, Masayoshi Son was the one that helped China export the TD technology to two large mobile markets: Japan and the US. The other large mobile operator that has adopted TD-LTE in its 4G network is Bharti Airtel in India.

Table 4: Significant Operators that Adopted TD-LTE in their 4G Networks

Operator	Country	No. of subscribers (m)	As of
China Mobile	China	866.5	Jun-17
Softbank	Japan	38.9	Jun-17
Sprint	US	58.7	Mar-17
Bharti Airtel	India	276.5	Apr-17

Source: China Mobile, TCA, Fierce Wireless, The Economic Times

The migration from 4G to 5G will be much more radical than from 3G to 4G

3G migrating to 4G was less radical

The migration from 3G to 4G is less complicated because 1) it still aims to serve consumers using mobile handsets, and 2) the major objective is to increase data speed and spectral efficiency (i.e., more capacity with a given spectrum). 4G spectrum has been allocated mostly at 2GHz to 3GHz, and the spectrum size is usually 2x20MHz (paired spectrum for FD-LTE) or 20MHz to 50MHz for TD-LTE (unpaired spectrum).

But there are still some major changes in the network design

Since 4G is intended to be a more data-centric network than 3G (voice will be handled by the operator's 2G/3G network in circuit switched, or by the 4G network if it has built the VoLTE functionality), the major considerations of the 4G network design are: 1) a 100% IP-based core network, 2) a modulation methodology that can transmit data efficiently to multiple users simultaneously with minimum interference, 3) integrating TD with FD in the duplexing end because TD proves to be a much more efficient duplexing method for data transmission (but most operators around the world have FD-based 3G networks – so 3GPP members would have to protect their legacy investments).

3GPP chose OFDM as the downlink access scheme and SC-FDMA as the uplink scheme

The 3GPP decided to choose OFDM (orthogonal frequency-division multiplexing) over CDMA as the 4G downlink access scheme (from base station to handset) mainly because OFDM enables efficient transmission of high bandwidth data with high resilience to reflection and interference. On uplink (from handset to base station), it chose SC-FDMA (single-carrier, frequency division multiple access) as the access scheme since it provides lower peak-to-average power ratio, which means lower power requirement on the RF power amplifier in the handset, reducing both the cost and size of the handset.

Table 5: 4G LTE Basic Specification

Parameter	Details
Peak downlink speed 64QAM (Mbps)	100 (SISO), 172 (2x2 MIMO), 326 (4x4 MIMO), 1024 (8x8)
Peak uplink speeds (Mbps)	50 (QPSK), 57 (16QAM), 86 (64QAM)
Data type	All packet switched data (voice and data)
Channel bandwidths (MHz)	1.4, 3, 5, 10, 15, 20
Duplex schemes	FDD and TDD
Mobility	0 - 15 km/h (optimised),
	15 - 120 km/h (high performance)
Latency	Idle to active less than 100ms
	Small packets ~10 ms
Spectral efficiency	Downlink: 3 - 4 times Rel 6 HSDPA
	Uplink: 2 -3 x Rel 6 HSUPA
Access schemes	OFDMA (Downlink)
	SC-FDMA (Uplink)
Modulation types supported	QPSK, 16QAM, 64QAM (Uplink and downlink)

Source: 3GPP

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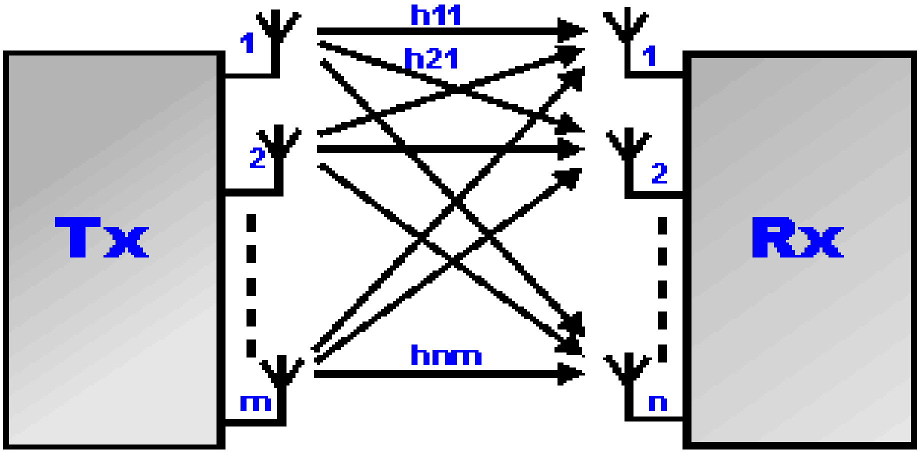
MIMO technology in 4G enhances the data transmission capacity

Another important technology deployed by 4G to increase spectral efficiency is multiple input, multiple output (MIMO). MIMO uses multiple signal paths enabled by the use of multiple antennas at both the transmitting equipment (i.e., base station in a cellular network) and receiving equipment (i.e., handsets) to increase the amount of data that can be transmitted within a channel. It also requires more digital signal processing power at the transmitting and receiving equipment (i.e., chipsets). In 3GPP Release 10 (2011), high-order MIMO was introduced, which can accommodate 8x8 downlink (max 8 antennas at the base station) and 4x4 uplink (maximum 4 antennas at the handset). However, the majority of 4G LTE base stations nowadays have only 4 antennas, and most 4G handsets have 2 antennas.

Chart 5: Basic Scheme of MIMO in a Cellular Network



Tx = Transmitting equipment (base station)
m = number of antenna at the transmitting equipment
Rx = Receiving equipment (handset)
n = number of antenna at the receiving equipment

Source: Jefferies

The 3 5G use cases include eMBB, m-MTC and URLLC

5G will be a completely different technology because its intention is to serve both consumers and machines, and is designed to satisfy three use cases:

- **eMBB** – enhanced mobile broadband – this is to provide consumers with very high speed data services (up to 10Gbps at the peak) using handsets
- **m-MTC** – massive-machine type communications – this is to provide simultaneous connections with a much larger number of devices (e.g., handsets, sensors, wearables) per square kilometer, mainly for IoT services
- **URLLC** – ultra reliable, low latency services – the purpose of this design is to reduce the current average data transmission latency in the mobile network from 10-40ms to 1ms or below, in order to support services such as autonomous driving (where long latency could result in crashes), remote drone control and telemedicine.

The ITU proposed the minimum performance requirement for 5G in Feb 2017

In February 2017, the ITU officially published a set of minimum performance requirements for 5G (or IMT-2020 as officially named in the ITU), which is a result of extensive discussions among regional standards bodies, network operators, equipment makers, government regulators and academic research institutions. This set of requirements is expected to be officially approved by the ITU-R Study Group 5 in November 2017.

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The key features are much higher data speed, massive connectivity, much higher reliability and much lower latency

Table 6: 5G Minimum Performance Requirements

Data Rate	**Downlink**	**Uplink**
Peak data rate	20 Gbit/s	10 Gbit/s
Peak spectral efficiency	30 Gbit/s/Hz	15 Gbit/s/Hz
User experienced data rate	**100 Mbit/s**	50 Mbit/s
Latency	**eMBB**	**URLLC**
User plane latency	**4ms**	**1ms**
Control plane latency	20ms	
Connection density		**1,000,000 devices/km2**
Energy efficiency	Efficient data transmission in a loaded case	
	Low energy consumption when there is no data	
Reliability		1-10^-5 success probability of transmitting a layer 2 PDU of 32 bytes within 1ms
Mobility (at which usable)	**Mobility**	**Normalized traffic channel link data rate**
Indoor Hotspot - eMBB	0-10 km/h	1.5 bit/s/Hz
Dense Urban - eMBB	0-30 km/h	1.12 bit/s/Hz
Rural - eMBB	0-120 km/h	0.8 bit/s/Hz
	120-500 km/h	**0.45 bit/s/Hz**
Mobility interruption time	0 ms	
Bandwidth	100 MHz	

Source: ITU

The latest 3GPP timetable of 5G standardization is as follows:

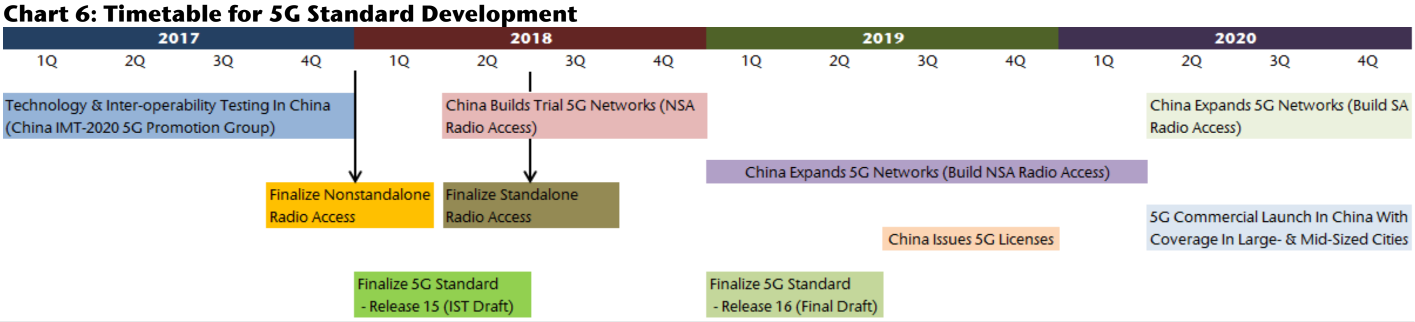
End of 2017 – finalize the non-standalone (NSA) radio access technology. NSA means it will be backward compatible with 4G LTE, by adopting the 4G LTE standard at the control plane of the mobile network. The NSA radio access will be capable of satisfying the use case of eMBB, but not, fully, those of m-MTC and URLLC.

1H2018 – publication of the final version of Release 15, which is the first draft of 5G standard

Mid-2018 – finalize the standalone (SA) radio access technology. SA means it will not be backward compatible with 4G LTE. Both the control plane (CP) and user plane (UP) of the mobile network will be newly designed. The SA radio access will be capable of satisfying all three ITU-defined 5G use cases: eMBB, m-MTC and URLLC.

1H2019 – publication of the final version of Release 16, which will be the first full version of 5G standard.

Chart 6: Timetable for 5G Standard Development



Source: 3GPP, China IMT-2020 5G Promotion Group, Jefferies

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One may be surprised to find out that the minimum performance requirements of 5G will be officially approved at a similar timeframe as the first version of the 5G technology will also be finalized. The simple question is, should the performance requirements have been finalized first before the ITU started developing the technology standard?

The 5G performance requirements are developed as the standards are being worked on

This reflects the iterative aspects of the ITU process as well as the amount of procedures and bureaucracy in this organization. While the group has come up with a set of performance expectations for 5G, the technological development would start before the performance requirements are finalized. The technology development process would provide feedback on what performance requirements are achievable and realistic, while the members of the ITU continued to discuss and negotiate what performance requirements could be dropped and what had to be kept. Therefore, the two processes took place in parallel. This way, the final set of minimum performance requirements will definitely be technologically and commercially achievable.

The key 5G technology components

The physical layer is sometimes called the "crown jewel"

Radio access is one of the most important technologies of a mobile network

The core technology of a mobile network is radio access. It is about how signals (voice or data) are transmitted between a base station and the terminal (i.e., a mobile phone or a wearable device). In the early days, only voice was transmitted, and the challenge was how to allow more users and thus voice traffic to be transmitted within a limited amount of spectrum. Now the challenge is how to transmit 1) much more data and at a much higher speed over the network using the same amount of spectrum, 2) to a much larger number of devices simultaneously, and 3) at a low latency (i.e., transmission time, but different from speed). Another key consideration is the amount of spectrum and frequency level that can be made available for 5G. Since spectrum is a public resource, the decision on how much spectrum and at what frequency level that can be allocated for 5G service is inevitably a government's decision in each country. However, the amount of spectrum and frequency level available will have impact on the performance and requirement of the mobile technology.

The amount of spectrum and frequency allocated will also affect radio access

CELLULAR THROUGHPUT FORMULA:

Throughput* = *Cell Density* x *Available Spectrum* x *Spectrum
(bit/s in area) (Cell/Area) (in Hz) (bit/s/Hz/Cell)

The above formula is a simple relationship between the total throughput (amount of data transmitted per second) in an area (usually per square kilometer) of a mobile network and the three major factors: A) cell density, B) available spectrum, and C) spectral efficiency. If B) and C) are held constant, a mobile operator can increase a network's capacity by building more base stations per square kilometer. However, it is a very expensive option and impractical most of the time because the operator will unlikely be able to find enough physical sites to house a large number of base stations in a small area.

Merely increasing cell density to boost throughput can be expensive

As far as the amount of spectrum goes, it is limited by government allocation since it is a scarce public resource. In many markets (e.g., USA, Europe, India and Hong Kong), spectrum is auctioned by the government to operators and, therefore, the upfront cost to operators could be very high. In all countries, spectrum allocation is managed by the government. It is highly unlikely that an operator can obtain more spectrum after an allocation/auction, which is usually associated with the issue of a mobile license.

Acquiring more spectrum from the Government could also be costly

Consequently, the focus of mobile operators and equipment makers has been to increase spectral efficiency. As the amount of data traffic has been skyrocketing, and the amount of spectrum is limited, one of the key objectives in designing the 5G technology is to deliver 10x to 20x faster data speed (20Gbps peak data rate) and drastically increase data volume capacity per unit of spectrum.

Enhancing spectral efficiency is the focus of operators

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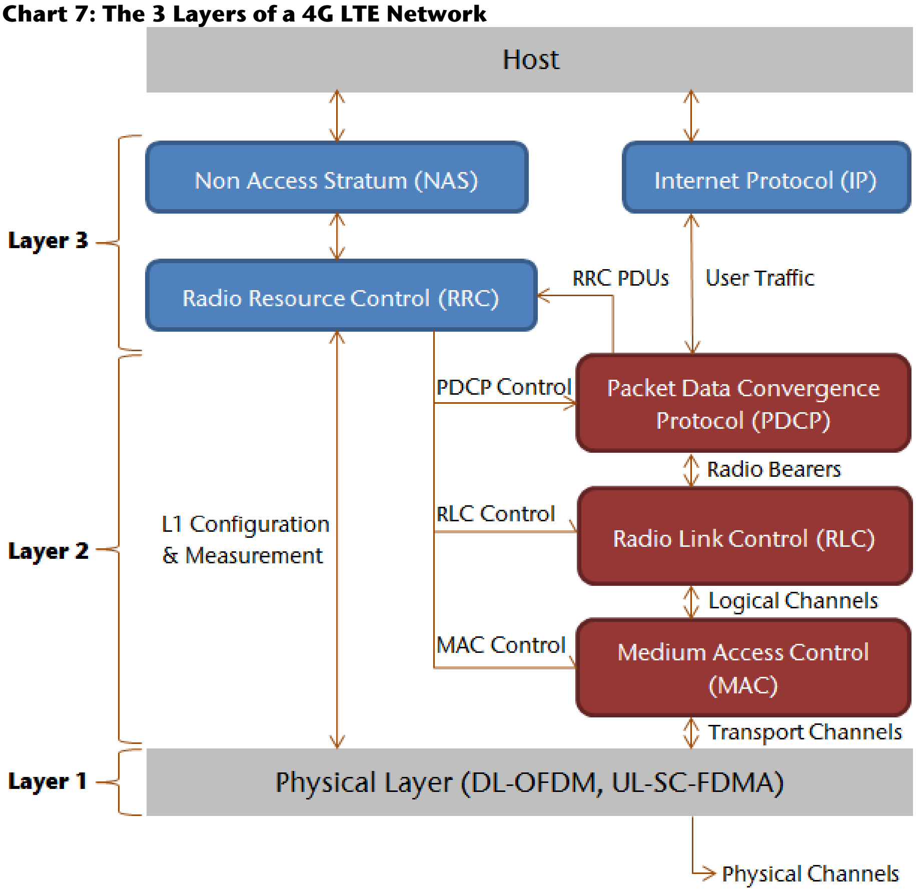
Chart 7: The 3 Layers of a 4G LTE Network



Source: Jefferies

The OSI model enables telecommunications and computing network to work together

Modern cellular networks are the result of very complex engineering work, and are typical of the multi-layered communications model, Open Systems Interconnection (OSI). OSI is a model used by the ICT industry to standardize telecommunications and computing networks so that they can interconnect and work with one another. It defines seven layers as follows.

Table 7: The 7 Layers of a Typical Open System Interconnection (OSI) Model Network

	Layer	Protocol data unit (PDU)	Function
Host Layers	7. Application	Data	High-level APIs, including resource sharing, remote file access
	6. Presentation		Translation of data between a networking service and an application; including character encoding, data compression and encryption/decryption
	5. Session		Managing communication sessions, i.e. continuous exchange of information in the form of multiple back-and-forth transmissions between two nodes
	4. Transport	Segment (TCP)/Datagram (UDP)	Reliable transmission of data segments between points on a network, including segmentation, acknowledgement and multiplexing
Media Layers	3. Network	Packet	Structuring and managing a multi-node network, including addressing, routing and traffic control
	2. Data Link	Frame	Reliable transmission of data frames between two nodes connected by a physical layer
	1. Physical	Bit	Transmission and reception of raw bit streams over a physical medium

Source: Wikipedia

The cellular protocol stacks are similar to the first three layers of OSI: the physical layer (layer 1), the data link layer (layer 2) and the radio resource control layer (layer 3).

The physical layer:

The physical layer defines and translates requests from the data link layer into operations

It is the protocol's interface with the outside world, which consists of signal transmitting and receiving hardware and software. Its purpose is to transmit and receive data through

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the protocol's defined physical channels. The physical layer defines the means of transmitting raw bits instead of data packets, and translates communication requests from the data link layer into hardware-specific operations that enable transmission or reception of electronic signals.

Since the shapes and properties of electrical connectors, the frequencies to broadcast on, the modulation scheme to use and other basic parameters are all specified here, the physical layer is considered the most high-profile part of a cellular technology standard. A large part of the industry's R&D efforts are focused on the physical layer.

The data link layer:

The data link layer relays the information of users among different base stations

It is responsible for moving data across the physical links in the network (e.g., transferring data to another user on the same mobile network but connected with a different base station). It ensures that an initial data connection has been set up, divides output data into frames, and takes care of the acknowledgement messages from the data recipients. It will also ensure that incoming data has been received properly.

In 4G LTE, the data link layer is sub-divided into PDCP, RLC and MAC. When the IP layer (core network) sends a data packet to the mobile radio, the PDCP will conduct header compression (from minimum 20 bytes to 1-4 bytes) before passing it onto the RLC. The RLC re-arranges the packet (divides it into several packets if it is large, or group small packets into a large one to maximize efficiency) and sends it to the MAC, which adds its own header (to identify the packet) and then sends it to the physical layer for transmission to the physical channels.

The radio resource control layer

The radio resource control layer is in charge of the connection between the base station and the user equipment

Layer 3 consists of the radio resource control (RRC) protocol and non-access stratum (NAS) protocol. RRC is in charge of the connection (i.e., establishment, maintenance and dropping) between the base station and the user equipment (handsets or other devices), bearer establishment, and broadcast of system information. RRC is guided by a state machine, which defines certain specific states that the user equipment is in. Different states will be associated with different levels of radio resource that the UE can use, which will affect the user experience and battery consumption of the user equipment.

NAS protocol forms the highest level of the control plane between the user equipment and the core network's mobility management entity (MME). MME is responsible for authenticating the user equipment (such as a mobile phone). Furthermore, NAS supports the mobility of the user equipment and maintains the IP connection between the user equipment and the packet data network's gateway.

Waveform, Modulation and Duplexing

Table 8: Key Technologies of the Physical Layer of RAN

Standard	Waveform	Modulation	Duplex	Channel Coding
GSM	FDMA/TDMA	Gaussian Frequency Shift Keying (GFSK)	FDD	Turbo
CDMA	CDMA with a carrier spacing of 1.23 MHz (direct sequence, spread spectrum)	quadrature-phase shift keying (QPSK)	FDD	Turbo
WCDMA	CDMA with a carrier spacing of 5 MHz (direct sequence, spread spectrum)	mainly based on Phase Shift Keying (PSK)	FDD	Turbo
CDMA2000	CDMA with a carrier spacing of 1.25 MHz (direct sequence, spread spectrum)	QPSK, 8PSK and 16QAM as possible modulation schemes depending on the handset's RF environment	FDD	Turbo
TD-SCDMA	TDMA/CDMA with a carrier spacing of 1.6 MHz	QPSK/8PSK/16QAM	TDD	Turbo
4G LTE	OFDM (downlink) and SC-FDMA (uplink), with a carrier spacing of 180KHz. Channel width scalable at 1.4, 3, 5, 10, 15 or 20MHz	QPSK/16QAM/64QAM	FDD or TDD	Turbo

Source: ITU and 3GPP

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Waveform, modulation and duplexing define the physical layer

These three technology elements are the core of the physical layer, and have great bearing on the system's spectral efficiency. When we migrated from 2G to 3G, the change in the waveform and modulation technology, and the adoption of a version that involves TD duplexing, was to increase both voice and data capacity, as well as to increase data speed. When we moved to 4G from 3G, the adoption of OFDM for downlink and SC-FDMA for uplink as the new waveform aimed to further increase spectral efficiency, raise data speed and transform the cellular network into a data-centric network.

TD duplexing is more efficient in handling data than FD but is adopted less due to commercial reasons

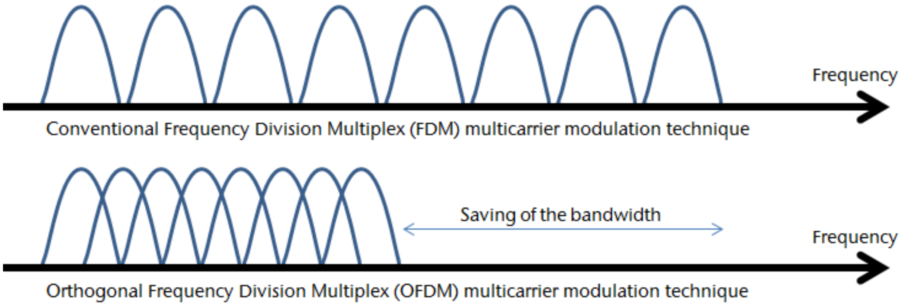
On the other hand, TD duplexing already proves to be much more efficient in handling data than FD. However, 4G still supports both FDD and TDD because there are many more FDD 3G networks globally (ie, WCDMA and CDMA2000 networks), who would find it less expensive to migrate to an FDD-based 4G standard. Therefore, the fact that the 4G standard supports both FDD and TDD is a commercial consideration, even though TDD offers superior spectral efficiency.

How does OFDM work?

OFDM transmits multiple data streams over multiple adjacent sub-carriers without interference and thus saves bandwidth

OFDM is a broadband multi-carrier modulation method. It transmits multiple data streams over the same radio spectrum, and each data stream is modulated onto multiple carriers adjacent to one another within the same spectrum. Normally when each carrier is located very close to each other (i.e., minimum carrier spacing), the transmission will be subject to interference. In OFDM, the sub-carrier frequencies are chosen so that the sub-carriers are orthogonal to each other, eliminating cross-talk between sub-channels and the need of inter-carrier guard bands. That removes interference and saves bandwidth.

Chart 8: Orthogonal Frequency Division Multiplex Transmission



Source: Jefferies

Implementation of OFDM

Implementation of OFDM could be complicated

There is some complicated mathematics inside OFDM. First, when we say the signals are created "orthogonally," in practice it means the sub-carriers need to be spaced by any amount equal to the reciprocal of the symbol period of the data signals. Second is the fast Fourier transform (FFT). Fourier is a French mathematician who discovered that any complex signal could be represented by a series of harmonically related sine waves all added together, and he developed the math to prove it. If one takes an analog signal, converts it into digital by an analog-to-digital converter (ADC), takes the result and puts it through the FFT process, one will obtain a digital version of a spectrum analysis of the original analog signal.

IFFT (Inverse fast Fourier transform) is just the reverse of FFT. All the individual carriers (or sub-carriers) with modulation are in digital form. After they are subject to an IFFT mathematical process, a single composite signal will be created and transmitted (from the transmitting equipment). The FFT at the receiving equipment sorts all the signals to re-create the original data stream.

Implementation of OFDM could be difficult with significant computational power

Imagine there are hundreds or even thousands of carriers and sub-carriers, and thus hundreds of thousands of FFT and IFFT calculations per millisecond. The computation will require powerful digital signal processing (DSP), and it is usually done by DSP integrated circuits and an appropriately programmed FPGA.

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Key strengths of OFDM

- ***High spectral efficiency*** *– since spacing among subcarriers can be minimized*
- ***Immunity to selective fading*** *– relative to single-carrier systems, OFDM divides the overall channel into multiple narrowband signals that are affected only individually as flat fading sub-channels*
- ***Resilience to multi-path interference at high frequencies*** *– High frequencies mean short wave lengths. Short wave-length signals normally travel in a straight line from the transmit antenna to the receive antenna. But objects such as buildings, trees, planes and humans could cause reflections of these signals. Reflected transmissions could cause signal cancellation and other anomalies. But in OFDM, data are sent serially (bit after bit) and divided into many lower-speed serial data signals. This lengthens the bit, so multipath time delays are less of an issue. The more sub-carriers are used over a wider bandwidth, the more resilient it will become to multi-path interference (since serial data will be divided into even more lower-speed signals).*

Key shortcoming of OFDM

- ***High peak to average power ratio*** *– the OFDM signal has a noise like amplitude variation and thus a relatively high dynamic range. Therefore, the RF power amplifier will need to be more powerful and thus expensive.*
- ***More sensitive to carrier frequency offset*** *- The OFDM signal is easily subject to distortion if the transmitting equipment's frequency does not exactly match that of the receiving equipment (as signals need to be re-assembled from many subcarriers).*

3GPP chose SC-FDMA over OFDM in 4G LTE standard for uplink

The shortcoming of having high peak to average power ratio is a particularly big problem for the handset, because that could translate into an RF power amplifier that is both bigger and more expensive, impacting the form factor and cost of the mobile phone. Therefore, the 3GPP chose **SC-FDMA (single-carrier, frequency-division multiple access)** as the waveform for uplink traffic (from user equipment to base station) in the 4G LTE standard. SC-FDMA is similar to OFDM but the former leads only to a single-carrier transmit signal. The adoption of SC-FDMA as the uplink waveform eliminates the problem of having a high peak to average power ratio at the user equipment (i.e., handset), but at the expense of spectral efficiency. However, since most mobile operators experience a very high downlink to uplink ratio (i.e., much more downlink traffic than uplink traffic), 3GPP decided the tradeoff between spectral efficiency and RF requirement in the user equipment justified the adoption of SC-FDMA.

3GPP adopted OFDM for NSA New Radio (5G) downlink; and SC-FDMA for uplink

On August 28, 2017, the 3GPP made a decision on the New Radio (NR) for Release 15 (Phase 1, NSA radio access). On the downlink, it adopted OFDM with a cyclic prefix (CP). For uplink, it adopted SC-FDMA. For duplexing, the operation will continue to support both FD and TD.

Quasi-cyclic LDPC code is adopted for large blocks; and Polar coding for small blocks

On channel coding, quasi-cyclic LDPC codes will be used for transport blocks, while Polar coding will be used for physical broadcast channels (PBCH) and control information. This is consistent with 3GPP's previous decision.

Table 9: Features of 5G NSA New Radio (Phase I)

	Downlink	Uplink
Waveform	OFDM (cyclic prefix)	SC-FDMA (cyclic prefix)
Modulation	QPSK, 16QAM, 64QAM, 256QAM	Pine/2-BPSK, QPSK, 16QAM, 64QAM and 256QAM
Channel coding	Quasi-cyclic LDPC codes for transport blocks, Polar codes for PBCH & Control information	

Source: 3GPP

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The Phase 1 physical layer of 5G is very similar to the current LTE standard

As expected, the Phase 1, non-standalone NR's physical layer is very similar to the current LTE standard. The waveform, modulation and duplexing are the same. However, the channel coding method has changed. Turbo coding has been dropped because it is not robust enough (i.e., transmission error) in the complicated channel conditions in 5G, such as super high speed, low latency and vast connections. 3GPP has selected low-density parity-check (LDPC) coding system for transport blocks (i.e., large blocks), and Polar coding for the control channel (i.e., small blocks) in the eMBB use case.

The similarity with LTE is acceptable only because Phase 1 is not expected to support the m-MTC and URLLC use cases

We need to bear in mind that the NSA radio access:

1) has to be backward compatible with 4G LTE, thus it will use the LTE control plane
2) It will not be able to fully support the m-MTC and URLLC use cases

That is why the NSA NR's physical layer is remarkably similar to that of 4G LTE, except for channel coding. It is also in the new channel coding choice that we can see the rising Chinese influence in the standard setting process.

Let us take a look at who have been behind the development effort of those three coding methodologies:

Turbo coding is generally viewed as a European technology

Turbo coding – invented by Claude Berrou, a French computer scientist, around 1990/1991. Further developed by FT Orange (now FT) and Ericsson. It is viewed as a European technology.

LDPC coding is supported by Qualcomm, Nokia and Intel

LDPC – also known as Gallager codes, in honor of Robert G. Gallager, who developed the LDPC coding concept at MIT in 1960. Considered too difficult to implement, LDPC was only rediscovered in 1996, when Turbo coding was already the most popular coding methodology for communications networks. However, LDPC was continuously improved in the US to achieve a lower error rate and higher code rates (i.e., higher speed data transmission). In the 3GPP, LDPC is mainly supported by Qualcomm, Nokia and Intel.

Polar coding is supported by Huawei

Polar coding – it was invented by Erdal Arikan, a Turkish computer scientist, around 2008, and is a linear block error correcting code. It is attractive owing to its structure that makes encoding at the transmitter easy to be implemented. It has been actively deployed by Huawei in its 5G trial. In May 2016, Huawei announced that its trial in China based on F-OFDM waveform, SCMA multiple access and Polar code showed that Polar code provided coding gain from 0.5dB to 2.0dB compared with Turbo code.

Polar coding is accepted as NSA NR by 3GPP for eMBB use case

The 3GPP's final acceptance of Polar coding as part of its NSA NR (for eMBB use case) for the control channel surprised many in the industry, mainly because Polar coding has not been deployed in scale anywhere. More important, prior to this decision, the 3GPP already decided to adopt LDPC as the coding method for the transport block (i.e., data channels, or large blocks) of the NSA NR. Most engineers would prefer to see a single coding method adopted in the entire system. Therefore, it shows China's tremendous power to campaign for support in certain key issues within 3GPP and the ITU, given its rising influence in those organizations as well as in the global political scene generally.

The 3GPP will continue to work on the details of the SA NR, which will support all three 5G use cases and not have to be backward compatible with 4G LTE. Currently the timetable is to finalize the SA NR around middle of 2018, which will become part of the Release 16 to be published in 1H2019.

Among the proposed new waveforms for SA NR, the following are the most likely candidates:

FB-OFDM (ZTE)

FB-OFDM as an evolved form of OFDM has a higher spectral efficiency and lower out-of-band radiating

Filter-bank OFDM is an evolved form of OFDM, and tries to eliminate the two main disadvantages of OFDM: 1) lower spectral efficiency due to the insertion of cyclic prefix, and 2) higher out-of-band radiating. By adding generalized pulse shaping filters, it

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produces a well localized sub-channel with no leakage in both the time and frequency domain. Therefore, no cyclic prefix is needed while spectral efficiency has improved.

F-OFDM (Huawei)

F-OFDM as another evolved form of OFDM is more flexible in supporting different MA schemes and configuring latencies

Filter OFDM is another improved form of OFDM. A subband filter is added on top of CP-OFDM. Flexibility remains with the subcarrier spacing, CP length and latency configuration for each subband. Its flexibility will allow the air interface to support co-existence of different multiple access schemes and flexible latency configurations.

UF-OFDM (Nokia)

UF-OFDM as another evolved form of OFDM reduces the out-of-band spectral emissions

Universal-filtered OFDM is another evolved form of OFDM. Each subband is filtered by a filter, and the responses from the different subbands are summed. The filtering is done to reduce the out-of-band spectral emissions. Different filters per subband can be applied. However, the introduction of filters increases implementation complexities. An algorithm that performs shorter-length FFTs will be able to reduce complexity.

NOMA (DoCoMo)

NOMA introduces power as the 3rd dimension to separate traffic, which in turns also maximizes the number of connections per unit of time

Non-orthogonal multiple access introduces power as a dimension of separating traffic. It does real-time power allocation in order to increase power to those devices that have weak signals while reducing power to those devices that have strong signals, so that the system can maximize the number of connections per unit of time. However, it requires high computational power to implement real-time power allocation and successive interference cancellation (SIC) algorithm.

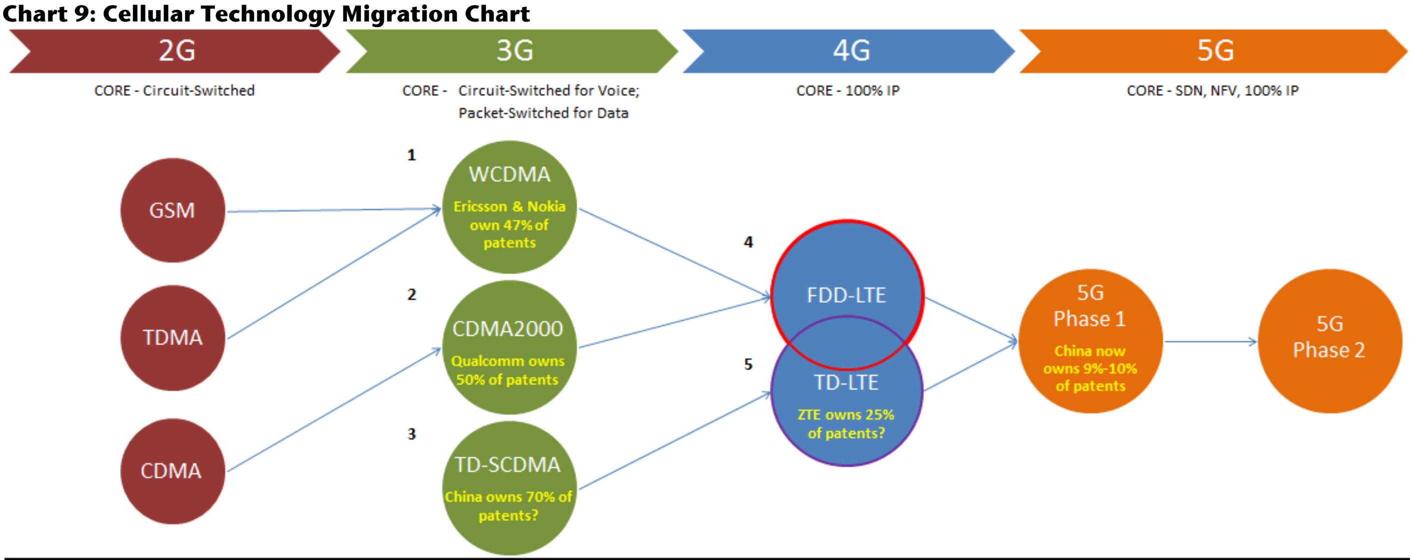
CP-OFDM (Ericsson)

CP-OFDM is the current 4G LTE standard

This is exactly the air interface that is being used in the current 4G LTE standard

The major multiple access candidates are as follows:

Chart 9: Cellular Technology Migration Chart



	3G	4G	5G Phase 1	5G Phase 2
Modulation	**1** CDMA **2** CDMA **3** CDMA	**4 & 5** DL: CP-OFDM UL: SC-FDMA	**Phase 1** DL: CP-OFDM UL: SC-FDMA	**Phase 2** ?
Duplex	**1** FD/TD **2** FD **3** TD	**4** FD **5** TD	**Phase 1** Support both FD/TD Will be mostly TD	**Phase 2** ?

Source: Jefferies

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Massive MIMO

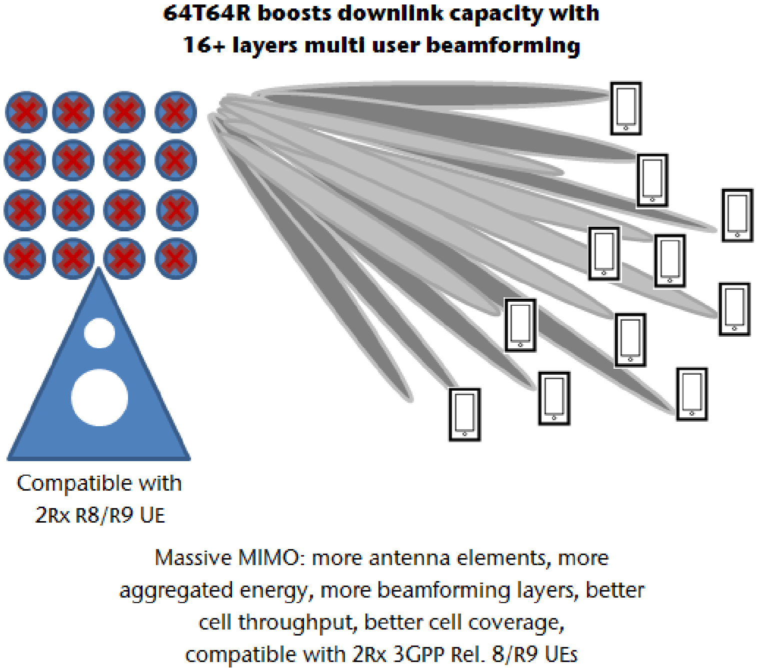
Massive MIMO deliver beams that can track and reach the handset more easily and reduces both interference and total radiated power

Massive multiple-input, multiple-output technology deploys a large number of 2-dimensional arrays of active antennas at the base station in order to increase signal strength and deliver more focused beams that can track and reach the handset (user equipment) more easily. The larger number of antenna elements (an element is typically a metal rod in the antenna and is electrically connected to the receiver or transmitter; there could be many elements per antenna) allow the base station to focus its energy only where it is needed, thus reducing both interference and total radiated power.

Massive MIMO can simultaneously serve a large number of users with sufficient signal strength

The following diagram shows how Massive MIMO with 64T64R (64 transmitting antenna elements x 64 receiving antenna elements = 4x4 antennas with 4 elements per antenna) can simultaneously serve a large number of users because the much more focused beams can reach different handsets with sufficient signal strength. In Release 12 of the 4G LTE standard, higher-order MIMO was introduced to accommodate of up to 8 antennas in the base stations. But for Massive MIMO in 5G, the specification calls for a minimum of 64 antennas, and up to 256.

Chart 10: Massive MIMO



Source: GSA, Jefferies

Massive MIMO at 3.3GHz – 4.2GHz could increase download speed by over 10x compared with a 2T2R base station

According to GSA, the adoption of Massive MIMO (64T64R) at 3.3GHz to 4.2GHz with 100MHz bandwidth will increase cell download speed by over 10x compared with a 2T2R base station deployed at 1.8GHz with bandwidth of 20MHz (middle on Chart 7). As the 5G NR frame structure is shorter, Massive MIMO will be able to achieve reduced latency and more robust channel stability.

China Mobile's trial on Massive MIMO in Shanghai suggests a 6-7.7x higher downlink speed vs. the current base station with 8T8R configuration, with or without interference

Based on China Mobile's trial of Massive MIMO in Shanghai late last year (64T64R), downlink speed of 650Mbps was achieved, 6x higher than the current base station with 8T8R configuration. In another test with interference by China Mobile also in Shanghai, downlink speed of 341Mbps was achieved, 7.7x higher than the 8T8R configuration. Massive MIMO also improved China Mobile's coverage in high-rise buildings, owing to the 3D beam directions that help reach the higher floors even if the base station is installed only at 25m above ground.

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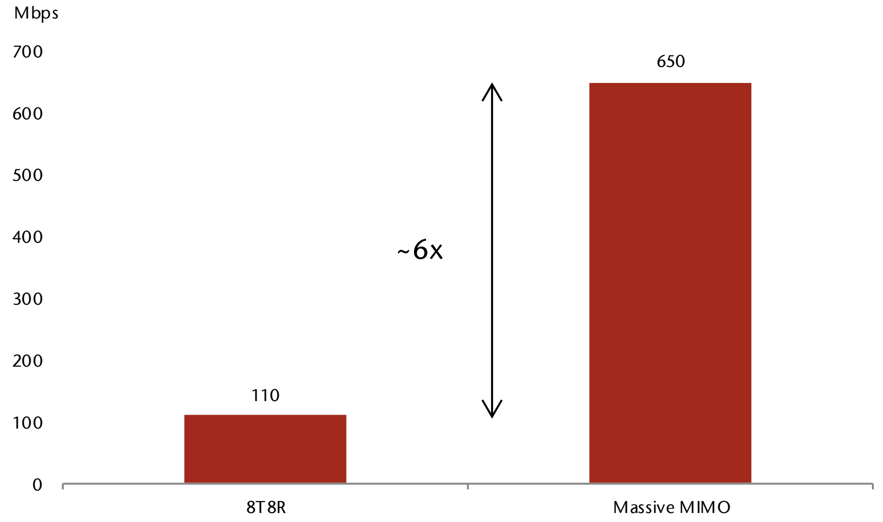
Chart 11: Downlink Peak Rate of Massive MIMO and 8T8R



Source: GSA, Jefferies

Massive Beamforming

It uses smart antennas to send strong and highly focused beams to targeted receivers.

Massive beamforming is sometimes regarded as part of the Massive MIMO technology. In a smart antenna, there can be many elements, each of which can transmit a highly directed beam to aim at the target receiver. At higher frequencies (eg, above 2GHz), the propagation loss will be higher and the transmission distance will be shorter. However, the upside is that as the frequency increases, the antennas become smaller, and it becomes possible to pack more elements into a smaller antenna. For example, according to Ericsson, a smart antenna for 2.6GHz is roughly one meter tall, and can have up to 20 elements. At 15GHz (mmWave frequencies), it is possible to design an antenna with 200 elements that is only 5cm wide and 20cm tall.

The higher the frequency, the smaller the antennas; and more elements can be packed in the antennas

With more antenna elements, the beam becomes narrower. It then becomes key that the beam be steered to focus its transmission toward the targeted receiver (handset). Since each cell may serve thousands of users at the same time, the direction of each beam may have to change many times per millisecond. In this case, it will require powerful computational capabilities and a complicated algorithm at the baseband to accommodate such activities. Otherwise the quality of connection will suffer.

The key is to steer the beam toward the targeted receiver while the direction may change many times per millisecond

Owing to the more powerful and focused beams, 5G base stations that adopt Massive MIMO and directed beamforming may be able to achieve the same coverage of a 4G base station that does not have Massive MIMO but operates at a lower frequency. It will depend on the frequency difference. For example, a 5G base station with Massive MIMO and directed beamforming operating at 3.5GHz may be able to achieve similar coverage to a 4G base station without Massive MIMO and beamforming that operates at between 2GHz and 2.5GHz. But if the 5G base station operates at 4.5GHz or above, the coverage may not be able to match 4G. The coverage difference will eventually depend on the details of the 5G implementation, including baseband processing power and RF capabilities.

Even at high frequencies, the more powerful and focused beams can achieve the same coverage of a 4G station that operates at a lower frequency

C-RAN

RAN was run as a combination of independent base stations which communicate with each mobile terminal individually

Radio access network (RAN) traditionally has been run as a combination of a large number of independent base stations, each of which has its only RF, baseband processor, backhaul connection with the core network, backup battery, monitoring system, and so on. Each base station directly communicates with each mobile terminal by sending signals back and forth. Each base station is housed in a small room and likely located at the bottom of

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a tower. It is then connected by RF cables with the antenna that will be situated at the top of the tower.

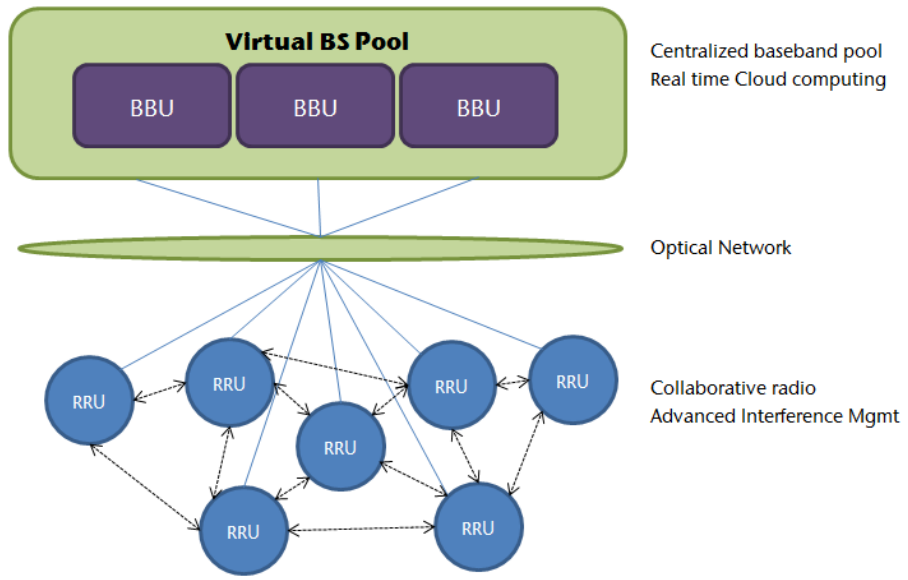
During the 2G to 3G migration, RAN has become a more distributed architecture and reduces the signal loss

When we moved from 2G to 3G, the RAN has become a more distributed architecture, in which the remote radio head (RRH) is separated from the baseband unit (BBU). The RRH can be installed at the top of the tower near the antenna, reducing the loss that results from using a long cable to send the RF signal from the traditional base station to the antenna at the top of a tower. The fiber connection between the RRH and BBU allows more flexibility in network planning because the BBU can be located further away from where the tower is.

C-RAN has a large number of RRUs being controlled by a single software-driven BBU to achieve high bandwidth and low latency

Cloud-RAN is a further evolution of the distributed BTS architecture, in which a large number of RRUs will be controlled by a single, software driven BBU. The maximum distance is 20km of fiber link in the 4G standard, but could be expanded further in the 5G standard. The centralized BBU will be based on open platform with virtualization capability, and can easily and dynamically allocate radio resources among the RRHs based on real-time usage, and monitor the performance of the RRHs. The RRHs can also communicate with one another with high bandwidth and low latency, regarded as collaborative radio technologies.

Chart 12: Cloud-RAN Concept



Source: ITU, Jefferies

Core Network – Service based architecture, SDN + NFV

Service based architecture is already adopted for the 5G core network

3GPP has already adopted the concept of service-based architecture for the 5G core network, which consists of 1) network slicing, 2) mobile edge computing and 3) the separation of user plane and control plane. Network slicing means the network is flexible enough to dedicate parts of the entire network for different types of services (eg, eMBB, m-MTC and URLLC), by allocating network resources, bandwidth and capacity to properly deliver the required services.

SDN and NFV together allows customized elements to serve the customers

The enabling technology is software defined network (SDN) and network function virtualization (NFV), which allows traditional structures of a telecom network to be broken down into customizable elements that can be combined in different ways using software to provide just the right level of connectivity and service quality desired by the customers.

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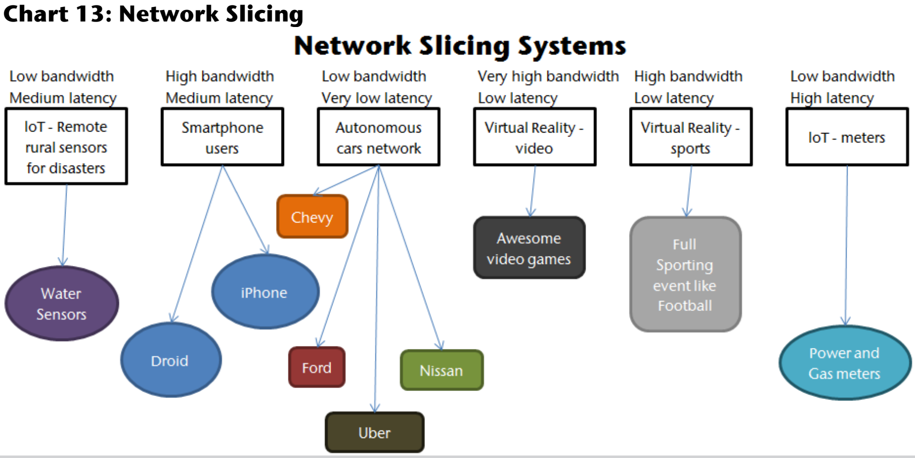
Chart 13: Network Slicing



Source: ITU, Jefferies

Mobile edge computing reduces the transmission time, network congestion and core net resources consumption

Mobile edge computing in an architecture in which applications and the related processing tasks are run much closer to the cellular customer so that transmission time and network congestion can be reduced. What that means effectively is to enable cloud computing capabilities and software application environment at the edge of the cellular network. A mobile operator will need to open up its radio access network to third party developers and content providers so that customers can directly access the applications or content that are located at the radio access network or base stations, saving transmission time, lowering latency and consuming less core network resources.

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The trillion dollar question – who owns the cellular technology

China has little IPR share in 2G, 3G and 4G

The IPR distribution of cellular technology is very fragmented

Cellular technology is very unique in that the ecosystem combines a wide variety of technology elements, so that no single company controls the technology. No single company can claim that its technology alone will be enough to power the entire ecosystem. In order for cellular networks and devices to be built, companies that own critical technology elements enter into cross-licensing agreements with one another. However, owing to the vast number of components in the ecosystem and thus technology elements, intellectual property rights (IPR) lawsuits have been abundant in this industry.

The IPR situation for the cellular industry has always been murky. First, most technology or solutions are a combination of hardware and software design. Therefore, two technologies may be very similar to each other but the underlying methodologies used to achieve the same outcome may be different. Second, the timing of who has come up with the technology first is sometimes controversial.

China has no IPR in 2G cellular technology

China claimed it owned a majority in 3G TD-SCDMA-related IPRs

It is important to realize that China's participation in the cellular technology development is quite late. In the 2G era, China did not participate at all. When China started developing the TD-SCDMA standard for 3G, the rest of the world was focusing on CDMA and GSM technology. Therefore, even though TD-SCDMA was recognized by the 3GPP as one of the three 3G standards, it was not adopted anywhere in the world except by China Mobile in China. Therefore, China owns no IPRs in 2G, nor WCDMA and CDMA2000 in 3G. As far as TD-SCDMA is concerned, even though China claimed it owned a majority of the IPRs, Qualcomm challenged it because the fundamental waveform in the physical layer was still CDMA, which is a Qualcomm technology. We believe Qualcomm and China reached a private settlement on the IPRs related to TD-SCDMA, the details of which are not available.

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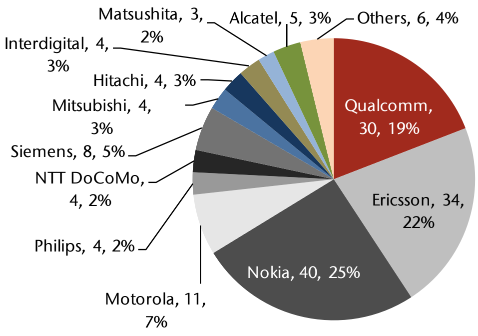
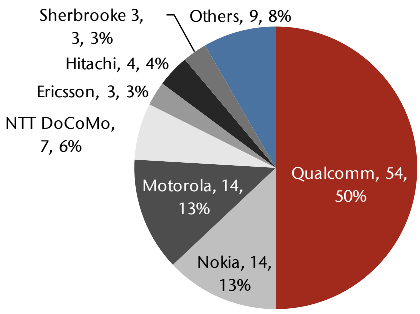
Chart 14: Owners of IPRs Judged Essential for WCDMA



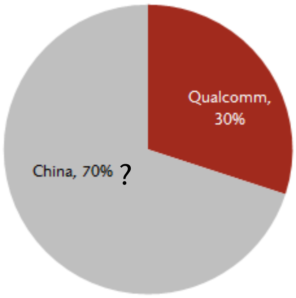
Source: 2005 IEEE

Chart 15: Owners of IPRs Judged Essential for CDMA2000



Source: 2005 IEEE

Chart 16: Owners of IPs Judged Essential for TD-SCDMA



Source: Jefferies estimates

Do note that IPR shares in different sources could differ

The analysis of IPR shares among major players is complicated by the fact that it is very difficult to judge which IPRs are really “standard essential.” Standard-essential technology elements are those that are so important that if the ecosystem does not adopt them, it will not be able to provide users with the proper functionalities. Therefore, IPR share estimates done by different organizations are rarely similar.

A Jefferies proprietary analysis in 2011 suggests ZTE and Huawei hold some LTE-essential IPR share

For 4G LTE, according to a proprietary analysis done by Jefferies in 2011, LG was the biggest LTE-essential IPR holder followed by Qualcomm. However, ZTE was found to have a 6% share of LTE-essential IPRs, while Huawei had 1%. Therefore, these two Chinese entities had a 7% share by Jefferies’ estimates.

Table 10: LTE-Essential IPRs

Patent	% Ownership of LTE-Essential IPRs
LG	23%
Qualcomm	21%
InterDigital	9%
Motorola	9%
Nokia	9%
Samsung	9%
ZTE	6%
Nortel	4%
ETRI	2%
TI	2%
Ericsson	2%
NSN	2%
RIM	1%
Freescale	1%
Huawei	1%
NEC	1%

Source: Jefferies estimates

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iRunway, a US technology consulting firm that specializes in patents and IP licensing, published a detailed report in 2012 analyzing 4G LTE IPRs. According to its analysis, the top 5 IPR holders (including all claimed LTE related) are 1) Samsung, 2) Qualcomm, 3) Panasonic, 4) InterDigital and 5) Nokia. But if it is based on what iRunway believed to be "seminal" to 4G LTE, the top five IPR holders would be 1) Qualcomm, 2) Samsung, 3) Intel, 4) Ericsson and 5) Nokia.

Table 11: Top IPR Holders of 4G-LTE and Seminal 4G-LTE IPRs

Company	Count of All 4G-LTE IPR	Share of All 4G-LTE IPRs	Count of Seminal 4G-LTE IPRs	Share of Seminal 4G-LTE IPRs
Samsung	1,177	9.36%	79	12.15%
Qualcomm	710	5.65%	81	12.46%
Panasonic Corporation	389	3.10%	13	2.00%
InterDigital	336	2.67%	23	3.54%
Nokia Corporation	293	2.33%	27	4.15%
Ericsson	247	1.97%	29	4.46%
LG Corp.	224	1.78%	26	4.00%
Motorola Solutions, Inc.	192	1.53%	13	2.00%
Motorola Mobility Holdings, Inc.	32	0.25%	12	1.85%
Sony Corporation	189	1.50%	14	2.15%
NEC America Inc.	180	1.43%	3	0.46%
Texas Instruments	173	1.38%	6	0.92%
Harris Corporation	160	1.27%	6	0.92%
Nortel Networks Corporation	152	1.21%	11	1.69%
Intel Corporation	145	1.15%	36	5.54%
Total	4,599	36.58%	379	58.29%

Source: iRunway 2012

From iRunway's report, no Chinese companies or institutions were mentioned as 4G LTE IPR holders

Both sources mentioned suggest China owns a low share of patents in 4G LTE

In the iRunway's report, the top 4G LTE IPR holders do not include any Chinese companies or academic institutions, while Jefferies' proprietary analysis in 2011 found ZTE and Huawei to be on the list. As we pointed out, the results of different surveys are bound to be different, as the definition of "standard-essential" is controversial. However, both reports do suggest that China had a very low share of IPRs in 4G LTE, even though we believe TD-SCDMA and TD duplexing are home-grown technology in China.

To China, 5G IPRs = bargaining power + lower cost + more global influence

China put more emphasis in IPRs in recent years

Over the past five years, China has increasingly focused on developing proprietary technologies in a wide range of industries. As wages in China continue to rise, it will not be able to sustain high economic growth by relying on labor-intensive, low-value-added manufacturing. "Copycatting" foreign products and technology is not sustainable either, because 1) China has been under tremendous pressure to enforce and protect foreign IPRs since its WTO entry, and 2) affluent Chinese consumers are increasingly asking for authentic brands and products.

China has aggressively engaged in 5G R&D work

Becoming a leading digital country is now one of China's 13-5 targets

Ever since the ITU started the "IMT-2020 and Beyond" initiative in 2012, various Chinese entities have actively engaged in R&D work in 5G. Having witnessed the difficulties that China's TD-SCDMA technology has encountered in global adoption, and having realized that 5G will be a single, global standard, China is determined to be a major player in 5G, with a meaningful IPR share. That has also become in sync with China's other strategic objectives in its 13th five-year plan (2016-2020): becoming a leading digital country; aggressively adopting IoT, big data and cloud across all industries; developing its leadership position in next-generation communications technology.

LexInnova reported that China owns about 10% of 5G-essential IPRs

Based on an estimate done by LexInnova, a US IPR law firm, at the beginning of this year, China in total owned about 10% of "5G-essential" IPRs. It divided 5G technology into three areas: radio access (e.g., multiplexing, channel coding and data rate enhancements), modulation (mainly at the physical layer) and core networking. China was estimated to have the highest IPR share in radio access (13.3%), likely due to China's

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early adoption of TD duplexing. Among all Chinese entities, Huawei was estimated to have the most "5G-essential" IPRs, followed by ZTE.

Chart 17: IPR Shares for 5G Radio Access
13.3% by China

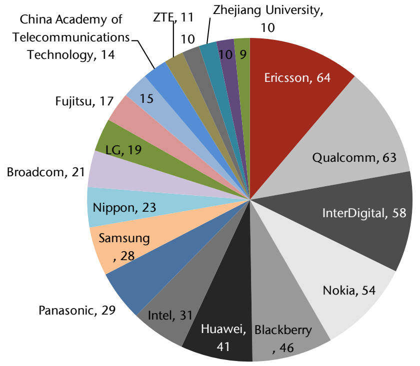


Chart 18: IPR Shares for 5G Modulation
8% by China

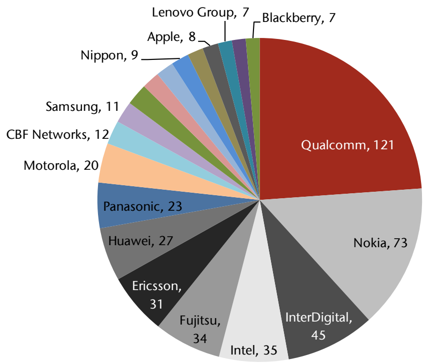


Chart 19: IPR Shares for 5G Core Networking
9% by China

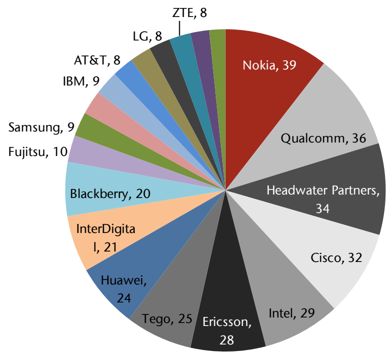
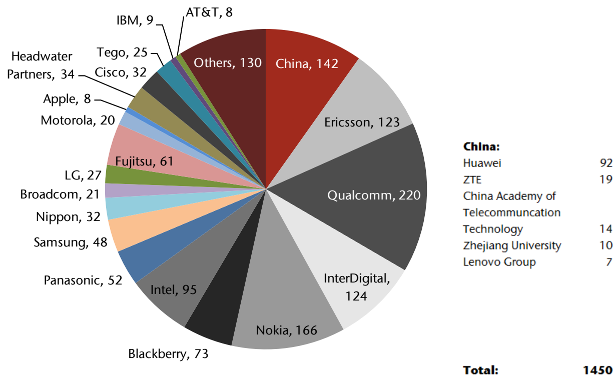


Chart 20: Overall 5G IPR Shares
9.8% by China, expected to be much higher in the end



Source: Jefferies estimates, LexInnova

Huawei's Polar coding being accepted gives us confidence in a rise in China's IPRs in 5G

The 5G IPR situation will continue to evolve as the technology standard is being developed at the 3GPP. For example, since Huawei's Polar coding was accepted by the 3GPP as the coding methodology for the control channel in the NSA NR, we expect it will lead to a rise in China's IPRs in 5G. The ultimate IPR share of China in 5G will depend heavily on whose proposed solutions will be adopted for the SA NR, core network design and system architecture.

China's eventual share in 5G-essential IPRs will be more than 10%, in our view

Assuming LexInnova's estimate of a 10% 5G IPR share for China was somewhat accurate, we believe China's eventual share will very likely be above that level. Moreover, as the technology standard continues to be improved, China will be able to contribute to future 3GPP releases of 5G and win more IPRs.

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Spectrum coordination a major source of geopolitical tension

The World Radio Conference (WRC)

Spectrum allocation not only depends on local government policies but also global coordination

Spectrum allocation is a critical part of providing cellular services. Spectrum is a scarce public resource, and thus the allocation is always done by the government in each country. The amount of spectrum and level of frequency affect the cellular technology design as well as cost of deployment. More importantly, spectrum allocation needs to be coordinated globally since:

1) A lack of coordination may result in frequency interference with neighboring countries
2) The lack of unified frequency level for a particular technology will reduce the scale of equipment production and increase the cost of building networks and/or producing handsets.
3) A unified frequency level will make global roaming easier as consumers increasingly travel outside of their home country with their mobile devices.

It is difficult to find spectrum at commonly available frequency levels in a large number of countries

However, cellular communication started only about 25 years ago, and did not become an extremely popular and important service globally until the last 10-15 years. In almost every country, spectrum has been allocated for a wide range of services since a much longer time ago, including radio and TV broadcasting, satellite communications, military, air and sea transportation, etc. Therefore, it is increasingly difficult to find spectrum at commonly available frequency levels in a large number of countries.

Global spectrum coordination is done at World Radio Conferences, which are held every 3-4 years. The next one will be held in Oct 2019

Global spectrum coordination is done at the World Radio Conference (WRC), which is managed by the ITU. WRCs are held every three to four years. The general scope of the agenda of every WRC is established four to six years in advance, with the final agenda set by the ITU council two years before the conference (and rectified by the majority of member countries). The last WRC was held in 2015. The next one will be held in October 2019, and 130 member countries are expected to participate.

The Radio Regulations will be reviewed and revised at the WRC

The WRC is responsible for reviewing, and revising if necessary, the Radio Regulations, which is the international treaty governing the use of radio frequency spectrum and satellite orbits. In WRC-19, the main agenda would be to:

1) study further spectrum allocation for international mobile services, and
2) study coordination issues of previously allocated spectrum (in 2015) for 5G to ensure there will be no interference with incumbent users at some of those frequencies.

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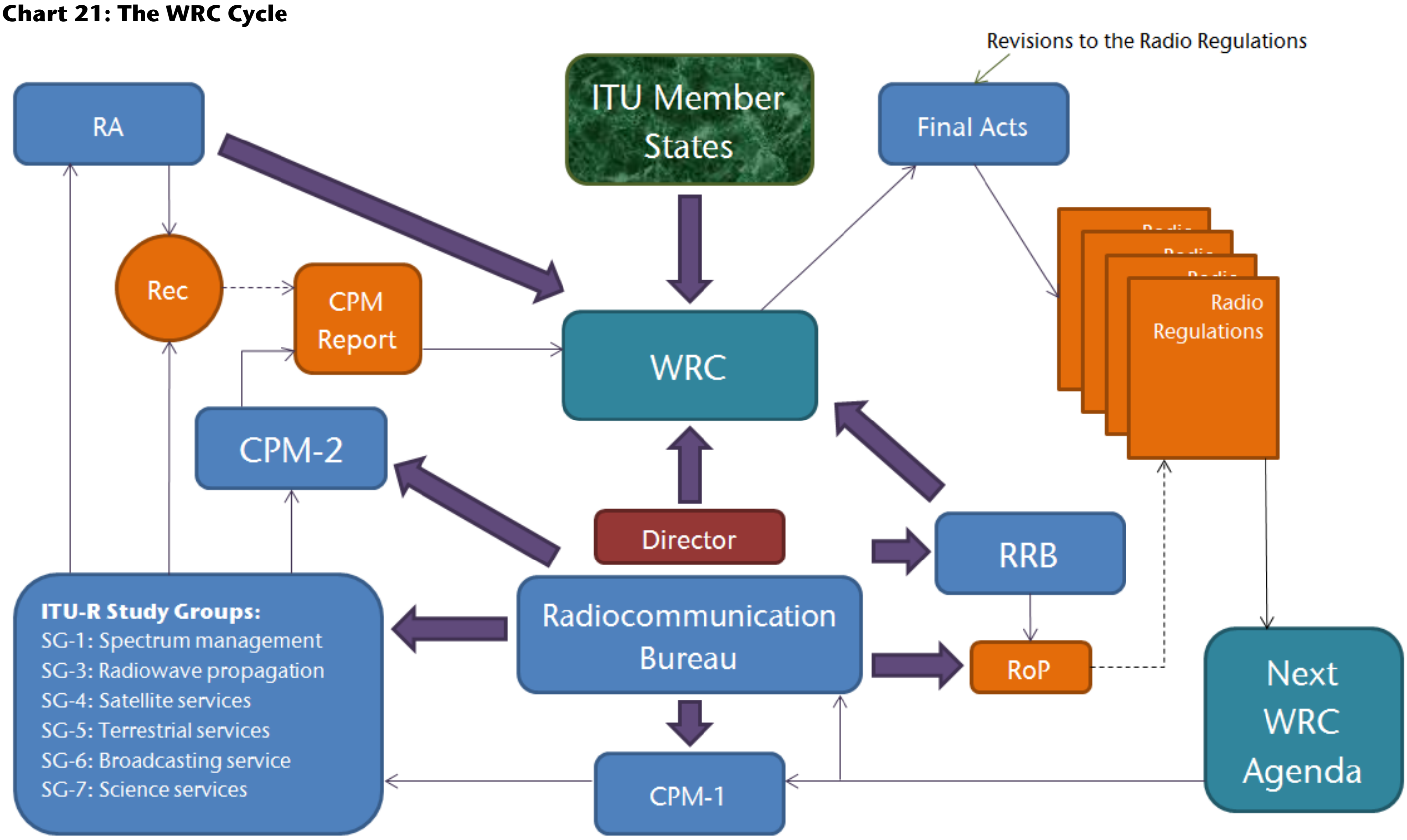
Chart 21: The WRC Cycle



CPM:	Conference Preparatory Meeting	RRB:	Radio Regulations Board
Rec:	ITU-R Recommendation	SGs:	Radiocommunication Study Groups
RoP:	Rules of Procedure	RA:	Radiocommunication Assembly
RR:	Radio Regulations (treaty status)	WRC:	World Radiocommunication Conference

Source: WRC/ITU, Jefferies

Current spectrum allocation for 5G

The WRC has made the following definition of frequencies for the purpose of 5G and future mobile communications:

High frequencies: 6GHz or above
Low frequencies: Below 6GHz

Low-frequency-level spectrum is particularly scarce

Spectrum is always a scarce resource, especially low frequencies. It is because all traditional broadcasting and communication networks were based on low frequencies, as low frequencies mean longer wavelengths and longer transmission distance, translating into lower cost in covering a wide area. The issue of multiple licenses for 2G, 3G and 4G cellular services in most countries has also occupied a lot of spectrum at below 3GHz.

One 5G requirement on the spectrum allocation is a minimum of 100MHz contiguous spectrum to provide a high data speed and capacity

As demand for mobile data services is skyrocketing, the 5G technology is being designed to provide even faster data speed, higher data capacity and provide the ability to simultaneously connect with many more devices. One important technology requirement that will enable much higher data speed and capacity is the availability of much more radio spectrum. The 3GPP has established the specification that, in order to provide proper 5G services, a cellular network will, ideally, need minimum contiguous spectrum of 100MHz. The data speed and capacity will be even higher if a 5G network can work on spectrum wider than 100MHz.

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Table 12: Spectrum Requirement Forever Expanding

Mobile Standard	Average frequency spectrum allocation per operator
1G	5MHz - 10MHz
2G	10MHz - 20MHz
3G	20MHz - 40MHz
4G	20MHz - 50MHz
5G	Minimum 100MHz contiguous (ideally)

Source: Jefferies estimates

It is easier to find 100MHz of contiguous spectrum at higher frequencies than at lower ones in all countries

In all countries, it is almost impossible to find contiguous spectrum of 100MHz at below 3GHz, still less several pieces of 100MHz spectrum, assuming most countries have more than one telecom operator. Therefore, the only choice is to move up the frequency curve. Not only is it physically easier to find large chunks of spectrum at high frequencies (i.e., higher than 6GHz), but it is much less occupied in most countries.

Some frequency bands were identified at the WRC-15 and now being considered for 5G usage

The WRC-15 has identified frequency bands that will be considered for 5G in both low and high frequency bands. These frequency bands will need to be harmonized globally in order to produce the most commonly acceptable sets of spectrum that most countries will deploy for 5G purpose.

Table 13: Spectrum Identification for 5G at WRC-15

Low Frequencies (GHz)	High Frequencies (GHz)
3.4 -4.2	24.25 - 27.5
	31.8 - 33.4
	37 - 43.5
	45.5 - 50.2
	50.4 - 52.6
	66 - 76
	81 - 86

Source: WRC-15

Most, but not necessarily all, member countries at the WRC could make the above frequencies available for 5G

Note that the frequencies that have been identified at the WRC-15 are those that most member countries believe can be made available for 5G in the future. It is a consensus and certainly does not mean every country will be able to allocate exactly the same spectrum at the same time for 5G. As discussed above, most of the spectrum identified are high frequencies (i.e., above 6GHz), owing to the wide spectrum requirement of 5G and the lack of availability at below 6GHz.

Low frequencies vs high frequencies

Consensus rarely means 100% agreement among all member countries. This is especially the case for spectrum allocation because:

1) spectrum availability differs widely among countries, depending on how they are being utilized right now; it is almost always difficult to move current users off a frequency level (expensive and may not be desirable by the government)
2) the choice of low vs high frequencies has serious implications for technology, because physics dictates that higher frequencies mean shorter wavelengths, which will translate into shorter transmission distance, and the transmission will be more vulnerable to blockage by such objects as buildings, walls, trees, cars, humans and even rain. These technological challenges need to be mastered.

Different operators and governments have different preferences for spectrum choice

Owing to different availability of spectrum, and different views on what certain technology can accomplish, the views of certain countries on frequency preference have been split. Even different operators in the same market would have preference for different frequencies and/or technology.

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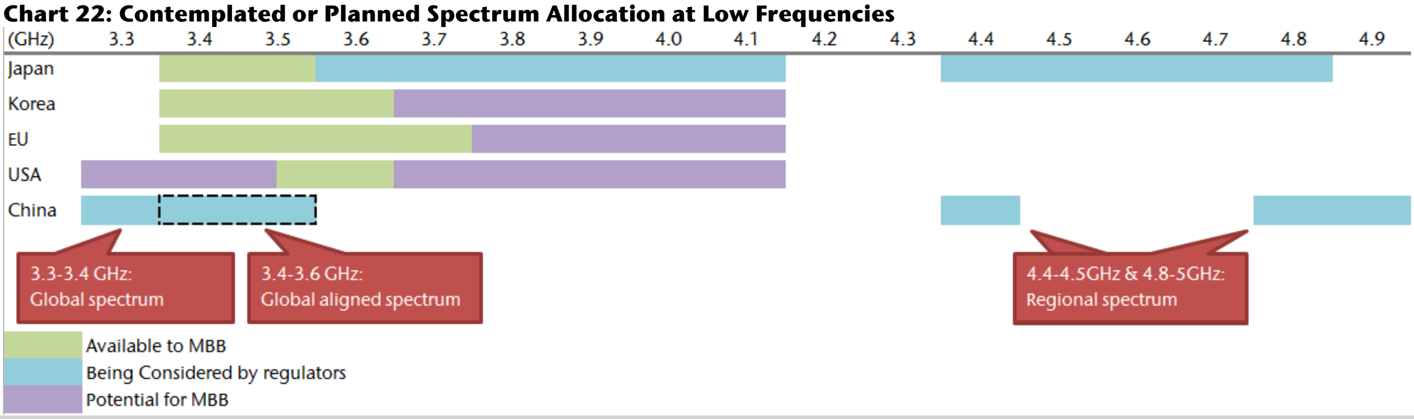
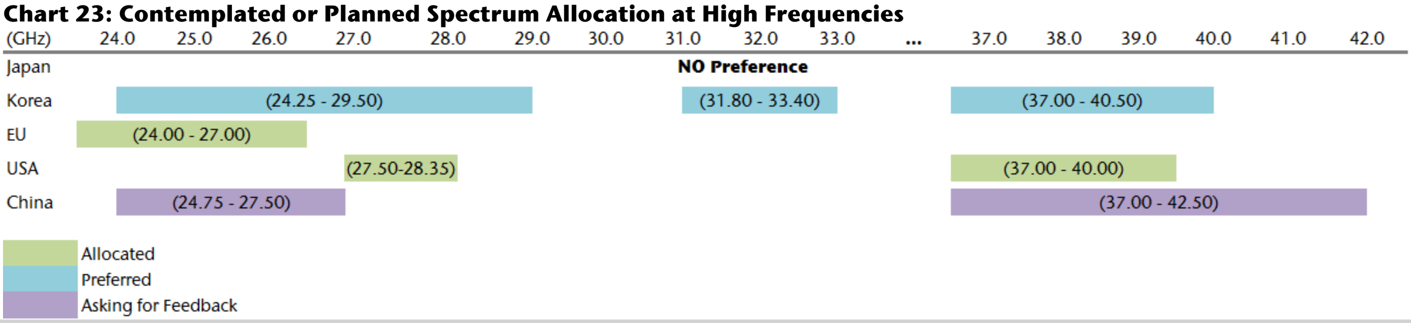
Based on the latest development of frequency studies and allocation by various regulators, we presented in the following the latest preferred/likely spectrum allocation for 5G in major regions/countries, divided into low and high frequencies.

Chart 22: Contemplated or Planned Spectrum Allocation at Low Frequencies



Source: GSA

Chart 23: Contemplated or Planned Spectrum Allocation at High Frequencies



Source: FCC, MIIT, EU and MSIP

US is the most keen on high frequencies, in our view

We believe **the US is the most keen on high frequencies**. In July 2016, the US FCC officially allocated 3.85GHz of spectrum at 28GHz, 37GHz and 39GHz for 5G service. For the EU, it has allocated spectrum at 700MHz, 3GHz-6GHz and 24GHz-27GHz for 5G purpose. Korea indicated that it preferred high frequencies, but would also examine low frequencies when the WRC-19 arrives at a harmonized allocation.

Japan has not indicated any preference on frequencies

Japan's regulator (MIC) has not indicated any particular preference. However, we understand that NTT DoCoMo prefers to use 28GHz, but Softbank believes high frequencies have too much transmission loss and thus strongly prefer to use low frequencies. Softbank also has plans for Sprint in the US to develop 5G at 2.5GHz.

China prefers low frequencies for wide coverage and high-speed hotspot requirements

China has clearly indicated its preference for low frequencies. The government believes that low frequencies (mainly 3GHz to 6GHz) provide the best balance of wide coverage and high-speed hotspot requirements in densely populated urban areas. China emphasizes the importance of wide-area coverage as it has ambitious initiatives of Internet of vehicles and Internet of Things.

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Table 14: China's 5G Spectrum Scenarios (LF –Low Frequencies, HF – High Frequencies)

eMBB			
Indoor Hotspot	Dense Urban	Rural Coverage	High Speed
LF and/or HF	**LF and/or HF**	**LF**	**LF**

m-MTC	URLLC
Urban Coverage	Urban Coverage
LF	**LF**

Source: China IMT-2020 5G Promotion Group

China has already officially indicated that the following spectrum will be reserved for 5G if there is no public opposition:

1) 3.3GHz to 3.6GHz (total 300MHz)
2) 4.4GHz to 4.5GHz (total 100MHz)
3) 4.8GHz to 5.0GHz (total 200MHz)

A total of 600MHz is already reserved at low frequencies in China

Therefore, a total of 600MHz has been reserved so far at low frequencies. However, China is not ruling out high frequencies, but believes those are only "supplement" to low frequencies in 5G. On June 7, 2017, the MIIT issued a request for detailed feedback on the potential deployment of high frequencies for 5G at 24.75GHz to 27.5GHz and 37GHz to 42.5GHz. This is not just asking whether there is public opposition. Instead the MIIT is asking for detailed deployment plans and technological solutions if operators would like to utilize such high-frequency spectrum.

Therefore, the following are our observations in the competition for frequency choice:

China treats low frequencies at the core while the US treats high frequencies at the core

- **China treats low frequencies as the core**, and high frequencies as a supplement
- **The US treats high frequencies as the core**, and low frequencies as a supplement, likely because most of its low frequencies are being occupied, and some by military uses.
- **Some US operators seem to be keen to have early deployment of 5G at 28GHz, but this frequency is not included in the WRC-15 identification list**. We understand that there is also no plan for WRC-19 to consider 28GHz, and the US is upset about this.
- **Korea seems to support US choice of high frequencies**. KT is launching limited 5G services during the Winter Olympics in 2018 at 28GHz.
- **The MIC of Japan seems to be neutral on spectrum choice**. However, NTT DoCoMo is supporting high frequencies while Softbank is keen on low frequencies.

EU has made allocation at both low and high frequencies

- **The EU is practical and has made allocation at both low (including super low 700MHz) and high frequencies**.
- Both low (3GHz to 6GHz) and high frequencies (25GHz to 40GHz) as identified by WRC-15 will overlap with satellite communications (C-band and Ka band). Therefore, it needs to be coordinated in different countries to ensure there will be no interference.

The spectrum choice has important implications for 5G technology:

- **The 3GPP technical specification work so far is focused on utilizing low frequencies**.
- It seems that even if 3.3GHz to 4.2GHz will finally be chosen as a globally harmonized spectrum for 5G, not every country can make the entire frequency range available for 5G.

Different countries might allocate different sub-bands for 5G

- It is likely that different countries will allocate different sub-bands in this frequency range for 5G.

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As long as 5G usesTDD, the different sub-bands adopted within the proposed low frequency range will not be an issue for equipment harmonization

- **As long as the multiplexing is based on TDD, national decisions to pick a smaller range will not affect equipment (i.e., handsets and other mobile devices) harmonization**. A TDD device would be able to work in different sub-ranges within the wider band, without emitting signals outside of those country-specific ranges.

Some might question whether it is a must to allocate a contiguous spectrum of 100MHz for 5G

Do operators really need contiguous spectrum of 100MHz for 5G? It is an interesting question since some argue that one way to solve the problem of a lack of wide spectrum is to use carrier aggregation (CA) technology to combine smaller pieces of spectrum at low frequencies to achieve high capacity and high speed. CA is an evolution of the 4G LTE standard (widely regarded as 4.5G). This is an attractive alternative for many operators, since they will be able to reuse its 2G, 3G and 4G spectrum to provide high-speed data services (assuming they are allowed by their regulators).

Carrier aggregation is not as efficient as 5G NR operated with a contiguous wide spectrum

However, according to work done by the 3GPP, **carrier aggregation cannot replace the deployment of 5G NR with contiguous wide spectrum**, since:

- The design of Massive MIMO and active antennas is based on the availability of contiguous wide spectrum; otherwise the absolute gains in speed and capacity will be much smaller
- 5G NR on wide spectrum will reduce power consumption and front-end complexity at the handsets (or other types of mobile devices)
- Wideband carriers and flexibility in sub-carrier spacing will result in a more efficient RF front-end for the handsets, and improved power consumption and processing at the baseband (per Mbit/s and per MHz)
- As the number of channels in CA increases, LTE will become less efficient than 5G NR deployed with a wide spectrum, TD duplexing and Massive MIMO.

Table 15: Theoretical 5G Data Rates per Channel Bandwidth

RF channel Bandwidth	Peak data rates[1]	Average data rates[2]
40 MHz	1.2 Gbit/s	0.312 Gbit/s
100 MHz	3 Gbit/s	0.78 Gbit/s
200 MHz	6 Gbit/s	1.56 Gbit/s
400 MHz	12 Gbit/s	3.12 Gbit/s

[1]Peak spectral efficiency (SE) of NR: 30 bit/s/Hz in DL (from draft New Report IMT-2020.TECH PERF REQ in ITU-R WP 5D). Peak data rate in IMT-2020.TECH PERF REQ is 20 Gbit/s in DL (roughly equivalent to a total of 667 MHz with the considered SE)

[2]Average spectrum efficiency (SE) of NR: 7.8 bit/s/Hz in DL for Dense Urban scenario (3 x SE of IMT-Advanced, also considered in IMT-2020.TECH PERF REQ)

Source: 3GPP

mmWave – the technological vs political considerations

Technology related to wavelength shorter than 1cm is referred to as mmWave

Wavelength shortens as frequency goes higher. At the high frequencies as defined by the WRC and ITU (24GHz and above), the wavelength will be shortened to below 1cm. Therefore, the technology is commonly known as millimeter-wave, or mmWave.

Researches, mainly at the US, suggested that Massive MIMO could solve the challenges of mmWave

Historically, mmWave has had serious technological drawbacks such as propaganda loss and signal interference, so it has never been chosen by the industry. However, some academic research, mainly in the US, suggested that many challenges of mmWave could be overcome with Massive MIMO (i.e., a large array of antennas) and massive beamforming technology. Some US academia claimed they have developed new mathematical models, using stochastic geometry, that will allow mmWave cellular networks with high enough cell density to achieve comparable performance (measured by SINR) to that of low-frequency networks, but with a much higher data speed and capacity owing to much wider spectrum available for mmWave.

mmWave technology offers a much higher data speed and capacity

Propaganda loss, or attenuation, is the most fundamental problem of high frequencies

The most fundamental problem of high frequencies is propaganda loss. The loss is measured by dB/km (i.e., loss of signal power measured by dB per km of transmission).

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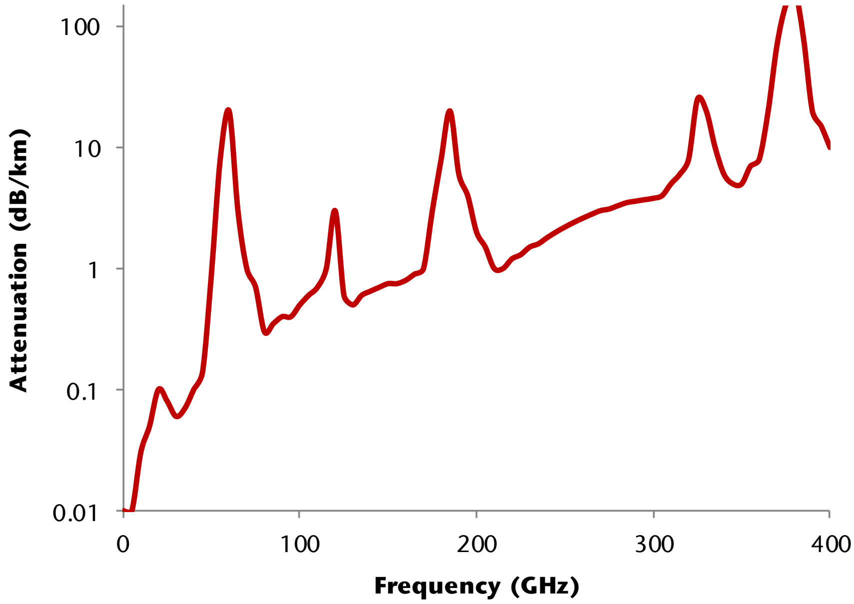
The key reason for transmission loss (which in proper engineering term is called "attenuation"), even if it is in a wide open area with no physical objects, is atmospheric absorption. The attenuation at sea level can rise 10x if the frequency goes up from a few GHz to 20GHz. Then it will fall somewhat before skyrocketing by 100x when it rises to 60GHz. As the amount of vapor in the air rises, the attenuation will deteriorate. If it rains heavily (22mm per hour), the attenuation at 28GHz is estimated at 5 dB/km, significantly worse than below 0.1 dB/km when it is dry.

Chart 24: mmWave Attenuation Loss vs Frequency Level (GHz)



Source: NYU Tandon School of Engineering, May 29, 2013, Jefferies

mmWave can be used for high-speed, high-capacity wireless communication with acceptable noise level and propaganda loss

Academic research and experiments at NYU Tandon School of Engineering (led by Prof. Theodore S. Rappaport), University of Texas at Austin (led by Prof. Robert W. Heath Jr.) and University of Wisconsin at Madison (led by Prof. Xinyu Zhang) have all shown that mmWave can be used for very high-speed, high-capacity wireless communications with acceptable noise level and propaganda loss at a sufficient level of cell densification. In layman terms, that means if the base stations are located closely enough to one another (eg, 200m) with line of sight, the reliability will be acceptable, and, because of the huge bandwidth available (200MHz or more), very high-speed and high-capacity connections can be achieved. It is interesting to note that the research at NYU has been partly funded by Samsung.

Verizon would start offering "fixed wireless" 5G service at the end of 2017 using the mmWave technology

The largest US operator Verizon is very excited about mmWave technology. It announced that it would start offering "fixed wireless" 5G service at 28MHz in suburbs at the end of 2017. It also plans to roll out super high-speed 5G services in major cities based on 28GHz, although no specific timing has been given. Verizon's fixed-wireless plan is based on the idea that they will design and provide a 5G router for home use. Then they will build micro base stations in suburbs that are connected by fibers to their core network. The 5G router in a customer's home will be wirelessly connected with Verizon's micro base stations in the area (likely on the same street). Therefore, the 5G fixed-wireless service contemplated by Verizon is effectively a replacement of the last-mile fiber connection to the home (FTTH).

Verizon collaborated with Cisco, Ericsson, Nokia, Intel, Samsung and LG to develop the 5G fixed-wireless technology via V5GTF

In 2015, Verizon formed the Verizon 5G Technology Forum (V5GTF) together with Cisco, Ericsson, Nokia, Intel, Samsung and LG in order to develop the 5G fixed-wireless technology using spectrum at 28GHz and 39GHz. It said that it would share all the development work with 3GPP, and would likely modify their 5G networks to be compatible with 3GPP standards once the latter has completed its standardization work.

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mmWave's feasibility being challenged by other researchers

However, there has been other research that offers a less optimistic view on the feasibility of mmWave technology. Softbank, for example, presented its mmWave experiment results at the Shanghai Mobile World Congress In June 2017. It concluded that mmWave would be hard to manage with high diffraction loss at the edge of buildings and high foliage blockade (i.e., by wood, leaves and trees). The realistic workable distance between two base stations would be 100m and requires line of sight. Therefore, Softbank is not keen to deploy mmWave technology in either Japan or the US. In the US, Sprint will likely build 5G at 2.5GHz.

mmWave research is also done in China...

In China, mmWave research is being led by Prof. Wei Hung's team at Southeast University. Prof. Hung's team is also in charge of helping establish the standard of IEEE 802.11aj, which utilizes spectrum at 45GHz to establish indoor LAN that is capable of delivering data speed of 15Gbps with a coverage radius of 100m.

...and results suggest there are some challenges to be overcome before this technology can be commercialized

Prof. Hung's team summarized the following challenges of mmWave technology for mobile communications that need to be addressed, before it can be commercialized:

- mmWave relies heavily on Massive MIMO and Massive Beamforming to extend its transmission distance. When the number of users connected to a base station significantly increases, the computational requirement for channel information will be massive, which has not yet been resolved.
- In theory, when the number of antenna elements doubles, the transmission power will increase by 3 dB. Therefore, using large antenna arrays at mmWave would help it achieve a coverage area of 100m to 200m. However, the transmitter or receiver will need to scan and aim accurately at the right device with its fixed beams before a connection can be established with the antenna. How to achieve that in milliseconds and accurately remains a big challenge.
- The use of large antenna arrays with lots of elements per antenna at high frequencies naturally results in much narrower transmission beams. These narrow beams will significantly increase the sensitivity of their connection with the device (e.g, handset). For example, when the device is moving quickly, it may find it hard to maintain a steady connection because the base station will keep connecting and disconnecting the device with different antennas based on different positions of the device. This remains a big challenge to solve.
- Designing a proper channel coding methodology is a challenge. There has been a lot of research on digital-analog channel coding for point-to-point communication at mmWave, but all the research has assumed the channel state information (CSI) is already known. Obtaining precise information of the CSI in Massive MIMO is a big challenge.
- The computational power requirement and complexity of algorithm on the baseband chip is extremely high owing to high sampling rates (driven by very wide bandwidth at high frequencies) and low latency requirements. This needs to be addressed in a cost effective manner.

mmWave is not unanimously supported by US operators

Even among the US wireless operators, not all of them are excited about mmWave.

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Table 16: 5G Plans of US Wireless Operators

Operator	5G Plan
Verizon	Deploy 28GHz/37GHz in fixed wireless for suburbs and build super hotspots in large cities.
AT&T	Introduce 4.5G services by end of 2017 (but marketed as 5G). Plan to start building real 5G networks in 2018/2019 timeframe using 3GPP Phase 1 standard and then upgrade to Phase 2. Will conduct tests at 15GHz, 28GHz, 39GHz and 64GHz frequency bands.
T-Mobile	Recently spent US$8bn buying a big chunk of the 600MHz spectrum in the US auction. Expected to build 5G using 3GPP standard at 600MHz.
Sprint	Expected to build 5G at 2.5GHz using 3GPP standard since it owns a large chunk of spectrum at 2.5GHz and it does not have confidence in high frequencies.

Source: Jefferies estimates

The US government has recently auctioned 70MHz of spectrum at 600MHz for US$19.8bn

It is worth pointing out that the US government completed a highly successful auction of spectrum at 600MHz in April 2017. Approximately a total of 70MHz was available for auction and it raised a total of US$19.8bn. Part of the proceeds will be used to pay certain TV operators to move to an even lower frequency level. The three major winners are T-Mobile, Comcast and Dish. It is widely believed these buyers will use the spectrum bought to build 5G networks. Currently both Comcast and Dish do not provide mobile services. Therefore, it is very likely that competition in the US mobile market will intensify as new operators will enter the game.

The auction winners will likely combine 600MHz with 3.5GHz or mmWave frequencies to provide 5G services, in our view

As discussed earlier, 5G can be done at low frequencies (below 1GHz) if there is enough bandwidth (700MHz has been reserved for 5G in the EU). But large bandwidth at below 1GHz is rarely available. For the US operators who have won spectrum 600MHz, because it is less than 70MHz, they will likely have to combine it with frequencies at 3.5GHz or even mmWave frequencies to provide truly 5G services with large capacity.

China could deploy low frequency for 5G, leveraging SAPPRFT's 100MHz of spectrum at 700MHz

We continue to believe China is one country that potentially can deploy super low frequency for 5G (in addition to frequencies at between 3GHz and 6GHz), since SAPPRFT is estimated to have 100MHz of spectrum at 700MHz freed up by its migration from analog to digital broadcasting. That spectrum is largely un-utilized currently. The government will be motivated to engineer a deal between SAPPRFT and China Unicom so that SAPPRFT will obtain an equity stake in Unicom's A share co in exchange for assigning its rights to the spectrum at 700MHz to Unicom.

Outside of China, two operators seem very supportive of mmWave technology for 5G: KT in Korea and DoCoMo in Japan.

China needs FIRST MOVER ADVANTAGE:

China likely needs to make a first move in building 5G at low frequencies

Given 1) the US's intention to push mmWave technology, 2) the potential support shown by DoCoMo and KT of mmWave, both of which want to launch 5G quickly, 3) China's belief that low frequencies serve its wide coverage objective much better, and 4) China's view that mmWave technology is not yet mature, it will be in China's interest to make a first move in building 5G at low frequencies in a big scale and as soon as the technology is available.

Once 5G at low frequencies is in scale, lower handset and network costs will create a virtuous circle

Once China has deployed 5G at low frequencies successfully in scale, we believe that the technology will be visibly proven to all those operators who have not yet built out 5G, the equipment cost (both network and devices) will fall, and handset selections will become plentiful. We expect it to significantly reduce the chance that mmWave will become the dominant mobile technology.

This will also support China's goal to introduce IoT, big data and cloud aggressively

In addition to satisfying China's goal to become a leader in the next-generation communications technology, building 5G fast and in scale would also help China implement ambitious initiatives in industrial IoTs, big data and cloud to help upgrade all major industries and sustain healthy economic growth.

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IoT - different but still part of the 5G game

Is IoT part of the 5G technology

MIIT targeted to have 400K base station by the end of 2017 and 1.5m by 2020

China obviously has an aggressive IoT initiative for all major industries, which is clearly specified in its 13th FYP for TMT. On June 16, the MIIT issued a notification on NB-IoT's development, targeting to have 400K base stations by the end of 2017 and 1.5m by 2020. The MIIT's quantitative targets surprised the industry, and are a strong indication that the government wants to 1) aggressively develop IoT services, and 2) support the 3GPP-developed NB-IoT standard in order to drive out SigFox and LoRa.

NB-IoT can work on any FDD networks

It offers low power and a wide area coverage; but limited mobility

It works best at low frequencies which could further enhance its coverage and penetration

NB-IoT, as its name implies, is a narrow-band, low-power and wide-area data transmission technology that can work on any 2G, 3G or 4G networks that use FD duplexing. In other words, it does not work on TDD networks. The major features of NB-IoT are 1) low power (so that the battery on a device can last 10 years), 2) wide area (very narrow transmission beams will mean longer transmission distance), and 3) limited mobility (that helps lower power consumption). Ideally, NB-IoT should be implemented at low frequencies (e.g., 800MHz or 900MHz) so that it will further enhance its coverage area and penetration power (so that it can reach devices that are installed below ground or deep in the basement).

3GPP already planned to integrate NB-IoT features into 5G

Therefore, NB-IoT is currently not part of the 5G technology. However, 3GPP has a clear migration path to integrate NB-IoT features into 5G in the next two to three years.

Why is China pushing the NB-IoT standard

We believe there are many reasons:

The three Chinese telcos are already developing IoT services, allowing China to gain experience before 5G IoT services arrive

- China has aggressive industrial IoT initiatives. Therefore, China wants to start now given the technology is already available. Since the NB-IoT initiative was published, the three Chinese telcos have aggressively started developing IoT services, mostly with local government, on a wide range of services such as smart meters, smart water quality sensors, smart air quality sensors and smart parking systems. An early start will allow China to gain experience and have established infrastructure (eg, billing system, a knowledgeable sales force) when more sophisticated 5G IoT services arrive.

NB-IoT is a standard developed by 3GPP and is aggressively supported by China

- NB-IoT is a standard developed by 3GPP. Since China is now an active participant in 3GPP, and it will embrace the concept of a single, global standard, its aggressive support of the NB-IoT standard should not be a surprise. It will also increase China's influence in the 3GPP and ITU.

Other IoT standards exist in the global market

- There are competing IoT standards in the market, such as LoRa and Sigfox. LoRa has attractive features and is widely used for IoT services both in China and globally. China's official support of the NB-IoT standard will quickly drive out these private standards.

Table 17: All IoT Technology Standards

IoT Tech	LoRa	SigFox	LTE Release 8	LTE-M Release 13	NB-IoT Release 13	NB-IoT Release 14/15
Standard body	LoRa Alliance	N/A	ITU-3GPP	ITU-3GPP	ITU-3GPP	ITU-3GPP
Peak data rate	10 kbps	100 bps	Up to 10 Mbps	Up to 1 Mbps	<100 kbps	Expected improvements:
Bandwidth	125 kHz	0.1 kHz	Up to 20 MHz	1.4 MHz	200 kHz	1) Single-cell multicast
Duplex mode	Wide-band linear FM pulses	Start topology	Full duplex FDD/TDD	Full or half duplex FDD/TDD	Half duplex FDD	2) Device Positioning 3) Lower Latency
Mobility	No mobility	No mobility	Full mobility	Limited to full mobility	Cell reselection only	4) Higher Data Rate (5 MHz) 5) Energy Reduction
Voice	No voice support	No voice support	VoLTE	VoLTE	No voice support	6) Cell Size Extension (100 km radius)
Spectrum	Unlicensed	Unlicensed	Licensed	Licensed	Licensed	7) TDD Support (Release 15)

Source: Qualcomm, www.rfwireless-world.com, Jefferies estimates

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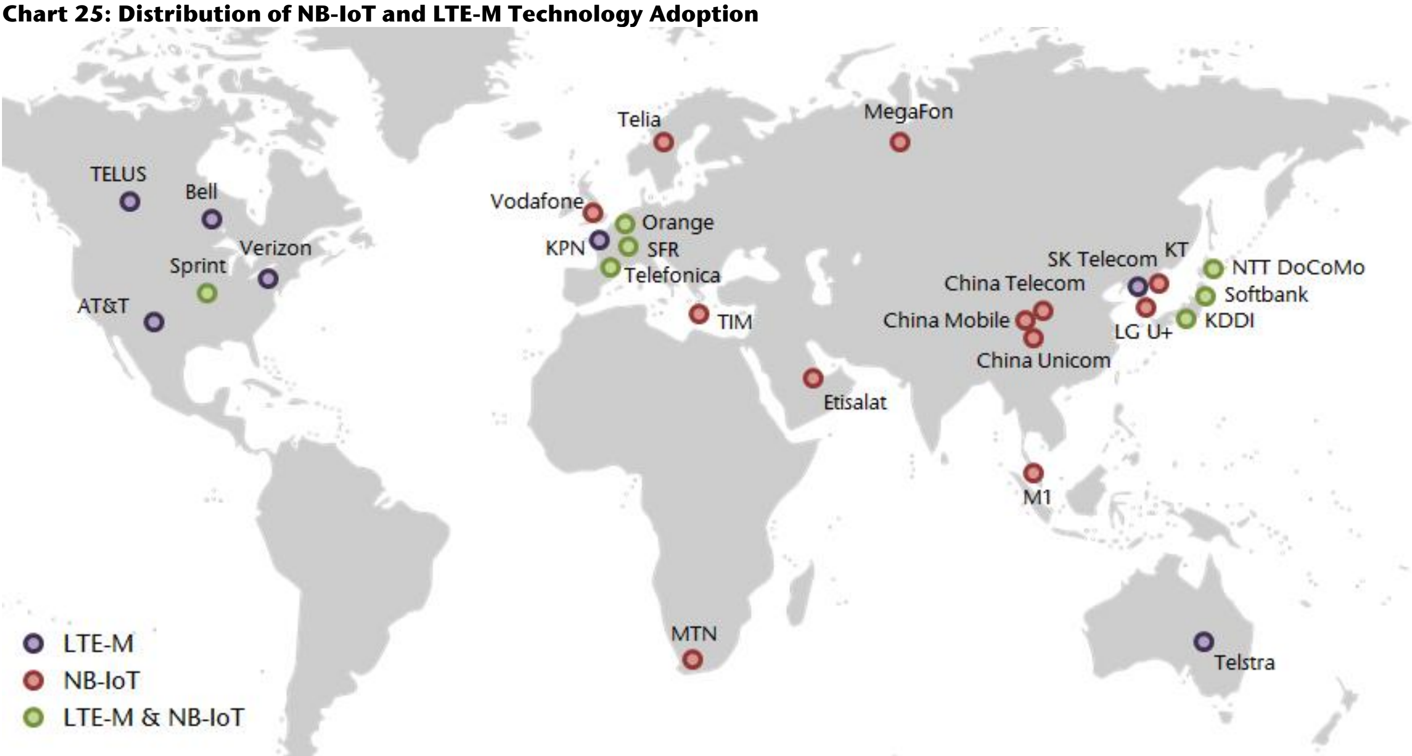
China supports NB-IoT over LTE-M for its lower power consumption and higher adoption rate by European operators, in our view

A more interesting question is: why does China aggressively support NB-IoT but not LTE-M, both being 3GPP-developed IoT standards? We believe there are two possible reasons: 1) LTE-M provides higher mobility feature but also require higher power consumption, therefore may not be an ideal technology to promote as a starting point for IoT services in China; 2) NB-IoT has been predominantly adopted by European operators, while LTE-M mainly by US operators. China is willing to subsidize NB-IoT devices and chipsets in order to scale up this technology, so that it will likely be able to be a key IoT equipment supplier to the rest of the world (perhaps except the US, but US operators do not buy telecom equipment from China anyway).

Chart 25: Distribution of NB-IoT and LTE-M Technology Adoption



Source: ITU, Openclipart, Jefferies

China Mobile and China Telecom will roll out LTE-M service as well; but we believe NB-IoT will still prevail in the longer term

Both China Mobile and China Telecom indicated that they would roll out LTE-M services later, which suggests that China is not trying to support ONLY NB-IoT. The two technology standards are complementary since they offer different features and functionalities. But LTE-M's features of higher mobility, higher transmission speed but higher power consumption may make it vulnerable to being replaced by NB-IoT Release 14/15 when it is integrated into 5G. That may also be another reason why the government wants to focus on NB-IoT instead of LTE-M.

Even though NB-IoT today is not part of the 5G technology, we believe China views it as part of the overall "technology package" of 5G and would like to be an early adopter in order to gain knowledge and experience ahead of eventually building 5G early and aggressively.

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The ITU and 3GPP is a political arena

What is the ITU and 3GPP

ITU is a United Nations-led organization on issues related to telecommunications

The ITU is an organization under the United Nations in charge of coordinating among member countries on all issues related to telecommunications. In the early days, the most important issue was to maintain common technology standards and compatible systems on the fixed line networks so that every country's telephone network could "talk" to each other. Then it extended into coordination work of satellite communications, including frequency and orbital slot allocation.

ITU took over cellular tech's standard development and coordination work in the early 90s

Cellular technology emerged in the early 90s. The ITU was the natural organization that took over the technology standard development and coordination work. Spectrum allocation and coordination has become much more important with the rising popularity of cellular communications, and it is handled by the WRC.

The ITU consists of three main departments

The ITU currently consists mainly of three departments: Telecommunication Standardization Bureau, Telecommunication Development Bureau and Radiocommunication Bureau.

The ITU is currently led by Mr. Houlin Zhao, who is the first Chinese official elected as the ITU's Secretary-General

The ITU is led by its Secretary-General, who is elected to a four-year term by the member states. Currently, the Secretary-General is Mr. Houlin Zhao from China. Zhao was elected at the end of 2014 to be Secretary-General and his term will expire in January 2019. Zhao is the first Chinese official who has been elected Secretary-General at the ITU. Prior to becoming the Secretary-General, Zhao served as the ITU Deputy Secretary-General between 2007 and 2014, and was Director of the ITU's Telecommunication Standardization Bureau from 1999 to 2006.

Mr. Houlin Zhao was elected at the end of 2014. His term will expire in Jan 2019

Table 18: ITU's Previous Secretary-General

Name	Beginning of Term	End of Term	Country
Léon Mulatier	1-Jan-50	31-Dec-53	France
Marco Aurelio Andrada	1-Jan-54	18-Jun-58	Argentina
Gerald C. Gross	1-Jan-60	29-Oct-65	United States
Manohar Balaji Sarwate	30-Oct-65	19-Feb-67	India
Mohamed Ezzedine Mili	20-Feb-67	31-Dec-82	Tunisia
Richard E. Butler	1-Jan-83	31-Oct-89	Australia
Pekka Tarjanne	1-Nov-89	31-Jan-99	Finland
Yoshio Utsumi	1-Feb-99	31-Dec-06	Japan
Hamadoun Touré	1-Jan-07	31-Dec-14	Mali
Houlin Zhao	**1-Jan-15**	**Present**	**China**

Source: Wikipedia

How is a cellular technology standard developed at the 3GPP

3GPP was established in 1998 when ETSI convinced the other standards development organizations to work together

3GPP, or the 3rd Generation Partnership Project, was formed in 1998 when the European Telecommunications Standards Institute (ETSI) convinced other standards development organizations to work together to develop specifications of new cellular technology. ESTI was heavily influenced by the 2G GSM standard because that standard was developed mainly by European equipment makers. At around the same time, Qualcomm led the efforts to form a similar organization (there were common members) to develop new cellular technology. The organization was called 3GPP2, which was focused on CDMA since CDMA was originally developed by Qualcomm.

3GPP developed WCDMA for 3G; while 3GPP2 developed the CDMA2000. They were merged later on for a more converged 4G standard

3GPP developed the WCDMA standard for 3G, and 3GPP2 developed the CDMA2000 standard. China on its own developed the TD-SCDMA standard, which was recognized by the ITU as the third 3G standard. When they realized in mid-2000 that consumers were looking for even faster data speed and more capacity, the work on 4G started. Having recognized that CDMA2000 was still a minority standard globally, the Qualcomm-led

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3GPP2 agreed to merge with 3GPP to develop a more converged 4G standard, called Long-term Evolution (LTE). China also started participating in 3GPP.

3GPP is now within the scope of the ITU to develop new cellular technology

Today 3GPP is a specification development organization within the scope of the ITU to develop new cellular technology. Its main members are regional standards bodies (called Organizational Partners) and industry alliances (called Market Representative Partners). Individual operators and equipment makers participate in the 3GPP via their membership in the regional standards bodies and/or industry alliances.

Chart 26: 3GPP Organizational Partners (SDOs)

Regional Standards Organizations:

ARIB (Japan)	**TTA (Korea)**
ATIS (USA)	**TTC (Japan)**
CCSA (China)	**TSDSI (India)**
ETSI (Europe)	

Source: 3GPP

Chart 27: 3GPP Market Representative Partners

14 Market Partners Representing the Broader Industry:

5G Americas	**MDG (formerly CDG)**
COAI	**NGMN Alliance**
CTIA	**Small Cell Forum**
GCF	**TCCA**
GSA	**TD Industry Alliance**
GSMA	**TD-Forum**
IPV6 Forum	**UMTS Forum**

Source: 3GPP

3GPP will submit the results on behalf of its members to the ITU for approval as a global standard

3GPP currently consists of more than 400 companies from 39 countries. 3GPP's job is to develop technical specifications for cellular technology and, therefore, is an engineering organization. Once the specifications are developed and agreed upon, 3GPP will submit the results jointly in the name of the Organizational Partners (ie, regional standards bodies) to the ITU for approval as a standard. Since the submission is supported by all the regional standards bodies, the development effort is a global initiative.

The development process is collaborative and democratic and work is done on a piece-meal basis

The specification development process is a collaborative and democratic one, which means every member can submit their proposals on any aspects, but the work is divided up in different parts and members can choose to participate in certain parts that they find more useful or interesting. Work is done on a piece-meal basis because a member does not have to be involved in designing all the pieces, although the ultimate objective is to deliver an end-to-end solution as a standard.

There are different working groups responsible for different parts of the cellular technology within 3GPP

Since the work of the organization is to develop specifications of cellular technology, it has set up working groups that are responsible for different parts of the technology. There are three main technical specification groups (TSG): radio access, service/system aspects and core network and terminal. Each large group is subdivided into small working groups to work on the detailed specifications. Currently there are 16 specification development sub-groups.

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Table 19: 3GPP Distributed Organization Structure

Radio Access Network (RAN)	Service/System Aspects (SA)	Core network & Terminals (CT)
Technical Specification Group	**Technical Specification Group**	**Technical Specification Group**
Defines the radio communications between UEs and core network	*Responsible for overall architecture & service capabilities*	*Responsible for core network; defines terminal interfaces & capabilities*
RAN WG1 Layer 1 (Physical) spec	**SA WG1** Service requirements	**CT WG1** Mobility Mgmt, Call Ctrl, Session Mgmt
RAN WG2 Layer 2 and 3 (RR) protocols	**SA WG2** Architecture	**CT WG3** Policy, QoS and Interworking
RAN WG3 Access network interfaces + O&M	**SA WG3** Security	**CT WG4** Network protocols
RAN WG4 Performance requirements	**SA WG4** Codecs, multimedia system	**CT WG6** Smart card application
RAN WG5 UE conformance testing	**SA WG5** Telecom management	
RAN WG6 Legacy RAN, e.g. GSM, HSPA	**SA WG6** Mission-critical services	

Source: 3GPP, Qualcomm

A large organization like 3GPP inevitably consists of many members of diverse interests and motivations. Therefore, although it is intended to be a democratic organization, the process will need control, coordination and supervision. Without such the collaboration efforts may take forever to come up with a solution that every member will accept. The primary basis of any decision on a specification is via consensus building, after extensive discussions and negotiations among members during and outside official meetings.

The Chairman at each working group has certain influence in deciding the specification

If a consensus decision cannot be made, the Chairman can decide to take a vote. A proposal will be deemed to be approved if 71% of the votes cast are in favor. Abstentions or failure to submit a vote will not be included in the vote count. It is the Chairman's responsibility to ensure that the question to be voted upon is clearly defined in a yes/no manner, with 71% required to approve the question.

Each voting member is entitled to only one vote, but each voting member may carry proxy votes for up to five other voting members, as long as they are accompanied by proper authorization letters.

How does China play the ITU/3GPP game

China's influence in the 3GPP and ITU can be observed from the number of representatives in different groups, in our view

It is interesting to see how China's influence has risen in the 3GPP and ITU over time, by observing how many representatives from Chinese organizations have been elected to be chairman or vice chairman in different groups.

The ITU set up the Focus Group on IMT-2020 in 2015 to analyze how emerging 5G technologies will inter-act in future networks as a preliminary study into the networking innovations required to support the development of 5G systems. This group, which finished its work by the end of 2016, has two Chinese representatives.

There are two Chinese representatives in the ITU Focus Group on IMT-2020

Table 20: The ITU Focus Group on IMT-2020

Chairman	**Peter Ashwood-Smith**	**Huawei**
Vice Chairman	**Wachen Wang**	**China Mobile**
Vice Chairman	Nam-Seok Ko	ETRI, Korea
Vice Chairman	Yoshinori Goto	NTT
Vice Chairman	Luca Pesando	Telecom Italia

Source: ITU

In the 3GPP's technical specification groups (TSG) and sub-groups, the chairman and vice chairman are elected every two years, and there can be a maximum of three vice chairmen. All TSG groups and sub-groups had an election in 2017.

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The following are our observations in the change in chairman and vice chairman in these groups since 2013:

Number of Chinese representatives has risen from 8 in 2013 to 10 in 2017 out of total of 57 positions

- **The number of Chinese representatives has risen from 8 in 2013 to 10 in the most recent election (out of a total of 57 positions).**

The number of China Mobile representatives has risen from 1 to 3

- In 2013, 7 out of the 8 Chinese representatives were from Huawei (one from China Mobile). In 2017, only 5 out of the 10 Chinese representatives are from Huawei. **The number of China Mobile representatives has risen to 3 (from 1)**, and one is from ZTE and the other one from CATT (China's Academy of Telecommunications Technology).

The first Chinese representative was elected at the RAN TSG in 2017

- **In 2017, for the first time a Chinese representative (from China Mobile) has been elected as a vice chairman at the Radio Access network TSG,** which helps supervise and coordinate the work of the six subgroups in radio access.

- The number of Chinese representatives in the radio access network TSG and subgroups have risen from 3 in 2013 to 5 in 2017, which, interestingly, coincides with the estimate made by LexInnova that China's share of 5G-essential IPRs is the highest in radio access.

The first Chinese chairman of a TSG was elected in 2017

- In 2017, a Chinese representative (from Huawei) was elected chairman of the core network and terminal TSG. It is the first time that a Chinese representative has been elected chairman of a TSG (not a sub-group).

No Chinese representatives at the RAN1 TSG sub-group (physical layer) which we reckon to be the most important layer of the radio network

- **No Chinese representatives have ever been elected chairman or vice chairman of the RAN1 TSG sub-group**. Note that RAN1 works on the physical layer of the radio network, which is the most important.

- **In the 2017 election for chairmanship for the RAN1 subgroup, a Huawei representative ran against a Qualcomm representative, and the Huawei representative lost.** The Qualcomm representative was previously the vice chairman of RAN1.

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Table 21: List of Chairman and Vice Chairman of TSG and TSG Sub-groups – 2013

TSG Radio Access Network			**TSG Service/System Aspects**			**TSG Core Network and Terminal**		
Chairman	Dino Flore	Qualcomm	Chairman	Mr Balazs Bertenyi	Nokia Siemens	Chairman	Atle Monrad	Ericsson
Vice chairman	Takaharu Nakamura	Fujitsu	Vice chairman	Gary Jones	T-Mobile	Vice chairman	Adrian Neal	Vodafone
Vice chairman	Giovanni Romano	Telecom India	Vice chairman	Daisuke Yokota	Softbank	Vice chairman	Martin Dolly	AT&T
Vice chairman	Sharat Chander	AT&T	**Vice chairman**	**Christian Toche**	**Huawei**	Vice chairman	Katsutoshi Nishida	DoCoMo
RAN1 - Physical Layer			**SA1 - Service Requirement**			**CT1 - Mobility Management, Call Control, Session Mgt**		
Chairman	NAGATA, Satoshi	DoCoMo	Chairman	Toon Norp	KPN	**Chairman**	**MAYER, Georg**	**Huawei**
Vice chairman	CHEN, Wanshi	Qualcomm	Vice chairman	YOUNGE, Mark	T-mobile	Vice chairman	WASS, Mikael	Ericsson
Vice chairman	BAKER, Matthew	Alcatel-Lucent	Vice chairman	NAPOLITANO, Antonella	Telecom Italia	Vice chairman	CHIN, Chen-ho	Intel
RAN2 - Radio Resource Protocol (Aug 21, 2017)			**SA2 - System Architecture**			**CT3 - Policy, QoS and Interworking**		
Chairman	NA		Chairman	GUTTMAN, Erik	Samsung	**Chairman**	**QIAO, Weihua**	**Huawei**
Vice chairman	YI, SeungJune	LG Electronics	Vice chairman	GUARDINI, Ivano	TELECOM ITALIA S.p.A.	Vice chairman	FERNANDEZ, Susana	Ericsson
Vice chairman	**Dr. Nan Hu**	**China Mobile**				Vice chairman	ARAI, Kenjiro	NTT
Vice chairman	WIEMANN, Henning	Ericsson						
RAN3 - Access Network Interface			**SA3 - Security**			**CT4 - Network Protocols**		
Chairman	**REININGER, Philippe**	**Huawei**	Chairman	Anand Prasad	NEC	Chairman	BERRY, Nigel. H	Nokia
Vice chairman	GODIN, Philippe	Alcatel-Lucent	Vice chairman	Alf Zugenmaier	DoCoMo	Vice chairman	MORAND, Lionel	Orange
Vice chairman	ISRAELSSON, Martin	Ericsson	**Vice chairman**	**ZHU, Hongru**	**China Mobile**	Vice chairman	KOZA, Yvette	Deutsche Telekom
RAN4 - Radio Performance Requirements			**SA4 - Codec for Speech, Audio, Video and Multimedia Systems**			**CT6 - Smart Card Applications**		
Chairman	SÄYNÄJÄKANGAS, Tuomo	Nokia	Chairman	JÄRVINEN, Kari	Nokia	Chairman	JOLIVET, Paul	LG Electronics
Vice chairman	JI, Tingfang	Qualcomm	Vice chairman	KYUNGHUN, Jung	Samsung	Vice chairman	BERIONNE, Michele	Qualcomm
Vice chairman	**CHEN, Xiang (Steven)**	**Huawei**				Vice chairman	KRUSE, Heiko	Morpho Cards
RAN5 - Mobile Terminal Conformance Testing			**SA5 - Telecom Management**					
Chairman	BAUSTERT, Nick	Sprint	**Chairman**	**TOCHE, Christian**	**Huawei**			
Vice chairman	JOHN, Jacob	Motorola	Vice chairman	Jean Michel Cornily	Orange			
Vice chairman	GOWDA, Pradeep	Qualcomm	Vice chairman	TOVINGER, Thomas	Ericsson			

Source: 3GPP

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Table 22: List of Chairman and Vice Chairman of TSG and TSG Sub-groups – 2015

TSG Radio Access Network			**TSG Service/System Aspects**			**TSG Core Network and Terminal**		
Chairman	Dino Flore	Qualcomm	Chairman	Erik Guttman	Samsung	**Chairman**	**Georg Mayer**	**Huawei**
Vice chairman	Takaharu Nakamura	Fujitsu	Vice chairman	Daisuke Yokota	Softbank	Vice chairman	Nigel Berry	Alcatel-Lucent
Vice chairman	Giovanni Romano	Telecom Italia	Vice chairman	Gregory Schumacher	Sprint Corp	Vice chairman	Martin Dolly	AT&T
Vice chairman	Sharat Chander	AT&T	**Vice chairman**	**Christian Toche**	**Huawei**	Vice chairman	Atsushi Minokuchi	DoCoMo
RAN1 - Physical Layer			**SA1 - Service Requirement**			**CT1 - Mobility Management, Call Control, Session Mgt**		
Chairman	NAGATA, Satoshi	DoCoMo	Chairman	Toon Norp	KPN	Chairman	Ricky Kaura	Samsung
Vice chairman	CHEN, Wanshi	Qualcomm	Vice chairman	YOUNGE, Mark	T-mobile	Vice chairman	Peter Leis	Nokia
Vice chairman	BAKER, Matthew	Alcatel-Lucent	Vice chairman	LEE, Ki-Dong	LG Electronics	Vice chairman	CHIN, Chen-ho	Intel
RAN2 - Radio Resource Protocol (Aug 21, 2017)			**SA2 - System Architecture**			**CT3 - Policy, QoS and Interworking**		
Chairman	BURBIDGE, Richard	Intel	**Chairman**	**Dr. Frank Mademann**	**Huawei**	**Chairman**	**QIAO, Weihua**	**Huawei**
Vice chairman	PANI, Diana	Intel	Vice chairman	Puneet Jain	Intel	Vice chairman	FERNANDEZ, Susana	Ericsson
Vice chairman	**HU, Nan**	**China Mobile**	Vice chairman	Kristian Kiss	Apple	Vice chairman	ARAI, Kenjiro	NTT
RAN3 - Access Network Interface			**SA3 - Security**			**CT4 - Network Protocols**		
Chairman	**REININGER, Philippe**	**Huawei**	Chairman	Anand Prasad	NEC	Chairman	BERRY, Nigel. H	Nokia
Vice chairman	GODIN, Philippe	Alcatel-Lucent	Vice chairman	Alf Zugenmaier	DoCoMo	Vice chairman	MORAND, Lionel	Orange
Vice chairman	ISRAELSSON, Martin	Ericsson	Vice chairman	Adrian Escott	Qualcomm	Vice chairman	KOZA, Yvette	Deutsche Telekom
RAN4 - Radio Performance Requirements			**SA4 - Codec for Speech, Audio, Video and Multimedia Systems**			**CT6 - Smart Card Applications**		
Chairman	ZHOU, Xutao	Samsung	Chairman	Frederic Gabin	Ericsson	Chairman	JOLIVET, Paul	LG Electronics
Vice chairman	**XIZENG, Dai**	**Huawei**	Vice chairman	Gilles Teniou	Orange	Vice chairman	BERIONNE, Michele	Qualcomm
Vice chairman	UMEDA, Hiromasa	DoCoMo	Vice chairman	LEUNG, Nikolai	Qualcomm	Vice chairman	KRUSE, Heiko	Morpho Cards
RAN5 - Mobile Terminal Conformance Testing			**SA5 - Telecom Management**					
Chairman	Jacob John	Motorola Mobility	Chairman	Thomas Tovinger	Ericsson			
Vice chairman	**CHEN, Xiaozhong**	**CATT**	Vice chairman	Jean Michel Cornily	Orange			
Vice chairman	GOWDA, Pradeep	Qualcomm	**Vice chairman**	**Christian Touche**	**Huawei**			
RAN6 - Legacy Mobile Technology (GSM, EDGE, HSPA)			**SA6 - Mission Critical Applications**					
ESTABLISHED in 2016			Chairman	HOWELL, Andrew	HOME Office			
			Vice chairman	Chitturi Suresh	Samsung			
			Vice chairman	CHATER-LEA, David	Motorola			

Source: 3GPP

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Table 23: List of Chairman and Vice Chairman of TSG and TSG Sub-groups – 2017

TSG Radio Access Network			**TSG Service/System Aspects**			**TSG Core Network and Terminal**		
Chairman	Balazs Bertenyi	Nokia	Chairman	Erik Guttman	Samsung	**Chairman**	**Georg Mayer**	**Huawei**
Vice chairman	Vince Spatafora	AT&T	Vice chairman	Kim Lae Young	LG Electronics	Vice chairman	Behrouz Aghili	InterDigital
Vice chairman	**Xiaodong Xu**	**China Mobile**	Vice chairman	Gregory Schumacher	Sprint Corp	Vice chairman	Johannes Achter	Deutsche Telekom
Vice chairman	Satoshi Nagata	DoCoMo	Vice chairman	Yusuke Nakano	KDDI	Vice chairman	Atsushi Minokuchi	DoCoMo
RAN1 - Physical Layer			**SA1 - Service Requirement**			**CT1 - Mobility Management, Call Control, Session Mgt**		
Chairman	Dr. Wanshi Chen	Qualcomm	Chairman	Toon Norp	KPN	Chairman	Ricky Kaura	Samsung
Vice chairman	Dr. Younsun Kim	Samsung	Vice chairman	YOUNGE, Mark	T-mobile	Vice chairman	Peter Leis	Nokia
Vice chairman	BAKER, Matthew	Nokia	Vice chairman	LEE, Ki-Dong	LG Electronics	Vice chairman	KAURA, Ricky	Samsung
RAN2 - Radio Resource Protocol (Aug 21, 2017)			**SA2 - System Architecture**			**CT3 - Policy, QoS and Interworking**		
Chairman	Richard Burbidge	Intel	**Chairman**	**Dr. Frank Mademann**	**Huawei**	Chairman	Susana Fernandez	Ericsson
Vice chairman	Johan Johansson	Mediatek	Vice chairman	Puneet Jain	Intel	Vice chairman	Yoshihiro Inoue	NTT
Vice chairman	**Dr. Nan Hu**	**China Mobile**	Vice chairman	Kristian Kiss	Apple	**Vice chairman**	**Zhenning Huang**	**China Mobile**
RAN3 - Access Network Interface			**SA3 - Security**			**CT4 - Network Protocols**		
Chairman	Gino Masini	Ericsson	Chairman	Anand Prasad	NEC	Chairman	Lionel Morand	Orange
Vice chairman	**Mrs. Yin Gao**	**ZTE Corp**	Vice chairman	Alf Zugenmaier	DoCoMo	Vice chairman	Yvette Koza	Deutsche Telekom
Vice chairman	Sasha Sirotkin	Intel	Vice chairman	Adrian Escott	Qualcomm	**Vice chairman**	**Peter Schmitt**	**Huawei**
RAN4 - Radio Performance Requirements			**SA4 - Codec for Speech, Audio, Video and Multimedia Systems**			**CT6 - Smart Card Applications**		
Chairman	Hiromasa Umeda	DoCoMo	Chairman	Frederic Gabin	Ericsson	Chairman	Heiko Kruse	Morpho Cards
Vice chairman	**Dr. Xizeng Dai**	**Huawei**	Vice chairman	Gilles Teniou	Orange	Vice chairman	BERIONNE, Michele	Qualcomm
Vice chairman	UMEDA, Hiromasa	DoCoMo	Vice chairman	LEUNG, Nikolai	Qualcomm	Vice chairman	KRUSE, Heiko	Morpho Cards
RAN5 - Mobile Terminal Conformance Testing			**SA5 - Telecom Management**					
Chairman	Jacob John	Motorola Mobility	Chairman	Thomas Tovinger	Ericsson			
Vice chairman	**Xiaozhong Chen**	**CATT**	Vice chairman	Jean Michel Cornily	Orange			
			Vice chairman	**Christian Touche**	**Huawei**			
RAN6 - Legacy Mobile Technology (GSM, EDGE, HSPA)			**SA6 - Mission Critical Applications**					
Chairman	Juregen Hofmann	Nokia	Chairman	LAIR, Yannick	LG Electronics			
			Vice chairman	Chitturi Suresh	Samsung			
			Vice chairman	CHATER-LEA, David	Motorola Solutions			

Source: 3GPP

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The rising influence of China in the ITU has drawn attention from other countries, e.g. US

The rising influence of China in the ITU and 3GPP has naturally raised concerns in some countries. The best example is the **comments made by Michael O'Rielly, a US FCC Commissioner,** in his address to the Free State Foundation about 5G technology on July 25, 2017. We extracted his comments in the following:

"…the ITU is being used by authoritarian governments to push their myopic agendas. Controls need to be put into place to ensure that the ITU remains focused on its core mission as opposed to engaging in mission creep, such as their activities to regulate the Internet, to placate certain governments."

"Traditionally, standards bodies have been the domain of industry, engineers and tech geeks. However, lately, there has been a concerted effort by some countries to manipulate these multi-stakeholder bodies. I have heard several reports that some authoritarian governments are now focusing their attention on leadership positions at these organizations so that they can promote their agendas and dictate the future design of not only wireless networks, but also the Internet."

"If the US does remain involved, I suggest that we need to play a bigger role in the ITU leadership. It is ironic that we are the second largest contributor of funds to the ITU, but only one Secretary General has come from the US in 150 years and the last American sector head was approximately 25 years ago."

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Conclusion

Aggressive 5G and IoT rollout in China

- China would like to build the most advanced infrastructure in order to promote its aggressive industrial IoT, big data and cloud initiatives
- China believes 5G deployed at low frequencies (below 6GHz) best serves its objective of having both wide-area and urban hotspot coverage. It wants to have a first-mover advantage against the US, which promotes mmWave technology and seems to have a technological edge.
- KT in Korea and DoCoMo in Japan support mmWave. If the US, KT and DoCoMo deploy mmWave early and aggressively to obtain scale, China may lose its technological edge and fail to become a global leader in the 5G supply chain.
- Note that US carriers do not buy equipment from China, and the US carriers' technology partners of Cisco, Ericsson, Nokia, Samsung and Qualcomm in fact are all China's competitors.
- China wants a headstart in IoT services so that the supply chain and operators will easily integrate them into future 5G services.

The government has high expectations on China Mobile in 5G

- Based on the 3G experience, the government believes China Mobile has the best scale and capability to deploy a new technology in scale.
- This ability will be boosted by the fact that 5G will be a single, global standard and China has done a lot of R&D on it.
- China Mobile's rapidly rising participation in the 3GPP indicates the government has high expectations on it and it has also done a tremendous amount of work already.
- Its extremely strong balance sheet will enable it to build 5G quickly and in big scale

ZTE is well positioned for 5G in China and globally

- China is set to aggressively invest in building 5G networks starting from 2019, and ZTE's rising share in China will put it in a strong position to benefit from the next capex cycle.
- For the first time, a ZTE representative has been elected a vice chairman in the RAN3 TSG subgroup. This shows ZTE's aggressive participation in 3GPP and likely its improvement in pre 5G and 5G technology.
- It seems even in the SA NR, the duplexing will likely be TD because it is the most efficient for data transmission. With ZTE's strength and experience in building TD-SCDMA and TD-LTE networks, it will have a stronger advantage in that scenario.
- Given a heavily consolidated global telecom equipment industry, ZTE's improved products and technology will allow it to gain market share outside of China when 5G buildout starts, even if industry capex outside of China may not rise into the 5G upgrade cycle.

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Glossary

Term	Definition
3GPP	The 3rd Generation Partnership Project. It unites 7 telecommunications standard development organizations (ARIB, ATIS, CCSA, ETSI, TSDSI, TTA, TTC) to produce commonly agreed Reports and Specifications that define 3GPP technologies.
5G	The 5th generation mobile communications. It aims to handle 3 different user environments with other quantitative criteria. Its finalized standard is still under discussion.
CDMA	Code Division Multiple Access. It is one of the 2G standards developed by Qualcomm, using a "spread-spectrum" technique whereby electromagnetic energy is spread to allow for a signal with a wider bandwidth. This allows multiple users on multiple cell phones to be multiplexed over the same channel to share a bandwidth of frequencies.
CDMA2000	Code Division Multiple Access 2000. One of the 3G standards developed by 3GPP2 (later merged into 3GPP). Similar to WCDMA, it supports conventional cellular voice, text and MMS services but carry data with a pair of 1.25MHz wide channels for data transmission and reception.
control plane	It is the part of a network which carries information necessary to establish and control the network.
C-RAN	Cloud-RAN. It is a centralized, cloud computing-based architecture for radio access networks that support 2G, 3G, 4G and future wireless communication standards.
downlink	Transmission from base station to handset
eMBB	Enhanced mobile broadband. It is one of the 3 user environments mentioned in 5G technology to provide consumers with very high speed data services.
FDD	Frequency Division Duplex. It refers to duplex communication links where separate frequency bands are used at the transmitter and receiver side.
FFT	Fast Fourier transform. A process to obtain digital version of a spectrum analysis of the original analog signal
GOCA	Group orthogonal coded access. It exploits a dual-sequence: a non-orthogonal sequence for group separation and an orthogonal sequence for the user separation within a group.
GSM	Global System for Mobile Communications. It is one of the 2G standards developed by the European Telecommunications Standards Institute (ETSI) described as a digital, circuit-switched network optimized for full duplex voice telephony. It is the world's most widely used cellphone technology.
IDMA	Interleave Division Multiple Access. As one of the multiple access scheme for 5G radio networks, it examines a simple iterative chip-by-chip multi-user detection strategy for spread spectrum communication systems.
IEEE	Institute of Electrical and Electronics Engineers. It is the world's largest association for educational and technical advancement of electrical and electronic engineering, telecommunications, computer engineering and allied disciplines.
IFFT	Inverse fast Fourier transform. This reverse process of FFT creates and transmits a single composite signal from the digital form.
IGMA	Interleave-Grid Multiple Access. As one of the multiple access scheme for 5G radio networks, it uses bit level interleavers and/or grid mapping pattern to separate user equipments.
IMT-2020	An ITU-project group specializes in determining 5G standards.
ITU	International Telecommunication Union. The United Nations' specialized agency for information and communication technologies.
LDPC code	Low-density parity-check code. A linear error correcting code to transmit a message over a noisy transmission channel
LTE	Long Term Evolution. It is the long-term evolution of 3G and is generally referred to as 4G with OFDM as its core technology. There are two types of LTE, both also recognized by 3GPP - FDD-LTE and TDD-LTE.
MAC	Media Access Control. A subdivision of the data link layer to transmit data packets to and from the network-interface card and to and from another remotely shared channel.
MIMO	Multiple-input and multiple-output. A method for multiplying the capacity of a radio link using multiple transmit and receive antennas to exploit multipath propagation.
MME	Mobility management entity. It is responsible for authenticating the user equipment.
m-MTC	Massive-machine type communication. It is one of the 3 user environments mentioned in 5G technology to provide simultaneous connections with a much larger number of devices per square kilometer, mainly for IoT services.
mmWave	Millimeter wave. It refers to wave whose wavelength < 1cm. It can be used for very high-speed, high-capacity wireless communications.
Multiple Access	It allows multiple mobile users share the allotted spectrum in the most effective manner.
Multiplex	A networking technique to integrate multiple analog and digital signals into a signal transmitted over a shared medium.
MUSA	Multi-User Shared Access. According to ZTE, this new technology can deliver over 200% improvement in the overload radio, leveraging non-orthogonal complex spreading sequences at the transmitter side for modulation and uses successive interference cancellation at the receiver side to remove interference and recover the user data.
NAS	Non-access stratum. A subdivision of the radio resource control layer to manage the establishment of communication sessions and maintain continuous communications with the user equipment as it moves.
NB-IoT	Narrow Band Internet of Things. It is a narrowband radio technology designed for the Internet of Things, focused in indoor coverage, low cost, long battery life and enabling a large number of connected devices.
NCMA	Non-orthogonal Coded Multiple Access. It is a non-orthogonal multiple access scheme proposed for 5G radio networks. It obtains the non-orthogonal sequences by solving a Grassmannian line packing problem.
NFV	Network functions virtualization. It increases and improves network function and manages networks by chaining different classes of network nodes together.
NOCA	Non-orthogonal coded access. It is a non-orthogonal multiple access scheme proposed for 5G radio networks. It utilizes the LTE sequences defined for uplink reference signals for data transmission.
NOMA	Non-orthogonal Multiple Access. It allows multiple user equipments with different scrambling sequences to be transmitted on the same resource.

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Glossary

Term	Definition
NR	New Radio, usually refers to the new radio technology used in 5G
NSA	Non-standalone radio access. It refers to the 5G technology which will be backward compatible with 4G LTE.
OFDM	Orthogonal frequency-division multiplexing. Each data stream is modulated onto multiple carriers adjacent to one another within the same spectrum to remove interference and save bandwidth
OFDMA	Orthogonal frequency-division multiple access. It is a multi-user version of OFDM, assigning subsets of subcarriers to individual users. This allows simultaneous low-data-rate transmission from several users.
OSI	Open Systems Interconnection. A model used by the ICT industry to standardize telecommunications and computing networks for interconnecting and working with one another.
PBCH	Physical Broadcast Channels. It is used to broadcast the Master Information Block using broadcast channel as transport and broadcast control channel as logical channel.
PDCP	Packet Data Convergence Protocol. A subdivision of the data link layer that transfers user plane and control plane data, conduct header compression ciphering and integrity protection to the upper layers in the Open Systems Interconnection.
PDMA	Pattern Division Multiple Access. It is a non-orthogonal multiple access scheme proposed for 5G radio networks. The PDMA pattern defines the mapping of transmitted data to a resource group that can consist of time, frequency and spatial resources of any combination of these resources.
QAM	Quadrature amplitude modulation. It is a combined form of phase modulation and amplitude modulation, representing bits as points in a quadrant grid known as a constellation map.
QPSK	Quadrature Phase-Shift Keying. As a modulation method, it encodes two bits per symbol by leveraging 4 points on the constellation diagram with Gray coding.
RAN	Radio access network. Being part of a mobile telecommunication system, it connects individual devices to other parts of a network through radio connections.
RDMA	Resource Division Multiple Access. As one of the multiple access scheme for 5G radio networks, it uses open loop communication for the edge of cloud-based radio resource to directly transmit without the need of feedback signal or signaling overhead, reducing latency and increasing data rate in network.
RLC	Radio Link Control. A subdivision of the data link layer that offers a series of functions including to transfer upper layer PDUs and to conduct error correction.
RRC	Radio Resource Control. A subdivision of the radio resource control layer in charge of connection between the base station and the user equipment (handsets or other devices), bearer establishment, and broadcast of system information.
RSMA	Resource Spread Multiple Access. As one of the multiple access scheme for 5G radio networks, it uses combination of low rate-channel codes and scrambling codes with good correlation properties.
SA	Standalone radio access. It refers to the 5G technology which will not be backward compatible with 4G LTE.
SC-FDMA	Single-carrier, Frequency division multiple access. It deals with the assignment of multiple users to a shared communication resource. It has been adopted as the uplink multiple access scheme in 3GPP LTE or E-UTRA
SCMA	Sparse Code Multiple Access. It is a non-orthogonal multiple-access technique developed for possible use with 5G. In SCMA, different incoming data streams to be transmitted are directly mapped to code-words of different multi-dimensional cookbooks, where each code-word represents a spread transmission layer.
SDN	Software-defined networking. An emerging computer networking architecture that separate the control from the hardware and implement in software.
spectral efficiency	The more capacity with a given spectrum, the more spectral efficient
TDD	Time Division Duplex. It refers to duplex communication links where uplink is separated from downlink by allocation of different time slots in the same frequency band.
TDMA	Time Division Multiple Access. It is one of the 2G standards. It divides each digital cellular channel into three-time slots for transmitting and receiving within the same frequency channel without causing interference, enhancing the spectrum efficiency.
TD-SCDMA	Time Division Synchronous Code Division Multiple Access. One of the 3G standards developed and used in China as a substitute for WCDMA. It is more suitable in densely populated locations and low mobility instances.
TSG	Technical Specification Groups. These are the subgroups at the 3GPP. The 3 subgroups are "Radio Access Networks", "Services & Systems Aspects" and "Core Network & Terminals".
uplink	Transmission from handset to base station
URLLC	Ultra reliable, low latency services. One of the 3 user environments mentioned in 5G technology to reduce data transmission latency and precision to support services like autonomous driving and telemedicine.
user plane	It is the part of a network through which user packets are transmitted.
WCDMA	Wideband Code Division Multiple Access. One of the 3G standards developed by 3GPP. Based on GSM technology, it supports conventional cellular voice, text and MMS services but can also carry data at high speeds with a pair of 5MHz wide channels for data transmission and reception.
WRC	The World Radio Conference. Managed by the ITU, WRCs are held every 3-4 years to review and revise if necessary the Radio Regulations, which is the international treaty governing the use of radio frequency spectrum and satellite orbits.

Source: Jefferies, ITU, 3GPP, ZTE, Technopedia, Wikipedia, Airheads Community, lifewire.com, RF Wireless World, Radio electronics, IEEE, LG, Nokia, MediaTek., ResearchGate

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