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Review:

A tutorial on 5G and the progress in China*

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Abstract: 5G has been developing at high speed since 2012 and has become a global economic driver. In this paper, we offer a survey of 5G covering visions, requirements, roadmap, key technologies, standardization, frequency management, technology trials, industrial ecology, and a list of main 5G contributors. We also point out the contributions to 5G from China, aiming to be 'globally leading in 5G' by acting as a main 5G contributor in standardization and promoting/enhancing the Chinese 5G industry. Finally, progress on 5G is reviewed mixed with our rethinking of 5G.

Key words: 5G; IMT-2020; Key technology; Standardization; Field trial
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1 Introduction

Driven by services and technology, a generation of mobile communication upgrades almost every 10 years. 5G has become the hottest topic amongst communication academics and industries since the IMT-Advanced specifications of 4G terrestrial mobile telecommunication were approved by the International Telecommunication Union's radio department (ITU-R) at the World Radio Conference 2012 (WRC-12). Most countries, organizations, and units are actively investing in 5G to bring new economic growth and new development opportunities. On the government side, several organizations have been launched since 2012. Among them, the IMT-2020(5G) Promotion Group from China, 5G Industry Association (5GIA) from Europe, 5G Mobile Forum (5GMF) from Japan, 5G Forum from Korea, 5G Americans, and later 5G Brazil are official 5G organizations. To push forward the global unified 5G standard and to promote the 5G industry, these organizations emphasize international cooperation by, e.g., initiating global 5G summits running twice a year. The summits discuss topics including government policies, spectrum collaboration, technology and standards trends, deployment and service provision, trials and solutions, requirements and expectations of verticals and eco-industries, and cross-regional activities for 5G. The first global 5G summit was successfully organized in Beijing in May 2016. Following summits are continuing in Rome, Tokyo, and Seoul. In 2018, two summits will be held in Austin and Brasilia. With the promotions of the summits, 5G has been moving forward rapidly. For example, in 2013, various technical reports and white papers were issued to give a general outlook on 5G. In 2014, 5G visions and requirements were clearly specified and approved by the ITU with a triangle-type figure describing three scenarios, and a radar-type figure describing eight performance requirements. In 2015, 5G key technologies converged from a collection of all potential technology suggestions. In 2016 key milestones were specified. One is about standardization: the 3rd Generation Partnership Project (3GPP) officially launched the 5G New Radio (NR) study item in

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release 14 and planned to finish the 5G standard with two versions, including an initial 5G version in release 15 and an enhanced 5G version in release 16. The others are technology trials: the Chinese government officially launched its 5G trial plan in 2016, including a phase of three-step R&D before 2018 organized by the Ministry of Industry and Information Technology (MIIT), and a phase of product and networking followed and organized by operators. Following this breaking news, 5G is on the way toward becoming commercial.

To better understand 5G, we give a comprehensive overview, including vision and requirements, key technologies, standardization, frequency management, technology trials, roadmap, and industrial ecology. We also describe the progress of 5G in China to illustrate China's leading position and its contribution.

2 5G vision and requirements

Different from the former generations of mobile communication, 5G is expected to serve not only the telecommunication itself, but also the whole information society. As described by IMT-2020(5G) Promotion Group (2014), Mobile Internet and the Internet of Things are two typical kinds of services of 5G, and the overall vision for 5G is defined as 'information in hand, everything in touch'. In the future, 5G will penetrate all life around home, work, leisure, transportation, etc. 5G will provide fiber bandwidth data and 'negligible' latency as user experiences. 5G will be capable of connecting 100 billion worldwide devices and deliver a consistent experience across a variety of scenarios. 5G will also be able to provide intelligent optimization based on services and user's awareness, and will improve energy and cost efficiency over a hundred-fold.

Fig. 1 shows the definition of 5G requirements from ITU-R (2015). The triangle-type (Fig. 1a) represents usage scenarios of IMT for 2020 and beyond; the radar-type (Fig. 1b) represents the importance of key capabilities in different usage scenarios. In total, three typical scenarios and eight key capabilities are defined for 5G. Each scenario has its own differentiated capabilities. For these 5G capabilities, there are evident improvements on 4G (Table 1). In particular, peak data rate, connection density, and delay are the three most important capabilities satisfying enhanced mobile broadband (eMBB), massive machine type communications (mMTC), and ultra-reliable low latency communications (URLLC) scenarios, respectively.

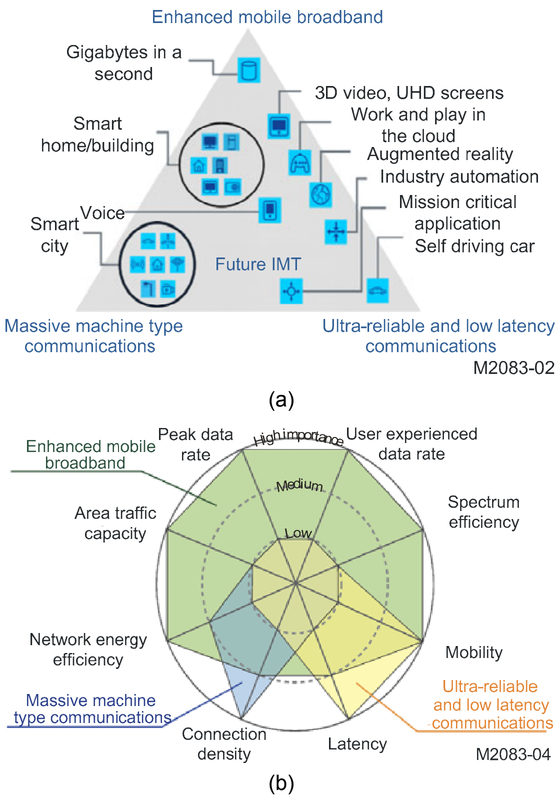

Fig. 1 5G requirements defined by ITU: (a) usage scenarios of IMT for 2020 and beyond; (b) importance of key capabilities in different usage scenarios (ITU-R, 2015)

3 5G key technologies

To realize 5G key requirements, evolution and revolution are two basic technology routes (Chen and Zhao, 2014; Chen et al., 2016a). The evolution route consists of enhancing LTE-Advanced by continually increasing the system capacity, spectrum efficiency, user experience, and operational efficiency of 4G cellular systems. This is called LTE-A Pro in 3GPP. The revolution route means exploring innovation ideas and novel technologies to make a large jump of system performance. This is called 5G new radio in 3GPP. FDD and TDD will be tightly integrated in LTE-A Pro and 5G new radio, and TDD will play a more important role which had not existed before. Many evolution and revolution technologies have been suggested and adopted, including mainly massive multiple-input multiple-output (MIMO), non-orthogonal multiple access (NOMA), ultra dense networking (UDN), advanced coding and modulation, flexible spectrum access, flexible air interface design, vehicle-to-everything, and novel network architecture (Chen et al., 2015a).

Table 1 Capability improvement of 5G over 4G

Key performance index	Value for 5G by ITU	Improvement compared with 4G
Traffic density	10 Tbps/km^2	1000 times
Connection density	1 million/km^2	1000 times
Delay	1 ms (RTT for radio interface)	1/10 times
Peak data rate	10/20 Gbps	100 times
User experience data rate	0.1–1 Gbps or 0.1 Gbps+description	10 times
Mobility	500 km/h	<5 times
Spectrum efficiency	[2/3/5]x	<5 times
Energy efficiency	100x (network)	100 times

3.1 Wireless key technologies

3.1.1 Massive MIMO

MIMO will be further enhanced in 5G and massive MIMO has been approved to be the most efficient technology for enhancing spectrum efficiency (Marzetta, 2010; Larsson et al., 2014). With more than one hundred antennas and dozens of antenna ports equipped in a base station, massive MIMO can be used for centralized or distributed type. For each type, technology needs to be improved and optimized including the design of reference signals, channel estimation, channel information feedback, multi-user scheduling mechanism, and receiving algorithms.

As shown in Fig. 2, though massive MIMO can be used in both TDD and FDD, the use of channel reciprocity in TDD alleviates the heavy computing needed for channel state information (CSI) acquisition, so that TDD can achieve a higher spectrum efficiency (Chen et al., 2016b). This makes TDD a more promising candidate for 5G systems with large antenna arrays.

3.1.2 Non-orthogonal multiple access (NOMA)

In past generations of wireless communication systems, orthogonal multiple access schemes in the time, frequency, or code domain have been the main choices because of the limited processing capability in transceiver hardware and the modest traffic demands in both latency and connectivity. However, for a 5G system, connecting 1 million devices per square kilometer requires much evolved hardware capability. Non-orthogonal multiple access has been identified as a promising technology to achieve the targets in terms of system capacity, user connectivity, and service latency (Dai et al., 2015; Ding et al., 2017; Cai et al., 2018; Chen et al., 2018).

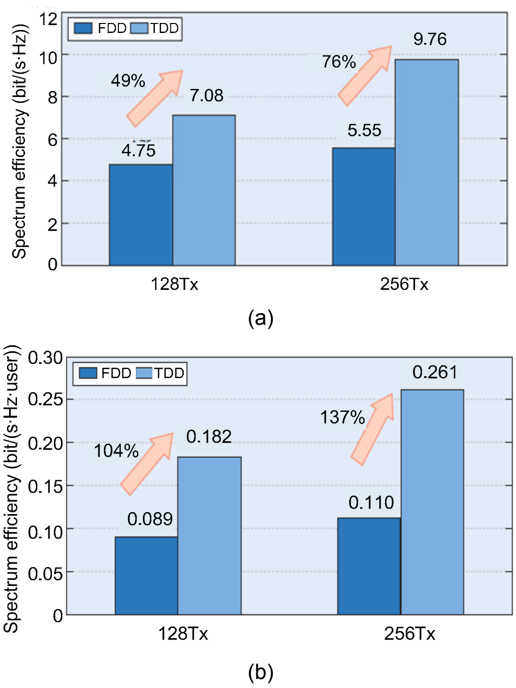

Fig. 2 Performance of massive MIMO in FDD and TDD: (a) cell average spectrum efficiency; (b) cell edge spectrum efficiency (Chen et al., 2016b)

Diverse non-orthogonal multiple access schemes (Takahashi, 2016) have been proposed, such as PDMA (Chen et al., 2017a), SCMA (Nikopour and Baligh, 2013), MUSA (Yuan et al., 2016), RSMA (3GPP, 2016b), and IGMA (3GPP, 2016a). They are intensely discussed in 3GPP NR study items and work items.

3.1.3 Ultra dense networking (UDN)

UDN is aimed to provide a very high data rate to each user for indoor and hotspot scenarios, including offices, dense residential areas, stadiums, and open-air-gathering environments. Typical supports of UDN are for very high user density, very high traffic density, and very high access point (AP) density (Ge et al., 2016).

Traditional cellular system usually provides seamless coverage for a large area. Distinct differences between UDN and a traditional cellular network are summarized in Table 2 (Chen et al., 2016c).

Key challenges of UDN include interference management, cell virtualization, integrated access, wireless backhaul, and user-centric design (Chen et al., 2016c).

Table 2 Comparison between ultra dense networking (UDN) and traditional cellular network

Parameter	UDN	Traditional cellular network
Deployment scenarios	Indoor, hotspot	Wide coverage
Access point density	Comparable to the user density	Much lower than user density
Access point types	Small cell, pico, femto, UE relay, relay	Macro/micro base station
Typical coverage	Around 10 m	Several hundred meters and more
Coverage characteristics	Heterogeneous, irregular	Single layer, regular cell
User density	High	Low/medium
Backhaul	Ideal/non-ideal, wired/wireless	Ideal, wired
User mobility	Low mobility	High mobility
Data rate requirement	High	Low/medium
Spectrum bands	Higher, wider	Lower, limited

3.1.4 Advanced coding and modulation

In addition to traditional binary Turbo code and quadrature amplitude modulation (QAM), 5G needs to support advanced coding and modulation methods for wider services. For high data rate services, low density parity check (LDPC) (Zhu et al., 2016), new constellation mapping, and faster-than-Nyquist (FTN) (Qi et al., 2017) can be used to further improve link spectrum efficiency. For low data rates and small packet services, polar codes (Tian et al., 2016) and low code rate convolution codes can be used to approach the Shannon capacity limit in cases of short code length and low SNR. For low latency services, coding schemes with fast encoding and decoding algorithms are preferred. For high reliability services, the ‘error floor’ effect of decoding algorithms needs to be avoided. In addition, there may be a number of wireless backhaul links in a dense network, and the backhaul system capacity can be increased by network coding.

In 3GPP, LDPC coding was accepted for the NR data channel, while polar coding was accepted for the NR control channel.

3.1.5 Flexible spectrum access

Different from past generations, 5G involves both low-frequency (LF) bands of below 6 GHz and high-frequency (HF) bands of 6–100 GHz, where the LF bands are the core bands of 5G used for seamless coverage and the HF bands are the supplementary bands to achieve high data rates in hotspot areas. To fully exploit the advantages of different frequencies, 5G needs to support hybrid networks with LF and HF bands to simultaneously meet the requirements of seamless coverage, ultra-high data rates, and ultra-high capacity.

Considering the big differences between HF bands and traditional LF bands, research on 5G spectrum access focuses mainly on key technologies including channel measurement and modeling, new air interface design, networking technology, and radio frequency components for HF mobile communications.

Besides technologies discussed for HF bands and other traditional methods for spectrum efficiency, innovative spectrum utilization methods are also efficient ways to extend the usable frequency for 5G systems. Potential flexible spectrum sharing schemes include intra-operator inter-RAT, inter-operator, spectrum sharing in unlicensed band, and in secondary access.

3.1.6 Flexible air interface design

To support the ITU-defined three typical scenarios, 5G needs flexible air interface designs, covering frame structure, duplex mode, waveform, etc.

To achieve a unified air interface framework, key parameters of 5G frame structure, such as bandwidth, subcarrier spacing, cyclic prefix (CP), transmission time interval (TTI), and uplink-downlink configuration, can be flexibly configured for diverse scenarios and services. In addition, the reference signals and control channels can be flexibly configured to support applications of key technologies.

Except for traditional FDD and TDD, 5G will support flexible duplex. On one hand, FDD or TDD can be selected according to the frequency band; e.g., FDD is adopted usually in the LF band, while TDD can be adopted in both LF and HF bands. On the other hand, uplink and downlink time and frequency resources can be flexibly allocated to better adapt to non-uniform and dynamic service distribution. Full duplex may be a further solution supporting simultaneously transmitting and receiving at the same frequency resource.

In addition to traditional OFDM and single-carrier waveforms, 5G will possibly adopt new waveforms based on optimized filtering, such as filter bank multicarrier (Chen et al., 2013), filtered-OFDM (Wunder et al., 2014), and universal filtered multi-carrier (Vakilian et al., 2013). With very low out-of-band leakage, these waveforms can improve spectrum utilization efficiency, efficiently use fragmented spectrum, and coexist with other waveforms.

3.1.7 Vehicle-to-everything (V2X)

Vehicle-to-everything (V2X) includes vehicle-to-vehicle (V2V), vehicle-to-pedestrian (V2P), vehicle-to-infrastructure (V2I), and vehicle-to-network (V2N) communications. V2X improves road safety, traffic efficiency, and the availability of infotainment services (Chen et al., 2017b).

Benefiting from the global deployment and fast commercialization of Long Term Evolution (LTE) systems, LTE based V2X called LTE-V (Chen et al., 2016d) or LTE V2X has been standardized in 3GPP. LTE-V provides two complementary communication modes: one is LTE-V-Cell as a centralized architecture and the other is LTE-V-Direct for decentralized V2V communications. To meet the performance requirements of V2X communications, LTE-V uses demodulation reference signal (DMRS) structure enhancement, coordinated synchronization between Global Navigation Satellite System (GNSS) based and eNB-based synchronizations, frequency division multiplexing (FDM), and time division multiplexing (TDM) for resource multiplexing across vehicles, semi-persistent scheduling (SPS), sensing-based resource allocation, etc.

3.2 Novel network architecture and key technologies

Compared with the revolution of previous generations marked by multiple access technology, 5G has been extended from the wireless side to the scope of a complete network. Driven by 5G service requirements and new technologies, such as software defined network (SDN) and network function virtualization (NFV), a 5G network is expected to support diverse radio access technology scenarios, to meet the requirements of end-to-end user experience, and to provide the capability of flexible network deployment and efficient operations. Therefore, 5G network needs to take technology innovations and coordinated developments in the domain of new infrastructure and architecture to accomplish the total network revolution (Agyapong et al., 2014; IMT-2020(5G) Promotion Group, 2015a).

The present telecommunication infrastructure is constructed on a dedicated hardware platform. By introducing information technology and virtualization technology, the 5G network will have a brand new infrastructure platform with industrial standard hardware to overcome the shortage of legacy infrastructure platforms which have high cost, inflexible resource configurations, and a long development time to market. For the architecture, concepts like ‘control and forwarding separation’ and ‘control function reconstruction’ are considered the basic direction of architecture innovation (IMT-2020(5G) Promotion Group, 2015a). The new 5G network architecture is constituted by a high performance access network, simplified yet with efficient core network control and forwarding function, to meet the complex 5G scenario requirements, to support smart operation, to expose network capacities to third parties, and to promote end-to-end network services. Based on this novel architecture, related key networking technologies are involved including SDN, NFV, mobile edge computing (MEC), network slicing, decoupling of control and forwarding plane, control functions reconstruction, new connection, and mobility management (Wang CX et al., 2014; Chen et al., 2015b; Wang HC et al., 2015, 2017).

MEC is a capability that provides IT service and cloud computing to mobile users at the closest position. It pushes content delivery capabilities to the places near the user, e.g., edge of the base station, to deploy the application, service, and content in a highly distributed environment, so that it can excellently meet the low latency and high bandwidth requirements in 5G. As an emerging technology, MEC faces a lot of challenges, such as collaboration, security, mobility, and charging.

Network slicing is an efficient way to realize on-demand networking. The 5G network physical infrastructure is virtualized into several parallel network slices according to the scenarios. Each network slice can tailor its network functions and orchestrate its network resources based on the scenario requirements and the traffic pattern. A network slice can be seen as an instance of the 5G network. The operator can further divide the virtualized network resources and create sub networks inside a network slice. As shown in Fig. 3, one network can support one or several end-to-end (E2E) network slices, and a network slice can provide the functionality of a complete network, including radio access network functions and core network functions (e.g., potentially from different vendors).

Control function reconstruction is to divide the control plane functions into independent modules with different control logics, in which case these modules can be composed to form specific network control planes for different scenarios. These address the existing problems of the current core network, where the control functions are redundant, the number of the network interfaces is large, and the work on standardization is time-consuming. Differentiated network features can be delivered by combing different modules to meet the demand for the network diversity in the 5G era.

4 5G standardization and technology trial

4.1 5G standardization

Many organizations have been involved in 5G, such as ITU, 3GPP, and NGMN.

ITU: ITU started the preparation work for 5G in the early 2010s and issued files such as IMT.trend (ITU-R, 2014) and IMT.vision (ITU-R, 2015). Also, ITU named 5G officially IMT-2020. Afterwards, ITU prepared 5G technical collection and technical evaluation, expecting to issue the collection satisfying all requirements as a 5G standard on the 36th Meeting of ITU-R WP5D in 2020.

3GPP: 3GPP approved some 5G-related study items even in release 13, such as channel modeling and 5G requirements. Then 3GPP launched the 5G NR work from a study item in release 14, followed by work items in release 15 and further. According to the planning for release 15 by 3GPP, the 5G standard is divided into non-standalone (NSA) and standalone (SA) parts. To meet the deployment plan of some operators, 5G NSA froze at the end of 2017, earlier than the scheduled freeze date. It gives a transitional solution, which is dual-connected using LTE and 5G NR to deploy 5G in the existing LTE network. As there is no independent signaling plane, 5G NSA aims mainly at improving hotspots. Compared with 4G, 5G NR brings a lot of changes, such as much wider bandwidth up to 400 MHz, scalable sub-carrier spacing with $n\times2^N$, flexible frame structure with variable numerologies, LDPC and polar coding, massive MIMO, millimeter wave, and split of the control unit and distributed unit.

Since present 5G NR lays mainly the groundwork for eMBB, more enhancements are needed subsequent to release 15. Among them, V2X represents an important feature for URLLC. As shown in Fig. 4, LTE V2X is regarded as phase 1 of 5G cellular V2X (C-V2X). Phase 2 is the present work in release 15, including LTE eV2X work item and V2X evaluation study item. Phase 3 will be future work in release 16 and beyond. Potential work may include NR

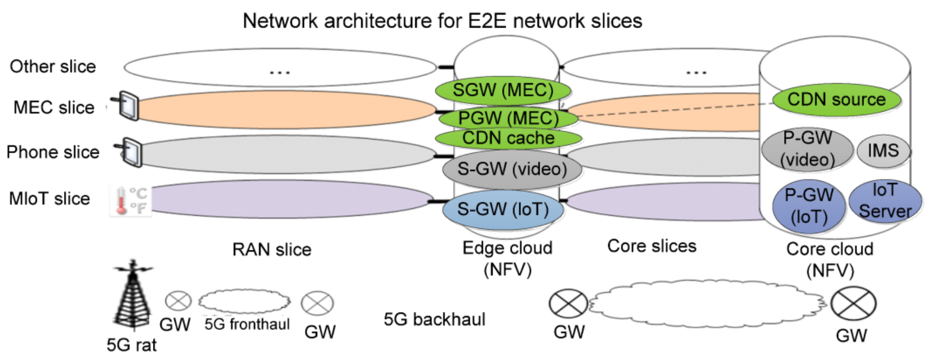

Fig. 3 Illustration of network slicing

V2X and its enhancement. For those 25 use cases identified in System Architecture Working Group 1 (SA1), each case supporting Uu and sidelink operation for NR V2X, the framework of the newly proposed NR V2X study item is thus expected to include NR Uu enhancement and NR sidelink. LTE V2X and NR V2X will coexist to target their respective applications; e.g., LTE V2X will be used for the basic safety services, while NR V2X will be used for additional use cases.

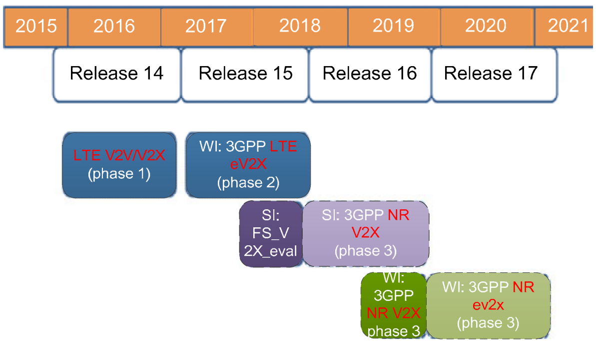

Fig. 4 3GPP C-V2X standard time plan

5G SA will freeze in June 2018, and it will form a unified 5G NR standard supporting independent and non-independent networking. It will satisfy both eMBB and URLLC scenarios, laying out the foundation for the establishment of a globally standardized 5G ecosystem. To obtain a final version satisfying all the requirements defined by the ITU, further enhancement should be done for 5G NR in 3GPP release 16. Topics under discussion include air interface enhancement, MIMO enhancement, unlicensed use, relay, non-orthogonal multiple access, C-V2X, positioning enhancement, terminal energy saving, Industrial Internet of Things (IIoT), and big data collection and utilization.

Besides ITU and 3GPP, organizations like NGMN and GSMA started their discussions on 5G around 2015, and issued a series of white papers (NGMN Alliance, 2015).

4.2 5G frequency management

As described above on key technologies, 5G will work on both LF bands of below 6 GHz and HF bands of 6–100 GHz, to satisfy the data rate related requirements. For LF bands, an early estimation from the ITU shows that the total spectrum requirements of 1340–1960 MHz were seen for the IMT system towards 2020. Excluding the already allocated or identified spectrum, an additional bandwidth of up to 1 GHz was required. However, for HF bands, above 10 GHz bandwidth will be needed to support the 20 Gbps peak data rate and wide application in verticals. For example, IMT-2020(5G) PG in China estimated a demand of 808–1078 MHz for LF bands and 14–19 GHz for HF bands.

For WRC-15 and item 1.13 of WRC-19, a series of candidate frequencies was suggested. These frequencies are being intensely discussed and coordinated in the ITU. Table 3 shows the current planned LF and HF bands from 5G major organizations.

Table 3 Suggested frequency bands for 5G from major organizations in different countries and regions

Country/Region	LF band	HF band
EU	L band, 3.4–3.8 GHz	24.25–27.5 GHz, 31.8–33.4 GHz, 40.5–43.5 GHz
USA	UHF band	27.5–28.35 GHz, 37–40 GHz, 66–71 GHz
Japan	3.6–3.8 GHz, 4.4–4.9 GHz	27.5–29.5 GHz
South Korea	3.4–3.7 GHz	26.5–29.5 GHz
China	3.3–3.6 GHz, 4.8–5.0 GHz	24.25–27.5 GHz, 37–42.5 GHz

4.3 5G technology trial

Different from previous generations, the 5G technology trial was conducted early in the same period as 5G standardization to serve as a guide to the standard. As shown in Table 4, major organizations have issued their 5G testing or commercial plan, making a huge investment to invite international vendors and operators to attend. Among them, China is leading the world's first and fastest 5G technical tests, and the Chinese government has released a 5G frequency plan to speed up 5G application, and also opened C-V2X pilot areas to speed up LTE V2X application.

4.4 5G roadmap

A consensus roadmap for 5G is shown in Fig. 5. From the standards aspect, we have an initial 5G NSA standard by 2017, and will further have an initial 5G SA standard in the middle of 2018. We will then expect a complete 5G standard from 3GPP in 2019 and even an approved 5G version from the ITU around 2020. Simultaneously, from the industry aspect, we have witnessed the 5G R&D trial on key technologies and technology schemes in typical scenarios by 2017, may further witness the 5G R&D trial on the system and the 5G R&D product trial this year, and then expect 5G pre-commercial and even a commercial network towards 2020.

Table 4 5G test and commercial plans from major organizations in different countries and regions

Country/Region	Test and commercial plans
EU	Investing €1.4 billion on 5GPPP projects Planning to conduct 5G scale tests in 2018 to verify 5G standards
USA	A local 5G standard was led by Verizon in mid-2016 Released frequency in 2016 and planned to spend $400 million in the next seven years to build a pilot 5G network in four cities
Japan	Carrying out 5G technology trials with leading operator NTT DoCoMo Planning to offer formal 5G commercial services ahead of the 2020 Summer Olympics
South Korea	Released its 5G national strategy in 2017 Planning to launch a pre-commercial 5G trial at the 2018 Winter Olympics and then commercialize at the end of 2020
China	Led the 5G trial since the plan was issued in 2016 Preparing for 5G networking in 2018

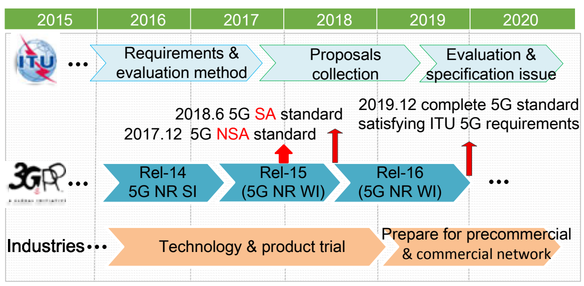

Fig. 5 5G roadmap

5 5G eco-industry with IC opportunity and challenges

Since 5G is in the critical period of standards formation and industrialization, all major countries regard 5G as a high priority area of development in their national digital strategies, and have thus strengthened their industrial layout and shaped new competitive positions. As shown in Fig. 6, the 5G industry development chain not only includes mobile communications itself as traditional paths, but also brings new industrial areas such as integrated circuits (IC), information safety, and all kinds of vertical applications. 5G will be combined with innovative technologies such as robots, unmanned aerial vehicles (UAV) and drones, artificial intelligence, virtual reality, and automatic drive to improve existing industrial levels, and to create new industries and formats, to trigger the information revolution, and to build the infrastructure of the digital economy as a general technology like traditional water supply or power supply. In particular, it is worth mentioning that 5G will stimulate vertical industry applications such as car networking, UAV networking, mobile healthcare, and industrial Internet, given its superior performance of ultra-high reliability and ultra-low latency.

With this new ecosystem, a nation's digital economy will increase to a new level. For example, in the prediction report IMT-2020(5G) Promotion Group (2017) in China, 5G may bring a direct contribution of 3.3 trillion CNY to the economy in 2025, and even 6.3 trillion CNY in 2030.

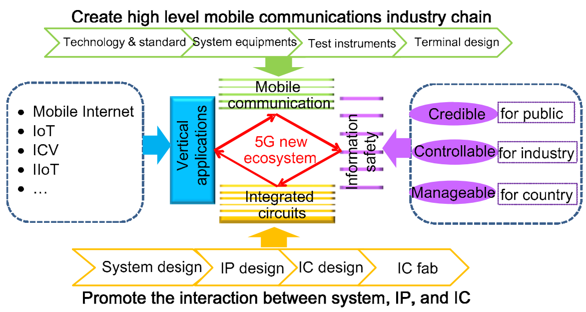

Fig. 6 Industrial layout of the 5G ecosystem

Related IC is a critical layer of the 5G ecosystem. Thanks to the fast development of the mobile communication industry, the smart phone has surpassed personal computer (PC) as the largest application market for global semiconductor business. Since different terminals and base stations will be produced because of a variety of scenarios like eMBB, mMTC, and URLLC, 5G OEM will bring a market at least several times larger than the 4G market to IC industry.

Different terminals need different chips with different requirements and roadmaps. For example, eMBB chips guarantee high performance for smart phone terminals, especially supporting virtual reality (VR) applications. Seldom can companies offer more than 10 tera operations per second (TOPS) flexible computing with less than 1 W power consumption. The chips for URLLC require ultralow latency, high reliability, fault tolerance, and security with a relatively long life cycle. Lower latency equals higher performance. For example, if baseband modem latency requirement is from 10 ms down to 1 ms, its requirement on computing performance will be 10 times higher. For mMTC chips, low price, low power, and long battery life are essential requirements. Most mMTC chip suppliers will be out if they cannot offer huge volume, low price, and other requirements at the same time.

Another group of challenges is from the RF transceiver (including both ICs and passive components) and mixed circuit (analog-to-digital converter and digital-to-analog converter) when carrier frequencies are higher than 20 GHz and the baseband bandwidth is up to 1 GHz. One example is the control on chip price and power consumption. Another example is the noise and jitter control for an ultra-wide band RF transceiver when the carrier frequency is more than 40 GHz.

To summarize, for the coming 5G, the requirements including at least high data rate, high frequency, high bandwidth, low latency, high reliability, ultra high number of connections, and low power consumption will bring new challenges for the IC industry. The first challenge will be the huge initial investment and simultaneously low shipment volume when introducing the eMBB chips to market. The second challenge will be to customize vertical applications and fragments in application scenarios for mMTC chips. The third challenge will be the mix of high reliability and security, as well as ultralow computing latency with limited price for the Industrial Internet and Internet of Vehicles in URLLC chips.

6 5G progress in China

5G was given high priority in China. To push forward 5G, several organizations were involved. Among them, IMT-2020(5G) PG is the official 5G organization launched jointly by three ministries in China including the MIIT, Ministry of Science and Technology, and Reform Commission. It coordinates 5G promotion from the viewpoints of research, standards, technical trials, industry layout, project planning, international cooperation, etc. Future Forum also launched a 5G working group and offered a series of technical white papers every year. As a national standards organization, China Communication Standard Association (CCSA) has been engaged in preparing 5G standards documents. In addition, related vertical alliances like the Alliance of Industrial Internet (AII) and Internet of Vehicles Alliance (IOVA) show much interest in 5G.

IMT-2020(5G) PG has been hosting 5G summits, which showcase 5G progress, every year. For example, in 2014, 5G vision and requirements were released. In 2015, 5G concept and 5G key technologies including wireless and network architectures were released. In 2016, a 5G trial working group was established and the technology trial plan issued. In 2017, a C-V2X working group was established and pilot areas built for LTE V2X. In 2018, the original requirement working group has been changed to an application working group, aiming to push 5G typical applications in vertical industry. Also, guided by the four '5' policy (5G at 5 cities with 50 base stations and 5 hundred users) from the China Reform Commission, operators in China are building 5G scale networks, preparing for pre-commercialization and commercialization.

6.1 5G contributions on standards from China

Considerable contributions have been made by the IMT-2020(5G) PG of China.

In the ITU, the name IMT-2020 was suggested by China. The vision specifying three typical scenarios and eight requirements was originated from a white paper of IMT-2020(5G) PG (2014). In this paper, four typical detailed scenarios were defined and a 'blooming flower' for 5G requirements was exhibited. Six petals represent performance requirements and three leaves represent efficiency requirements. In addition, in the issued white papers formulating 5G wireless technology and 5G network architecture (IMT-2020(5G) Promotion Group, 2015a, 2015b), enormous enabling technologies have been accepted by the ITU report IMT.trend (ITU-R, 2014).

Further, China is currently taking charge of the 5G evaluation work in the ITU.

In 3GPP, Chinese companies take active roles in 5G NR, especially on important features such as massive MIMO, NOMA, UDN, V2X, and serving network architecture. For example, Datang Telecom Group has been the co-reporter of massive MIMO. Datang launched the world's first and largest 256 element (128 channels) massive MIMO system in 2016, and achieved a 4-Gbps peak data rate. Datang, Huawei, and ZTE proposed specific NOMA technologies (PDMA, SCMA, MUSA), which are expected to become important technology solutions to 5G massive connection scenarios. Also, ZTE and Datang are leading the NOMA SI in release 15. In addition, Huawei and other Chinese companies successfully pushed polar code to become the control channel coding scheme of 5G NR. China Mobile and other Chinese companies are jointly leading the 5G requirement formations and also promoting the service-oriented architecture into the control plane architecture of the 5G core network. Furthermore, Datang, Huawei, and other Chinese companies are promoting LTE V2X technology and verifying them with the automotive industry in pilot areas including Shanghai, Chongqing, and Beijing.

In 3GPP, at least one third of the proposals, reports, and standards documents for 5G came from Chinese companies.

6.2 5G technical tests and field trials in China

From 3G TD-SCDMA to 4G TD-LTE, China became a key member of the global mobile communication society. A cooperative promotion mechanism has been well established among Chinese universities, research institutes, and industry companies, and the mechanism works well. As shown in Fig. 7, this cooperative promotion mechanism usually goes on over a five-year period and is divided into two phases, technology R&D trial and product field trial, with three steps for each phase. Guided by MIIT, the technology R&D trial phase includes tests of key technologies, technology schemes, and systems. Promoted by operators, the OEM product field trial phase includes small-scale, lager-scale, and pre-commercial trials.

IMT-2020(5G) PG of China has planned and is executing the five-year plan of the 5G test from 2016 to 2020. The objectives of the 5G test are to promote the R&D of 5G key technologies, technical solutions, and global unified standards, to accelerate the development of 5G products and to build a 5G ecosystem.

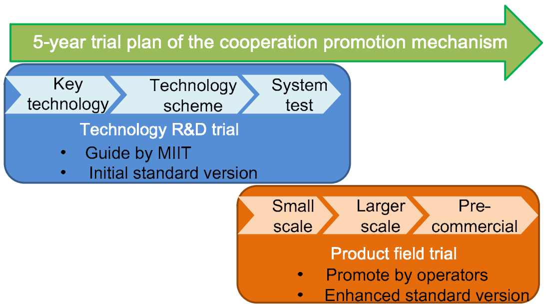

Fig. 7 Cooperative promotion scheme for mobile communications in China

To support 5G technology R&D, the National High-Tech R&D Program (863) of China supported two issues covering totally 20 projects on 5G research. Also, among the projects supported by the National Science and Technology Major Project (No.3) in China over the past years, more than half are 5G projects, in the fields of wireless technology, network and service, and key equipment/modules/platforms. The 5G wireless system prototypes, UE prototypes, and network prototypes resulting from these projects meet the time schedule of 5G trials in China.

By the end of 2017, IMT-2020(5G) PG of China had finished two steps of the first-phase 5G trial organized by MIIT. The first two steps focus mainly on sub-6 GHz frequency bands and the eMBB scenario, including part of considerations of mMTC and URLLC scenarios. The first trial step conducted in 2016 and totaling 10 enabling technologies were tested, including massive MIMO, NOMA, UDN, advanced coding, network slicing, and MEC. The second trial step conducted in 2017 and all 5G requirements specified by the ITU have been implemented. Here we show part of the exciting trial results: in sub-6 GHz bands the cell peak data rate exceeds 10 Gbps@200 MHz bandwidth for eMBB, the traffic density is much higher than 10 Mbps/m^2 (e.g., Datang reached 61 Mbps/m^2) for a hotspot, the one-way air interface delay can be less than 0.5 ms for URLLC, and 600% access ability can be achieved with NOMA for mMTC. All major international operators and vendors participated in the trials in China, including

China Mobile, China Telecom, China Unicom, NTT Docomo, Huawei, Ericsson, ZTE, Datang, Nokia, Samsung, Spreadtrum, Qualcomm, Intel, and MTK.

In January 2018, China launched the third-step trial for system verification and the trial will be finished by the end of 2018. All companies will conduct verifications using the standardized 5G versions. The scaled trial for R&D products will start in July 2018, and at least 100 sites will be set up in each city. Products, networking, services, and user experience will be tested before 2020. It is thus certain that China will start 5G massive commercial deployment in 2020.

7 Rethinking of 5G

The key technologies, standards progress, and technical testing of 5G have been described in this paper. We need to think deeply about the future of 5G. The following shows our (re)thinking:

1. 5G is an era where everything is interconnected.

The first generation (1G) to the fourth generation (4G) focus on mobile communications between people, while 5G goes far beyond that, not only on people but also on physical things and cyber physical systems. 5G will be an era where everything is interconnected, and it has three major new characteristics, i.e., big data, huge connectivity, and scenario experiencing. The information society will be marked by data and connectivity.

2. 5G is a software-defined era with ITnization.

5G is a new generation of mobile communications. Its technology will be characterized by deep convergence of communication technology (CT) and information technology (IT). It will be software defined, with intelligence, and is a platform.

5G will be defined by software including SDN, NFV, and software-defined radio access interface. It will thus make 5G network and radio access interface programmable, and will lead to a 5G network easily able to adopt a general hardware platform and general software platform, and possibly to introduce or bring in open source software.

3. 5G is an era of the Cloud closer to users.

The trend of 5G to be Cloud is characterized by cloud RAN (C-RAN), MEC, and fog computing.

C-RAN means integrating multiple baseband units (BBUs) to form a baseband processing pool serving hundreds up to thousands of remote radio units (RRUs). In this case, baseband processing will be replaced by a cloud of virtual computing resource with ultralow latency for the RAN.

MEC means that 5G will provide IT services, and computing services will thus be closer to end users. MEC will deploy applications, services, and contents in a mobile distributed environment. Through localized deployment, much more radio bandwidth resources can be released, and offering all services in real time will be possible.

5G terminals can also be clouded by introducing fog computing. With the evolution of IC technologies, the resources (including computing, memory, and sensors) in terminals will be enhanced dramatically, and these resources can also be shared, especially for social network applications and vehicle networks.

4. 5G is an era of cellular structure revolution.

From 1G to 4G, mobile communication systems are all based on a traditional cellular structure, composed of hexagonal-like cells. The system is an interference restricted system. By introducing UDN, 5G will adopt more access points, such as home stations, radio relays, micro-stations, and distributed antenna systems. The network structure will be irregular, with amorphous installation and overlapping coverage. The structure will become heterogeneous and hierarchical.

In a 5G network, the traditional regular cellular network will no longer exist, and a de-cellular concept (Chen et al., 2016c) will be introduced, which starts a revolution of the structure.

8 Concluding remarks and future work

Thanks to a new opportunity offered by economic growth, 5G has gained wide attention and is developing very fast. As expected, 5G will bring unprecedented changes to people's daily life and even to the whole society. The 5G NSA standard has been formulated, and the SA standard will be formed in the middle of 2018. The 5G trial has gone through the technology R&D phase, and the product field trial is in progress. Up to now, the 5G field trial networks have all been focused on eMBB, and are very limited in mMTC and URLLC. So, field trials of mMTC and URLLC should be carried out. The 5G industrial ecosystem is at a building phase, and the involvement of and cooperation with industry need to be strengthened. 5G is finally expected to be large-scale commercial in 2020.

With the rapid development of 5G, research on what comes after 5G will be started gradually. There have been some interesting topics in discussion by academics and industry, for example, the application of artificial intelligence and big data to make smart 5G, high frequency communication in THz bands, satellite and terrestrial integrated mobile communications, and joint sensing and communication. It can be foreseen that a new 10-year generation of mobile communications is coming.

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