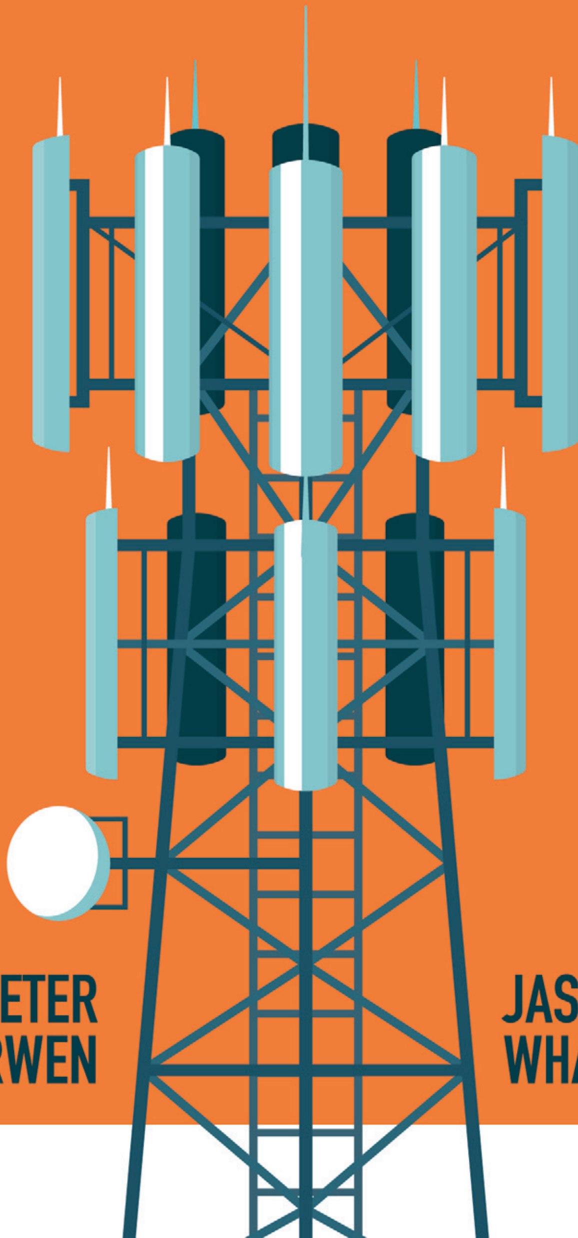
UNDERSTANDING 5G MOBILE NETWORKS

A Multidisciplinary Primer



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INVESTOR IN PEOPLE

This book is dedicated to Hilary Curwen who has endured much shouting at the computer

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List of Abbreviations

2G	Second generation
3G	Third generation
3GPP	Third Generation Partnership Project
4G	Fourth generation
5G	Fifth generation
6G	Sixth generation
APT	Asia-Pacific Telecommunity
AWRI	Advanced Wireless Research Initiative
BRS	Broadband Radio Services
CA	Carrier aggregation
CBN	China Broadcasting Network
CBRS	Citizens Broadband Radio Service
CIoT	Cellular IoT
CoMP	Co-ordinated multi point
DCC	Digital Communications Commission
D-MIMO	Distributed MIMO
DSS	Dynamic spectrum sharing
D2D	Device-to-device
EBS	Educational Broadband Service
EC-GSM-IoT	Extended coverage GSM IoT
eICIC	Enhanced inter-cell interference coordination
eMTC	Enhanced machine type communications
EU	European Union
FDD	Frequency division duplex
FTTP	Fibre to the premises

FWA	Fixed-wireless access
Gbps	Gigabits per second
GSM	Global System for Mobile Communications
GSA	Global Mobile Suppliers Association
HSPA	High-speed packet access
IEEE	Institute of Electrical and Electronics Engineers
IIoT	Industrial Internet of Things
IMT	International Mobile Telecommunication
IoT	Internet of Things
ITU	International Telecommunication Union
LAA	Licence-assisted access
LBT	Listen before talk
LoRaWAN	LoRa wide-area network
LPWAN	Low-power wide-area network
LSA	Licensed shared access
LTE	Long term evolution
LTE-A	Long term evolution-Advanced
LTE-A Pro	Long term evolution-Advanced Pro
LTE-U	LTE in unlicensed spectrum
Mbps	Megabits per second
MEC	Multi-access edge computing
MIMO	Multiple input Multiple output
mmWave	Millimetre wave
mMTC	Massive machine type communications
MOCN	Multi-operator core network
MORAN	Multi-operator radio access network
MTC	Machine type communications
MU-MIMO	Multi-user MIMO
MVNE	Mobile virtual network enabler
MVNO	Mobile virtual network operator
M2M	Machine-to-machine
NB-IoT	Narrowband IoT
NB-LTE	Narrowband LTE

NFV	Network function virtualisation
NR	New radio
NSA	Non-standalone access
OFDM	Orthogonal frequency-division multiplexing
PAL	Priority access licence
PEA	Partial economic area
QAM	Quadrature amplitude moderation
RAN	Radio access network
RAT	Radio access technology
RSPG	Radio Spectrum Policy Group
SA	Standalone access
SDI	Software-defined infrastructure
SDL	Supplementary downlink
SDN	Software-defined networking
SEP	Standards essential patent
SIM	Subscriber identity module
SCRF	State Commission for Radio Frequencies
TDD	Time division duplex
TF	Technical Forum
TRAI	Telecom Regulatory Authority of India
UMB	Ultra mobile broadband
UMFUS	Upper microwave flexible use service
UMTS	Universal mobile telecommunications system
URLLC	Ultra-reliable and low latency communications
VHA	Vodafone Hutchison Australia
W-CDMA	Wide-band code division multiple access
WFA	Wi-Fi Alliance
Wi-Fi	Wireless Fidelity
WOAN	Wholesale open-access network
WRC	World Radiocommunication Conference

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List of Key Terms

5G
Licences
LTE
Mobile
Networks
Spectrum
Vendors

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About the Authors

Peter Curwen joined Sheffield Hallam University in 1970. He took early retirement in 2002 having risen to the position of Professor of Economics. Having switched his research interests from privatisation to telecommunications pre-retirement, he took up the post of Visiting Professor of Mobile Communications, first at Strathclyde University and subsequently at the Newcastle Business School, departing in 2017 to become a 'gentleman scholar'.

Jason Whalley joined Newcastle Business School in 2013 as Professor of Digital Economy, after a brief period as a consultant followed by more than a decade spent at Strathclyde University. His research focuses on the telecommunications industry, both fixed-wire and mobile. He has published extensively on the development of broadband markets, the Internet of Things and the use of ICT in the Himalayas.

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Preface

This book began life as a 5G database, compiled as a companion for those that had previously been compiled for both 3G and 4G and which had each evolved into a book (Curwen, 2002; Curwen & Whalley, 2013). However, in this case, the original idea had been to publish the 5G database in two separate articles covering country case studies because the need to analyse the technological aspects of 5G – far more extensive and complicated than those that needed to be explored and explained for 3G and 4G – appeared to be too problematic to combine with the country studies while restricting the content to the wordage permitted for articles.

In the event, it proved very frustrating to get the articles into print, especially as the country studies grew rapidly as time passed, so the decision was taken to investigate whether it would be practical to expand what had already been written into book form along the lines of Curwen and Whalley (2013). To achieve this, it would be necessary to add two other aspects of 5G to the existing country studies; firstly, a review of everything that had already been published about 5G and, secondly, a chapter (or two) exploring the technical underpinnings of 5G.

It rapidly became clear that whereas a number of highly technical books about 5G were already available – see, for example, Dahlman, Parkvall, and Skold (2020) and Osseiran et al. (2016) – these could only be properly understood by a reader with a scientific/engineering background. The other publications produced by non-academic sources consisted almost entirely of reports, some covering technical matters in reasonable detail, some concentrating upon country studies and some covering both but not in much detail. The only exception appeared to be Webb (2016) which was essentially polemical in nature.

So far as the academic literature was concerned, this tended to be fairly technical and often concerned with forecasting how 5G would affect things in the future – see Chapter 3. Given that 5G standards had yet to be fully agreed, this was a speculative activity at best.

What accordingly appeared to be wholly absent was any form of book that addressed the needs of non-specialist readers who nevertheless sought an insight into 5G either for professional reasons because they were studying telecommunications or were simply interested in something that they had been told would transform their lives.

In essence, compiling the country studies has been relatively straightforward, albeit time-consuming because there is always some disagreement between different sources as to matters such as dates that needs to be resolved. The main problem has been how to deal with the technology. As noted in Chapter 1, 5G is part of a technological progression from 1G to 5G, and hence 5G cannot be treated independently of what has gone before. However, that essentially applies to so-called 'Non-Standalone' 5G which builds upon and coexists with the fourth generation of technology known as long term evolution (LTE). It is much less applicable to the independent strand of 5G which is commonly known as 'Standalone' – the distinction is clarified in Chapter 2.

For this reason, it became apparent to the authors that an initial understanding of 5G necessitated a prior understanding of LTE. Hence, a chapter would need to be devoted to explaining the development of LTE which was itself highly sophisticated – the modern smartphone that operates over LTE networks is to all intents and purposes a powerful mini-computer capable of processing data that has been downloaded at tens of megabits per second. A further chapter would then have to be added to cover the technological advances made during the past decade that have developed mobile technology well beyond the specifications of LTE and which underpin Standalone 5G.

This is not a straightforward matter because, as is evident from the above, there are two processes going on simultaneously. The first – which is what concerns the proverbial (wo)man on the omnibus – is essentially concerned with speeding up LTE in a world increasingly dominated by the need to download video (and to play sophisticated games). What (s)he wants is that massive video files, perhaps in the form of films, become downloadable within seconds rather than minutes without consuming too much of the data allowed within a standard mobile contract.

However, this process involves human participation whereas what is increasingly needed is to improve machine-to-machine (M2M) communication via what is generally known as the Internet of Things (IoT). The IoT is expected to connect up tens of billions of 'things', but without using the same transmission methods as those involving humans – for a start, there is nothing like enough licensed spectrum to meet the demands associated with the IoT. This means that new spectrum bands need to be exploited, largely in the absence of licences, and new technologies introduced to make this happen efficiently and economically.

For the purposes of this book, the major issue was not simply to introduce all of the relevant technology in a manner that would be understandable to readers, but to present it in a sensible sequence. The underlying principle has been that where the authors, who are not engineers, consider that they fully understand the basic principles underlying the technology it is presented as they understand it having checked multiple sources to avoid obvious errors. Anything that cannot be explained adequately in terms comprehensible to a non-engineer is outlined and extensively referenced, so readers can delve deeper if they wish.

The sequencing of material has been extremely problematic if only because the technology has not appeared in a series of finite steps. Rather, a substantial number of strands have developed over a lengthy period with multiple overlaps. The sequencing has been adjusted on numerous occasions during the drafting process, but it has to be admitted that there simply is no ideal way to do this.

So far as the country studies are concerned, the underlying principle has been to concentrate upon licence awards and launches. There are obviously large numbers of ongoing 5G trials at any given point in time, but to enumerate these would occupy far too much space. Furthermore, one of the key virtues of this book is that it provides a link between auctions and other forms of licence awards to network roll-outs and launches that have been achieved or are likely to occur during 2020. It should be added that the databases will be almost fully up-to-date at the time of publication, despite the time lag between manuscript submission and publication, as the coronavirus pandemic brought licence awards to a grinding halt in February 2020, and there was an associated disruption in the launch and dissemination of devices capable of handling 5G.

Finally, it is worth noting that because this book is, at least for the time being, unique, it is not going to be possible to assess how well the authors have met their objectives in comparison to other texts. All that can be said ultimately is that they hope that the book has achieved what it set out to do and that it will indeed prove to be useful to a wide range of readers.

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Chapter 1

5G: A Multigenerational Approach

Introduction

Technological change lies at the heart of the mobile communications sector. It seems hard to believe, for example, that the Apple iPhone – the first true smartphone – only arrived in 2007 given that virtually every person in advanced countries now carries one, often in an ostentatious manner, and that using a mobile device to make a voice call seems quaintly old fashioned.

Naturally, rapid technological change is not confined to the mobile sector, but what is unique to it is the pace at which change has occurred during the past three decades. For example, whereas Curwen and Whalley (2008) contained a full chapter on the subject of technology, little more than one page was given over to a preliminary discussion of what was referred to as '4G'. Within the space of 2 years, 4G had become a reality and, shortly afterwards, interest began to be expressed in the next technological step forward known as '5G'.

The use of the terms 4G and 5G – not to mention their predecessors, 1G, 2G and 3G – results from a tendency to explain technological change as proceeding via a series of 'generations' or 'part-generations'. It should be borne in mind that the divisions between generations are less clear-cut than might be imagined. For example, 4G is now effectively a synonym for long term evolution (LTE) although in practice, as noted below, basic LTE should strictly be described as lying somewhere between 3.75G and 4G with LTE-Advanced (LTE-A) the first technology that meets the agreed specifications for 4G.

Part of the confusion resides in the fact that a mobile technology can also be described in terms of the speed at which data are transferred via either an uplink or a downlink, expressed in megabits per second (Mbps) or gigabits per second (Gbps) (Wisegeek, 2016). Given that it is possible to speed up a technology used in an earlier generation, there is an inevitable overlap between generations once the older technology achieves speeds at least comparable to the lower range of speeds available via the subsequent generation. It must also be borne in mind that in the real world some countries will be introducing one generation at the same point in time when other countries are introducing the next generation.

Broadly speaking, each generation takes 10 years to establish before being overtaken. Thus, 3G lasted roughly from 2000 to 2010 and 4G has so far lasted

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roughly from 2010 to 2020 as shown in Table 1.1. It accordingly comes as no surprise that 6G is already under discussion with a target launch date of 2030 – see Telecompaper (2020) and conclusion of Chapter 2.

3GPP Releases

There are various ways to produce a timeline for the introduction of 5G, but the main difficulty arises from integrating the role played throughout the process by key bodies such as the Third Generation Partnership Project (3GPP – see www.3gpp.org), which is associated with a series of so-called Releases, and the World Radiocommunication Conference (WRC) which brings together all parties interested in spectrum use every few years.

The 3GPP is a key player in the development of mobile technology although it only covers the development of GSM-based technology (Wikipedia, 2020a).[1]

Table 1.1. LTE Network Launches by Region: Nationwide Incumbent Terrestrial Networks.

	Total	Western Europe	Eastern Europe/CIS	Middle East	Asia-Pacific	North America	Latin America[a]	Africa
2009	2	2	0	0	0	0	0	0
2010	16	11	2	0	2	1[e]	0	0
2011	28	11	2	5	4	3	3	0
2012	78	27	11	3	16	5	9	7
2013	86	30	2[c]	8	15	4	19	8
2014	80	14[b]	6	6	18	1	24	11[e]
2015	92	19	11[d]	5	15	2	23	17
2016	89	2	6	8	18	2	26	27
2017	46	3	0	1	16	1	8	17
2018	38	2	3	2	8	0	6	17
2019	16	0	2	0	2	0	2	10[f]
Total	571	121	45	38	114	19	120	114

[a]Including the Caribbean;
[b]Hutchison acquired fellow licensee Telefónica in 2014;
[c]MTS Uzbekistan, which launched in 2010, had its licence revoked in 2013. It re-appeared under changed ownership as Universal Mobile Systems which launched in 2016;
[d]In Belarus, a single wholesaler beCloud has provided a service to every operator since 2013. One national incumbent signed up as a MVNO in December 2015;
[e]In Rwanda, a single wholesaler provides a service to every operator. Two national incumbents signed up as MVNOs in November 2014;
[f]Net of the shut-down of Smart in Tanzania in October.
Source: Compiled by authors.

3GPP brings together seven telecommunications standard development organisations 'and provides their members with a stable environment to produce the Reports and Specifications that define 3GPP technologies' (3GPP, 2020).

3GPP is not a standards body as such but submits its proposals – in this case concerning International Mobile Telecommunication system-2020 (IMT-2020) to the International Telecommunication Union Radiocommunications Sector (ITU-R) (Wikipedia, 2020b). The ITU-R issued the requirements for IMT-2020 in 2015. These are specified in Wikipedia (2020b) in respect of 5G candidate radio access technologies (RATs). A RAT is the underlying physical connection method for a radio-based communication network – a modern smartphone contains RATs in the form of 2G, 3G, 4G and possibly 5G. The non-radio aspects of IMT-2020 are dealt with in ITU-T (Wikipedia, 2020c).

IMT-2020 – which is discussed in more detail in Chapter 2 – specifies a number of key performance indicators. For example, the peak theoretical downlink was specified as a minimum of 20 Gbps – 200 times faster than LTE – and the uplink as a minimum of 10 Gbps while the peak downlink spectral efficiency was set at a minimum of 30 bits/Hz and the uplink at a minimum of 15 bits/Hz. Other indicators included latency, mobility interruption time, reliability, connection density, battery life and coverage (International Telecommunication Union, 2017; Keysight, 2020).

As noted above, 3GPP is particularly associated with a series of Releases – where each Release incorporates hundreds of individual standard documents which undergo a continuous state of revision – that were denoted by dates until 2000 and numbered consecutively starting with Release 4 in 2001 – see https://www.3gpp.org/specifications/67-releases. Release 7 in 2007 was primarily concerned with upgrades to 3G as discussed below (3G Americas, 2007), while those commencing with Release 8 were concerned with the route to 4G and, subsequently the route to 5G (Keysight, 2015).

The most recent Releases that are significant in terms of what follows are Release 14 (end-date June 9, 2017), Release 15 (end-date June 7, 2019), Release 16 (end-date June 19, 2020) and Release 17 (end-date September 17, 2021) – see Chapter 2. Once a Release is 'frozen', no further additional functions can be added as the functions are deemed to be 'stable'.

Harmonisation and the WRC

The edicts of regionally based bodies such as the European Union apply to only 30 or so countries and there are some 225 altogether worldwide, which is where the WRC comes in. Its task is to harmonise the spectrum preferred by the EU, the USA, China, South Korea and so forth – no easy task.

The WRCs are organised by the International Telecommunication Union (ITU) to review and, as necessary, revise the Radio Regulations. These take the form of 'an international treaty governing the use of the radio-frequency spectrum and the geostationary-satellite and non-geostationary-satellite orbits'. Under the terms of the ITU Constitution, the WRC can, inter alia, revise the Radio Regulations and any associated frequency assignment and allotment plans. The WRC as such has met in 1993, 1995, 1997, 2000, 2003, 2007, 2012, 2015 and 2019 although it met previously under different auspices (Wikipedia, 2020d). Information concerning the WRC can be found at http://www.itu.int/ITU-R/go/wrc/en.

The Early Generations

Technology upgrades are achieved via improved software, hardware or both. An important point is that whereas it is quite cheap and easy to upgrade a technology (largely via software) provided it remains within the same spectrum band, it is relatively expensive to introduce a new technology in a previously unused band because a new set of hardware is required. An intermediate step in terms of cost is to open up a different spectrum band for a technology already in use, the reason being that much less new hardware is needed.

2G was the first digital technology designed primarily to carry voice, whereas 3G – known most commonly either as wide-band code division multiple access (W-CDMA) or universal mobile telecommunications system (UMTS – see Wikipedia, 2020e) – was designed to cope with the transmission of modest amounts of data – modest because transfer speeds were very slow by modern standards. W-CDMA was superseded by high-speed packet access (HSPA – see Wikipedia, 2020f) which had the advantage that it could be upgraded successively either by doubling up the number of channels (dual-carrier) or through the use of multiple input multiple output (MIMO) antennas – see 3G.co.uk (2009) and De Grasse (2016). Adding MIMO to HSPA helped to convert it to HSPA+ which was capable of yet higher speeds, and even these speeds could be doubled through the introduction of 64 QAM (quadrature amplitude modulation) (Radio Electronics, 2016).

It may be helpful to clarify the role of MIMO at this point. MIMO means that antennas at both the tower and end-user device send and receive multiple data streams within one channel. Most smartphones were designed initially to support 2×2 MIMO but towers were upgraded to cope with four data streams – that is, 4×2 MIMO. 4×4 MIMO is common on the latest devices but this can be distinguished from Massive MIMO which is widely viewed as a synonym for at least 16×16 MIMO with 8T8R MIMO – now the common way to describe MIMO where T stands for 'transmit' and R stands for 'receive' – as an intermediate level (De Grasse, 2016 and see Chapter 2).

In the USA, the 3G technology of choice was cdma 2000 1×EV-DO (evolution-data optimised). This was expected to develop through a sequence of upgrades to what became known as ultra mobile broadband (UMB – Techopedia, 2016), However, as a consequence of the widespread commitment by 1×EV-DO operators to move towards the adoption of LTE during 2008, UMB was effectively abandoned at the year-end.

It is also helpful to refer here to TD-SCDMA – the 'TD' refers to time division duplex (TDD) which means that the signal travels in both directions within the same spectrum band (GSMarena, 2020). This was developed by China in an attempt to prove that it was not dependent upon Western technology and the Chinese government, which owns the three incumbent operators, has continued to express a preference for TDD in the development of 4G and 5G. TDD is also known as unpaired spectrum while paired spectrum is used for FDD. With unpaired spectrum, the uplink and downlink can be asymmetrical with the downlink using up to nine times more spectrum than the uplink.

Development of Spectrum Bands

By the end of the 1990s the spectrum allocated for 2G was often too congested to cope with the additional demands arising from data-rich downloads. There were two ways of dealing with this problem: Firstly, as noted above, a change in technology that would allow the existing spectrum to be used more efficiently and, secondly the opening up of new spectrum bands.

Both solutions were adopted for the introduction of 3G. In particular, in the European Union, the 2100 MHz (2.1 GHz) band was adopted as it was fortuitously unoccupied. However, the situation with respect to LTE was more contentious. Certainly, the intention was always there to open up new spectrum bands, in particular the 2.6 GHz and digital dividend bands (see below), but a widespread failure to make these available in good time meant that, with 3G networks operating in separate bands, there was pressure to re-farm 2G bandwidth for LTE. In practice, this primarily involved the 1800 MHz band during the initial years of LTE provision. As a consequence, the development of LTE frequently involved multiple spectrum bands – and, indeed, LTE-A requires that a minimum of two bands be used in tandem, known as carrier aggregation (CA). Although up to five bands are currently used by individual operators, the most common combination consists of the 800 MHz, 1800 MHz and 2.6 GHz bands.

Spectrum bands are not used consistently for 3G, 4G or 5G across the globe. The ITU has sought to address this issue with a threefold distinction. Geographical areas are defined in short by the ITU as follows: Region 1 is Europe, the Middle East & Africa; Region 2 is The Americas; and Region 3 is Asia-Pacific. More specifically, Region 1 comprises Europe, Africa, the former Soviet Union (FSU), Mongolia and the Middle East west of the Persian Gulf but including Iraq. Region 2 comprises the Americas – Canada, the USA, the Caribbean and Latin America – plus Greenland and certain eastern Pacific islands. Region 3 comprises most of non-FSU Asia east of, but including, Iran together with most of Oceania (4G-LTE, 2018).

A variety of spectrum bands have been designated as suitable for LTE and, in certain cases as shown in the country case studies, for 5G (Wikipedia, 2020g, 2020h). Certain spectrum bands are popularly referred to as 'digital dividend' because they are bands where spectrum can be released by switching from analogue to more efficient digital signals. The analogue signals are predominantly used for broadcast TV but the specific spectrum involved spans a wide range of (possibly overlapping) frequencies. For example, the complete 700 MHz band is 698–806 MHz. However, in the USA, this is divided into several sub-bands within the 699–798 MHz band (Global mobile Suppliers Association, 2020a) and, in effect, the main incumbents have sought to annex different sub-bands thereby creating difficulties in roaming across networks.

800 MHz translates as the 790–862 MHz band in ITU Region 1 containing a 30 MHz uplink and a 30 MHz downlink (791–821 MHz paired with 832–862 MHz). In contrast, the digital dividend band in most of Asia spans 470–960 MHz although many individual countries (for example, Brunei, Indonesia, Malaysia and Singapore) have opted for the 700 MHz band, specified by the Asia-Pacific Telecommunity (APT) as 703–748 MHz paired with 758–803 MHz – see Global mobile Suppliers Association (2020b) and 4G Americas (2011, pp. 64–69).

The 700 MHz band was expected to come up for discussion at the World Radiocommunication Conference in 2015 (WRC-15) – the initial agreements covering the Americas and the Asia-Pacific region date back to WRC-07 – but the preliminary groundwork was brought forward in the hope that all regions would be able to agree on harmonised use of the band at WRC-15. At WRC-12, the decision was taken to co-allocate it by 2015 for mobile and broadcasting services, but it was not established whether it would be used for FDD or simply as a supplemental downlink. At WRC-15 (NTIA, 2016), they duly allocated the 700 MHz band for mobile use on a worldwide basis (Aubineau, 2016; Bicheno, 2015) – this is discussed further in Chapter 2.

Harmonisation and the European Union

As the above discussion indicates, some spectrum bands are used throughout the world but most are not truly harmonised in the sense that the operators involved all use exactly the same bands. The organisation that has tried hardest to introduce harmonisation is the European Commission, a process it has applied successively to 2G, 3G and 4G. The Radio Spectrum Policy Programme (Decision 243/2012/EU) set out to identify 1200 MHz that should be harmonised across the European Union by 2015, and although that was seemingly an over-optimistic target it was largely achieved in practice. The next significant element, introduced in May 2015, involved the 1452–1492 MHz band and brought the grand total of harmonised spectrum to the 1,030 MHz mark. Member States were expected to have harmonised the band by the end of 2015 although existing usage by terrestrial digital audio broadcasting (T-DAB) needed to be protected.

The European Union has sought to impose harmonised use of digital dividend spectrum. The European Commission, together with the Council and Parliament, agreed a text which required national regulators to authorise the use of digital dividend spectrum by January 2013. This formed part of the Radio Spectrum Policy Programme noted above – the standards body on which it relies is the European Telecommunications Standards Institute (ETSI – see Wikipedia (2020m) and www.etsi.org). Naturally, it is one thing to authorise the use of a band and another to clear it of existing users, a problem that is sensitive in this case because, firstly, there may be military usage and, secondly, it means switching off the analogue signal for TV and forcing consumers to purchase a new digital television which they cannot necessarily afford.

During 2014, the Pan-European technical authority, the Electronic Communications Committee, determined that the lower edge of the 700 MHz band should be 694 MHz with the spectrum to be used divided into 703–733 MHz and 758–788 MHz, thus ensuring compatibility with the APT plan. In May 2016, the European Council approved the Commission's plan – part of the 5G Action Plan (IDATE Digiworld, 2019) – to open up the 700 MHz band by end-June 2020. Member States were required to adopt and make public a national plan by June 30, 2018 describing the process for implementation.

Given that many European countries were grappling with problems in developing the 800 MHz band, it seemed unlikely that they would be rushing to open up the 700 MHz band as well. Nevertheless, an auction that included spectrum in the band took place in Germany in June 2015 and an auction of spectrum in the band took place in France in November 2015.

In February 2016, the Commission presented a proposal for the use of the 700 MHz band which encompassed 694–790 MHz with 470–694 MHz remaining as a priority for audiovisual services. In December (Telecompaper, 2016) – by which point Finland had also auctioned the band – the EU agreed to open up the 700 MHz band by 2020 with an option for some countries to delay until 2022. The sub-700 MHz band would remain in the hands of broadcasters until at least 2030 although individual countries could negotiate an earlier switch of usage.

There was also some discussion concerning the possibility of opening up the UHF band, comprising 470–694 MHz, for LTE. Needless to say, broadcasters objected strongly to this possibility and they effectively won a victory – albeit one that strictly only lasted until WRC-19 – when WRC-15 decided to leave the status quo unchanged in ITU Region 1 (Aubineau, 2016).

'True' 4G/IMT-Advanced

The great majority of media reporting treats 4G and LTE as synonymous even though, as noted, this is not correct since LTE falls short of the technical specifications in important respects (Wikipedia, 2016i) – for those with a deep interest in the technical aspects see, for example, Sesia, Toufik, and Baker (2011) or Dahlman, Parkvall, and Skold (2011). The main contender for the right to be called 'true' 4G is LTE-Advanced (LTE-A). The term IMT-Advanced is often used as a synonym for 'true' 4G.

Both 3GPP and the ITU were involved in what was to become 'true' 4G. 3GPP released the specifications for 'true' 4G within Release 10 and Beyond – see Rohde and Schwarz (2015). In essence, for the 3GPP to sanction it, 'true' 4G had to deliver a 100 Mbps downlink with high mobility and wide area coverage, a 1 Gbps downlink and a 500 Mbps uplink when stationary, low latency of under 10 milliseconds round-trip delay and use wide spectrum bands of up to 100 MHz (Global mobile Suppliers Association (2015) and see www.radio-electronics.com).

Such a wide band can only be achieved via carrier aggregation – the combination of at least two separate spectrum bands (Arora, 2013; Wanstrom, 2013). Release 10 specified 'component carriers' of up to 20 MHz so the optimum manner to achieve a 100 MHz bandwidth is to aggregate five 20 MHz carriers (4G Americas, 2020a, 2020b). The carriers can either be contiguous or composed of several non-contiguous blocks. The above requirements are not met by LTE (which meets the specifications of Release 8 and Release 9) but they are met by LTE-A.[2] It should be noted that carrier aggregation is designed to be backwards-compatible – in other words, LTE and LTE-A must be able to co-exist across at least part of the bandwidth used for LTE-A.

For its part, the ITU operates through its Radiocommunications Sector (ITU-R) which, in late October 2010, chose LTE-A as one of its official candidates for 'true' 4G. In January 2012, the agreed technical specifications for IMT-Advanced were finally ratified by the ITU Radiocommunications Assembly – for details go to www.itu.int – and LTE-A was accepted as meeting those specifications (Telecompaper, 2012).

Auction Methods

Historically, spectrum was mostly allocated and assigned without much regard to how future demand for a finite band of frequencies useful for mobile communications was likely to develop. Hence, broadcasters and the military took possession of wide swaths of spectrum at zero or negligible cost and it became increasingly obvious that this initial set of assignments was not economically efficient. Market mechanisms became increasingly pervasive with the liberalisation of telecommunications commencing in the 1980s, and these were particularly associated with a switch to the use of auctions for assigning spectrum (Antonie & Colino, 2011; Wikipedia, 2020j).

In the case of 3G, although there was considerable emphasis upon the use of auctions – not surprisingly given that monies raised helped finance government expenditure – a number of countries preferred to use administrative methods known popularly as 'beauty contests' (Kuroda & Forrero, 2017) which were themselves sometimes applied in a hybrid format involving a beauty contest followed by an auction. The advantage of beauty contests is that licensees have more money left to invest in their networks, against which must be set arguments relating to the superior efficiency of auctions. By the time LTE licences came up for grabs – effectively post-2000 – the revenue-raising and efficiency virtues of auctions meant that virtually all bandwidth suitable for 4G was sold off to the highest bidder. In essence, auctions can take three main forms as follows:

- Simultaneous multi-round ascending (SMRA).
- Combinatorial clock (CCA) – see Mochon and Saez (2017).
- Sealed bid.

A SMRA can also come in a variant with augmented switching. The key point about a combinatorial clock auction is that bidders can make mutually exclusive package bids, and hence it is clearly suitable for occasions where spectrum in several bands is being sold simultaneously.