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Drivers for 5G: The ‘Pervasive Connected World’

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1.1 Introduction

We have been witnessing an exponential growth in the amount of traffic carried through mobile networks. According to the Cisco visual networking index [1], mobile data traffic has doubled during 2010–2011; extrapolating this trend for the rest of the decade shows that global mobile traffic will increase 1000x from 2010 to 2020.

The surge in mobile traffic is primarily driven by the proliferation of mobile devices and the accelerated adoption of data-hungry mobile devices – especially smart phones. Table 1.1 provides a list of these devices along with their relative data consumptions. In addition to the increasing adoption rate of these high-end mobile devices, the other important factor associated with the tremendous mobile traffic growth is the increasing demand for advanced multi-media applications such as Ultra-High Definition (UHD) and 3D video as well as augmented reality and immersive experience. Today, mobile video accounts for more than 50% of global mobile data traffic, which is anticipated to rise to two-thirds by 2018 [1]. Finally, social networking has become important for mobile users, introducing new consumption behaviour and a considerable amount of mobile data traffic.

The growth rate of mobile data traffic is much higher than the voice counterpart. Global mobile voice traffic was overtaken by mobile data traffic in 2009, and it is forecast that Voice over IP (VoIP) traffic will represent only 0.4% of all mobile data traffic by 2015. In 2013, the number of mobile subscriptions reached 6.8 billion, corresponding to a global

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Table 1.1 Data consumption of different mobile terminals.

Device	Relative data usage
Feature phone	1x
Smart phone	24x
Handheld gaming console	60x
Tablet	122x
Laptop	515x

penetration of 96%. The ever-growing global subscriber rate spurred on by the world population growth will place stringent new demands on potential 5G networks to cater for one billion new customers.

Apart from 1000x traffic growth, the increasing number of connected devices imposes another challenge on the future mobile network. It is envisaged that in the future connected society, everyone and everything will be inter-connected – under the umbrella of Internet of Everything (IoE) – where tens to hundreds of devices will serve every person. This upcoming 5G cellular infrastructure and its support for Big Data will enable cities to be smart. Data will be generated everywhere by both people and machines, and will be analysed in a real-time fashion to infer useful information, from people's habits and preferences to the traffic condition on the streets, and health monitoring for patients and elderly people. Mobile communications will play a pivotal role in enabling efficient and safe transportation by allowing vehicles to communicate with each other or with a roadside infrastructure to warn or even help the drivers in case of unseen hazards, paving the way towards autonomous self-driving cars. This type of machine-to-machine (M2M) communications requires very stringent latency (less than 1 ms), which imposes further challenges on the future network.

The 1000x mobile traffic growth along with trillions of connected devices is pushing the cellular system to a broadband ubiquitous network with extreme capacity and Energy Efficiency (EE) and diverse Quality of Service (QoS) support. Indeed, it is envisaged that the next-generation cellular system will be the first instance of a truly converged wired and wireless network, providing fibre-like experience for mobile users. This ubiquitous, ultra-broadband, and ultra-low latency wireless infrastructure will connect the society and drive the future economy.

1.2 Historical Trend of Wireless Communications

A new generation of cellular system appears every 10 years or so, with the latest generation (4G) being introduced in 2011. Following this trend, the 5G cellular system is expected to be standardised and deployed by the early 2020s. The standardisation of the new air interfaces for 5G is expected to gain momentum after the International Telecommunication Union-Radiocommunication Sector's (ITU-R) meeting at the next World Radiocommunication Conference (WRC), to be held in 2015. Table 1.2 summarises the rollout year as well as the International Mobile Telecommunications (IMT) requirements for the peak and the average data rates for different generations of the cellular system. Although IMT requirements for 5G are yet to be defined, the common consensus from academic researchers and industry is that in principle it should deliver a fibre-like mobile Internet experience with peak rates of up to 10 Gbps in static/low mobility conditions, and 1 Gbps blanket coverage for highly mobile/cell edge users (with speeds of > 300 km/h). The round-trip time latency of the state-of-the-art 4G

Table 1.2 Specifications of different generations of cellular systems.

Generation	Rollout year	IMT requirement for data rate	
		Mobile users	Stationary users
1G	1981	–	–
2G	1992	–	–
3G	2001	384 Kbps	>2 Mbps
4G	2011	100 Mbps	1 Gbps
5G	2021	1 Gbps	10 Gbps

system (Long-Term Evolution – Advanced; LTE-A) is around 20 ms, which is expected to diminish to less than 1 ms for 5G.

Global standards are a fundamental cornerstone in reaching ubiquitous connectivity, ensuring worldwide interoperability, enabling multi-vendor harmonisation and economies of scale. ITU-R is responsible for defining IMT specifications for next-generation cellular systems. Having defined two previous specifications (IMT-2000 for 3G and IMT-Advanced for 4G), it has already commenced activities towards defining specifications for 5G, which is aimed for completion around 2015. ITU-R arranges WRCs every three to four years to review and revise radio regulations. Allocation of new spectrum for mobile communications is already on the agenda of the next WRC, to be held in November 2015.

To understand where we want to be in terms of 5G, it is worthwhile to appreciate where it all started and to mark where we are now. The following provides a roadmap of the evolution towards 5G communications:

- **Before 1G (<1983):** All the wireless communications were voice-centric and used analogue systems with single-side-band (SSB) modulation.
- **1G (1983–):** All the wireless communications were voice-centric. In 1966, Bell Labs had made a decision to adopt analogue systems for a high-capacity mobile system, because at that time the digital radio systems were very expensive to manufacture. An analogue system with FM radios was chosen. In 1983, the US cellular system was named AMPS (Advanced Mobile Phone Service). AMPS was called 1G at the time.
- **2G (1990–):** During this period, all the wireless communications were voice-centric. European GSM and North America IS-54 were digital systems using TDMA multiplexing. Since AT&T was divested in 1980, no research institute like Bell Labs could develop an outstanding 2G system as it did for the 1G system in North America. IS-54 was not a desirable system and was abandoned. Then, GSM was named 2G at the time when 3G was defined by ITU in 1997. Thus, we could say that moving from 1G to 2G means migrating from the analogue system to the digital system.
- **2.5G (1995–):** All the wireless communications are mainly for high-capacity voice with limited data service. The CDMA (code division multiple access) system using 1.25 MHz bandwidth was adopted in the United States. At the same time, European countries enhanced GSM to GPRS and EDGE systems.
- **3G (1999–):** In this generation, the wireless communications platform has voice and data capability. 3G is the first international standard system released from ITU, in contrast to previous generation systems. 3G exploits WCDMA (Wideband Code Division Multiple

Access) technology using 5 MHz bandwidth. It operates in both frequency division duplex (FDD) and time division duplex (TDD) modes. Thus, we could say that by migrating from 2G to 3G systems we have evolved from voice-centric systems to data-centric systems.
- **4G (2013–):** 4G is a high-speed data rate plus voice system. There are two 4G systems. The United States has developed the WiMAX (Worldwide Interoperability for Microwave Access) system using orthogonal frequency-division multiplexing (OFDM), evolving from WiFi. The other is the LTE system that was developed after WiMAX. The technology of LTE and that of WiMAX are very similar. The bandwidth of both systems is 20 MHz. The major cellular operators are favourable to LTE, and most countries around the world have already started issuing licences for 4G using current developed LTE systems. The cost of licensing through auction is very high. Thus, we could say that migrating from 3G to 4G means a shift from low data rates for Internet to high-speed data rates for mobile video.
- **5G (2021–):** 5G is still to be defined officially by standardisation bodies. It will be a system of super high-capacity and ultra-high-speed data with new design requirements tailored towards energy elicited systems and reduced operational expenditure for operators. In this context, 5G envisages not only one invented technology, but a technology ecosystem of wireless networks working in synergy to provide a seamless communication medium to the end user. Thus, we can say that moving from 4G to 5G means a shift in design paradigm from a single-discipline system to a multi-discipline system.

1.3 Evolution of LTE Technology to Beyond 4G

A summary of IMT-Advanced requirements for 4G is as follows:

- Peak data rate of 100 Mbps for high mobility (up to 360 km/h) and 1 Gbps for stationary or pedestrian users.
- User-plane latency of less than 10 ms (single-way UL/DL (uplink/downlink) delay).
- Scalable bandwidth up to 40 MHz, extendable to 100 MHz.
- Downlink peak spectral efficiency (SE) of 15 bit/s/Hz.
- Uplink peak SE of 6.75 bit/s/Hz.

Paving the way to 5G entails both evolutionary and revolutionary system design. While disruptive radio access technologies (RATs) are needed to provide a step up to the next level of performance capability, we also need to improve the existing RATs. In this regard, we need to further improve the LTE system to beyond 4G (B4G). First targeting the IMT-Advanced requirements, LTE standard Release (R)-8 was unable to fulfil the requirements in the downlink direction (although it could meet all the requirements in the uplink direction) with a single antenna element at the User Equipment (UE) and four receive antennas at the Evolved Node B (eNB) [2]. In contrast, LTE-A is a true 4G technology (meeting all the IMT-Advanced requirements), requiring at least two antenna elements at the UE. As such, it was accepted as IMT-Advanced 4G technology in November 2010 [3]. Figure 1.1 illustrates the evolution of the LTE standard by the 3rd Generation Partnership Project (3GPP) to B4G. The innovations on this roadmap mainly include improving the SE and the area capacity while reducing the network operational cost to ensure fixed marginal cost for the operators. Finally, Table 1.3 summarises the main features of different Releases of LTE from R-8 to R-13, the latest one revealed in December 2013.

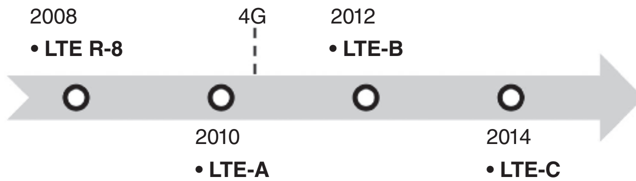

Figure 1.1 Evolution of LTE standard to beyond 4G.

Table 1.3 Main features of different LTE Releases.

Release		Features
LTE	R-8	• Supporting both frequency division duplex (FDD) and time division duplex (TDD) • Scalable frequency spectrum in six different bandwidths: 1.4, 3, 5, 10, 15 and 20 MHz • OFDM • Supporting up to four-layer spatial multiplexing with Single-User Multiple-Input Multiple-Output (SU-MIMO) • Achieving 300 Mbps in DL and 75 Mbps in UL • User-plane latency of less than 20 ms
	R-9	• Multicast and broadcast functionality
LTE-A	R-10	• Carrier aggregation to utilise up to 100 MHz bandwidth • Supporting up to eight-layer spatial multiplexing with SU-MIMO • Enhanced Multi-User (MU-)MIMO • Extended and more flexible reference signal • Relaying functionality • Peak data rate beyond 1 Gbps in DL and 500 Mbps in UL • User-plane latency of less than 10 ms
	R-11	• Coordinated multipoint (CoMP) transmission and reception • Enhanced support for Heterogeneous Network (HetNet)
LTE-B	R-12	• Local area enhancement (soft cell) • Lean carrier • Beamforming enhancement • Enhanced machine-type communication (MTC) • 3D-MIMO • Enhanced CoMP • Enhanced self-organising networks (eSON)
	R-13	• Radio Access Network (RAN) sharing enhancement

1.4 5G Roadmap

Figure 1.2 illustrates the roadmap for 5G [4]. We are in the early research stage for prototyping now. New spectrum is expected to be agreed upon in the WRC 2015, enabling IMT to define the requirements. This will be followed by the standardisation activities and the product development phase until 2020. It is expected that the first wave of 5G networks will be operational around 2021.

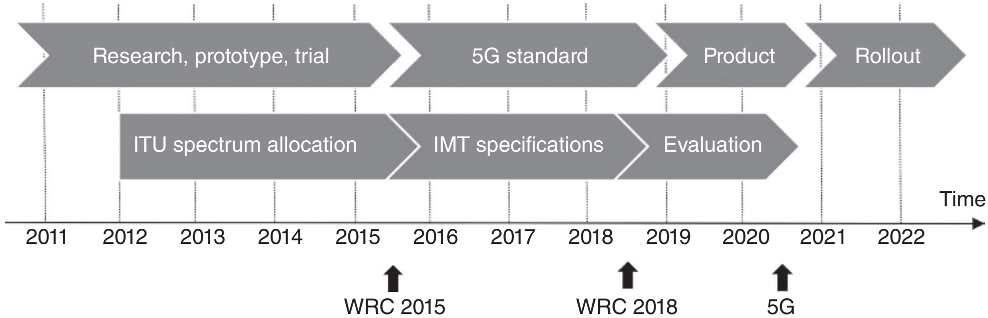

Figure 1.2 Roadmap for 5G.

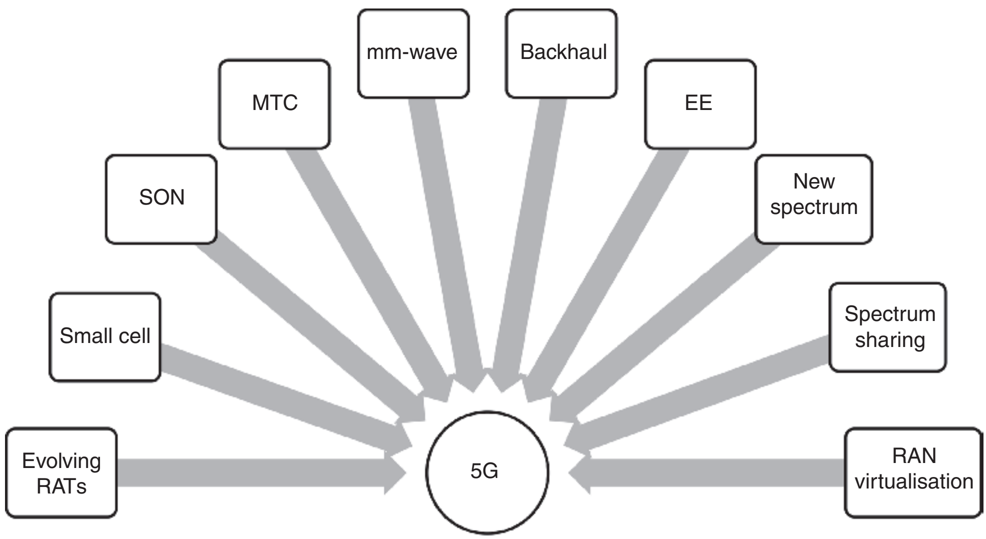

Figure 1.3 10 pillars of 5G.

1.5 10 Pillars of 5G

We identify 10 key building blocks for 5G, illustrated by Figure 1.3. In the following, we elaborate each of these blocks and highlight their role and importance for achieving 5G.

1.5.1 Evolution of Existing RATs

As mentioned before, 5G will hardly be a specific RAT, rather it is likely that it will be a collection of RATs including the evolution of the existing ones complemented with novel revolutionary designs. As such, the first and the most economical solution to address the 1000x capacity crunch is the improvement of the existing RATs in terms of SE, EE and latency, as well as supporting flexible RAN sharing among multiple vendors. Specifically, LTE needs to evolve to support massive/3D MIMO to further exploit the spatial degree of

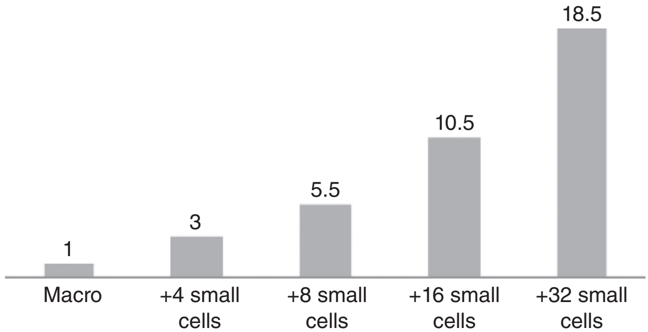

Figure 1.4 Capacity scales linearly with the number of added small cells.

freedom (DOF) through advanced multi-user beamforming, to further enhance interference cancellation and interference coordination capabilities in a hyperdense small-cell deployment scenario. WiFi also needs to evolve to better exploit the available unlicensed spectrum. IEEE 802.11ac, the latest evolution of the WiFi technology, can provide broadband wireless pipes with multi-Gbps data rates. It uses wider bandwidth of up to 160 MHz at the less polluted 5 GHz ISM band, employing up to 256 Quadrature Amplitude Modulation (QAM). It can also support simultaneous transmissions up to four streams using multi-user MIMO technique. The incorporated beamforming technique has boosted the coverage by several orders of magnitude, compared to its predecessor (IEEE 802.11n). Finally, major telecom companies such as Qualcomm have recently been working on developing LTE in the unlicensed spectrum as well as integrating 3G/4G/WiFi transceivers into a single multi-mode base station (BS) unit. In this regard, it is envisioned that the future UE will be intelligent enough to select the best interface to connect to the RAN based on the QoS requirements of the running application.

1.5.2 Hyperdense Small-Cell Deployment

Hyperdense small-cell deployment is another promising solution to meet the 1000x capacity crunch, while bringing additional EE to the system as well. This innovative solution, also referred to as HetNet, can help to significantly enhance the area spectral efficiency (b/s/Hz/m^2). In general, there are two different ways to realise HetNet: (i) overlaying a cellular system with small cells of the same technology, that is, with micro-, pico-, or femtocells; (ii) overlaying with small cells of different technologies in contrast to just the cellular one (e.g. High Speed Packet Access (HSPA), LTE, WiFi, and so on). The former is called multi-tier HetNet, while the latter is referred to as multi-RAT HetNet.

Qualcomm, a leading company in addressing 1000x capacity challenge through hyperdense small-cell deployments, has demonstrated that adding small cells can scale the capacity of the network almost in a linear fashion, as illustrated by Figure 1.4 [5]. That is, the capacity doubles every time we double the number of small cells. However, reducing the cell size increases the inter-cell interference and the required control signalling. To overcome this drawback, advanced inter-cell interference management techniques are needed at the system level along with complementary interference cancellation techniques at the UEs. Small-cell enhancement was the focal point of LTE R-12, where the New Carrier Type (NCT) (also known as the Lean Carrier) was introduced to assist small cells by the host macro-cell. This allows more efficient control plane functioning (e.g. for mobility management, synchronisation, resource allocation, etc.) through the macro-layer while providing a high-capacity and spectrally efficient data plane through the small cells [6]. Finally, reducing the cell size can also improve the EE of the network by bringing the network closer to the UEs and hence shrinking the power budget of the wireless links.

1.5.3 Self-Organising Network

Self-Organising Network (SON) capability is another key component of 5G. As the population of the small cells increases, SON gains more momentum. Almost 80% of the wireless traffic is generated indoors. To carry this huge traffic, we need hyperdense small-cell deployments in homes – installed and maintained mainly by the users – out of the control of the operators. These indoor small cells need to be self-configurable and installed in a plug and play manner. Furthermore, they need to have SON capability to intelligently adapt themselves to the neighbouring small cells to minimise inter-cell interference. For example, a small cell can do this by autonomously synchronising with the network and cleverly adjusting its radio coverage.

1.5.4 Machine Type Communication

Apart from people, connecting mobile machines is another fundamental aspect of 5G. Machine type communication (MTC) is an emerging application where either one or both of the end users of the communication session involve machines. MTC imposes two main challenges on the network. First, the number of devices that need to be connected is tremendously large. Ericsson (one of the leading companies in exploring 5G) foresees that 50 billion devices need to be connected in the future networked society; the company envisages ‘anything that can benefit from being connected will be connected’ [7]. The other challenge imposed by MTC is the accelerating demand for real-time and remote control of mobile devices (such as vehicles) through the network. This requires an extremely low latency of less than a millisecond, so-called “tactile Internet” [8], dictating 20x latency improvement from 4G to 5G.

1.5.5 Developing Millimetre-Wave RATs

The traditional sub-3 GHz spectrum is becoming increasingly congested and the present RATs are approaching Shannon’s capacity limit. As such, research on exploring cm- and mmWave bands for mobile communications has already been started. Although the research on this field is still in its infancy, the results look promising.

There are three main impediments for mmWave mobile communications. First, the path loss is relatively higher at these bands, compared to the conventional sub-3GHz bands. Second, electromagnetic waves tend to propagate in the Line-Of-Sight (LOS) direction, rendering the radio links vulnerable to being blocked by moving objects or people. Last but not least, the penetration loss through the buildings is substantially higher at these bands, blocking the outdoor RATs for the indoor users.

Despite these limitations, there are myriad advantages for mmWave communications. An enormous amount of spectrum is available in mmWave band; for example, at 60 GHz, there is

9GHz of unlicensed spectrum available. This amount of spectrum is huge, especially when we think that the global allocated spectrum for all cellular technologies hardly exceeds 780 MHz [9]. This amount of spectrum can completely revolutionise mobile communications by providing ultra-broadband wireless pipes that can seamlessly glue the wired and the wireless networks. Other advantages of mmWave communications include the small antenna sizes ($\lambda/2$) and their small separations (also around $\lambda/2$), enabling tens of antenna elements to be packed in just one square centimetre. This in turn allows us to achieve very high beamforming gains in relatively small areas, which can be implemented at both the BS and the UE. Incorporating smart phased array antennas, we can fully exploit the spatial degree of freedom of the wireless channel (using Space-Division Multiple Access (SDMA)), which can further improve the system capacity. Finally, as the mobile station moves around, beamforming weights can be adjusted adaptively so that the antenna beam is always pointing to the BS.

Recently, Samsung Electronics, an industry leader in exploring mmWave bands for mobile communications, has tested a technology that can achieve 2 Gbps data rate with 1 km range in an urban environment [10]. Furthermore, Professor Theodore Rappaport and his research team at the Polytechnic Institute of New York University have demonstrated that mobile communications at 28 GHz in a dense urban environment such as Manhattan, NY, is feasible with a cell size of 200 m using two 25 dBi antennas, one at the BS and the other at the UE, which is readily achievable using array antennas and the beamforming technique [9].

Last but not least, foliage loss for mmWaves is significant and may limit the propagation. Furthermore, mmWave transmissions may also experience significant attenuations in the presence of a heavy rain since the raindrops are roughly the same size as the radio wavelengths (millimetres) and therefore can cause scattering. Therefore, a backup cellular system operating in legacy sub-3 GHz bands might be needed as part of the mmWave solution [9].

1.5.6 Redesigning Backhaul Links

Redesigning the backhaul links is the next critical issue of 5G. In parallel to improving the RAN, backhaul links also need to be reengineered to carry the tremendous amount of user traffic generated in the cells. Otherwise, the backhaul links will soon become bottlenecks, threatening the proper operation of the whole system. The problem gains more momentum as the population of small cells increases. Different communication mediums can be considered, including optical fibre, microwave and mmWave. In particular, mmWave point-to-point links exploiting array antennas with very sharp beams can be considered for reliable self-backhauling without interfering with other cells or with the access links.

1.5.7 Energy Efficiency

EE will remain an important design issue while developing 5G. Today, Information and Communication Technology (ICT) consumes as much as 5% of the electricity produced around the globe and is responsible for approximately 2% of global greenhouse gas emissions – roughly equivalent to the emissions created by the aviation industry. What concerns more is the fact that if we do not take any measure to reduce the carbon emissions, the contribution is projected to double by 2020 [11]. Hence, it is necessary to pursue energy-efficient design approaches from RAN and backhaul links to the UEs.

The benefit of energy-efficient system design is manifold. First, it can play an important role in sustainable development by reducing the carbon footprint of the mobile industry itself. Second, ICT as the core enabling technology of the future smart cities can also play a fundamental role in reducing the carbon footprint of other sectors (e.g. transportation). Third, it can increase the revenue of mobile operators by reducing their operational expenditure (Opex) through saving on their electricity bills. Fourth, reducing the 'Joule per bit' cost can keep mobile services affordable for the users, allowing flat rate pricing in spite of the 10 to 100x data rate improvement expected by 2020. Last but not least, it can extend the battery life of the UEs, which has been identified by the market research company TNS [12] as the number one criterion of the majority of the consumers purchasing a mobile phone.

1.5.8 Allocation of New Spectrum for 5G

Another critical issue of 5G is the allocation of new spectrum to fuel wireless communications in the next decade. The 1000x traffic surge can hardly be managed by only improving the spectral efficiency or by hyper-densification. In fact, the leading telecom companies such as Qualcomm and NSN believe that apart from technology innovations, 10 times more spectrum is needed to meet the demand. The allocation of around 100 MHz bandwidth at the 700 MHz band and another 400 MHz bandwidth at around 3.6 GHz, as well as the potential allocation of several GHz bandwidths in cm- or mmWave bands to 5G will be the focal point of the next WRC conference, organised by ITU-R in 2015.

1.5.9 Spectrum Sharing

Regulatory process for new spectrum allocation is often very time consuming, so the efficient use of available spectrum is always of critical importance. Innovative spectrum allocation models (different from the traditional licensed or unlicensed allocation) can be adopted to overcome the existing regulatory limitations. Plenty of radio spectrum has traditionally been allocated for military radars where the spectrum is not fully utilised all the time (24/7) or in the entire geographic region. On the other hand, spectrum cleaning is very difficult as some spectrum can never be cleaned or can only be cleaned over a very long time; beyond that, the spectrum can be cleaned in some places but not in the entire nation. As such, the Authorised/Licensed Shared Access (ASA/LSA) model has been proposed by Qualcomm to exploit the spectrum in small cells (with limited coverage) without interfering with the incumbent user (e.g. military radars) [13]. This kind of spectrum allocation model can compensate the very slow process of spectrum cleaning. It is also worth mentioning that as mobile traffic growth accelerates, spectrum refarming becomes important, to clean a previously allocated spectrum and make it available for 5G. Cognitive Radio concepts can also be revisited to jointly utilise licensed and unlicensed spectrums. Finally, new spectrum sharing models might be needed as multi-tenant network operation becomes widespread.

1.5.10 RAN Virtualisation

The last but not least critical enabler of 5G is the virtualisation of the RAN, allowing sharing of wireless infrastructure among multiple operators. Network virtualisation needs to be pushed from the wired core network (e.g. switches and routers) towards the RAN. For network virtualisation, the intelligence needs to be taken out of the RAN hardware and controlled in a centralised manner using a software brain, which can be done in different network layers. Network virtualisation can bring myriad advantages to the wireless domain, including both Capex (Capital Expenditure) and Opex savings through multi-tenant network and equipment sharing, improved EE, on-demand up- or down-scaling of the required resources, and increased network agility through the reduction of the time-to-the-market for innovative services (from 90 hours to 90 minutes), as well as easy maintenance and fast troubleshooting through increased transparency of the network [14]. Virtualisation can also serve to converge the wired and the wireless networks by jointly managing the whole network from a central orchestration unit, further enhancing the efficiency of the network. Finally, multi-mode RANs supporting 3G, 4G or WiFi can be adopted where different radio interfaces can be turned on or off through the central software control unit to improve the EE or the Quality of Experience (QoE) for the end users.

1.6 5G in Europe

Past research efforts in Europe have delivered many advances in mobile communications we take for granted today. These include the 2G GSM standard (used today by 80% of the world's mobile networks) and the technologies used in the 3G Universal Mobile Telecommunications System (UMTS) and the 4G LTE standards. Timely development of the 5G technology is now of paramount importance for Europe to drive the economy, strengthen the industry's competitiveness, and create new job opportunities.

Leading the development of 5G technology is critically important for the European Union (EU), primarily because of its vital role in economic growth. As a whole, the ICT sector represents approximately 5% of EU GDP, with an annual value of €660 billion. It generates 25% of total business expenditure in Research and Development (R&D), and investments in ICT account for 50% of all European productivity growth.

Second, pioneering 5G is vitally important because this technology will play a key role in securing Europe's leadership in the global mobile industry. Historically, the European telecom industry was at the forefront of global competition from the early days of GSM technology to the UMTS and LTE technologies. It still represented approximately 40% of the worldwide telecom market of nearly €200 billion in 2012 in terms of network infrastructure supply. However, Europe is now falling behind its competitors and wants to catch up by leading the 5G technology.

Last but not least, leading 5G technology is of great importance for the EU as it can bring new job opportunities to Europe. European Commission Vice President Neelie Kroes announced during the Mobile World Congress 2013 in Barcelona: 'I want 5G to be pioneered by European industry, based on European research and creating jobs in Europe'.

However, the emergence of new eastern competitors such as China and South Korea may challenge these key ambitions.

1.6.1 Horizon 2020 Framework Programme

Europeans use 'Framework Programmes' as financial instruments to coordinate and fund their future research and innovation. They have successfully exercised this model by developing 3G (UMTS) and 4G (LTE) standards; now they intend to use the same model for 5G.

Table 1.4 B4G/5G projects funded by FP7 in 2013.

Project	Small cell	Virtualisation	mmWave	MTC
METIS	✓	–	–	✓
MCN	–	✓	–	–
COMBO	–	✓	–	–
iJOIN	–	✓	✓	–
TROPIC	✓	✓	–	–
E3NETWORK	–	–	✓	–
MOTO	–	–	–	✓
MiWEBA	✓	–	✓	–

The Framework Programme (FP) succeeding FP7 was supposed to be FP8, but the naming has been changed and instead it is called Horizon 2020. Running over a seven-year period from 2014 to 2020, Horizon 2020 is the biggest EU FP ever with nearly €80 billion funding (a significant increase on around €50 billion funding in FP7), in addition to the private investment that this money will attract. It intends to fuel and shape future research and innovation in Europe from basic research in labs to the uptake of innovative ideas in the market.

However, the EU has already adopted a proactive stance towards the 5G era by targeting core topics such ultra-high-speed broadband and MTC using energy-efficient techniques in the FP7 framework. Overall, from 2007 to 2013, EU investments through FP7 amounted to more than €700 million for research on future networks, half of which was allocated to wireless technologies, contributing to development of 4G/B4G. METIS [15], 5GNOW [16], iJOIN [17], TROPIC [18], Mobile Cloud Networking (MCN) [19], COMBO [20], MOTO [21], PHYLAWS [22], E3NETWORK [23], and MiWEBA [24] are some of the latest EU projects addressing the architecture and functionality needs of B4G/5G networks. Table 1.4 summarises some of these projects, classifying them in terms of the key 5G technology enablers they address, including small cells, virtualisation, mmWave and MTC.

1.6.2 5G Infrastructure PPP

5G Infrastructure PPP is a public-private partnership to formulate the research and innovation priorities in Horizon 2020 for developing the next generation of mobile communications infrastructure beyond 2020. Bringing together stakeholders from the entire value chain including industries, operators and regulatory and standardisation bodies, as well as academia and automotive industries, 5G Infrastructure PPP will create a shared vision of the 5G cellular system, a multi-annual strategic roadmap for research and innovation that will be updated yearly until 2020. The 5G Infrastructure PPP will become operational at the beginning of 2014 and will benefit from the activities of the existing Net!Works European Technology Platform (ETP), the think tank that was instrumental in creating and structuring the European communications technology community, ensuring close cooperation between industry and the research and academia sectors.

The 5G Infrastructure PPP will deliver solutions, architectures, technologies and standards for the ubiquitous next-generation communication infrastructures of the coming decade. Specifically, it will provide such advancements as a 1000x increase in wireless capacity serving over 7 billion people (while connecting 7 trillion ‘things’), save 90% of energy per service provided, and create a secure, reliable and dependable Internet with zero perceived downtime for services [25].

The total budget devoted by the public side to the 5G Infrastructure PPP is expected to be around €700 million in Horizon 2020, which is mirrored by around €700 million committed by the private side. In addition, the telecom industry will invest outside the partnership five to 10 times this amount in activities contributing to the objectives of the PPP. The budget for the first call is €125 million.

In 5G Infrastructure PPP, while the private side (representing more than 800 different companies and institutions), under the leadership of the industry, sets the strategic research and innovation agenda for Horizon 2020, the responsibility for implementation remains with the European Commission (as the public side), following the rules of Horizon 2020 in terms of calls, selection, negotiation and contracting of project proposals, as well as monitoring and payments of funded projects.

1.6.3 METIS Project

METIS (Mobile and wireless communications Enablers for Twenty-twenty Information Society) is an exploratory FP7 research project on 5G with a total cost of around €28.7 million. It has a consortium of 29 partners, spanning from telecom manufacturers and network operators to the automotive industry and academia, coordinated by Ericsson.

The project aims at developing a system concept that delivers the necessary efficiency, versatility and scalability, investigating key technology components to support the system and evaluating and demonstrating key functionalities. The conceptual architecture of the project is illustrated in Figure 1.5. The project also intends to lead the European-level development of future mobile and wireless communications systems and ensure an early global consensus on

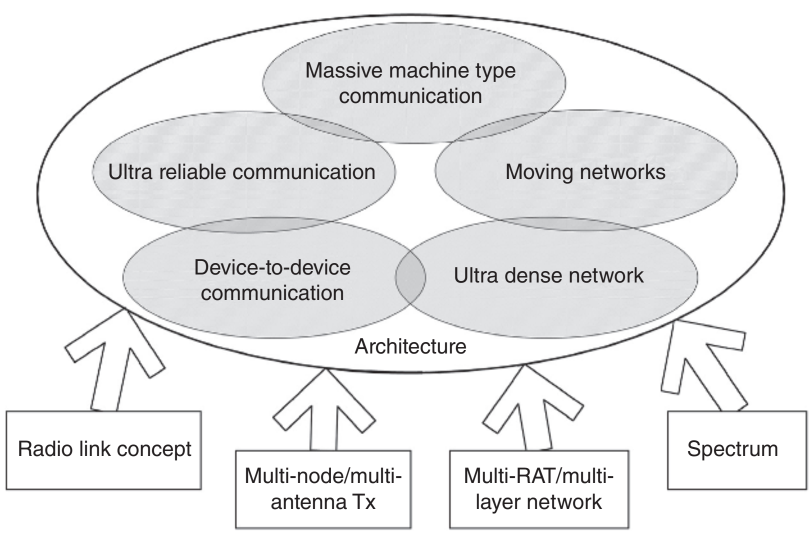

Figure 1.5 Conceptual architecture of METIS project [26].

these systems by laying the foundation for 5G, through providing a system concept that can support:

- 1000x higher area capacity
- 10 to 100x higher number of connected devices
- 10 to 100x higher typical user data rate
- 10x longer battery life for low power MTC
- 5x reduced end-to-end latency, compared to LTE-A.

1.6.4 5G Innovation Centre

In October 2012, the University of Surrey received £35 million from mobile operators, infrastructure providers and the UK Research Partnership Investment Fund to create the 5G Innovation Centre (5GIC) and install lamppost BSs around the university campus to create a network to test future technologies. Professor Rahim Tafazolli, director of Centre for Communication Systems Research (CCSR) at the University of Surrey, told the BBC [27]: 'The boundaries between mobile communication and the Internet are blurring, so the fifth generation is Internet on the move'. The 5GIC will be operational at the beginning of 2015, employing 130 researchers and about 90 PhD students, to spearhead the search for a successor to 4G technology.

1.6.5 Visions of Companies

In the following, we summarise the 5G visions of European telecom companies Alcatel-Lucent, Ericsson and NSN.

Alcatel-Lucent: 5G is about communication services that adapt to the consumer, rather than the consumer adapting to the communication service [28]. Network technology with 5G will remain stable and operational while handling billions of connected devices. Since the number of mobile devices that networks address is set to explode in the coming years, the main issue will be delivering connectivity smartly, with low latency. Bell Labs predicts that cloud processing will 'completely dominate' in the network, not only in terms of applications, but regarding operations as well [29]. Widespread M2M communications are also seen as one of the 5G drivers, and Bell Labs is working on a new 5G air interface that can support shorter packets for M2M communications.

Ericsson: 5G will enable a sustainable 'Networked Society' and realise the vision of unlimited access to information and sharing of data anywhere and anytime to anyone and anything. Everything that can benefit from being connected will be connected. This vision will be achieved by seamlessly integrating a combination of evolved RATs, including HSPA, LTE and WiFi, and complementary new RATs for specific use cases, and not by replacing existing RATs with a 'one technology fits all' solution [7]. Ericsson is now developing the fundamental concepts of the 5G system and aligning industry views through the METIS project. These concepts will hopefully reach standardisation phase within a few years.

NSN: Communications beyond 2020 will involve a combination of the evolving systems, like LTE-A and WiFi, with new revolutionary technologies designed to meet new requirements, such as virtually zero latency to support new applications such as real-time control or augmented reality. 5G is not just yet another technology but the integration of what we already know with new blocks designed for the most challenging use cases. NSN envisions that the 1000x traffic surge will be addressed by a 10x increase in the available spectrum, a 10x increase in the number of BSs through small-cell deployments and WiFi offloading, and a 10x improvement in the SE of the RATs [30].

1.7 5G in North America

The research in North America is in general different than that in Europe and tends to be more academia- and industry-based. Unlike in Europe, there is no public funding coordinating research efforts in the United States or Canada. Of course, in the United States, the research funding at universities comes from public sectors such as the National Science Foundation (NSF) and the Defense Advanced Research Projects Agency (DARPA). However, the research at universities tends to be more based on individual interests. In terms of 5G, universities and private industries partner together to examine some of the potential technologies. For example, the Polytechnic Institute of New York University (NYU-Poly) and Samsung have partnered together to study and develop mmWave solutions for 5G.

1.7.1 Academy Research

NYU-Poly: The 5G project at NYU-Poly (conducted by Professor Ted Rappaport) aims to develop a smarter and far less expensive wireless infrastructure by means of smaller and lighter antennas with directional beamforming operating at less crowded mmWave spectrum [31].

Carleton University: The 5G project at Carleton University (lead by Professor Halim Yanikomeroglu) is conducted by Ontario Ministry of Economic Development and Innovation (2012–2017). The industrial partners are Huawei Canada, Huawei China, Apple US, Telus, Blackberry (RIM), Samsung Korea, Nortel and Communications Research Centre Canada.

1.7.2 Company R&D

Qualcomm: While Qualcomm is not publicly saying much about 5G, it is conducting a considerable amount of research on ways to enhance cellular systems to address the 1000x capacity challenge. Qualcomm has been actively working on direct device-to-device (D2D) discovery and communications modes, called ProSe (Proximity Services), which have been proposed to 3GPP [32]. Qualcomm has proposed operating LTE in the unlicensed band [33], adopting the ASA/LSA spectrum sharing model [13], and using HetNet to address the 1000x challenge [5].

Intel: After leading a successful charge to bring 60 GHz to wireless LANs, Intel is driving research to exploit mmWave wireless in next-generation cellular systems. Working on a technology demonstration of 60 GHz as a backhaul link for the small-cell BSs, Intel is researching 28 GHz and 39 GHz as access links to mobile devices, targeting a throughput of 1 Gbps or more at distances of at least 200 metres [34].

Agilent: Agilent Technologies has recently signed a memorandum of understanding with China Mobile Communications Research Institute (CMRI), the research division of China

Mobile, to support development of the 5G system by providing test and measurement solutions for next-generation wireless communication systems [35].

Broadcom: Broadcom has promoted 5G WiFi (IEEE 802.11ac + hotspot 2.0), which can have data rates up to 3.6 Gbps and complement LTE and the Gigabit Ethernet. Its new features provide enhanced range, coverage and network efficiency due to its Multi-User MIMO (MU-MIMO) and beamforming technologies [36].

1.8 5G in Asia

Asia is following a similar suit to Europe in creating a 5G roadmap. In South Korea, the 5G forum was created, whilst China is responsible for the IMT 2020 programme. Although in general many other initiatives exist, some of these receive funding from the government, while the others are just coordination efforts to create 5G awareness among industry at the regional level or, beyond that, at the national level.

More specifically, China, Japan and South Korea are the main countries in Asia conducting research on 5G. The research in China, initiated by the government and jointly conducted through industry-academia partnerships, is generally in its early stages. Those in Japan and South Korea, both initiated and conducted jointly through industry-academia partnerships, have achieved some results, such as the communication test network for 5G, established by NTT (Nippon Telegraph & Telephone) and Samsung Electronics, with 10 Gbps and 1 Gbps transmission rates achieved in 11 GHz and 28 GHz carrier frequencies, respectively.

1.8.1 5G in China

Behind the 5G mobile communications in China are the Chinese Ministry of Industry and Information Technology (MIIT), National Development and Reform Commission, and Ministry of Science and Technology (MOST) which backed the establishment of the IMT-2020 (5G) Promotion Group and the FuTURE Forum.

Established in February 2013 in Beijing as a platform of 5G technology, research and standard promotion in China, IMT-2020 (5G) Promotion Group aims to promote 5G global standards through industry-academia partnerships and international cooperation. It groups 5G core technologies into 10 aspects: dense network; direct communication between terminals; application of Internet technologies in 5G; joint networking with WiFi; new network architecture; new multi-antenna multi-distributed transmission; application of new signal processing, modulation and coding techniques in 5G; high-band communications; sharing of frequency; and network intelligence. In May 2013, the operators, domestic and foreign equipment manufacturers, and experts from Chinese universities attended the IMT-2020 (5G) Prospect Summit in Beijing and discussed the prospects and developments of 5G wireless mobile communication technologies. At the twelfth meeting of the Frequency Group of the IMT-2020 (5G) Promotion Group held in Beijing on 25 June 2013 attended by the Chinese three leading operators, China Mobile, China Telecom, and China Unicom, issues such as the domestic research on 2500–2690 MHz radio frequency indicators, testing of co-existence of 3.4–3.6 GHz LTE-Hi and FSS (fixed satellite service) and the status quo of international research on frequency bands of 6 GHz and above were discussed. The importance of frequency requirement forecasting, frequency sharing technique and high-frequency band research in support of the future IMT-2020 (5G) was made clear and a work plan was developed accordingly.

In October 2005, FuTURE Forum was co-founded as an international NGO (Non-Governmental Organisation) by 26 colleges, academic institutions, mobile communication operators and manufacturers both domestic and foreign, including Tsinghua University, Southeast University, Shanghai Jiaotong University, Beijing Jiaotong University, Chinese telecom operators, DoCoMo, France Telecom, Shanghai Bell, Ericsson, NEC, Hitachi, NSN, Motorola and Samsung. Dedicated to sharing technologies and information in the future and promoting international R&D and partnerships, FuTURE has shifted its objectives from promoting the research for B3G/4G to developing both 4G and 5G communication technologies through integration.

In June 2013, MOST launched the Preliminary R&D (Phase 1) Project of the 5G Mobile Communication System under the 863 Program for National High-Tech Development with RMB 160 million funding to meet the mobile communication demand in 2020. It studies:

- 5G wireless network architecture and key technologies including the new network architecture, denser distributed coordination and ad hoc network and heterogeneous system radio resource joint allocation technologies that can support high-speed mobile inter-connect.
- Key technologies for 5G wireless transmission, breakthroughs in the technical bottleneck concerning large-scale coordination and new key technologies such as array antenna and low-power configurable radio frequency under the condition of large-scale coordination.
- General technologies for the 5G Mobile Communication System including 5G business application and demand, business modes, user experience modes, network evolution and development strategy, frequency spectrum demand and air interface technology and signal propagation characteristics, measurement and modelling oriented to 5G spectrum.
- Technical evaluation and test validation technologies for 5G mobile communications including technical evaluation and testing of the 5G mobile communication network, the establishment of evaluation platforms for simulation testing of the 5G mobile communication network and transmission technology.

Its overall objective is to fulfil the performance evaluation and prototype system design, supporting a speed of up to 10 Gbps and increasing SE and EE of air interface to 10x higher than 4G. This project has attracted many Chinese colleges, academic institutes and operators and some enterprises at home and abroad. Besides the members of FuTURE Forum, there are over 50 participants, including the Telecommunications Research Institute of MIIT, Academy of Telecommunications Technology, National Radio Monitoring Center, Shanghai Wireless Communication Research Center, Computing Institute of CAS, and China Electronics Technology Group Corporation, that have been involved in jointly pushing ahead China's 5G theoretical research, cracking of key technologies, development of equipment and product R&D.

1.8.1.1 Company R&D

As for the activities of Chinese enterprises, those participating in 5G research mainly include Huawei, Datang Telecom, China Mobile, and ZTE. Since 2009, Huawei has conducted joint researches with foreign colleges such as Harvard University, University of California Berkley and Cambridge University on 5G technologies, such as broader radio frequency techniques and techniques supporting dynamic virtualisation of cells. As one of the initiators, Huawei participated in EU's METIS project. On 29 August 2013, Huawei's CEO Houkun Hu declared at the 5G Network Conference held by Forbes that Huawei had been working on 5G research in the past few years and that if everything went well, they would officially launch 5G in 2020.

Currently, Datang Telecom is in the process of promoting the 4G evolution technology LTE-Hi, which is a 4.5G mobile broadband technology oriented to hot spots and indoor scenarios. Some small coverage of high-frequency hot spots is realised through small BSs. This feature will be further demonstrated in the future 5G evolutions. In terms of the future network architecture, small BSs can be installed at various scenarios and better fused with surroundings. Moreover, Datang Telecom has jointly conducted the preliminary research on the key technology for 5G wireless transmission with 14 Chinese colleges, including Tsinghua University and Beijing University, and they have recently published a 5G white paper [37].

As one of the three major telecom operators in China, China Mobile has been the world's largest mobile phone operator with about 740 million subscribers by July 2013. Devoted to China's 5G promotion efforts, they are members of ITM-2020. The Head of Working Group (WG) 1 and the Vice Head of WG2 of FuTURE Mobile Communication Forum are from China Mobile and China Telecom, respectively. They are also the core members of the 863-5G Phase 1 Project of the Chinese Ministry of Science and Technology. The three operators have stated that they will do their best to promote the commercialisation of 5G in China by 2020.

The management of China Mobile stated that the company has devoted itself to the R&D of 5G network although the commercialisation of 4G network has yet to be officially unfolded. As for the constant changes and construction of 2G, 3G, 4G and 5G networks and possible repeated construction and resource waste, they stated that as 4G being paved nationwide is almost the same as the original network in transmission and core networks with a few alterations made resultantly to the BSs, the new generation network makes full use of legacy infrastructure, reducing the operator's capital investment in upgrading the network.

As China Mobile develops its 5G vision for 2020, the Academy of China Mobile (an R&D institution directly under China Mobile) is taking active part in various domestic 5G forums and national-level projects. On 12 September 2013, the Team of Dr Zhiling Yi, Chief Scientist of the Academy of China Mobile in wireless technology, and experts including Guangnan Ni, an academician of the Chinese Academy of Engineering (CAE), and Professor Zhaocheng Wang, Director of Tsinghua University's Key Laboratory for Broadband Communication, participated in the 'Exchange Meeting on Joint R&D of Innovative Technologies by Academy of China Mobile and Micro-Optic Electronics Company' held at an industrial park in Quanzhou. At the meeting, Kunjie Zhuang, Chief Scientist of Micro-Optic Electronics Company, said that the direction of the research and development of the future mobile communication radio frequency technologies should follow the principle of being small-sized, large-scale, ultra-wide band, highly isolated and active. The research emphasis of the Academy of China Mobile is the design of the small-sized active antenna modules used for the large-scale antenna system and of the highly isolated antennas used for the full duplex system. After discussions, the Academy of China Mobile and Micro-Optic Electronics Company proposed an array antenna with 128 elements at D-band (2570–2620 MHz) as the objective of their initial research and a 1,024-antenna array at the optional frequency bands of the next-generation system as the long-term objective. Dr Zhiling Yi stated that, by the end of 2014, they will build the prototype consisting of 128 antenna array elements that will conform to requirements.

Besides the super-large-scale antennas, other issues such as the key technologies of integration of radio frequency antennas and co-frequency co-time full duplex were discussed as well.

The Academy of China Mobile was first to propose the evolution architecture C-RAN for 5G in the radio access field ("C" stands for Centralised Processing, Collaborative Radio and Real-time Cloud Computing). C-RAN is a collaborative wireless network consisting of far-end radio frequency units and antennas based on a centralised baseband treating unit, composed of the real-time cloud infrastructure based on open platform. Its innovative green network architecture can effectively reduce energy consumption, decreasing Capex and Opex, improve SE, increase users' bandwidth, support multiple standards and smoothly upgrade and provide the end users with more friendly Internet services. It is the various advantages created by its innovative framework that make C-RAN the focus of attention of many foreign operators and equipment manufacturers. Besides partners such as IBM, Intel, Huawei, and ZTE, in April 2010 the Academy of China Mobile announced another six partners attracted, including France Telecom Orange, Chunghwa Telecom, Alcatel-Lucent, NSN, Ericsson and Datang Mobile. Meanwhile, China Mobile is in the process of discussing C-RAN cooperation with Microsoft and HP. Both China Mobile and South Korea SK Telecom have listed C-RAN as one of their key cooperation projects in their corporate strategic cooperation. Xiaoyun Wang, Vice President of the Academy of China Mobile, stated that, compared with traditional RAN, C-RAN is revolutionary in its way of networking and its selection of technologies, and will be further promoted using the features of 5G mobile systems. With the prototype system being validated, the onus will be on the telecom equipment and IT system manufacturers in partnership to make breakthroughs and develop industrialisation.

The deputy general engineer of China Telecom, Dongbin Jin, said on 11 September 2013 that China Telecom was paying great attention to 5G and that he hoped that the 5G networks would not be divided into TDD (Time-Division Duplexing) and FDD (Frequency-Division Duplexing) networks, similar to the 4G networks. He added that the 5G networks were expected to be more intelligent and could be highly convergent with other networks. In general, the telecom operator expected a single standard for the 5G system.

1.8.2 5G in South Korea

In South Korea, 5G mobile communication technologies are mainly promoted by South Korea's Electronic Communication Academy and some mobile communication manufacturers such as Samsung, LG and Ericsson-LG with the South Korean Future Creation and Science Ministry and the telecom operators as the intermediaries.

On 28 June 2013, the Future Creation and Science Ministry of South Korea (ROK) and the MIIT of China jointly held the China-ROK 5G Exchange Meeting in Beijing, China, where the 'China IMT-2020 (5G) Promotion Group' and the 'South Korea 5G Forum' signed the China-ROK 5G Memorandum of Understanding. Meanwhile, the CNCERT (China National Computer Network Emergency Response Technical Team) and KrCERT (Korea Computer Emergency Response Team) signed the China-ROK Cooperation Memorandum of Understanding on Network Security. The experts from China and Korea discussed how to strengthen the cooperation and jointly promote 5G international standards. Mr Bing Shang, Vice Minister of MIIT, stated that two important consensuses were reached at the meeting: (1) establishing the ministerial strategic dialogue for Sino-South Korean cooperation in information communication; (2) promoting cooperation between the Sino-South Korean research institutions and enterprises in future mobile communication technologies, especially 5G standards and new operations. Zonglu Yun, Vice Minister of the Future Creation and Science Ministry of South Korea, stated that mobile communications have developed rapidly in both countries and become an important driving force for their respective economies. China and South Korea should cooperate to jointly promote and lead the development of global mobile communication technologies.

Jointly built by big South Korean companies such as Samsung and LG and its Electronic Communication Academy, the new 5G network architecture consists of three layers: Layer 1 is the server gateway; Layer 2 is the outer cellular; and Layer 3 is the inner cellular. The inner cellular first transmits data to the outer cellular through the backhaul; then, the outer cellular conducts the packet switching with the server gateway through optical fibres. The BSs in the cellular network use narrow-beam directional antennas for transmit-receive coverage to reduce co-channel interference, and the direction of antennas thereof can be intelligently controlled. In May 2013, Samsung announced its mmWave 5G technology. In outdoor experiments near Samsung's Advanced Communications Lab, in Suwon, South Korea, a prototype transmitter using 64 antenna elements was tested. It could reach a rate of 1.056 Gbps at the carrier frequency of 28 GHz, and the transmission range could reach up to 2 km under LOS conditions; for non-LOS (NLOS) communications, the range shrank to about 200–300 metres. With the 5G network, hundreds of times faster than the 75 Mbps 4G network in South Korea, mobile users will be able to download a movie in less than one second. Committed to the commercialisation of this technology in 2020, Samsung plans to carry out the commercial promotion of the 5G network in the coming years.

There are three major operators in South Korea, namely SK Telecom, Korea Telecom (KT) and LG U+ (LG Uplus). SK Telecom is the biggest and the most innovative mobile communication operator in South Korea, mainly distinguished for its drive and perspective on disruptive and advanced networking technologies in addition to its business innovation. Some ICT technicians of SK Telecom point out that to respond to the soaring data needs, a new-generation network technology – so-called "Super Sell" – should be constructed which can increase the circulation of benchmark data by 1000x while reducing the expenses by 10x.

On 30 May 2013, the general assembly of the Korea 5G Forum was held in Seoul which was jointly founded by the above-mentioned three operators and mobile communication manufacturers such as Samsung, LG and Ericsson-LG. Standardisation issues of 5G in 2015 and the prospects of its commercialisation in 2020 were discussed. Zonglu Yun, Vice Minister of the Future Creation and Science Ministry of South Korea, said that 5G technologies were expected to be commercialised in 2020 and South Korea was still at the preparatory stage. Across the globe, new technologies were being developed to respond to the increasingly fast-changing ICT climate so as to be a leader in 5G. It was widely believed that 5G could not only bring convenience to life, but also help enterprises and countries with their economic growth. With the imminent 5G, the intelligent machines with 1000x higher efficiency and lower power consumption were expected to be launched. If standardised around the globe in 2015, 5G would have its debut at the Pyeongchang Winter Olympics in South Korea in 2018.

South Korea's innovative operator SK Telecom is now linking up with Bell Labs, owned by Alcatel-Lucent, to focus on new-generation communications research, including B4G or 5G technology. The information published by SK Telecom and Alcatel-Lucent identifies several areas of interest in what they call ‘post-4G or 5G wireless telecommunication technologies and intelligent network technologies’:

- defining the architecture of B4G and 5G networks
- developing methods for enabling increasingly complex networks to manage and configure themselves
- technologies that can be applied at the core of operator networks within the next two to three years, such as cloud computing.

1.8.3 5G in Japan

Similar to South Korea, Japan’s 5G mobile communication technology is also mainly promoted through industry-academia partnerships. During 29–30 October 2013, supported by some international and regional organisations such as Japan’s Yokosuka Research Park (YRP) R&D Promotion Association, South Korea’s 5G Forum, Taiwan’s Wireless & Information Technology Communication Leaders United Board (WIT CLUB), China’s Future Forum, the EU’s METIS project team and China Mobile, the Summit on Future Information and Communication Technology (5G) (abbreviated as 5G Summit) was held in Beijing. The government representatives, experts, telecom operators and leading software and hardware manufacturers from Europe, China, Japan, South Korea and other countries and regions made keynote presentations with respect to the overall development strategy and R&D plan for 5G. Issues such as research on systematic 5G definition, research on 5G standardisation requirements, 5G spectrum planning and suggestions, 5G marketing analysis and visions, 5G innovative service applications and requirements, 5G-oriented novel wireless transmission and networking technologies, strategies for future network evolution and convergence and international cooperation were discussed.

In February 2013, NTT DoCoMo, a Japanese telecom operator, announced, with the technical assistance of the Japanese Tokyo Institute of Technology, that it had successfully conducted an outdoor experiment on the transmission of 10 Gbps at the 11 GHz frequency band on Ishigaki Island, proving the technology to be far more powerful than LTE and LTE-A. Three technologies were mainly used in the outdoor transmission of mobile signals: MIMO, 64 QAM and turbo detection, which means a feedback is given upon the reception of the signals.

In October 2013, NTT DoCoMo displayed its 5G communication technology at the Combined Exhibition of Advanced Technologies (CEATEC) in Japan claiming to feature ‘ultra-high speed and low delay’. The mobile device is installed with 24 antennas and can be seen as an action BS fully loaded with communication equipment. NTT DoCoMo hoped to keep the actual rate at over 5 Gbps at the final stage and make it the future standard. Furthermore, NTT DoCoMo intends to use 5G in wearable equipment for users to conveniently carry out various operations without using hands, including augmented reality, face identification, word identification, translation, and so on.

Japan’s major telecom operators include NTT DoCoMo, KDDI, SoftBank and E-mobile in charge of mobile data operation and the Personal Access System company Willcom, to which NTT DoCoMo is the biggest contributor, in charge of the development of Japan’s 5G technology. NTT DoCoMo has been involved in international 5G research and promotion for a long time and was in charge of one of the working groups of the METIS project. DoCoMo is devoted to the development of 5G technologies oriented to mobile communication services in 2020. To increase the communication capacity and improve users' throughput capacity, it actively advocates small cells – the output power of the traditional macro-cell BSs is 10–40 W. By allocating multiple cells with even lower output power (tens to hundreds of mW), this technology covers certain areas with higher communication demand within the macro-cells. In a nutshell, the macro-cell BSs – responsible for the 'surface' coverage of vast areas – use the low-frequency bands, while the small cells in the 'point' areas demanding higher data rates use the high-frequency bands. For example, the small cells will use the 3.5 GHz frequency band in the near future and high-frequency bands at 10 GHz or above in the future. At this time, the control signals that judge which cell the terminal is to connect are all transmitted by macro cells. This concept is called 'Phantom-cell' [38]. DoCoMo planned to propose the Phantom-cell to 3GPP. As other communication equipment manufacturers have proposed the same concept, DoCoMo will focus on the use of small cells to promote technical development.

At the comprehensive IT exhibition CEATEC Japan 2013, held on 1 October 2013 at Makuhari Messe (in Mihama Ward, Chiba), NTT DoCoMo simulated the new-generation mobile communication '5G' it conceived. In an interview with Engadget, a representative of NTT DoCoMo said that the biggest challenge in constructing the 5G network was how to deal with the limitation of high-frequency communication bands. To address this problem, they have planned to realise the signal transmission at high-frequency bands using a large number of antenna components. For the simulation, DoCoMo considered Shinjuku, Tokyo, as the model and set seven macro-cells using 26 MHz bandwidth in the 2 GHz frequency band and 12 small cells using 1 GHz bandwidth at the 20 GHz frequency band to construct the HetNet system. As the frequency band used for small cells is the 20 GHz band featuring strong rectilinear propagation, the small cells become the LAN covering a few to tens of meters. The antennas used for the macro cells are 2x4 MIMO and those used for the small cells are 128x4 MIMO (i.e. Massive MIMO). According to DoCoMo, 'the aim of using Massive MIMO is to bar jamming through the beamforming technology'.

At the Broadband World Forum (BBWF) 2013, NTT DoCoMo studied the possibility of launching 5G services at the 2020 Tokyo Olympics. 'Although it seems to be far-fetched, we still need to consider it carefully', said Takehiro Nakamura, Director of the Wireless System Design Team of NTT DoCoMo, in his speech. He added that, at the conception stage, what 5G entails depends on who the lecturer is. According to NTT DoCoMo, 5G represents the increase in the capacity of the access network by 1000x. Takehiro predicted that this would require the support of the 'wireless connection to multiple personal terminals' in the next few years. DoCoMo proposed the use of more spectrum from high-frequency bands and the large-scale MIMO technology to realise such a huge increase in capacity. MIMO technology has remarkably increased the number of convergence antennas in the access network. Takehiro said that, based on the simulation test of this operator, the increase in the capacity by 30x can be realised using 100 MHz bandwidth at 3.5 GHz in 12 small cells, and the use of 400 MHz spectrum at 10 GHz in the same number of small cells can accommodate the increase by 125x. To realise the incredible capacity increase of 1000x, Takehiro said, the use of 1–20 GHz spectrum in 12 small cells with the use of large-scale MIMO technology can help the operators attain such a goal. However, he admitted the use of such high-frequency spectrums could only benefit the outdoor network environment. 'We should consider new RATs to create the great gains we need', said Takehiro. But he insisted that 5G should be a technology that industry should carefully take into consideration.

1.9 5G Architecture

As illustrated by Figure 1.6, 5G will be a truly converged system supporting a wide range of applications from mobile voice and multi-Giga-bit-per-second mobile Internet to D2D and V2X (Vehicle-to-X; X stands for either Vehicle (V2V) or Infrastructure (V2I)) communications, as well as native support for MTC and public safety applications. 3D-MIMO will be incorporated at BSs to further enhance the data rate and the capacity at the macro-cell level. System performance in terms of coverage, capacity and EE will be further enhanced in dead and hot spots using relay stations, hyperdense small-cell deployments or WiFi offloading; directional mmWave links will be exploited for backhauling the relay and/or small-cell BSs. D2D communications will be assisted by the macro-BS, providing the control plane. Smart grid is another interesting application envisaged for 5G, enabling the electricity grid to operate in a more reliable and efficient way. Cloud computing can potentially be applied to the RAN,

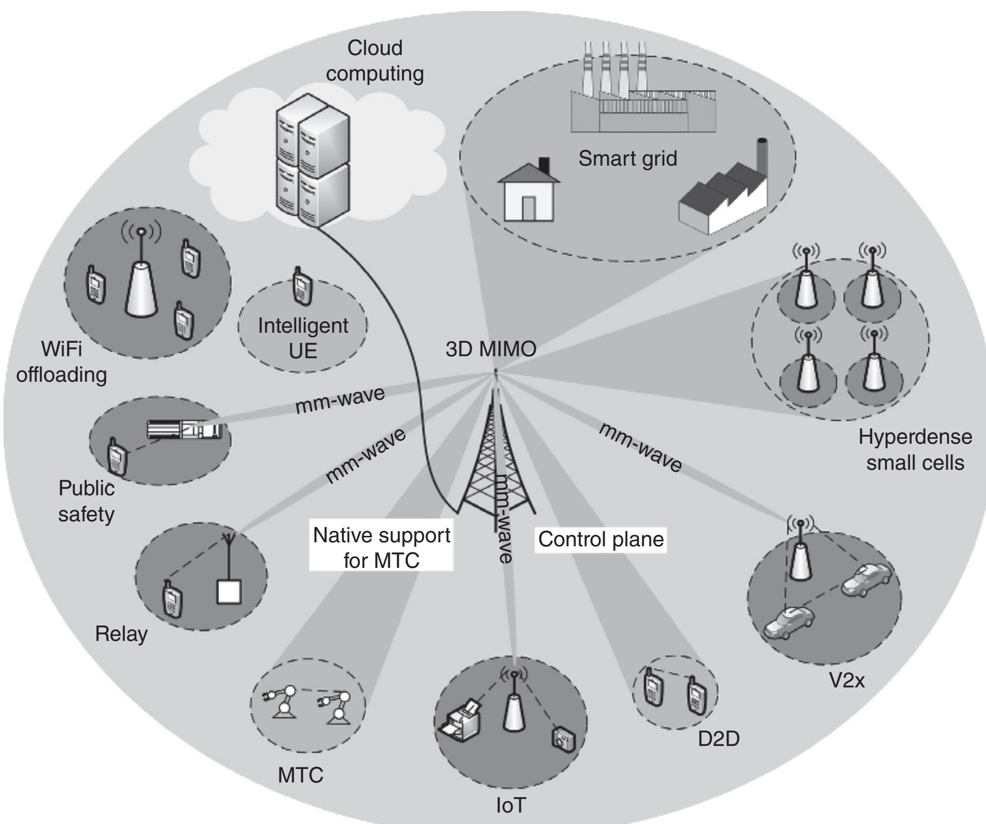

Figure 1.6 5G system architecture.

and beyond that, to mobile users that can form a virtual pool of resources to be managed by the network. Bringing the applications through the cloud closer to the end user reduces the communication latency to support delay-sensitive real-time control applications.

It is envisaged that 5G will seamlessly integrate the existing RATs (e.g. GSM, HSPA, LTE and WiFi) with the complementary new ones invented in mmWave bands. MmWave technology will revolutionise the mobile industry not only because of plenty of available spectrum at this band (readily allowing Gbps wireless pipes), but also because of diminishing antenna sizes, enabling the fabrication of array antennas with hundreds or thousands of antenna elements, even at the UE. Smart antennas with beamforming and phased array capabilities will be employed to point out the antenna beam to a desired location with high precision, rotated electronically through phase shifting. The narrow pencil beams will enable the exploiting of the spatial DOF, without interfering with other users. The small antenna sizes will enable Massive/3D MIMO at BSs and eventually at UEs. The mmWave technology will also provide ultra-broadband backhaul links to carry the traffic from/to either the small BSs or the relay stations, allowing further deployment flexibility for the operators, compared to the wired (copper or fibre) backhaul link. Hyperdense small-cell deployment is another promising solution for 5G to meet the 1000x capacity challenge. Small cells have the potential to provide massive capacity and to minimise the physical distance between the BS and the UEs to achieve the required EE enhancement for 5G. The traditional sub-3 GHz bands will be employed for macro-cell blanket coverage, while the higher frequency bands (e.g. cm- and mmWave bands) will be employed for small cells to provide a spectral- and energy-efficient data plane, assisted by a control plane served by the macro-BS [38].

Along with the development of new RATs and the deployment of hyperdense small cells, the existing RATs will continue to evolve to provide higher SE and EE. The data plane latency (round-trip time) of the LTE-A system is around 20 ms, which is expected to be reduced to less than 1 ms in its future evolutions [30]. Moreover, the SE of the existing HSPA system is 1 b/s/Hz/cell, which is expected to increase 10x by 2020 [30]. The EE of the cellular system is expected to improve 1000x by 2015, compared to the 2010 level [39]. The PHY (physical) and MAC (medium access control) layer techniques will be revisited for carrying short and delay-sensitive packets for MTCs [18]. Virtualisation will also play a key role in 5G for efficient resource utilisation in cellular systems, through a multi-tenant network where a mobile operator will not need to own a complete set of dedicated network equipment; rather, network equipment (e.g. BS) will be shared among different operators. The existing cloud network concept mainly involves the data centres. Mobile network virtualisation will push this concept towards the backhaul and the RAN to allow sharing of backhaul links and BSs among different operators. Last but not least, it is envisaged that 5G UEs will be multi-mode intelligent devices. These UEs will be smart enough to autonomously choose the right interface to connect to the network based on the channel quality, its remaining battery power, the EE of different RANs, and the QoS requirement of the running application. These smart and efficient 5G UEs will be able to support 3D media with speeds up to 10 Gbps.

1.10 Conclusion

5G is expected to be deployed around 2020, providing pervasive connectivity with ‘fibre-like’ experience for mobile users. Apart from the expected 10 Gbps peak data rate, the major challenge for 5G is the massive number of connected machines and the 1000x growth in mobile traffic. The ultra-broadband and green cellular system will be the driving engine for the future connected society where anyone and anything will be connected at anytime and anywhere. In this chapter, we gave an overview of the potential enablers of 5G along with research and development activities around the globe, including Europe, North America and the Asia-Pacific region. Being in the prototype stage, standardisation is the next milestone to achieving 5G, which will be followed by the development phase for two to three years. The last phase is network deployment and marketing, which may take another couple of years, foreseeing a potential commercial deployment by around 2020. In the final section of this chapter, we illustrated the foreseen architecture for 5G, harnessing all the common views on the current technology trends and the emerging applications. In a nutshell, mmWave technology, hyper-dense HetNet, RAN virtualisation and massive MTC are all major breakthroughs being considered for upgrading the cellular system to achieve 5G capability. However, these technology developments need to be fuelled by the allocation of new spectrum for mobile communications, expected to happen in the upcoming WRC meeting.

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