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A Technology that Changed the World

Mobile communications and the internet are widely regarded as the most influential technologies that reshaped human behaviour and interactions over the last 30 years. Today, there are more mobile connections worldwide than the global human population. Mobile networks are functional from the teeming mega cities to the sparsely populated arid lands. From humble beginnings in the early 1980s, the industry has experienced phenomenal growth fuelled by technological advancement. Today, the challenge of providing 'anywhere, anytime' communications and connectivity has mostly been achieved. Yet, the industry is facing a new set of challenges, created largely by its own success.

In this book, we will focus not just on the past successes of the mobile industry, but also on the current challenges it is facing and the likely shape it will take in future. Technologically, the mobile industry, from its inception, has endeavoured to provide faster, more reliable and cheaper connectivity to its customers. We will cover the basics of cellular network deployment and progress to the most advanced technologies used today, with special emphasis on the technical challenges the industry faced and the ingenious solutions it has developed. We will discuss the technological journey, from the first widespread mobile generation (2G) to the current 5th Generation (5G) and look at what likely shape the next wave of deployments, the 6G will take. From a business perspective, the mobile industry has evolved into a complex ecosystem generating huge revenues and touching the lives of billions of people. We will analyse this ecosystem, paying special attention to the business aspects of the mobile operator. Basically, this book is an attempt to introduce not just what happened and what is happening in the industry but to answer why, looking closely at both the technical and business rationale.

We will begin with a brief chapter guide and recommend streams for technical and non-technical reading. We will endeavour to keep the maths to a bare minimum and use it only in the technical chapters, where its usage would help clarify complex concepts. Where mathematical concepts are introduced, we will provide thorough references, so the interested readers can delve deeper into these concepts. As this is meant to be an introductory book, the intention is not to fill readers with in-depth knowledge on a certain topic, but to equip them with an overall understanding of the mobile technology and industry, which hopefully will make them more eager to explore further.

The Technology and Business of Mobile Communications: An Introduction, First Edition.
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The next part of Chapter 1 is dedicated to illustrating the social and economic impact the mobile communications industry is exerting to improve lives globally. Then, we will skim through the history of the industry, spanning from 1G to 5G, also briefly looking at the likely shape it will take in thefuture. In Chapter 2, we will look at the main players in the mobile industry ecosystem, with special emphasis on the interactions amongst them. Chapter 3 is focussing on the business of a mobile operator with the major costs and revenues explained and also looking at the interactions with the other ecosystem players. Being the most prominent part of the industry, we will examine the current challenges faced by mobile operators and the business innovations (backed by technology) prompted to counter these. As a highly dynamic industry, its reliance on research, innovation and standardisation cannot be overemphasised. We dedicate Chapter 4 to discussing the matters related to research and standardisation, especially a historical examination into why certain standards became so successful and others did not. From Chapter 5 until Chapter 10, we delve a little deeper into technical matters. Chapter 5 is a journey through the mobile generations from 2G to 5G, examining the evolution of basic technical features across the generations and network features governing each mobile generation. We will also discuss the successes and limitations in technologies adapted for each generation, giving clues as to why it was necessary to move into newer generations. Chapter 6 provides an introduction to the fundamentals of mobile network planning, with the intention of familiarising the reader with the meticulous planning process carried out before network deployment. Chapter 7 will look at the management of radio spectrum, which is the single most essential component for all radio communications. The basic signal processing techniques (mainly at the receiver), required to extract the wanted signal from a mixture with noise and interference, are presented in Chapter 8. Chapter 9 is an appreciation of the early technical challenges faced by the industry and the innovative solutions developed to tackle them. In Chapter 10, we look at how the cells have evolved to become smaller, how some significant revolutionary aspects were introduced with the small cells in the recent past and the likely contribution they will make in the future. From Chapter 11, we revert back to a non-technical style of writing. Chapter 11 is a look at the main challenges facing the mobile industry today and the nature of the solutions envisaged to tackle these issues. The concluding Chapter 12 is a holistic look at the changing face of mobile telecoms and what could be expected in the future.

For readers who may want to explore both the deeper technical and business aspects of the industry, we suggest they follow the orderly chapter sequence, from Chapters 1 to 12. For readers who may want to omit the deep technical details, we suggest a reading sequence from Chapters 1 to 4, Chapter 7 and Chapters 11 and 12.

1.1 Social and Economic Impact of Mobile Communications

We will first look at the social and economic impact the mobile communications industry is having today, to truly appreciate this potent technology. Mobile communications have made virtually everyone in the world reachable at the touch of a button, whenever or wherever they are. When the power of mobile internet is added to this, truly remarkable capabilities in the social and economic domains have been achieved. We will briefly look through some of the shining examples in these domains. Many of the socio-economic development enablers in developing countries are cited from the supportive work the GSMA (GSM Association – the trade body of the mobile operators) is conducting through their 'Mobile for Development' initiative [1].

1.1.1 Social Impact

Before the mobile communications era, you would always call a 'number' at a certain 'place', with no guarantee of being able to reach the person you intended to connect to. Mobile communications made the 'number' uniquely associated with a 'person' wherever he is, creating a new 'personal communications' phenomenon. The advent of mobile internet and the usage of social media have again revolutionised this personal communications space. Now, you can connect with not just one single person at a time, but simultaneously broadcast yourself to a preferred social group. The so-called 'social media' such as Twitter and Facebook enables you to be in touch with a social group, be it your family, friends or work colleagues at the touch of a button, wherever you are. In this era of 'selfies' and Instagram, sharing personal experiences with your social groups has never been easier. This 'social networking" also carries a significant political and business value. Most of the prominent politicians today operate their own twitter accounts, with millions of followers. They use these to subtly promote their policies and political views, ramping up their communications near election times. Many of the business leaders also have massive twitter followings and these are used to create a 'social aura' about themselves and their businesses. These social networking tools are not just a tool for the rich and powerful but also for the dissenting voices in our society. Many of the demonstrations, rallies and uprisings of today are organised and publicised though these tools, by-passing mainstream media.

The mobile internet era has given rise to hundreds and thousands of 'Mobile Apps', which can make your life easier whilst on the move. These Apps utilise the 'always on' feature of the mobile as the mobile is the first device the user will revert to, whenever or wherever he is. These Apps can help you find a restaurant or a parking space in an unfamiliar city (e.g.: Four square location App), as well as plan your travel route considering live traffic information etc. Many of the Apps (like Waze for travel planning) utilise 'crowd sourcing', to gather, corroborate and analyse data and present it in optimal ways. Data analytics on the data gathered from social Apps (whilst still an evolving science) can achieve far-reaching social, political and commercial objectives. Mobile data connectivity (commonly known as Mobile broadband) has also blurred the boundaries of work and personal spaces and has enabled people to work from anywhere, be it at home, whilst travelling or even from a coffee shop. Whilst some people argue that this has altered the work/life balance negatively, mobile broadband has opened up so many possibilities, giving flexibility and choice of work to employees.

In terms of entertainment, mobile gaming and mobile TV are becoming ever more popular. These applications are again capitalising on the fact that the user can connect to them wherever or whenever he wants to, through the mobile. Many of the video or movie streaming services have the option to include your mobile device to the subscription. With the advancements of the cellular connectivity, many of the games can now be played on your mobile interactively against other users. The lower latencies and higher data rates supported by the newer cellular generations and the video quality of today's Smartphones make this a seamless experience. Streaming music to your mobile has had a phenomenal growth in the last decade, with Apps like Spotify, Apple Music and Deezer becoming the main tools through which the young enjoy their music.

The social impacts of mobile technology extend into the fields of health and education. With ageing populations, developed countries are facing increasing costs in providing elderly care. Countries like Japan are looking for innovative ways of utilising mobile technology so the elderly can be provided with 'assisted living'. The elderly, even with serious conditions, can continue to live in their own homes and their conditions can be monitored with the use of wearable communication devices. In developing countries, providing healthcare to rural communities has always been a challenge with the available limited resources. Mobile technology has stepped in as a means of disseminating basic medical and sanitary information in these countries. A successful scheme in Bangladesh armed 100 000 health volunteers with mobile phones. When they meet a pregnant woman, they enlist her details and her (or a close relative's) mobile number and start to text regular standard advice on prenatal and later, postnatal care [2]. In Pakistan, a mobile and web-based telemedicine scheme 'Sehat Kahani' was launched in 2017, which connects female doctors with patients in underserved areas and communities remotely. There were special walk-in-clinics created with qualified nurses and health workers acting as intermediaries in these remote consultations. Whilst enabling affordable, good quality healthcare to these underserved communities (mainly women) it has also opened the door for female doctors in Pakistan to continue with their profession, where the majority of female medical students do not move into their profession after graduation [3]. This telemedicine solution is now also linked to a Mobile money application, so the patients can book and pay for these services through their mobiles.

The lower rates of birth registration in some developing countries has been a significant barrier for socio-economic development of affected children, with impacts lasting throughout their lives. There have been successful efforts by mobile operators in some of these countries (like Tanzania, Ghana and Bolivia) to partner with government agencies and UNICEF to equip the registry points with mobile devices and software to record births digitally and upload them to a central database [4]. These schemes have increased the availability of registration points by many fold, making long journeys to a central point unnecessary.

There are numerous examples of the use of mobile technology in disaster and emergency situations, to provide warnings efficiently and to coordinate relief efforts. There is a big push in the US and UK to replace traditional emergency communication networks (like TETRA) with cellular LTE-based mobile networks. We will look at this shift in detail in Chapter 12. On a personal level, the mobile is the one communication device that is likely to be with you always, even of you get lost on a mountain or in a jungle. There are numerous location-based apps emerging now (for example, what3words), which can quickly trace a precise location and assist the emergency services. Even after a major disaster, mobile communications tend to be the first line of connectivity that could be restored, providing vital information and advice to affected people. With adverse extreme weather conditions becoming more frequent as a result of climate change, the role mobile communications can play in these support operations will continue to grow.

In education too, the prevalence of mobile coverage is helping to bridge the 'social divide'. The 'English in Action' scheme in Bangladesh, for example, is utilising mobile phones (amongst other methods) as a simple, low-cost learning device and has helped millions of people to take the first steps in improving their English language proficiency. A digital education platform launched by Eneza Education in 2016 in Kenya is now enabling millions of children to access educational resources through SMS, mobile web or android apps [5]. This platform features 'an ask a Teacher' service where students ask real, live questions to teachers and get responses within 15–30 minutes, send Wikipedia content through SMS (Short Message Service) texts, reader boards and other non-curriculum content such as health education. With mobile being the only communication device available for many families in rural and under-privileged communities, these kinds of services go at least some way to bridge the enormous divide in the quality of education available to their children.

1.1.2 Economic Impact

In the last three decades, mobile communications have grown to become major economic pillars in most countries. The industry employs hundreds of thousands of people and contributes significant tax returns to national revenues. In many countries, the mobile spectrum auctions, where frequency bands are licensed for mobile operations, continue to raise billions of pounds for government coffers. The industry is sustaining sizeable research and development activities spread out across its own subsidiaries, universities and other institutes, contributing to develop and sustain knowledge-based economies. All these direct contributions to the macroeconomic growth have been widely acknowledged [6]. For example, the GSMA reported that the mobile industry ecosystem directly and indirectly contributed \$3.9 Trillion (or 4.6% of the global GDP) to the global economy in 2018 [7]. Figure 1.1 is an illustration of the various components of this economic contribution.

Mobile communications also contribute in numerous indirect ways to the economic growth of communities. This indirect economic impact is perhaps best felt in developing countries. Traditionally, vast areas of many developing countries, except the main cities

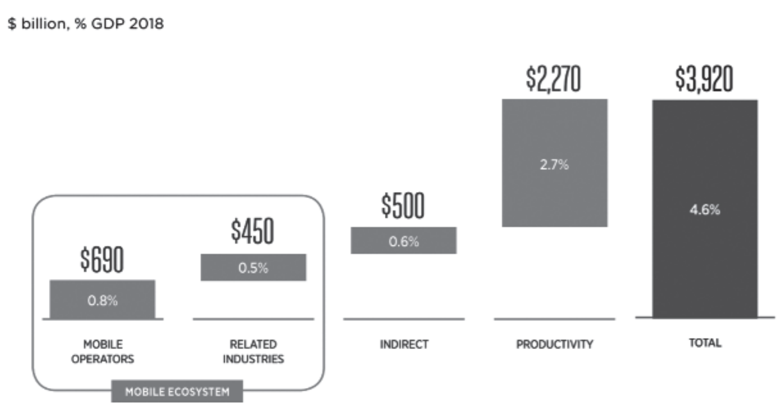

Figure 1.1 The global economic contribution of Mobile Telecoms – 2018. (*Source* [7]).

and towns, are not well connected in either telecommunications or transport infrastructure. The introduction of mobile communications has meant that wireless connectivity for the 'last mile' of the telecommunications link was facilitated. This 'last mile' in rural communities literally extended to hundreds of miles, connecting towns and villages with their main cities and commercial hubs. This 'connectivity' opens up numerous economic opportunities for these rural communities. If this 'revolution' was not to have happened and the normal course of evolutionary infrastructure development was to solve this problem, it would have taken decades to achieve the same level of telecoms service penetration that we see in these countries today.

The advent of mobile communications in these communities was not just a social benefactor, but a potent economic enabler. People soon found numerous economic usages with their mobile phones that would otherwise not have been possible, even with the basic voice and text connectivity. Today, rural farmers in India check the prices for their crops in nearby towns before harvesting and transporting them to the most profitable market. Fishermen in Tanzania and Kerala (in India) check the prices for their catch whilst at sea, to agree on the best deal from any number of local harbour markets within their reach. Small local industries and craftsmen are advertising themselves through text messaging, without solely relying on word of mouth to expand their sales. Small hotel and lodge owners in remote tourist locations can now advertise their businesses to the whole world through mobile Apps, increasing their revenues many fold. The consumers of these Apps and services now have a major say through the feedback they provide and these transparent business models have also improved overall service quality.

Mobile communications in developing countries have even stepped into remedy the deficiencies in the financial and banking infrastructure. Many of these countries, especially in Africa, lack an adequate network of bank branches, ATM machines and financial transaction mechanisms that people in western countries take for granted. Many of their citizens lack sound financial knowledge and do not possess bank accounts, credit cards or other financial tools. Mobile telecommunications have ingeniously been adapted to fill this void and enable a smooth flow of financial activity. Perhaps the best example of this is the use of mobile money, known as M-Pesa in Africa. It originated in Kenya in 2007, enabling users to register accounts through their mobiles, top-up accounts by paying money at numerous agents and conduct financial transactions on these account credits through SMS messaging. This system has become so popular that by 2012, there were over 17 million M-Pesa accounts registered in Kenya. Mobile money systems have now spread to other countries in Africa and Asia and by the end of 2018, there were 866 million registered accounts with transactions over $1.3 billion per day [8]. Mobile money, now as an established payment platform, has enabled account holders to access other financial services and services in healthcare, education, social protection etc. These services have benefitted the most disadvantaged groups in society, including displaced communities due to war and natural disasters. Mobile money has also helped to teach the skills of saving and financial planning to absorb future shocks, by bringing financial literacy to their lives [8].

Another good example of mobile money is the award winning eZ Cash initiative in Sri Lanka [9]. Although Sri Lanka is fast moving towards a middle income country with 70% of adults having access to banking services, there is a significant proportion of lower income earners (mainly in rural areas) who are outside the formal banking scope. Also, the electronic banking tools are not well established even amongst the urban banking population. With more mobile subscriptions than country population and networks covering over 96% of the country, there is significant potential for mobile money solutions. The Central bank of Sri Lanka having realised this potential, opened up the mobile payment market to non-bank institutions in 2011. In June 2012, the largest mobile operator Dialog initiated the eZ Cash service, where any of its mobile subscribers could register and open an account by simply dialling a number. The registered users can send and receive cash directly through their mobiles and carry out payments on utilities and to certain institutions. Within the first month of launching, the service had attracted 300 000 subscribers. By August 2015, with the inclusion of two other operators to this service, the customer base has grown to more than 2 million with over 20 000 agents and merchant points supporting the system.

Some economic applications and disruptions with mobile communications are not limited to developing countries. Mobile banking is fast spreading in developed countries as an effective disruptor to established banking giants. With App-based mobile accounts, Monzo, Revolut and Starling are taking on the banking giants in the UK, for example [10]. Your debit/credit cards are linked to the App with instant updates of the transactions. The user identity verifications and credit checks to open accounts and obtain credit are all done through the Apps, with results obtained in minutes. The minimal operating costs in this model have helped reduce fees to a bare minimum, attracting mainly younger Millennials as tech savvy customers.

The App ‘Uber’ developed by a start-up in San Francisco, has revolutionised the ride sharing/call taxi-market sector. With the advanced localisation features enabled by Smart phones, the App could immediately identify user location and calculate the fare to the requested destination. The fare is calculated taking into account the demand for taxi services at that time. The transaction goes through the App, without the passenger paying directly to the driver. The reduced cost and wait times have made this App so popular, it is now functional in many cities of developed and developing countries. As a derivative of this concept, similar digital courier services for parcel and restaurant food delivery have sprung up in many large cities. From an employee perspective, these Apps enable you to select jobs convenient to you and plan your work times around other priorities. This is a fundamental shift in the traditional view of a worker and his rights [11], which have come to be questioned and legally challenged many times over recent months.

A similar disruption in the rental property market is spearheaded by the online and mobile App Airbnb. It allows millions of homeowners to list their spare homes or rooms on-line and match these with potential holiday makers. The growth of Airbnb really took off with the launch of their mobile App in 2012. It made listing your spare room or property with a collection of photos taken from your mobile very easy. Also, for consumers looking for the perfect property to rent, the Airbnb app uses deep linking technology [12] to provide the right content and provide personalisation so that users keep coming back to the App for future bookings. Again, the traditional model of listing properties permanently and paying a levy to city councils for this privilege has been disrupted by the Airbnb model, where home owners can now rent out whenever it suits their circumstances.

The social and economic restrictions put in place to help control the Covid-19 pandemic has made the mobile and landline broadband connectivity a lifeline for many people and businesses. Many small businesses have taken to introducing on-line ordering and delivery solutions to keep their businesses afloat. Working from home has become the norm for many industry and business sectors and broadband connectivity has become crucial in this regard. Mobile video-calling Apps have also become an essential tool for many of us, to keep in touch with our families and friends during these difficult and challenging times.

Here, we have only listed a handful of examples to showcase the potent social and economic contributions mobile communications continue to make all across the globe. With the advent of 5G and new disruptive technologies like artificial intelligence (AI), blockchain and quantum computing, the capabilities of today's smart phone will increase many fold in the next few years. This will, undoubtedly, open up new innovative use cases for the Mobile industry as it will continue to re-shape our socio-economic interactions in a highly connected world.

1.2 A Brief History of Mobile (Cellular) Communications

The basis of Mobile communications lies with the wireless connectivity enabled by radiowave propagation. The exploration of using radiowaves for communication was pioneered by Marconi, during the turn of the twentieth century. Most notable of his experiments was the Trans-Atlantic wireless telegraphy experiments of 1901 [13], where he showed that information embedded onto radio signals could traverse thousands of miles. These discoveries paved the way for many modern day wireless communication modes, including radio, television and Mobile telephony. Various forms of Mobile Telephony systems, employing a single transmission tower and multiple, mobile receiver units were operational from the early 1950s. These towers would provide radio coverage for around a 50-mile radius, enough to cover a large metropolis. It would typically be the government or emergency services such as the police or fire crews who would use these services. Heavy and bulky receiver units would be fitted into the vehicles of these services. Only one-way communication would be possible at a time (we call this half-duplex), with many systems featuring push-to-talk buttons. The coverage would often be patchy and there was no concept of fair radio resource sharing amongst users. The first users to connect would grab the available radio channels of the single transmitter and others would have to wait till radio channels became free. In some cases, a human operator would need to connect these radio channels to the required destination line. Due to these limitations, there was little scope for these systems to evolve as broad-based commercial operations. Some technologists term these pre-commercial mobile systems as 0th Generation or 0G [14]. As we move on to a generic overview of the actual cellular generations, a more technically inclined overview of these early mobile generations (1G to 3G) can be found in [15].

The advent of 1G heralded the first commercial deployments of Mobile communication services, in the early 1980s. Technological evolutions on several fronts made this possible. The advances in semi-conductor and power electronics fields made receiver units portable, although they were still bulky by today's standards. The cellular concept (although first presented in 1947 [14]) was adapted, marking a distinct change from previous Mobile networks. Rather than pumping very high power from a single tower to cover a vast area, the power and height of transmit towers was limited to restrict the coverage to a 'cell' and multiple cells, adjacent to each other, were enacted. This enabled the radio resources to be re-used (we will discuss the radio resources in detail in Chapter 5) and increase the number of simultaneous active users in the network. To support user mobility, basic handover protocols were developed. So, when an active user crossed from one ‘cell’ to another, the call would be picked up and supported by this new cell. The advances of switching technology meant that automated connectivity to other Mobile or landline fixed networks could also be established.

One of the core features that started with 1G was that governments offered (in many cases auctioned) dedicated spectrum bands for Mobile telephony use. Different regions developed specific standards for 1G operations. Amongst these, the more successful were TACS (Total Access Communication System) and NMT (Nordic Mobile Telephones) in Europe, AMPS (Advanced Mobile Phone System) in the US and TZ-801 in Japan. The first reported 1G network was initiated in Japan, in 1979. Two years later, the Nordic countries started their own 1G networks with the NMT standards. In 1983, the first 1G network in the US was launched in Chicago. The common feature in all these standards and networks was that Analogue techniques were used to modulate (or in simple terms embed) the voice signal onto the radio waves. We will introduce these technical details in Chapter 5. The sole emphasis was on voice transmissions; there was no capability for data transmissions as we see today. Each region operated to their specific standards, without worrying about interoperability or the provision of roaming for international travellers. However, the Nordic countries who deployed NMT standards had the provision for roaming within their region. At the peak of the 1G systems in and around 1990, they were globally supporting subscriber numbers reaching 11 million [16].

The key difference in moving from 1G to 2G Mobile was the introduction of the Digital Signal Processing (DSP) techniques to transform the analogue voice signal to a digital signal and embed into the radio carriers. For the first time, this enabled direct (although basic) data services such as SMS to be included. The digital revolution brought many benefits to mobile communications. The miniaturisation trends in DSP chips and circuitry meant that the Base station equipment and the mobile handsets could be made smaller, cheaper and more power efficient. Many signal processing techniques such as error correction coding and interleaving could be introduced in the digital signal domain, making the mobile signal reception more reliable. We will introduce some of these techniques in Chapter 8. Digital speech compression techniques enabled three times more voice calls to be carried on the radio spectrum as compared to 1G analogue transmissions. The lower costs of the network deployment and operation could be passed onto the customers, making subscriptions cheaper, which inevitably increased customer numbers.

The real success of 2G systems came with standardisation and one standard in particular, GSM (Global System for Mobile Communications or originally Groupe Spécial Mobile), enjoyed phenomenal growth. Started as a European standardisation effort in 1982, it quickly gained the support of many European governments. The EU heads of state endorsed the GSM standardisation project in 1986, making its success a firm priority for the European Commission [17]. The first commercial GSM network was deployed by Radiolinja in Finland in 1991. GSM networks mushroomed in many European countries soon after, enabling a true pan-European roaming capability. The success of these European deployments meant that GSM was set for global expansion. By 1998, GSM networks were operating in more than 100 countries, serving 100 million subscribers. This phenomenal growth continued into the twenty-first century. The global GSM subscriber numbers reached 1 billion in 2004 and in two-year steps it doubled to 2 billion by 2006 and 3 billion by 2008 [18]. Even today, many operators with advanced 3G and 4G networks have retained their GSM networks, mainly to provide fall-back, wide-area coverage. This is a testament to the durability and reliability of GSM technology. The global expansion of GSM networks is illustrated in Figure 1.2, captured as in January 2005 [19].

The huge proliferation of the GSM systems brought about the need for mobile technology to meet the rapidly-growing customer demands. By the turn of this century, the success of the wired internet meant that there was a growing demand to access the internet on the move, i.e. through mobile devices. Technically, this required much faster data rates to be supported by the mobile technology than the nominal GSM data rates of 9.6 kbps (or kilobits per second). GSM however, was designed with a voice communication-centric switching architecture, known as circuit switching. For data communications, a radical shift towards packet-switching systems was needed. (We will cover these aspects in detail in Chapter 5). GPRS or General Packet Radio System was the first successful standardisation move to make this shift. With support for packet switching, it could achieve data rates of up to a theoretical maximum of 172 kbps. In practice, many networks averaged around 100 kbps, which was a significant improvement over GSM. These data rates were capable of supporting basic internet browsing and web e-mail access systems. GPRS standards were still backward compatible with GSM, i.e. GSM voice calls could be still supported by GPRS systems. By the year 2000, the International Telecommunication Union (ITU) was setting the IMT-2000 specifications, an official specification list that true 3G standards should meet [20]. The GPRS data rates were far below these requirements. Thus, GPRS became known as a 2.5G system. The first commercial GPRS system was launched in the year 2000 and some systems are still operational today.

The next significant step in the GSM progression came with the EDGE (Enhanced Data rates for GSM Evolution) technology. This is actually an evolution from GPRS technology, to improve the data rates of packet switched networks. The novelty was a significant increase in spectral efficiency or, in simpler terms, the amount of data that could be carried

Figure 1.2 Worldwide proliferation of GSM networks as of January 2005. (*Source* [19]).

by a unit of radio spectrum. The process of embedding a data stream onto a radiowave (which is an analogue signal) is called modulation. GSM and GPRS used a simple modulation scheme called GMSK (Gaussian Minimum Shift Keying), where only one data bit per symbol (or radio resource component) could be embedded. Technological improvements in EDGE enabled the more advanced 8-PSK (Phase Shift Keying) modulation scheme to be incorporated. This allowed three data bits per symbol to be carried, which essentially can triple spectrum efficiency. We will cover these technical details in depth in Chapter 5. EDGE systems, in theory, could carry 384 kbps data rates but in practice it was, in most cases, around 200 kbps [21].

Due to the limited bandwidth (200 kHz) of legacy GSM systems used by EDGE, it could never reach the peak data rates stipulated by the IMT-2000 specifications. Thus, it was considered as a 2.5G standard, although some technologists called it 2.9G to differentiate from GPRS. One of the other advantages of EDGE was that the network modifications needed to implement EDGE were also the stepping stones for the all IP/packet-switching based 3G systems. Thus, investments on EDGE infrastructure by the operators were to be future proof for subsequent 3G systems. This kind of evolution in the technology, bringing in massive cost savings, was a key expectation from operators which could make or break a standard. You can read about these intricacies in cellular standards in Chapter 4. The first networks supporting EDGE technology became operational in 2003 and some operators still continue to use this technology.

The other 2G standard which gained traction in the industry was the IS-95 (or Interim Standard 95). It used quite a revolutionary technology (for the mobile industry at that time), known as CDMA (Code Division Multiple Access), which allocates users different codes and allows them to operate in the same frequency and the same time domain. CDMA was by no means a new discovery. It had been in use for decades, especially for military communication systems, where its properties of resilience against jamming and unauthorised detection were very useful. However, the use of it in cellular systems was a novel move, which subsequently paved the way for the 3rd cellular generation (3G) to adapt this. We will again discuss the technical details of this technology in Chapters 5 and 8.

The IS-95 CDMA technology became known as CDMA One. It operated in 1.25 MHz bandwidth and IS-95B standards could achieve 115 kbps data rates. The IS-95 systems were mostly deployed in North America and in some East Asian markets. By 2001, CDMA One and subsequent technologies accounted for roughly 13% of new mobile subscription numbers globally, concentrated mostly in the US [22]. CDMA quickly proved to be a robust technology and led to it being investigated as the prime candidate for 3G systems, which we cover in the next few paragraphs.

The need and demand for mobile data applications such as web browsing, e-mail and file transfer on mobile devices became clear even before the heyday of the 2G systems. As noted before, 2G/GSM was designed as a circuit switching, narrowband system to support voice communications. Although data rates were improved with GPRS and EDGE evolutions, the need for a true high-speed, packet-switching mobile data network was never really satisfied. Backed by extensive research, the cellular industry came to the realisation that much wider bandwidth systems (compared to 2G) were needed to support the high data-rate applications. The CDMA technology offered the possibility to significantly increase user data rates by using wider bands. Technically, 3G standards were required to meet the IMT-2000 set of requirements set by the ITU. The basic data rate requirements set by IMT 2000 are 144 kbps for high mobility, 384 kbps for low mobility and 2 Mbps for stationary environments [19].

Different flavours of CDMA technology were adapted by different 3G standards. By far the most popular 3G standard, known as UMTS (Universal Mobile Telecommunication System) employed the W-CDMA (or Wideband CDMA) technology with a 5 MHz system bandwidth. UMTS was the first mobile standard to be developed with truly global collaboration. A new body called the 3GPP (3rd Generation Partnership Project) was initiated in December 1998 by the European Telecommunications Standards Institute (ETSI), with participation of other national and regional standards organisations of Asia and North America [23]. The 3GPP oversaw development of UMTS as a natural successor to the GSM standard, with the view of providing a truly global standard.

UMTS was intended to be a technology operable in a globally harmonised spectrum. Specific bands in the 1800–2200 MHz range were originally year-marked as a global band for deploying UMTS networks. Having a globally harmonised spectrum was intended to bring down network equipment and handset costs, helped by economies of scale in mass scale manufacturing for the global market. However, the 3G-spectrum costs in many developed countries spiralled out of control, due to anticipated demand for 3G data services. In the 3G-spectrum auction in UK, for example, bidding by incumbent and prospective operators pushed up the total auction price to almost £22.5 billion, which was about four times the expected value the auction would raise. In Germany, the operators dished out £28.5 billion for 12 frequency blocks. This excessive pricing of 3G spectrum had a hugely negative impact on the European cellular industry, with many analysts suggesting that European 3G deployments were set back by a number of years as a result [24].

The first commercial 3G network was launched by NTT DoCoMo in Japan, in October 2001, known as FOMA (Freedom of Mobile Multimedia Access). In Europe, Telenor of Norway launched their 3G network in December 2001. The UMTS-based 3G networks followed an evolution path of HSDPA (High Speed Downlink Packet Access), HSPA (High Speed Packet Access) and HSPA+. The HSPA+ standards, defined as 3GPP Release 7 in the year 2007, could achieve theoretical data speeds of 168 Mbps in the downlink (from Base station to Mobile) and 22 Mbps (from Mobile to Base station) in the uplink. The 3G services were not taken up by consumers in the expected market penetration rates, so this journey through the standard releases happened at a far slower rate in the commercial networks.

A competing 3G standard, known as CDMA 2000, was developed by the 3GPP2 partnership [24], as a continuation of the IS-95 standards stream. The basic standard, known as CDMA 2000 1x, utilised CDMA technology with a bandwidth of 1.25 MHz, being an evolution of the CDMA One technology used for IS-95. This technology achieved 153 kbps data rates in both downlink and uplink, and was recognised as an IMT 2000 technology. This strand of 3G technologies followed a path of CDMA 2000 1x EV-DO, EV-DO Rev B and EV-DO Rev. C. The EV-DO originally stood for Evolution Data Only, where voice calls could be routed through baseline CDMA 2000 or even IS-95 technology. Later EV-DO became known as Evolution Data Optimised. The EV-DO Rev B technology supported Multi-carrier CDMA, meaning more spectrum in the guise of 1.25 MHz chunks could be aggregated to support higher data rates. With a 20 MHz aggregated bandwidth, and with favourable radio channel and mobility conditions, EV-DO Rev B could achieve up to 73.5 Mbps data rates.

As with the 3GPP set of standards, all CDMA-2000 based standards were backward compatible, enabling co-existence. The EV-DO Rev B standard could be enforced with a software upgrade to the existing CDMA 2000 hardware. The EV-DO Rev C development later morphed into UMB (Ultra Mobile Broadband) an early competitor for the 4th Generation (4G) standards, which we will detail later. The first CDMA 2000-based 3G network was deployed in South Korea by SK Telecom in October 2000.

A third 3G standard, known as TD-SCDMA (Time Division – Synchronous CDMA) was developed mainly in China [25]. Whilst using CDMA technology, it also employed different time slots for uplink and downlink transmissions, in the same carrier frequency. The duration of these time slots can be varied, making TDD more suited to support asymmetric traffic like the mobile internet. The term ‘synchronous’ refers to having all active mobiles in a cell time aligned for transmissions. This makes it much easier to localise the mobiles to enable techniques like beamforming and also simplifies the use of multi-user detection (MUD) schemes. We will touch upon these schemes when we introduce advanced technologies in Chapter 8. The chip rate (or code rate) used in CDMA spreading codes is 1.28 Mcps, which is far lower than for W-CDMA.

The TD-SCDMA standard was developed in the late 1990s and was approved by the ITU-R group in May 2000. In March 2001, China joined the 3GPP group and TD-SCDMA was approved as a 3G standard, becoming part of the UTRA – TDD specifications. The Chinese government announced in 2006 that TD-SCDMA would be China’s official standard for 3G communications. The largest Chinese operator, China Mobile, started building a trial network of TD-SCDMA in 2006, but it was not until late 2008 that these trials were completed. The launch of other 3G standards in China was delayed until TD-SCDMA was ready for commercial launch. In 2009, the Chinese government took the unusual step of assigning TD-SCDMA, W-CDMA and CDMA 2000 1xEV-DO licenses separately to the three largest carriers in China. Following on from their trials, China Mobile deployed the commercial TD-SCDMA network. The standard did not find much success elsewhere. There are only a few examples of TD-SCDMA networks being deployed in developing countries.

At this point, it is perhaps worth taking a brief look at the reasons why the mobile industry generates and supports multiple standards within the same generation. There is clearly a regional emphasis on the generation of multiple standards. Traditionally, the US and Europe have favoured different cellular technologies, continuing to develop different standard threads across mobile generations. The standardisation process should not be viewed as purely a technical activity. There is also a significant commercial and political element to it. The commercial interests of the significant industry players in a specific region (mainly operators and equipment vendors) weigh heavily on the decisions for promoting different standards. It should be noted that the business model of mobile vendors depends on their ability to innovate, to protect their innovations through IPR and then to transfer these into a widely used standard. We will discuss this model in detail in Chapter 4. There are also political initiatives to promote the development of standards to secure industry leadership in certain technologies and to reduce dependency on another region’s technology. The TD-SCDMA development in China, for example, is viewed as an attempt to give local industries a head start in competing with the then global technology giants. Technically, having different standards can help to evaluate the performance of different technologies in actual deployments. For example, the adaptation of CDMA-based technologies for the 3rd Generation was massively supported by the knowhow gained through 2G CDMA One deployments.

The advent of the iPhone in June 2007 marked a watershed moment in the mobile telecommunication industry. Not only did it kick-off the Smartphone era, it also revitalised mobile operators' revenue streams. Up until then, mobile data consumption was a rather cumbersome experience for the user and it was nowhere near anticipated levels. The iPhone provided a seamless web interface to access the internet, making it as slick an experience for the user as sending a text. Apple iOS, the iPhone operating system, could navigate seamlessly between phone, text and numerous new data applications through the iPhone touch screen. It also revolutionised the mobile applications domain by introducing the Apple App store, where third-party developers could market their certified Apps to Apple device users. This Apps market soon grew into a substantial mini-economy and by mid-2012 there were more than 650 000 Apps available through Apple, who paid out more than $5 billion to the developers [26].

Soon after the launch of the iPhone, Google launched their own operating system for Smartphones. Named Android, it was commercially released for mobile devices in October 2008. It soon became the default choice for smartphone manufacturers competing with the Apple iPhone. By 2014, the Android-based Smartphones were dominating the market with around 85% of the market share [27]. The Android-based Apps market also expanded exponentially. Some estimates put the number of Android Apps available to be over 1.4 million by mid-2014.

Thus, the advent of Smartphones heralded an era of exponential growth in mobile data consumption. The following graph in Figure 1.3 shows how the mobile data traffic grew 350 fold from 2005 to 2010 [28]. At the beginning, mobile operators were delighted with this growth, as the extra capacity they provisioned with the 3.5G and 3.9G systems could be monetised. Many operators started providing packages with unlimited data bundles to spur demand. But soon the consumers' appetite for data was putting these networks under considerable strain and unlimited data bundles mostly vanished. We will discuss the advent of 4G systems under these circumstances, where mobile data was becoming dominant over mobile voice for the first time.

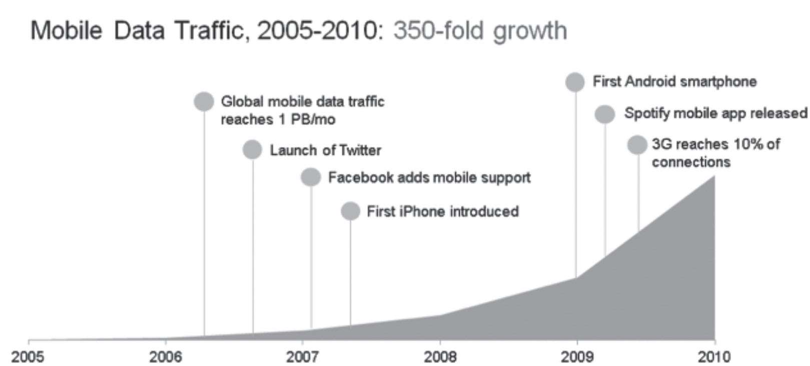

Figure 1.3 Mobile data traffic growth from 2005 to 2010. (*Source* [28]).

The development of 4G standards gathered pace in the mid-2000s, with the aims of providing much higher mobile broadband speeds and all IP (packet) based switching. In the beginning, there were three main strands of potential 4G standards. The 3GPP group were beginning the development of LTE (Long-Term Evolution) standards. One of the aims of LTE standardisation was to provide a smooth transition from 3G UMTS-based networks to LTE, hence it was named as a long-term evolution. The 3GPP2 group initiated work on UMB with a similar aim for transition from EV-DO systems. The IEEE entered the mobile standardisation foray with the development of the 802.16 series, better known as the WiMAX (Worldwide Inter-operability for Microwave Access) standards.

Soon, 3GPP2 decided to discontinue development of UMB, leaving LTE and WiMAX as the competing 4G standards. Both these standards opted for a new radio access technology, known as OFDMA (Orthogonal Frequency Division Multiple Access). Unlike in W-CDMA, the data stream would be split and embedded into a multitude of (mutually orthogonal) frequencies, which together would make up a wideband system. We will explain the technical details of OFDMA in Chapters 5 and 8. Also, both LTE and WiMAX opted for a flatter architecture than 3G, where the base stations (eNodeB as known in LTE) would connect directly to elements of the core network. This would be an all IP network where even the voice would be converted to voice over IP packets (VoIP or VoLTE) and transmitted, moving away from the circuit-switched components of the previous generations.

The WiMAX standardisation had a head-start over LTE, with the 802.16d fixed wireless system being released in 2004. This was intended to provide wireless broadband access to homes and offices, competing with cable and DSL service provisions. The mobile WiMAX standard 802.16e was released one year later in 2005. The Wireless Broadband (WiBro) standard developed by the South Korean Telecom Industry had many similarities to WiMAX and in 2005 WiBro was included in the 802.16e family of standards. The first LTE standard, LTE Release 8, came out in 2008. However, the performance of all these early systems did not reach 4G thresholds set by the ITU-R, through their IMT-Advanced specifications [29]. Under these IMT-Advanced thresholds, the peak downlink data rates for low-mobility users should reach 1 Gbps and, for high-mobility users, should reach 100 Mbps. In this context, the real 4G standards were the WiMAX 2.0 (802.16m) released in 2011 and LTE-Advanced (also known as LTE release 10), released in 2012.

Despite being first to the 4G market, backed by huge investments from industry promoters and being technically sound, WiMAX did not succeed in carving out a market share [30]. The first big mobile WiMAX deployments came out in 2008–09, amidst real optimism for the technology. But by 2011, all of the big WiMAX operators (including Sprint in the US) had announced the transition plans of their networks to LTE. We will analyse the reasons for WiMAX failure in more detail in Chapter 4, but a few salient points can be noted here. First and foremost, WiMAX did not have the support of wider established mobile operators, whilst LTE was their choice. LTE offered a long-term transition path for their 3G UMTS networks, rather than a complete revamp of the networks (with the associated huge cost) needed for WiMAX. WiMAX was mostly supported by new entrants, who saw an opportunity to establish a market presence under the Royalty free IPR policy WiMAX was promoting. Many observers point out that WiMAX did not attempt to build upon the relative success of 802.16d fixed wireless system in the mobile versions [30]. The 802.16e version was not backward compatible with 802.16d, preventing the fixed operators an opportunity to migrate to 802.16e whilst safeguarding their investments. Also, the finalising of the mobile WiMAX standard took far too long, allowing LTE to catch-up and, importantly, fit into the future plans of major operators. From the device perspective, WiMAX was supported by only very few vendors and none of the emerging Smartphones ventured into supporting WiMAX. The mobile WiMAX (being a Time Division – TD version) was perceived to have some advantage in emerging markets, with its lower cost of deployment and ability to utilise narrower spectrum. However, 3GPP also came up with a TD-LTE version, which was preferred to WiMAX in these markets. By 2014, even the WiMAX forum was acknowledging dominance of LTE, announcing plans to make WiMAX Advanced compatible with TD-LTE [31].

So, by 2015, for the first time in the history of mobile communications, the mobile market had only one single standard as the latest flag bearer, LTE. As of July 2015, there were 422 LTE networks deployed in 143 countries, providing services to over 755 million LTE subscribers. Over the next 4 years, LTE continued its impressive growth, becoming the dominant mobile technology accounting for more than half of all global mobile subscriptions by 2019 [32]. The peak data rates that can be achieved on the ground in some of the advanced LTE networks reaches 300 Mbps in the downlink. Evolution of the LTE standards continued at a rapid pace, with LTE Release 10 to Release 14 finalised from 2012 to 2016. The LTE Release 14 was the last of the 3GPP 4G standards and the focus shifted to 5G from Release 15. The later LTE releases have enabled carrier aggregation, with the aim of amalgamating multiple carrier frequencies spread over a wider range, thus providing more frequency resources to carry more data. In some small-cell (SC) deployments (a topic we will cover in Chapter 10) the targeted data rates with carrier aggregation and advanced multi-antenna configurations now extend up to 838Mbps [33]. These data rates were simply unimaginable and may have been deemed as totally excessive in the era before the Smartphones. Although it will have many more years as the dominant cellular technology, 4G LTE will be remembered as the standard that brought the mobile broadband concept to life, after bit of a false start with 3G UMTS.

Around 2012, researchers were already conceptualising how 5G should look, in early research projects like METIS [34]. 5G would encompass a much grander vision than any of the previous generations, which were only focussed on connecting the mobile consumer. A key aim for 5G would be to support different vertical industries, from Smart cities to vehicular communications to Industry 4.0, in addition to the mobile consumer. We will take a detailed look at these vertical areas in Chapter 12 and at 5G in general in Chapter 5. As a brief overview here, it would be suffice to say that the technical capabilities of 5G would span three dimensions. The traditional expansion of data rates would be captured in the eMBB (enhanced Mobile Broadband), where stationary data rates of 20 Gbps and mobile rates exceeding 1 Gbps are targeted. Then, for applications requiring URLLC (Ultra Reliable and Low Latency Communications) reliabilities over 5 '9's (99.999%) and latencies lower than 1 ms are targeted. Then, to facilitate massive deployment of sensor networks, mMTC (massive Machine Type Communication) with up to 1 million sensor devices per square kilometre (1 Mn/km^2) are targeted. The IMT-2020 specifications [35] are evolving to define exactly what requirements should be met by standards to be classified as 5G. An early conceptualisation of these IMT 2020 requirements in the above three and associated dimensions is captured in Figure 1.4, the spider diagram, produced by the ITU [35].

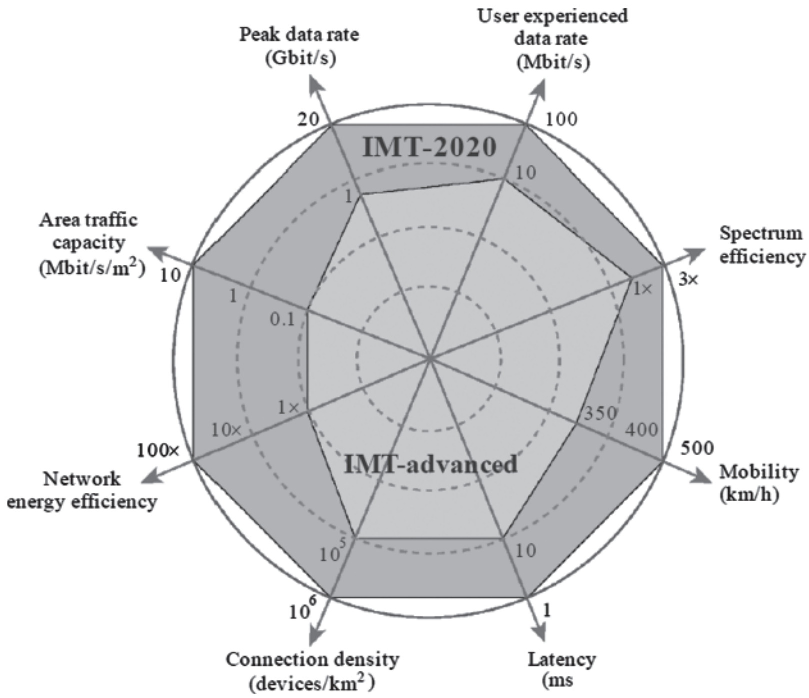

Figure 1.4 The IMT-2020 requirements to be met by 5G systems. (*Source* [35]).

3GPP, now as the sole entity responsible for developing cellular 5G standards, embarked on developing a channel model capturing the frequencies from 6 GHz to 100 GHz (the millimetre wave spectrum [mmWave]) as an enabler for 5G standardisation in 2016. Work on the first 5G version, termed as 5G-NR (5G New Radio) Release 15, started in 2017 and completed in 2018 [36]. This first 5G Release is seen as more of an evolution of LTE, aimed primarily at providing the eMBB capability. The same radio access method as LTE, OFDM, was utilised but now with wider bandwidths (including support for higher mmWave frequencies) and different frequency finger (known as sub-carrier) spacings. At the time of writing this chapter (late 2020), work in Release 16 has come to an end, with the standard frozen in July 2020. This is viewed as phase 2 of 5G-NR standards functionality and both Releases 15 and 16 will be included in the 3GPP submission to ITU-R, for certification as a 5G compliant standard.

The first 5G commercial networks came up in South Korea in April 2019, closely followed by a smaller scale launch in the US [37]. Launched separately by three South Korean mobile operators KT, SK Telecom and LG Uplus, these networks are expected to provide coverage accessible to more than half of the country's population of 52 million at the launch. Soon afterwards, Verizon in the US launched their 5G network in two cities, with a much smaller initial coverage footprint. Within the latter half of 2019, different operators from a number countries (including the UK) joined the 5G network operators' list but most of these have very limited initial coverage, confined to densely populated urban areas. We will see a wider expansion of 5G networks in 2020–21, when more network equipment and 5G enabled user devices will enter the market.

1.3 The Journey of Mobile Communications as Seen from User and Operator Perspectives

Thus, the story of the evolution of mobile communications is a story of continuous technological advancement through the generations 1G to 5G. Technological advancements have enabled a steady stream of new applications to come to the fore in this journey. Looking back from the user-experience perspective, the user devices (mobile phones) tell their own story. As depicted in Figure 1.5, each generation can be characterised by the features of the typical user devices. In 1G, the mobile phones were heavy and bulky with often unreliable connections. The phones were solely used for voice communications. In the 2G digital era, the phones became much smaller, lighter and more battery efficient. In addition to voice, short messaging (or texting) emerged as a killer application. In the 3G era of mobile data provision, there was initially an indifferent take-up of data services. The use of Blackberry type devices with web-mail applications gradually became popular, with their mini keypads to type in e-mails. But the real breakthrough came with the smartphones and their numerous apps. Thus, in the latter part of 3G, and mostly in 4G, the mobile phone transformed into a high-end device, capable of supporting a plethora of third-party applications. Throughout the mobile broadband age of the 4G, the mobile phones continued to grow in capabilities of primarily processing power, memory, screen resolution and camera specification. Displays were becoming sharper and screen sizes getting bigger to support continuing growth in mobile video consumption. As discussed, 5G will spread beyond the provision consumer mobile broadband to different verticals. The plethora of envisaged 5G devices is a testimony to this diversity of applications. These devices include Smartphones, AR/VR devices, IoT sensors, Automated/intelligent vehicles, industrial machines/robots and many more. Thus, 5G consumers will vary from single users to large industry players and service providers, creating a much more complex ecosystem than previous generations. An illustration of the representative devices in each mobile generation is depicted in Figure1.5, from [38].

When looking from the operators' business perspective, 1G was a niche market where the phones and line rentals came at high price points. Technological limitations and costs in the network connection and devices meant that the service was only appealing to a

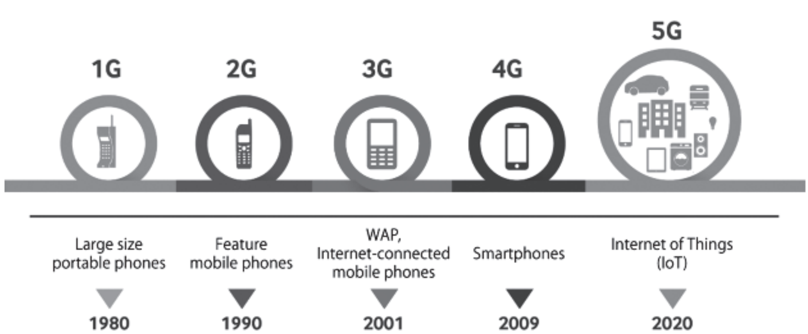

Figure 1.5 The evolution of mobile devices across the generations. (*Source* [38]).

limited customer base, mostly high-end business users. In 2G, the digital technology and ability to mass produce network equipment and devices of a single dominant standard (GSM) pushed prices down. This, in turn, made cellular communications more popular and attracted millions of customers. At the height of 2G success, device prices were pushed down almost to the level of a commodity. Voice call minutes and number of texts were stipulated in the price packages and voice was the main revenue generator for operators. With consumer numbers showing exponential growth in many markets, the operators' revenue growth relied heavily on adding new customers year on year. The market entered 3G with a lot of hype and expectation about mobile data but the lack of nimble mobile data applications meant take up was much slower. Having spent huge amounts on 3G spectrum, and with the subscriber numbers reaching saturation, many operators in developed markets found it difficult to record any business growth. Early 3G phones like the Blackberry did capture traction with business users, but it was the advent of Smartphones that really stimulated growth again. Smartphones gave a unique experience to the user with numerous applications of mobile data and users were willing to pay a premium price for these devices. The sheer magnitude of mobile data demand showed the limitations with 3G technology and paved the way for a quicker transition to 4G. For the mobile operators, who for so long relied on voice as their main source of income and started adapting to the new age of mobile data, new challenges emerged as over-the-top (OTT) Voice over IP (VoIP) packet applications enabled virtually free voice calls and text messages through data networks. OTT applications like Apple Facetime, WhatsApp, Viber, Skype, Wechat in China and Kakao Talk in South Korea made significant dents in mobile operator revenues [38] and, in turn, hastened transition to mobile data oriented business models in 4G.

In many countries now, we are at a stage where 4G networks have really matured and technological advances have driven down the cost per data bit significantly from 3G levels. Mobile data has established itself as the prime income source for operators in many advanced markets. Users now expect GB/month data packages, with the majority of the data consumed for mobile video. However, many advanced markets are seeing consistent drops in ARPU (Average Revenue Per User). An example from European markets is shown below in Figure 1.6 [39]. This is in the context that mobile data is not the first choice of data provision to Smartphones in many indoor environments, where Wi-Fi is predominantly used. Some estimates put that by 2022, only 20% of all IP traffic will be carried by mobile broadband [40].

We are entering the 5G era with many challenges, including falling ARPU facing the mobile operators, as we will detail in Chapter 3. 5G will be an entirely new business proposition for operators, who will have to build collaborative business models with many other vertical industries. Mobile data of many facets and types (eMBB, URLLC and mMTC) will feature in these 5G networks, which will feature partnerships with many stakeholders in both private and public domains. The technical and business aspects of some of these vertical partnerships will be covered in Chapter 12.

The mobile industry has shown a remarkable ability to sustain technological advancement and business vitality throughout its history, from 1G to 4G. It has been highly resilient in challenging times, particularly during the wobbly start to 3G and the shake-up of its voice-oriented business models in the early part of 4G. As 5G dawns, there is a lot of

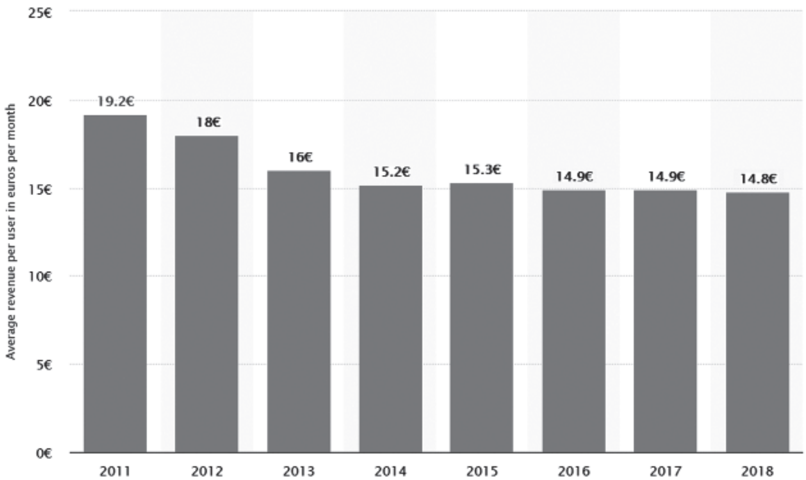

Figure 1.6 ARPU drop for mobile subscriptions in Europe. (*Source* [39]).

excitement in the industry about the wider scope of opportunities in a number of vertical industry areas. There will undoubtedly be a lot of challenges in realising the full potential of 5G, which will require new business partnerships with many of the established vertical industries. However, the mobile industry is well placed, with a single set of 5G-NR standards from 3GPP, progressive spectrum allocations in many countries and active industry bodies in the key verticals working to bridge the gap between ICT and the relevant industry domains. There is a lot to look forward to in this enduring journey of mobile communications.

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