Spectrum allocation methods for future wireless services in cellular networks

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Abstract

This thesis introduces three new spectrum allocation methods to meet the needs of future wireless services in cellular networks.

The first new method is called a Licensed Spectrum Park where upcoming spectrum band allocations are divided into two different license types. In addition to spectrum licenses, which allow successful auction bidders to roll out cellular networks as normal, a Licensed Spectrum Park would allow smaller operators to roll out specialized cellular networks on a short-term local site by site basis.

The second method is called Licensed Spectrum Sharing where spectrum is shared between two cellular network operators. This thesis quantifies the effects of spectrum sharing on capacity gains and it shows the effects of traffic profiles with asymmetric loads on the spectrum sharing dividends. The traffic profiles presented use actual time-of-day data from two different cellular operators using two shared 4G sites.

The third new spectrum allocation method is to use spectrum at mm wavelengths. This thesis discusses the engineering viability of using mm wavelengths, including coverage predictions and signal attenuation limitations, but focuses on the assignment of spectrum in this band from a regulation and policy use point of view.

This thesis compares these three allocation techniques against the definition of net social benefit and concludes that of these three techniques, the use of mm wavelengths is the recommended spectrum allocation technique for future wireless services. It notes that the definition of net social benefit excludes the economic value of spectrum. Finally, this thesis investigates the economic value of spectrum and concludes that the value should be given as a range, in this case bounded by the deprival method and the real options analysis.

Our analysis offers an important contribution for both spectrum operators and regulators. It provides the framework for spectrum allocation in parks for new market entrants and presents methods using measured data to calculate the benefits of sharing spectrum. This thesis also offers insights into spectrum valuation techniques and presents engineering and economic data on the use of mm wavelengths for cellular networks. This research helps sets policy, allocation rights and budgets for future spectrum allocation techniques.

Acknowledgements

I would like to express my thanks to my wife Tessa and my children Owen and Thomas for their patience and understanding while I research, read and work on this PhD. This work sometimes occurred late into the night and weekends, so I am thankful they allowed me time for this research.

I would also like to thank Professor Kevin Sowerby and Associate Professor Fernando Beltran for their time, efforts and support through my PhD journey. We have had some lively debates about spectrum theory and cellular network design, and I have enjoyed working with them both.

Undertaking this PhD as an older student has provided many positive aspects to this research. I have drawn on my knowledge of cellular networks and design gained from industry for this work. With that I would like to thank Spark New Zealand, Two Degrees Mobile and Huawei for allowing me to access data used in this research. Finally, I would like to thank the University of Auckland for the opportunity to do this research - their support of older students returning to academia is appreciated.

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Collaborative Research Project

This is a collaborative research project between the Engineering School - Department of Electrical and Computer Engineering and the School of Business - Department of Information Systems and Operations Management at the University of Auckland, New Zealand. This collaboration is ideal for this research, as the topic has both engineering and business components. The engineering component comes from determining how spectrum is used in cellular networks for wireless services. The research describes the relationship between spectrum and the increased capacity and coverage requirements. The business side of this research is more economics focussed. We research how spectrum is a resource to be bought, sold and traded and investigate spectrum valuation techniques.

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Abbreviations and Acronyms

3GPP	3rd Generation Partnership Project
ACMA	Australian Communications and Media Authority
ADSL	Asymmetric Digital Subscriber Line
AMPS	Advanced Mobile Phone System
AR	Augmented Reality
ARPU	Average Revenue Per User
ASA	Authorised Shared Access
COST	Coopération européenne dans le domaine de la recherche Scientifique et Technique
DAMPS	Digital Advanced Mobile Phone System, commonly marketed as 1G
dBi	Decibel with reference to isotropic radiator
dBm	Decibel with reference to one milliwatt
EIRP	Effective (or equivalent) Isotropic Radiated Power
eNodeB	Evolved Node B
EPC	Evolved Packet Core
ERO	European Radio Communications Office
E-UTRAN	Evolved-UMTS Terrestrial Radio Access Network
FCC	Federal Communications Commission
FDMA	Frequency Division Multiple Access
FSPL	Free Space Path Loss
GSM	Global System for Mobile Communication, commonly marketed as 2G
GWCN	Gateway Core Network
HLR	Home Location Register
HSS	Home Subscriber Server
IEEE	Institute of Electrical and Electronics Engineers
IEP	Journal of Information Economics and Policy
IMS	Internet Protocol Multimedia Subsystem
IMT	International Mobile Telecommunications
IoT	Internet of Things

ISD	Inter-site Distance
ISM	Industrial, Scientific and Medical radio bands (unlicensed)
ITS	International Telecommunications Society
ITU	International Telecommunication Union
LMDS	Local Multipoint Distribution Service
LSA	Licensed Shared Access
LSP	Licensed Spectrum Park
LSR	Load Symmetry Ratio
LTE	Long-Term Evolution, commonly marketed as 4G
M2M	Machine-to-Machine
MBIE	Ministry of Business, Innovation and Employment
MIMO	Multiple-Input Multiple-Output
MME	Mobility Management Entity
MOCN	Multi Operator Core Network
MSP	Managed Spectrum Park
NPV	Net Present Value
NR	New Radio
NTIA	National Telecommunications and Information Administration
OFCOM	The Office of Communications UK, regulatory and competition authority on spectrum
OFDMA	Orthogonal Frequency Division Multiple Access
PCRF	Policy and Charging Rules Function Server
PDF	Policy Decision Function
PDN / PGW	Packet Data Network Gateway
PTC	Pacific Telecommunications Council
QoS	Quality of Service
RAN	Radio Access Network
RSM	Radio Spectrum Management
RSPG	Radio Spectrum Policy Group
SAS	Spectrum Access System
SC-FDMA	Single Carrier - Frequency Division Multiple Access
SGW	Serving Gateway
SINR	Signal to Interference plus Noise Ratio
SMS	Short Message Service

SSD	Spectrum Sharing Dividends
TAS	Telecom Application Server
TDMA	Time Division Multiple Access
TPRC	Telecommunications Policy Research Conference
UE	User Equipment
UHF	Ultra High Frequency
UMi	Urban Micro as in UMi path loss model
UMTS	Universal Mobile Telecommunication System, commonly marketed as 3G
VHF	Very High Frequency
VoLTE	Voice over LTE
VR	Virtual Reality
WACC	Weighted Average Cost Of Capital
WCDMA	Wideband Code Division Multiple Access
Wi-Fi	Wireless Local Area Network (WLAN) products that are based on the IEEE 802.11 standards
WTS	Wireless Telecommunications Symposium

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Publications

The work presented in this thesis has produced the following peer reviewed publications:

Shaw, B.A., Beltrán, H. F. and Sowerby K. W. “Assigning spectrum fairly: Managing spectrum using long-term nationwide and short-term local spectrum licenses”. TPRC Conference. Washington DC, USA. 2014.

Shaw, B.A., Beltrán, H. F. and Sowerby K. W. “The use of spectrum at mm wavelengths for cellular networks”. Paper presented at Pacific Telecommunications Council Conference, Honolulu, USA. 2016.

Shaw, B.A. and Sowerby K. W "Traffic Profiles and Licensed Spectrum Sharing in Cellular Networks" IEEE 85th Vehicular Technology Conference. Sydney, Australia. 2017.

Shaw, B.A., Beltrán, H. F., and Sowerby K. W, "Valuing spectrum at mm wavelengths for cellular networks", 15th International Telecommunications Society (ITS) Asia-Pacific Regional Conference, Japan. 2017.

Chapter 1. Introduction

Wireless services from cellular networks have become an integral part of modern life. The increasing popularity of multimedia applications and the widespread penetration of smart phones and tablet devices means that the amount of traffic these services are carrying is increasing almost exponentially each year. Our increasing population, with high cell phone usage and future wireless services such as virtual reality and augmented reality, will only increase the amount of traffic or data rates on cellular networks.

To meet this demand, cellular operator’s frequently upgrade their networks to provide more coverage and capacity to the public. A key component required in networks to meet this requirement is spectrum – defining the frequencies used by the radio access network. The amount of spectrum and the frequency used determines both the capacity and coverage achievable over cellular networks. The result has been a huge demand to acquire spectrum management rights that are suitable for cellular networks.

There are limitations with the current command-and-control regulatory structure for licensing spectrum. Some regulators are struggling to cope with the spectrum demand from operators of cellular networks [1] with operators demanding faster turnaround of new spectrum for cellular networks [2]. There is also a finite amount of spectrum that is currently suitable for communication networks and this has given rise to spectrum license pricing that can be prohibitively expensive for some businesses trying to enter the wireless market [3]. Now many operators and regulators are considering alternatives to traditional methods to allocate spectrum.

It has been stated that "the key purpose of spectrum management is to maximise the value that society gains from the radio spectrum by allowing as many efficient users as possible while ensuring that the interference between different users remains manageable" [4]. This is defined as the spectrum net social benefit. This definition is key to many of the principles used to determine successful spectrum management techniques. Spectrum allocation must be useful to both the cellular operators, to provide both good coverage and capacity, but it must also provide access to as many users as possible and manage interference between these users of spectrum.

This leads onto the research proposed for this thesis. We work to answer the question – What is a good strategy to allocate spectrum to meet the future demands for wireless services in cellular networks?

Traditionally cellular networks use spectrum in the Ultra-High-Frequency (UHF) band, which allows good radio propagation and meets most of the current demand for capacity. Spectrum is normally allocated for a fixed term management right, normally 20 years in New Zealand, in large geographic areas, often country wide. To avoid interference spectrum is assigned for exclusive use with a fixed amount of spectrum.

This research looks at each of these items and investigates if alternative options are available. For instance:

- Instead of assigning spectrum purely in a fixed term management right for a large geographic area, what would be the implications of using license spectrum parks - using a variable term spectrum license in a small geographic area.
- Instead of assigning spectrum in the low frequency UHF band for cellular networks, what are the implications of using mm wavelengths i.e. extremely high frequency bands.
- Instead of assigning a fixed amount of spectrum for each operator, what are the implications of allowing operators to share spectrum.

In addition, the use of mm wavelengths is investigated further in the last part of this thesis:

- Valuing spectrum at mm wavelengths for cellular networks. This research investigates the value of mm wavelength spectrum to cellular network operators.

1.1 Thesis outline

This thesis starts by introducing current spectrum allocation methods in detail in Chapter 2. This includes a literature review describing the history of spectrum allocation, spectrum auctions, spectrum sharing, spectrum pricing and regulation and management of spectrum.

Chapter 3 presents future wireless services in cellular networks. This chapter seeks to establish a vision for cellular networks for 2020 and beyond by describing user, application and technology trends, the coverage and capacity requirements and the associated spectrum implications.

The structure of the rest of this thesis matches the research items described in this chapter's introduction.

Chapter 4 investigates the use of Licensed Spectrum Parks. A new method is proposed to divide upcoming spectrum band allocations into two different spectrum licence / management right types. The first, a spectrum license, would allow successful auction bidders to roll out mobile radio networks on a long-term nationwide scale as normal. The second is a new concept called a licensed spectrum park (LSP) and would allow smaller operators to roll out specialized mobile radio networks on a short-term local site by site basis. LSPs would be assigned by applying for a license based on a site specific, fixed base station location for a short timeframe that could be renewed periodically.

Chapter 5 quantifies the effects of sharing spectrum between two cellular network operators and its impact on the number of base stations required to meet capacity targets. In particular, it shows the effects of traffic profiles with asymmetric loads on the spectrum sharing dividends. The traffic profiles presented use actual time-of-day data from two different cellular operators using two shared 1800 MHz LTE sites, one urban and one rural. This research is useful to both cellular operators and to spectrum regulators. To operators, this chapter presents methods and examples using measured data to calculate the benefits of sharing spectrum. To regulators, this chapter offers data to show that sharing licensed spectrum between operators can reduce the total number of cell sites that are required to meet forecasted increases in capacity demand.

Chapter 6 summarises the benefits and limitations of using spectrum at mm wavelengths for radio access in cellular networks. It discusses the engineering viability of using mm wavelengths for cellular use but focuses on the assignment of spectrum in this band from a regulation and policy use point of view. In particular, the analysis considers whether mm wavelength spectrum should be used as licensed or unlicensed bands, or a combination of both, when used for cellular networks. This chapter shows that mm wavelengths for cellular use is best used where coverage is not expected to be continuous or ubiquitous, and used in areas where capacity demands cannot be met by using the UHF band. In addition, this chapter shows that there are benefits of assigning part of the mm wavelength band as unlicensed spectrum for private individuals or small networks, and part of the adjacent mm wavelength band as licensed spectrum for cellular operators.

Chapter 7 starts with a comparison of the three new spectrum allocation techniques, namely licensed spectrum parks, spectrum sharing with asymmetric loads and the use of mm wavelengths for cellular networks. This chapter then describes why one of these techniques (the use of mm wavelengths) is likely to be used for future wireless services on cellular networks.

Chapter 8 investigates the economic value of spectrum using mm wavelengths. The value of spectrum is very important to determine the best method to allocate spectrum. Frequencies with little value can be allocated using administrative techniques and spectrum with high value is often allocated by market-based techniques, like spectrum auctions. The analysis uses four techniques to value spectrum, namely a benchmarking comparison, a discounted cash flow analysis, a real options approach and a deprival method. The methods to calculate spectrum value presented in this chapter can be used for any spectrum band and in any country. However, to determine the value of mm wavelengths for cellular networks, data was used from New Zealand, specifically for the existing 700 MHz LTE network and for a hypothetical 28 GHz LTE network. These models are based on geographic data, population, cellular traffic analysis and LTE network design from this country.

Chapter 9 is the conclusion. It summarises why this work will be useful to both operators (spectrum managers) and regulators.

To operators, this thesis presents methods using measured data to calculate the benefits of sharing spectrum, offers insights into spectrum valuation techniques and presents engineering and economic data on the use of mm wavelengths for cellular networks.

To regulators, this thesis provides the framework for spectrum allocation for new market entrants enabling more competition in the mobile radio market, offers data to show that sharing licensed spectrum between operators can reduce the total number of cell sites that are required to meet forecasted increases in capacity demand and it offers insights into the engineering and economic value of mm wavelength spectrum which helps sets policy, allocation rights and budgets for future spectrum auctions.

1.2 Research contribution

Research presented in this thesis is original and has contributed to spectrum research in New Zealand and abroad.

The work on Licensed Spectrum Parks was new when published in 2014 [5]. Since then countries have implemented or are considering similar spectrum allocation techniques to Licensed Spectrum Parks. For instance, since 2014 there has been on-going work in the European Union and in the United States on Licensed Shared Access (LSA). Under the LSA regime, spectrum that is already occupied but underutilised would be shared, on a licensed basis, between incumbents and other cellular operators, under agreed frequency, location and time-sharing conditions. Spectrum has also been assigned in New Zealand as a managed spectrum park in the 2.5 GHz band with rules published in 2015 [6]. A managed spectrum park is similar to the work presented on Licensed Spectrum Parks, except that a managed spectrum park assigns local spectrum management rights from a dedicated band (2.5 GHz) and a Licensed Spectrum Park assigns spectrum from bands adjacent to that assigned for cellular use, either pre or post spectrum auction. These items are discussed in detail in Chapter 4.

The work presented in this thesis on traffic profiles is unique and a useful contribution to engineering as it shows actual cellular traffic profiles with real life data from New Zealand operators. This data presents the time variation in traffic profiles, useful if new operators want to use spectrum or data in off-peak periods of the day (proving that dynamic spectrum access is beneficial). This data is particularly useful to New Zealand cellular operators showing the gains from spectrum sharing specific to New Zealand conditions. This data has also been used by Chorus (the largest New Zealand telecommunications infrastructure provider) to help manage traffic demand from cellular operators.

In 2016 the paper [7] investigating the use of mm wavelengths for cellular networks was a new contribution in a new field. The use of mm wavelengths was not a band designated for 5G by the ITU or 3GPP in 2016 so this work was new and an original contribution to engineering. The following work valuing spectrum at mm wavelengths [8] was also new. Since this work was published in 2017, it has been used by the Japanese Government to help price spectrum for use in cellular networks in that country.

This research has made a valuable contribution to spectrum allocation methods to both regulators and operators. To regulators it offers insights into new spectrum allocation methods and the economic value of spectrum. To operators this research shows both the benefits of sharing spectrum and shows the benefits of using mm wavelengths to provide more capacity to meet the increasing amount of traffic or data on cellular networks.

Chapter 2. Spectrum Allocation Methods

This chapter introduces the current methods to allocate spectrum. These methods include spectrum auctions and spectrum sharing and how these methods are managed and regulated.

2.1 Introduction

The electromagnetic spectrum (henceforth spectrum) is the full range of all frequencies generated by electromagnetic radiation.

The full spectrum includes not only radio waves, which are the subject of this thesis, but also infrared, ultraviolet, X-rays, gamma rays and others [9] as shown in Figure 1. All these electromagnetic waves are effectively photons, each traveling in a wave-like pattern, carrying energy, moving at the speed of light, and able to be used for a variety of applications including wireless communications [10]. Of particular importance to communications is the radio frequency spectrum, as shown in Figure 2, in which frequencies or spectrum is assigned to particular radio communication applications.

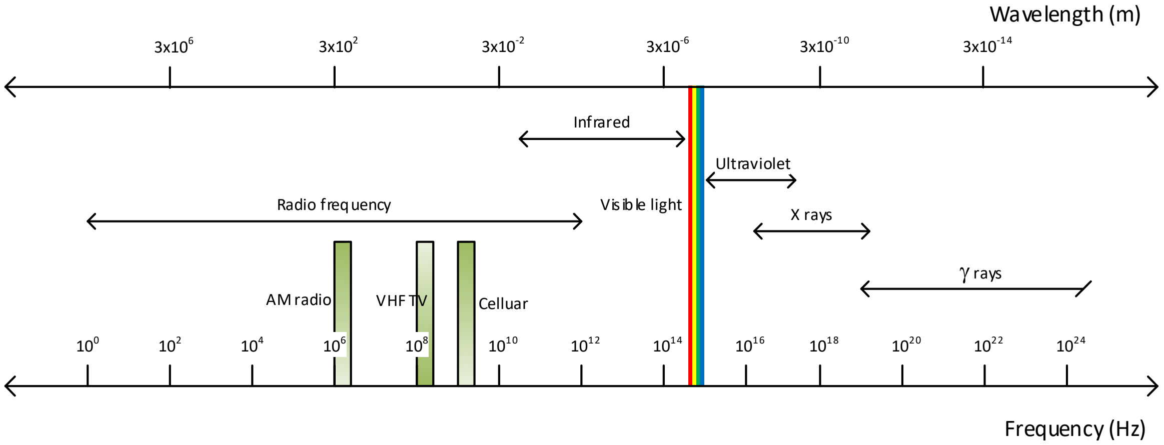

Figure 1. The electromagnetic spectrum.

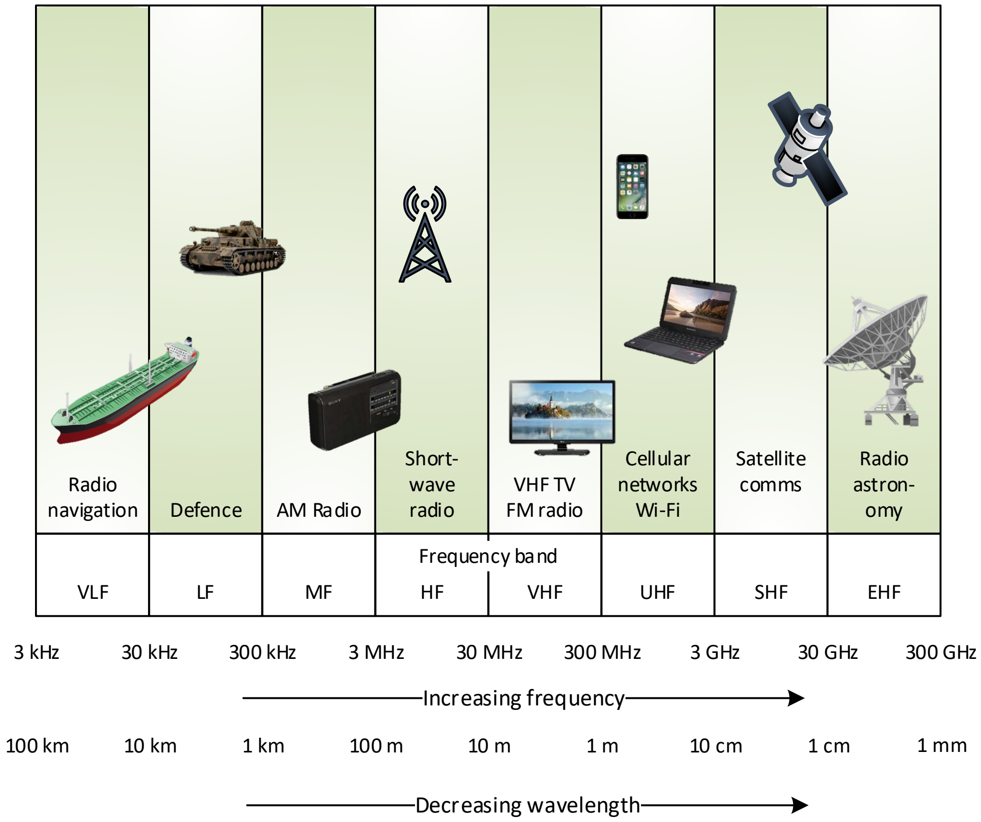

Figure 2. Radio frequency bands and examples of applications using specific bands of frequencies.

All wireless communications require spectrum to operate. As a resource, spectrum can be bought, sold and traded as a management right. For example, your favourite radio station has an assigned frequency or part of the spectrum and you tune into this part of the band. Similarly, as shown in Figure 2, TV transmission is assigned frequencies in a slightly higher part of the spectrum and mobile radio or cellular radios higher still. The assignment and management of spectrum in New Zealand is done by the Radio Spectrum Management group (RSM) within the Ministry of Business, Innovation and Employment (MBIE) [11].

It was only in the 19th Century that the electromagnetic spectrum was shown to be more than just visible light. In the 1860’s James Maxwell's equations predicted an infinite number of frequencies of electromagnetic waves, all traveling at the speed of light. This was (one of) the first indications of the existence of the entire electromagnetic spectrum [12]. Attempting to prove Maxwell's equations and detect such low frequency electromagnetic radiation, in 1886 the physicist Heinrich Hertz built an apparatus to generate and detect what is now called radio waves [13]. The unit of frequency of a radio wave is named the Hertz, in honour of him.

Later in the mid 1890's, M. G. Marconi devised a method for using radio waves for commercial wireless telegraphy [14]. By 1895 Marconi was field testing his system and was capable of transmitting signals up to 3.2 km [29]. Marconi's experimental apparatus proved to be the first engineering-complete, commercially successful radio transmission system, and was famously used to help save some of the survivors of the Titanic.

Spectrum allocation methods progressed from these early inventions. Up to the mid-20th century spectrum was heavily regulated and channel allocations came in a first come first served basis. Ronald Coase in 1959 presented the argument for an efficient market based on property rights in radio spectrum [15] — where central planning and regulation are inferior to the price mechanism. This was one of the first steps on the road to auctioning spectrum and was famously initially rebutted by the FCC [16], but auctions later became the default method to allocate spectrum.

The work of L. Friedman in 1956 was also important, developing auction strategies on first price sealed-bid auctions. He developed the profit expectancy [17] in his operations research on competitive bidding strategy. A few years later in 1961 W. Vickrey proposed the problem differently using game theory [18]. Vickrey like Marconi and many of these other notables received the Nobel Prize for their work.

2.2 Radio spectrum management

The 'command and control' management approach is the one currently employed by many regulators around the world. This approach advocates that the regulators be the centralized authorities for spectrum allocation and usage decisions.

The allocation decisions are often static in temporal and spatial dimensions, meaning that they are valid for extended periods of time, usually decades, and for large geographical regions, often country wide. The usage is often set to be exclusive; each band is dedicated to a single provider, thus allowing interference to be easily managed between limited users of this and adjacent spectrum bands. The command and control management model dates to the early days of wireless communications, when the technologies employed required interference-free mediums to achieve acceptable quality.

Modern spectrum allocation techniques still use command and control structure, where spectrum usage is controlled by a regulator, but techniques such as the use of market based or technology based allocation methods are allowing the use of unlicensed bands, moving the day-to-day management of spectrum to the end user, with regulators still controlling the overall strategy of spectrum allocation.

When evaluating administrative spectrum allocation techniques, research often refers to the two prevailing historical models - the "spectrum commons" and the "spectrum property rights" approaches [19]. The spectrum commons theory states that radio spectrum should be directly managed by its users rather than regulated by government ministries. An example of a spectrum commons is the use of the general user radio license or the use of unlicensed frequency bands. The original use of the term "the commons" was where the public had rights regarding use of property reservations - each person had access to commons, but these were not treated as property, nor were the rights "property" since they could not be traded. The term "tragedy of the commons" was popularized by Garrett Hardin [20]. The tragedy of the commons illustrates that destructive use of public reservations ("the commons") by private interests can result when the best strategy for individuals conflicts with the common good.

The "spectrum property rights" model advocates that the spectrum resources should be treated like land, i.e. private ownership of frequency bands should be permitted. The allocation of spectrum should be implemented by means of market forces, for example the owners should be able to trade spectrum in secondary markets. In addition, spectrum owners should be able to use any technology they prefer in their frequency band, to be application and technology neutral.

Modern spectrum allocation techniques are not quite a true spectrum property right but have different aspects of both commons and property rights in different allocation techniques. For example, although the spectrum property rights model advocates exclusive allocation of transmission rights, it is not the same as a licensed regime. The main difference is the application and technology neutrality advocated in the spectrum property rights approach, as opposed to requirements on services and communications technologies inherent in most licensed governance regimes.

These modern methods to allocate spectrum can be divided into three different techniques. These methods include:

1. Administrative spectrum allocation, including comparative tenders and administrative regulation.

2. Market-based spectrum allocation, including spectrum auctions and spectrum trading.
3. Technology-based spectrum allocation, including spectrum mobility, spectrum databases and equipment specific allocation techniques.

These spectrum allocation techniques are illustrated in Figure 3. Following one of these paths demonstrates how spectrum is allocated.

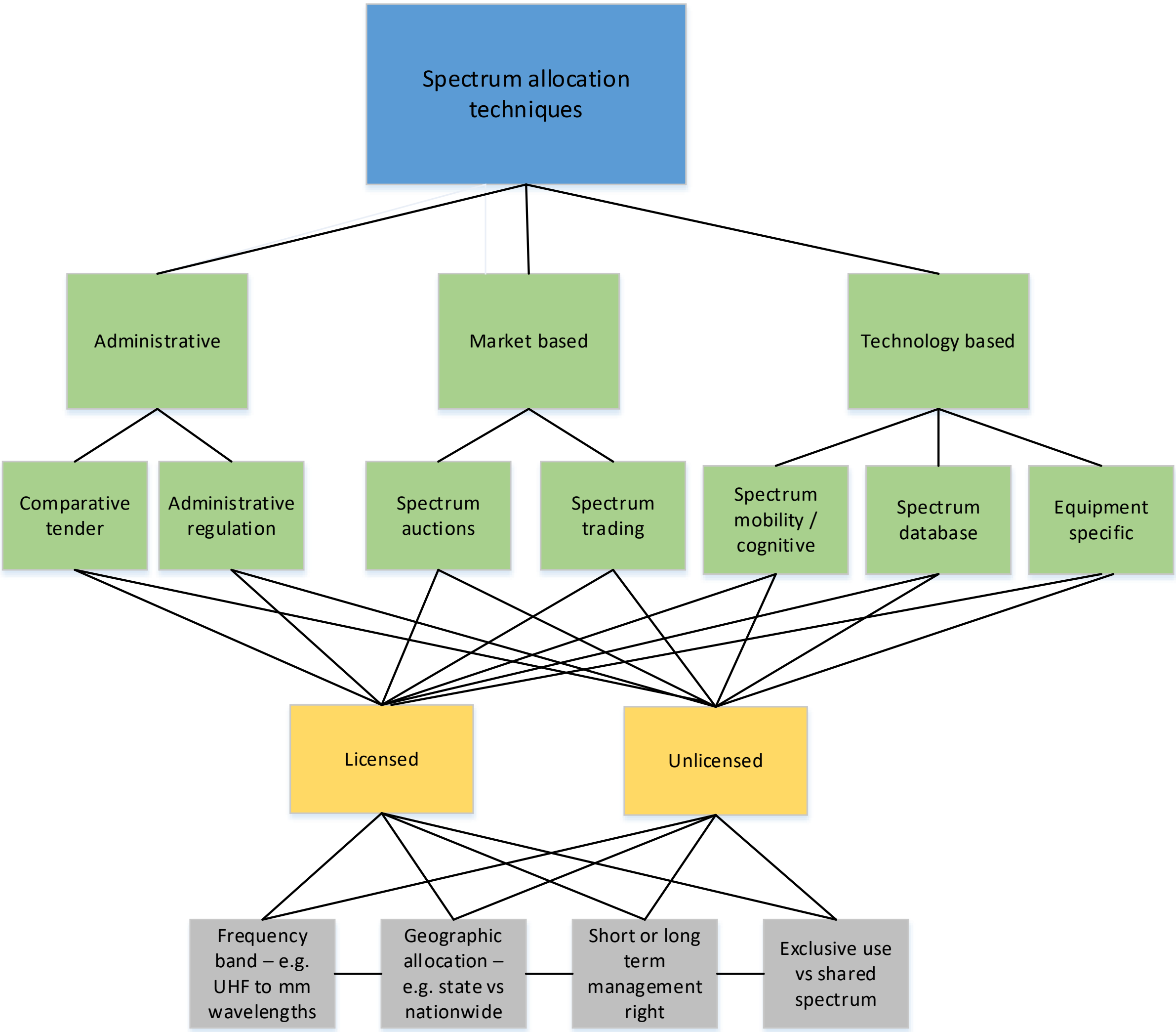

Figure 3. Spectrum allocation techniques.

Spectrum is allocated by following one of these paths. For example, spectrum for cellular networks is generally allocated using market based, spectrum auctions and is licensed, using frequencies in the UHF band, nationwide for a near 20-year management right in an exclusive use license. Spectrum for Wi-Fi networks is technology based, using equipment specific sharing techniques which limits the power (EIRP) of these radios, is unlicensed using the ISM frequency band (e.g. 2.4 GHz), is used nationwide using a general use long term management right, and is using shared spectrum.

The lower layer in Figure 3 is most important for the technical side of cellular networks that is the more specific spectrum allocation of: what frequency band is allocated; the geographical area where the spectrum is to be used; if this is a short-term or long-term management right and; if the spectrum is exclusive use or shared. These items shown in grey on the last line in Figure 3 are the subject of much of the research presented in this thesis.

More information on these spectrum allocation techniques is given in the sections below.

2.3 Administrative spectrum allocation

In the late 19th century the rights to access and use spectrum started to be regulated [21]. Regulation was introduced with the intent to minimise the risk of interference between different radio systems [22]. In addition, regulators were seeking to internationally harmonise the use of radio spectrum allowing inter-country communication. This also allowed technology (radio) standardisation allowing economies of scale in manufacturing [23]. Initially the regulation of spectrum allocation was administration based, radio licenses offered free of charge, on a first come first served basis or by means of a ‘beauty contest’.

In a beauty contest (also known as comparative tender), a committee typically sets several criteria to assign spectrum. Criteria may include available financial resources, reliability and investment in radio, and the requirement for geographic and/or population coverage, for example. Offers are evaluated and the candidate that meets these criteria is awarded the rights to use specific spectrum. Over time this administrative approach to assign spectrum showed flaws such as political or individual interference, or radio spectrum misallocation in assigning spectrum [24].

The traditional, administrative approach to spectrum policy is for a regulator to award an exclusive use management right to use spectrum for a particular purpose. The use will be subject to some engineering constraints such as power level control, guard bands and emission control of out of band transmissions. Exclusive use of a specific spectrum band allows operators to manage interference to other spectrum users. The downside is that this spectrum can be expensive both in the cost of spectrum itself and the associated hardware and software infrastructure to rollout a cellular network.

An alternative is to use unlicensed spectrum or a general user radio license. This means that there is no spectrum license to use a particular spectrum band although there are engineering constraints in the use of unlicensed band, such as power level controls (e.g. the 4W EIRP limit specified for Wi-Fi use). Examples of unlicensed bands included the ISM bands (Industrial, Scientific and Medical bands) used in cordless phones and for Wi-Fi. The downside is that interference between unlicensed devices is common and difficult to manage. Spectrum sharing is covered in more detail in later sections.

2.4 Market-based spectrum allocation

In the 1990's a new regulatory approach to assign spectrum became widespread. Spectrum management rights started to be assigned by auction. In general (although not always) licenses are assigned to auction bidders who are willing to pay the most for the spectrum. Market mechanisms, such as auctions, became an efficient spectrum assignment method. However, market mechanisms also have drawbacks. Auctions have sometimes led bidders to overpay for spectrum, sometimes auctions with high reserves have been used by Governments to extract revenue from operators, and auctions allow incumbents to preserve status-quo and fend off potential new market entrants.

2.4.1 Spectrum auctions

The 1990's bought about the first spectrum auctions as a method to sell spectrum rights [25]. Initially these were the simultaneous ascending auctions [26] but later other types of auctions were used including the Vickrey [27], sealed first price auction [28], and others [29]. More recently the combinatorial clock auction [30], [31], [32] and [33] has been used, good examples of which are the 700 MHz auction in New Zealand [34] and in the United States [35]. The analysis of which auction method is best has also generated significant literature, such as approaches to winning play in spectrum auctions [36] and [37], the winner's curse [38] and other equilibria behaviour in auctions [39].

There are many different types of auctions types for spectrum auctions. These spectrum auctions generate significant income for governments. In the 700 MHz auction alone, 19 billion US dollars was generated in the US, and almost 300 million NZ dollars was generated in New Zealand [34] and [35]. When these auctions first started, the auctions were the traditional ascending auction – similar to an auction for a house and property in New Zealand for example. But more recently different types of auction have been used to allocate spectrum.

Typical auctions include:

- Combinatorial Clock Auction (CCA). Where bids are placed on packages of 'goods'. Typically, CCA auctions comprise of three phases:
    - Clock phase – where for a given price, bidders will state how many blocks they want to purchase. Price ascends for each block while demand is greater than supply.
    - Supplementary round – was used in NZ to assign additional frequency in the 700 MHz band as supply was greater than demand [34].
    - Assignment round – where the optimal packages are assigned to successful bidders.
- English Auction, also known as the open ascending price auction [26].
- Dutch Auction, also known as the open descending price auction.
- Sealed First Price Auction, simultaneous sealed bid, in New Zealand these are called closed tenders [28].
- Vickrey Auction, sealed bid second price auction where the winner bidder pays the price of the second highest bid [27].
- VCG Auction (Vickery-Clark-Groves), is a multiple item, sealed bid auction, where each bidder submits a valuation for the items without knowing the bids of others in the auction. Winners pay the opportunity cost for items which equals the total bids of all other bidders that would have won the auction minus the total of the actual winning bid.
- Spectrum Incentive Auctions consist of both reverse (selling) and forward (buying) auctions. The incentive auction will allow sellers to bid to relinquish their spectrum rights in exchange for a share of the proceeds from an auction of the repurposed spectrum to parties who will bid on licenses for future use [40].

The most recent spectrum auction in New Zealand, in late 2013 to early 2014 used the combinatorial clock auction. In this case, spectrum was won by the three main operators Spark (previously Telecom), Vodafone and Two Degrees Mobile to rollout a 4G or LTE network. These operators won 20, 15 and 10 MHz of paired spectrum respectively. This means that Spark will have the capability to offer the highest data rates on their LTE network, then Vodafone and then Two Degrees Mobile – all other items in the network being equal. The last point means there are other potential points in the network that can limit capacity as described in Chapter 3.

Another example of a spectrum auction in New Zealand was the 900 MHz auction in 1990 which was a Vickrey auction. In this Vickrey auction there were seven frequency licenses to be sold and as per Vickrey auctions the winner didn’t pay the highest bid price but paid the second highest bid price. This caused some political controversy at the time due to the fact that for some of these frequency licenses the highest bid price far exceeded the second highest bid. In one example Telecom bid $7 million for a specific frequency license but had to pay only $5,000, the second highest bid (from Broadcast Communications Limited).

2.4.2 **Spectrum trading**

Operators can trade spectrum or spectrum management rights by purchasing spectrum from each other (following regulator guidelines), exchanging or swapping spectrum from different bands with each other or selling or returning unused spectrum back to the regulator. The spectrum trading problem has been modelled as a monopoly market in [41] in which the primary owner of the spectrum is responsible for setting the price and the quality of the spectrum being granted. The secondary user decides on purchasing the spectrum according to the right price, the quality, its own demand and the conditions laid down by the primary user.

Spectrum leasing is where an operator has the management right to use spectrum but decides to make available some part of this spectrum to a third party in return for some commercial gain. This is also called dynamic spectrum leasing. Various models have been formulated where spectrum leasing occurs, for example [42].

2.5 Technology-based spectrum allocation

More recent forms of spectrum regulation have a strong focus on using technology to allocate spectrum. More sophisticated radio equipment, for example cognitive radios, are bringing more opportunities to share spectrum. Modern databases and spectrum tracking techniques also allow more advanced spectrum sharing techniques - based on tracking where spectrum is geographical unused and available to be shared.

2.5.1 **Spectrum sharing**

There are many different models describing the best methods to share spectrum. Some of the literature states that spectrum sharing is likely for 5G cellular networks [43]. Others look at the economics of spectrum sharing [44], how contracts could be designed [45] and how game theory can be used to assign spectrum for dynamic spectrum access [46] or how secondary auctions can be used to share spectrum [47] and [48].

In general literature describes four main methods to share spectrum. These methods include:

- The increased use of unlicensed bands [49] and [50].
- Combining spectrum from licensed band operators to more efficiently use the resource [51].
- Cognitive radio approach, where technology is used to determine underutilised spectrum that can be used by other operators [52], [53] and [54].
- Geographical databases used to track areas where spectrum is likely to be unused e.g. TV white spaces [55].

Overall most of this literature agrees that there is a simple fact that there is not enough available (currently unused) spectrum at lower frequencies, currently desired by cellular operators to meet the future needs for wireless services. However, most of the literature cannot agree on the best method to allocate this spectrum.

2.6 Current methods to allocate spectrum for cellular networks

Of particular interest to this research is how spectrum is allocated for cellular networks. Referring back to Figure 3, spectrum allocation techniques, it can be seen that even after the general techniques are defined to allocate spectrum these techniques are refined to more specific spectrum allocation techniques including: what frequency band is allocated, the geographical area where the spectrum is to be used, if this is a short term or long term management right, and if the spectrum is exclusive or shared use. These items are described in the sections below.

2.6.1 **Frequency bands**

Spectrum is currently managed by dividing the spectrum into groups of different frequency or wavelength ranges, known as ‘bands’, a designated use assigned to each band. These bands (in general) follow international standards specified by either the ITU or the IEEE. These bands range from extremely low frequency (ELF) used in communications to submarines to tremendously high frequency (THF) used in applications like medical imaging as shown in Table 1.

Band name	Abbreviation	Frequency	Wavelength
Extremely Low Frequency	ELF	3–30 Hz	100,000–10,000 km
Super Low Frequency	SLF	30–300 Hz	10,000–1,000 km
Ultra Low Frequency	ULF	300–3,000 Hz	1,000–100 km
Very Low Frequency	VLF	3–30 kHz	100–10 km
Low Frequency	LF	30–300 kHz	10–1 km
Medium Frequency	MF	300–3,000 kHz	1,000–100 m
High Frequency	HF	3–30 MHz	100–10 m
Very High Frequency	VHF	30–300 MHz	10–1 m
Ultra High Frequency	UHF	300–3,000 MHz	1–0.1 m
Super High Frequency	SHF	3–30 GHz	100–10 mm
Extremely High Frequency	EHF	30–300 GHz	10–1 mm
Tremendously High Frequency	THF	300–3,000 GHz	1–0.1 mm

Table 1. ITU frequency band designation.

Frequencies for cellular network use are often allocated as paired spectrum, with a block of spectrum in the lower frequency band and an associated block of spectrum in an upper frequency band. With frequency division duplex (FDD) one band is used for the uplink (mobile (or UE) to base station) and one is used for the downlink (base station to mobile). The uplink and downlink bands are separated by a frequency offset called the duplex distance. Figure 4 shows how spectrum is allocated for 3G and 4G in paired spectrum blocks.

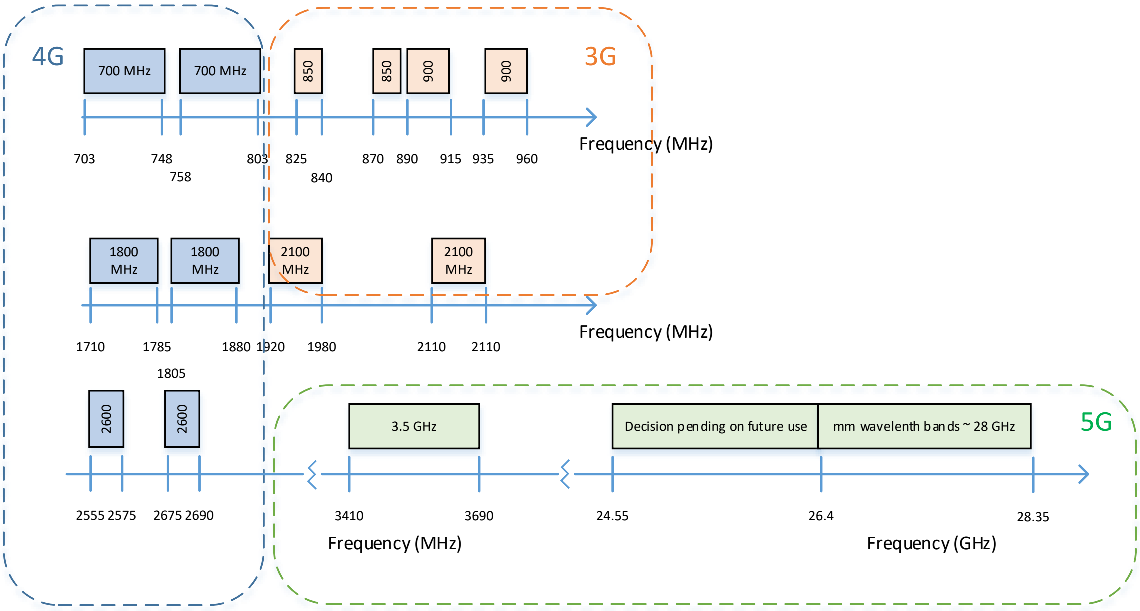

Figure 4. Spectrum used in New Zealand for cellular networks.

Spectrum allocation in New Zealand for cellular networks generally operates in the Ultra High Frequency (UHF) band (300 – 3000 MHz) as shown Figure 4. The exact frequencies used change with time and are slightly different depending on the exact operator (for example Vodafone NZ uses spectrum at 2600 MHz for 4G where-as the other operators use only 700 and 1800 MHz bands (to date)). Also shown in Figure 4 is the spectrum planned for 5G in New Zealand. This is based on a recent discussion document [56] and is subject to change and is discussed in later chapters of this thesis.

2.6.2 Management right

Currently spectrum for cellular networks is allocated in spectrum auctions in New Zealand. These auctions are run for a nationwide spectrum license for a long-term management right. Typically, the management right is for 18-20 years, and the spectrum license is for exclusive use, which means no other operator can use that particular spectrum. This is typically enforced by the operators themselves, with major disputes going to the court of law. The guidelines for the use of spectrum is set by Radio Spectrum Management (RSM) who set items like the maximum power, spectrum emissions and guard bands. More recently RSM have also set rollout guidelines with winners of spectrum licenses set coverage requirements for example 94% population coverage for new LTE licenses [34].

2.6.3 Geographical areas

Spectrum is usually assigned for large geographical areas. In New Zealand, for example, spectrum for cellular networks is typically assigned for nationwide use. In the United States spectrum is either assigned by large geographic areas such as per state or again for nationwide use.

2.6.4 Exclusive or shared use

Spectrum used for cellular services including voice, on-net data, video and messaging, uses exclusive use spectrum - that is spectrum dedicated for use solely by a particular cellular operator. However cellular *devices* also use Wi-Fi networks, which are unlicensed, that is spectrum is shared with other Wi-Fi equipment. This data is sometimes called off-net use.

2.7 Spectrum pricing

It is important to understand how different methods to allocate spectrum affect the price of spectrum. The price ultimately determines how affordable spectrum can be and influences the net social benefit of spectrum allocation - to maximise the value that society gains from the radio spectrum by allowing as many efficient users as possible while ensuring that the interference between different users remains manageable.

Recently a series of publications on communication networks with series editor J. Walrand [57] has specialised on wireless network pricing research. A good example from this series is Huang [58]. Other literature looks at pricing specifically of electromagnetic spectrum. The Smith-Nera method [59] is a pricing algorithm used to calculate spectrum prices based upon opportunity costs. Work by Bazelon et al [60] also looks at the value of spectrum in a discounted cash flow method. Doyle uses the incentive mechanism [61] to calculate value. These works have an underlining idea that radio spectrum is a scarce resource and understanding its economic value is one piece of information needed to manage it efficiently.

The economics work on game theory has contributed greatly to the theory of auctions and spectrum pricing. Game theory is the mathematical study of decision-making strategies in an interactive situation. Modern game theory usually traces its roots to the seminal "Theory of Games and Economic Behaviour", by John von Neumann and Oskar Morgenstern, published in 1944 [62]. Of particular interest in game theory is particular sets of strategies known as equilibria in games. When no player can reach a better outcome by switching strategies, the game reaches an impasse called the Nash Equilibrium, [63] and [64]. Modern game theory and game modelling has become a core tool to understand the winning play in spectrum auctions [65], [66], [67] and the application of game theory to wireless networks has also become a hot topic in literature [68], [69], [70], and [71].

2.8 International regulators

The International Telecommunication Union (ITU) is the part of the United Nations that helps set policy on the use of spectrum in the radio frequency band. The first sentence of the International Telecommunication Union (ITU) constitution fully recognises "the sovereign right of each State to regulate its telecommunication". Effective spectrum management requires regulation at national, regional, and global levels [72].

The ITU is divided into three Sectors. The first is the Radiocommunication Sector (ITU-R) which determines the technical characteristics and operational procedures for wireless services and plays a vital role in spectrum management of the radio frequency band. The Telecommunication Standardization Sector (ITU-T) develops internationally agreed technical and operating standards and the last sector is the Telecommunication Development Sector (ITU-D) that fosters the expansion of telecommunications infrastructure in developing nations throughout the world. The ITU Radio Regulations set a binding international treaty governing the use of the radio spectrum by some 40 different countries.

Most countries will have a spectrum regulator to control spectrum allocation. The frequency assignment authority is the power granted for the administration, designation or delegation to an agency or administrator via treaty or law, to specify frequencies, frequency channels or frequency bands, in the electromagnetic spectrum for use in radio communication services, radio stations or industrial, scientific or industry applications. In the US example, the Federal Communications Commission (FCC), as the regulator, determines how spectrum will be allocated and used. In the UK the regulator is Ofcom, ACMA is the Australian Communications and Media authority and in New Zealand spectrum is administrated by Radio Spectrum Management (RSM).

2.8.1 **European Union**

In Europe each country has regulatory input into the progress of European and International spectrum policy, standards, and legislation, governing spectrum allocation through their respective spectrum regulator.

Spectrum management for Europe is driven by several organisations. These include the European Conference of Postal and Telecommunications Administrations (CEPT) and the European Radiocommunications Office (ERO). Many countries in Europe have local spectrum management regulators. Ofcom is the independent regulator and competition authority for the UK communications industries. Ofcom recently published two reports the first on the mobile data strategy [73] and the second on the increased use of spectrum sharing [74] for mobile and wireless data. Both reports detail information on spectrum management for the UK. The report on mobile data strategy confirmed the growth in demand for mobile broadband capacity but also made the point that there are other demands for spectrum and that demand from other services is either increasing or remaining static. They also pointed out how much industry is now reliant on good cellular services, including high speed data rates.

2.8.2 **United States**

In the United States, primary spectrum authority is exercised by the National Telecommunications and Information Administration (NTIA) for the Federal Government and by the Federal Communications Commission (FCC) for non-Federal Government organizations.

A ‘report to the president’ in the US seeking to realise the full potential on Government held spectrum to spur economic growth [75], confirms the growth in global mobile data and states that finding spectrum to meet this demand is expensive and time consuming. In March of 2012, the NTIA concluded that clearing just one 95 MHz band by relocating existing Federal users to other parts of the spectrum would take 10 years, cost some $18 billion. Taking these and other developments into account, this report argues “that spectrum should be managed not by fragmenting it into ever more finely divided exclusive frequency assignments, but by specifying large frequency bands that can accommodate a wide variety of compatible uses and new technologies that are more efficient with larger blocks of spectrum”.

2.8.3 **Australia**

ACMA, the Australian Communications and Media authority commissioned two reports into the pricing and economics of spectrum management [76], [77]. One of the findings was that ‘policy making would benefit from a larger array of spectrum management options than the binary policy choices currently examined’. This confirms the research aim of this thesis to recommend new spectrum allocation methods for cellular networks.

2.9 Why cellular operators need spectrum

Cellular operators need more spectrum because the number of wireless devices and the data transmission rates from these radio devices is significantly increasing. This is important because the higher the data rates typically the more spectrum is required. This is perhaps best seen in the data rates of each generation of cellular networks. The 2G or second-generation networks started with a data rate of 14.4 kbit/s on the downlink and recent LTE or 4G networks now have the ability to transmit up to 326 Mbit/s. This is a 22,500 times increase in data rates in approximately 20 years. This matches the approximate 50% increase in data traffic per year seen in [78] and [79].

To meet this demand, cellular companies are demanding that greater amounts of spectrum be allocated for cellular use. Greater amounts of spectrum is desired by cellular companies for two main reasons:

- This allows for different types of technologies or generations of cellular networks to be used at the same time – for example GSM, UMTS and LTE networks run concurrently.
- This allows for greater transmission rates within each technology type. The maximum data rates from each technology type is limited by the spectrum available for use in that band.

However, the problem is that spectrum is a finite resource, with limited availability. This is especially true at the low frequencies desired by cellular operators. Typically, the lower the frequency the greater the range of the signal and the more desirable the spectrum. However, this is offset by the fact that most if not all spectrum at lower frequencies has already been allocated.

This leads to the next chapter. Future wireless services and the associated spectrum implications.

Chapter 3. Wireless Services in Cellular Networks

This chapter seeks to establish a vision for cellular networks for 2020 and beyond by describing user, application and technology trends, the coverage and capacity requirements and the associated spectrum implications.

It is important to do this research because in order to determine the best spectrum allocation method it is necessary to know how this spectrum will be used for future wireless services.

3.1 International mobile telecommunications for 2020 and beyond

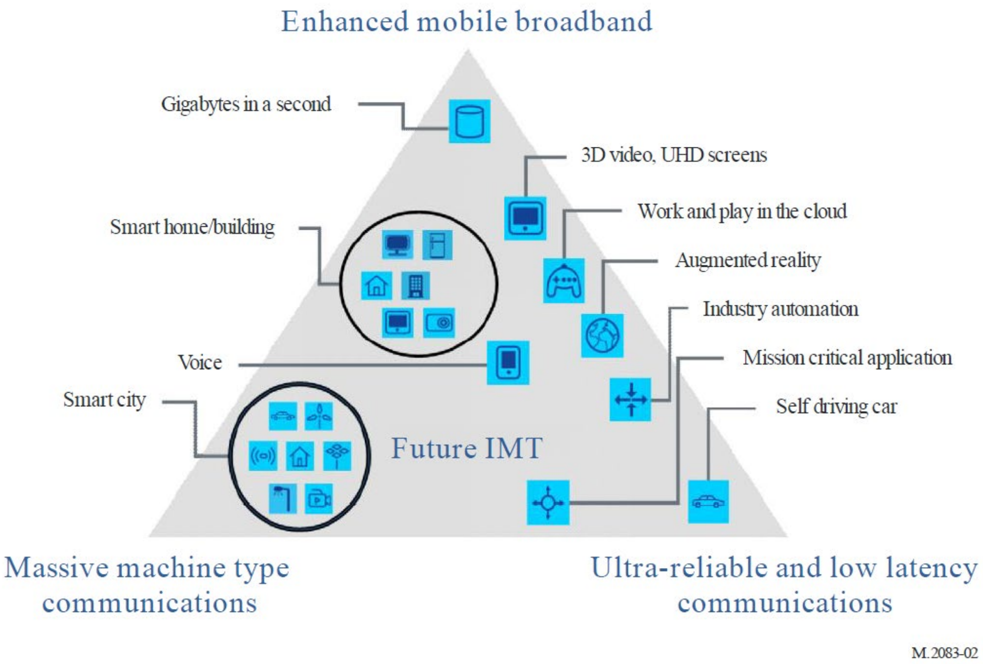

Figure 5. Usage scenarios of IMT for 2020 and beyond [80].

The future demand for mobile teleconnections from cellular networks can be divided into three directions, as shown in Figure 5, these are:

- Enhanced mobile broadband services. These shows the demand for higher capacity or data rates, such as the increasing use of ultra-high-definition video, data storage in cloud-based systems, and increasing use of augmented and virtual reality.

- Ultra-reliable and low latency communications. This shows the demand for services such as self-driving cars, and the reliability for emergency services and other mission critical services using cellular networks.
- Massive machine type communications. This shows the demand for IoT (Internet of Things) networks for devices such as home appliances and devices in cities (lights, bins etc) that contain electronics, software, sensors, actuators, and connectivity – IoT allows these things to connect, interact and exchange data.

These are described in more detail below.

3.2 Enhanced mobile services

The change from 4G[1] to 5G will see a continuing demand for high capacity data to meet the needs of an increasing population and increasing demand for enhanced mobile services. Cisco [81] forecast that global mobile data traffic will grow at a Compound Annual Growth Rate (CAGR) of 46 percent between 2017 and 2022, reaching 77.5 exabytes per month by 2022 (one exabyte is equivalent to one billion gigabytes). This trend of increasing traffic is shown in Figure 6.

This huge demand in capacity has a direct relationship with the amount of spectrum required. The Shannon Hartley theorem [82] shows that the greater the bandwidth available then the greater the maximum capacity achievable i.e.

$$C = B \log_2 (1 + S/N) \tag{1}$$

Where C is the channel capacity, B is the bandwidth of the channel and S/N is the signal-to-noise ratio (SNR). Sometimes the SNR is expressed as the carrier to interference ratio. This

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[1] G standards for generation, 4G for example is the fourth generation of cellular technology as defined by the radio sector of the ITU-R (International Telecommunications Union). The ITU-R set standards for 4G connectivity, requiring all services described as 4G to adhere to a set of speed and connection standards. For cellular use, including smartphones and tablets, connection speeds need to have a peak of at least 100 megabits per second, and for stationary use (for example mobile hot spots) at least 1 gigabit per second.

means to meet the high demands for capacity either, by the Shannon Hartley theorem, more spectrum is required or the signal to noise ratio must improve.

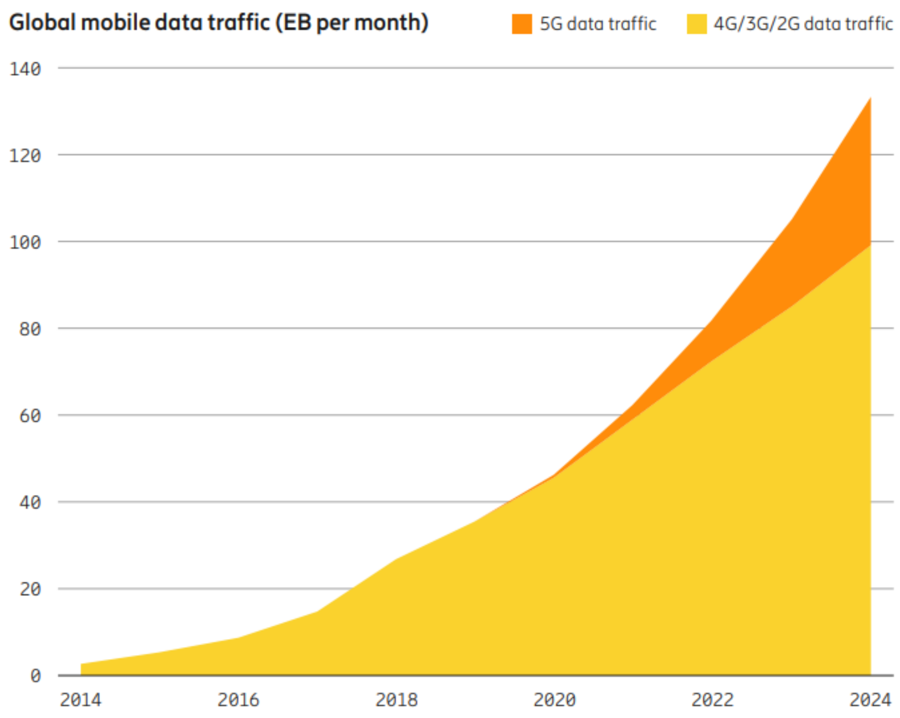

Figure 6. Global mobile data traffic [83].

This demand is currently driven by the increasing popularity of multimedia applications and the widespread penetration of smart phones and tablet devices. In addition, high definition video (e.g. 4K video) and the increasing population with high cell phone usage means that the amount of traffic carrying these services is increasing almost exponentially each year. Future wireless services such as virtual reality and augmented reality will only increase the amount of traffic or data rates on cellular networks.

3.3 Ultra-reliable and low latency communications

There is a further demand for ultra-reliable and low latency communications to provide services including driverless cars, enhanced mobile cloud services, real-time traffic control optimization, emergency and disaster response, smart grid, e-health and efficient industrial communications. Many of these services also require good cellular coverage in areas where traditionally cellular operators have not provided services [84]. For example emergency services and driverless cars may require coverage in very remote areas away from the high population areas currently covered with cellular services.

To meet these demands a cellular network needs to be upgraded to support low latency (a change from 10ms in 4G based cellular networks to 1ms in 5G and beyond) and high capacity (the user experienced data rates will increase from 10s of Mbit/s to 100s of Mbit/s and peak data rates from 1 to 20 Gbit/s). These enhancements of key capabilities are shown in Figure 7. In addition, the coverage in terms of geographic area will change from approximately 50% coverage to around 80% coverage depending on each country[2]. This is seen in New Zealand as new geographic coverage proposed for emergency services [84] and under the Rural Broadband Initiative [85].

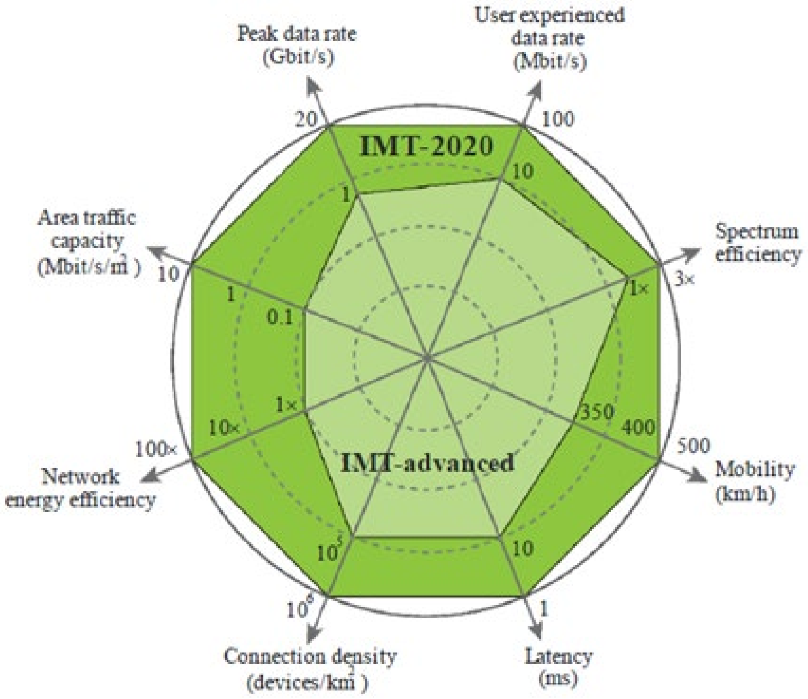

Figure 7. Enhancement of key capabilities from IMT-Advanced (4G) to IMT-2020 (5G) [80].

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[2] Most cellular operators target coverage to large population centres but frequently do not provide coverage to remote rural areas. A country like New Zealand may have 94% coverage by population but only 50% coverage by geographic area.

3.4 Massive machine type communications

The Internet of Things (IoT) refers to the concept of extending internet connectivity beyond conventional computing platforms such as PC's and mobile devices, and into any range of traditionally non-internet-enabled physical devices and everyday objects. In the majority of cases these devices will connect via wireless networks. We have seen that the future demands for capacity are driven by the demand for video and future wireless services like augmented and virtual reality, but the machine-to-machine communications on IoT networks is driving the next big acceleration in the volume of connected devices.

From a technology point of view, there are two main IoT network types, namely Narrowband IoT (NB-IoT) and Long-Range Wide Area Networks (LoRaWAN).

NB-IoT is an initiative by the Third Generation Partnership Project (3GPP), the organization behind the standardization of cellular systems, to address the needs of very low data rate devices that need to connect to mobile networks. As a cellular standard, the goal of NB-IoT is to standardize IoT devices to be interoperable and reliable. NB-IoT uses licensed spectrum, for example the LTE Cat-M1 network used by Spark in New Zealand, operating at 700 MHz (band 28) and 1800 MHz (band 3).

LoRaWAN is the protocol for WAN communications and LoRa is used as a wide area network technology. LoRaWAN uses unlicensed spectrum, which means an owner can setup and manage a private network, for example the network used by Kordia in New Zealand, operating at ~900 MHz. LoRa devices work well when they are in motion, which makes them useful for tracking assets on the move, such as shipments. LoRa devices typically have longer battery life than NB-IoT devices.

As shown in Figure 7 the effect of IoT devices (especially NB-IoT) on cellular networks will be to increase the number of connected devices from approximately 10^5 devices per km^2 to 10^6 devices per km^2 (in the near future) and the area traffic capacity or density of traffic will increase from 0.1 $Mbit/s/m^2$ to 10 $Mbit/s/m^2$.

3.5 Cellular networks

Spectrum is not the only component that will limit the capacity achievable on a cellular network. The radio access network (RAN) and Core partnership will determine the maximum capacity rates either through limits set up the cellular operator but also with maximum limits based on the technology used in the RAN e.g. LTE vs UMTS (see Appendix A for more information). The transmission network can also limit the capacity achievable, with both digital microwave radio and fibre optic limits set by the technology used. The technical components of the cellular network are shown in Figure 8, and include:

- Radio Access Network (RAN). The area of the network from the base station to the cell phone (sometimes called the 'last mile' access).
- Transmission – sometimes called backhaul. The area of the network from the base station to the Core. Often will use Optic Fibre or Microwave links to provide backhaul communications.
- The Core or Evolved Packet Core (EPC). The area of the network used to manage network traffic - offers gateways to other voice and data networks, authentication and tracking of users, Quality of Service (QoS) and policy enforcement.

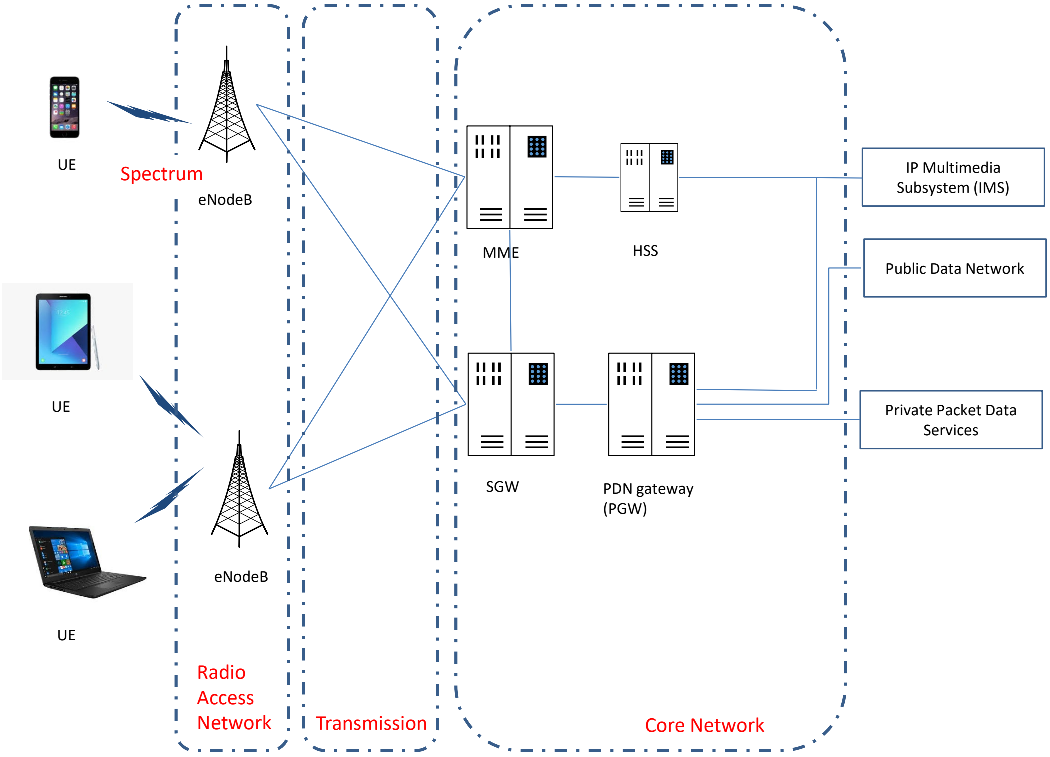

Figure 8. A 4G example of sources of data 'bottlenecks' in cellular networks. This includes Spectrum, Radio Access Networks, Transmission and Core Networks.

The 4G or LTE architecture as shown in Figure 8 is key to understanding how spectrum is used in these networks. It is important to know the functions and cost of each of the RAN, Transmission and Core components of cellular networks, since to determine the value of spectrum many of the valuation techniques for spectrum require accurate costs of the whole cellular network. To accurately cost the whole cellular network requires a thorough understanding of all its components, including number of units and when these need to be upgraded to meet future demands for coverage and capacity. The value of spectrum is important in determining the best method to allocate the spectrum, with high values stopping many smaller companies from being able to afford this resource. This is discussed in more detail in Chapter 8.

Therefore, a description of the key components of cellular networks is needed and is described below.

3.5.1 **Radio Access Networks**

The Radio Access Network (RAN) is the radio air interface between devices like smart phones and tablets to base stations (called eNodeB's). The RAN provides radio functions such as modulation, filtering and signal amplification but more specifically for cellular networks provides radio and packet processing and radio control functions.

The RAN (and Core) forms the basis of network upgrades and evolution to provide more capacity and cellular services, RAN technologies include:

- 2G networks use GSM (Global System for Mobile communication) or IS-95 / CDMA 2000 (Interim Standard 95). Both standards are voice centric and are circuit-switched but both have expanded over time to include limited data services.
- 3G networks use UMTS (Universal Mobile Telecommunications Service). A broadband, packet-based network allowing transmission of text, voice, video, and multimedia at data rates typically up to 2 Mbps.
- 4G networks use LTE (Long Term Evolution) - a standard for wireless broadband technology that offers increased network capacity over 3G, generally defined as offering data rates up to 100 Mbps downstream and 30 Mbps upstream[3].

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[3] Throughout this thesis different data rates are specified. These can be peak (the maximum achieved), at the edge (at the cell edge, typically the minimum achieved), or typical (what an average user will experience).

3.5.2 **RAN specifics for LTE networks**

The radio control function (RCF) is part of the LTE RAN and handles the load sharing and handover among different system areas and different radio technologies and controls the overall RAN performance. The packet processing function (PPF) handles the signal encryption and data scheduling and the multipath handling function for the dual connectivity anchors. Finally, the radio processing function handles the radio scheduler and is responsible for the selection of the MIMO scheme and the beam and antenna elements.

The modulation used on eNodeB's on LTE networks, uses OFDMA (orthogonal frequency-division multiple access) on the downlink and SC-FDMA (single carrier – frequency division multiple access) on the uplink.

OFDMA provides high data rates by using a large number of carriers, each carrying low bit rate data but combined allows high capacity networks. The large number of carriers also means that OFDMA is very resilient to selective fading, interference, and multipath effects, as well providing a high degree of spectral efficiency. OFDMA is processor and power use intensive making it suitable for operation from base stations rather than at cellular phones or tablets.

The modulation used on the uplink (from the cellular device to the base station) is SC-FDMA. This uses a hybrid form of OFDM - this combines the low peak to average ratio offered by single-carrier systems with the multipath interference resilience and flexible subcarrier frequency allocation that OFDM provides. Typically, the data rates or capacity achievable with SC-FDMA is less than OFDMA. In addition, the power achievable from the device will be less than that from base stations to enable longer battery life. This results in the uplink defining the max path length achievable from the base station to the device. This is important for the work presented in Chapter 5.

3.5.3 **Transmission**

The Transmission network is the link between the base station (or RAN) part of the network and the Core. This is sometimes called backhaul (as shown in Figure 8). Transmission is normally via a fibre optic cable or by digital microwave radio links in point to point configuration. However new mesh transmission networks are also possible in point to multipoint configurations but are not commonly used by cellular operators. Microwave radios are point to point radios using very high gain (normally parabolic) antennas which concentrate the signal (in a narrow beam) from the near-end to far-end antenna. As the radio wave is a narrow beam confined to a near line-of-sight from one antenna to the other, they don’t usually interfere with other microwave links.

The spectrum used for microwave links is normally in the microwave band (13, 15, 18 or 38 GHz for example). Because of the high frequencies used an area around the beam called a Fresnel zone should be free from obstacles (or at least the loss from the obstacle in the Fresnel zone should be taken into consideration when calculating the path loss).

Spectrum is allocated for microwave links in fixed link licenses. These are open to anyone wanting to implement a microwave link but will only allow operation between the two fixed end points of the link. These licenses typically last for one year but are renewed by paying a yearly administrative fee. Although part of the cellular network, the spectrum allocated for transmission is different to that discussed in this thesis for the radio access network. Fixed links are open to the public, are not in short supply and a relative cheap to purchase – almost the opposite from the spectrum for the RAN. However, spectrum allocation methods for transmission networks could be the subject for future work.

3.5.4 **Evolved Packet Core**

The last component of a cellular network is the Core. The Core includes gateways to handover traffic to other discrete networks and servers to control the quality and quantity of services offered over the cellular network. The EPC (Evolved Packet Core) is composed of several functional entities:

- The MME (Mobility Management Entity).
- The HSS (Home Subscriber Server).
- The SGW (Serving Gateway).
- The PDN Gateway (Packet Data Network).
- The PCRF (Policy and Charging Rules Function) Server.

The following sub-sections discuss each of these in detail:

The Mobility Management Entity (MME) oversees all the control plane functions related to subscriber and session management. From that perspective, the MME supports the security procedures (this relates to end-user authentication as well as initiation and negotiation of ciphering and integrity protection algorithms), the terminal-to-network session handling (this relates to all the signalling procedures used to set up Packet Data context and negotiate associated parameters like the Quality of Service), and the idle terminal location management (this relates to the tracking area update process used in order for the network to be able to join terminals in case of incoming sessions).

The Home Subscriber Server (HSS) is the concatenation of the Home Location Register (HLR) and the Authentication Centre (AuC). The HLR part of the HSS is in charge of storing, and updating when necessary the database containing all the user subscription information, including the user identification and addressing and the user profile information. The user profile includes service subscription states and user-subscribed Quality of Service information (such as maximum allowed bit rate or allowed traffic class). The AuC part of the HSS is in charge of generating security information from user identity keys. This security information is provided to the HLR and further communicated to other entities in the network. Security information is mainly used for mutual network-terminal authentication and radio path ciphering and integrity protection, to ensure data and signalling transmitted between the network and the terminal is neither eavesdropped nor altered.

The Serving GW (SGW) is the termination point of the packet data interface towards the Evolved-UMTS Terrestrial Radio Access Network (E-UTRAN). When terminals move across the eNodeB in E-UTRAN, the Serving GW serves as a local mobility anchor, meaning that packets are routed through this point for intra E-UTRAN mobility and mobility with other 3GPP technologies, such as 2G/GSM and 3G/UMTS.

The PDN GW (Packet Data Network Gateway) is the termination point of the packet data interface towards the Packet Data Network. As an anchor point for sessions towards the external Packet Data Networks, the PDN GW also supports Policy Enforcement features (which apply operator-defined rules for resource allocation and usage) as well as packet filtering (like deep packet inspection for virus signature detection) and evolved charging support (like per URL charging).

Policy and Charging Rules Function (PCRF) server manages the service policy and sends QoS setting information for each user session and accounting rule information. The PCRF Server provides the Policy Decision Function (PDF) and the Charging Rules Function (CRF). The PDF is the network entity where the policy decisions are made and makes decisions based on network operator rules, such as allowing or rejecting the media request, using new or existing context for an incoming media request and checking the allocation of new resources against the maximum authorized limits.

3.6 5G in New Zealand

Cellular operators in New Zealand are planning to implement the fifth generation (5G) of cellular networks by 2020. This is driven by the demand for enhanced mobile broadband with higher data rates as seen from global markets and by services such as enhanced machine communications and reliable and low latency communications.

As with any new generation of cellular technology, 5G is planned to be delivered as an overlay of existing network infrastructure alongside 4G services – not as a distinct, standalone network. This will enable 5G to be deployed on a geographic basis as and where traffic demand requires it, with customers having consistent 4G coverage where 5G coverage does not yet exist.

Like global markets, New Zealand cellular operators expect key applications to include:

- Enhanced mobile broadband to meet growing consumer demand for higher-definition (e.g. 4K and 8K) video, information and social media services.
- Enhanced Machine Type Communications to support connections and communication between tens of millions of connected devices to enable digital services that can help New Zealand industries and homes become more efficient, this includes smart city services, smart home services, real time tracking and management of stock, wearables.
- Ultra-reliable and low-latency communications: Supporting near-instantaneous communications between connected devices to support complex and integrated multi-user networks and services, such as:
    - Virtual and augmented reality for industrial and entertainment services.
    - Remote operation of health, educational and industrial equipment.
    - Autonomous vehicles and intelligent transport systems, for example in high-risk zones like airports or for urban transport routes.
    - Mission-critical applications, such as remote surgery.

Despite these services having widely different network performance requirements, each can be served over a common extendable 5G network. In each case, service-specific equipment may be required to be deployed at different parts of the network, and in some cases network density

– the number of cell-sites required to provide the required coverage - may need to be increased. But these will simply be extensions to the network, able to be deployed as and when there is enough demand.

To meet these demands the following technical specifications of 5G network are planned for New Zealand:

- Typical speed improvements of up to 10 times faster than today's experience, and peak speed improvement to 10 Gbps.
- Lower latency – less delay/greater responsiveness enabling real-time services to be delivered. Latency improvements to 10 milliseconds (ms) and potentially down to 1ms from a typical 50ms today. This allows extreme network responsiveness and will eventually enable mass uptake of augmented reality (AR) and virtual reality (VR), as well as support mission-critical applications for industry.
- The ability to connect many devices at once – sensors and smart devices that comprise the Internet of Things (IoT). Even today's 4G networks are limited in the number of devices they can connect to simultaneously, but in the future connected "things" – devices ranging from fridges to streetlights to farm gates – will far outnumber connected people, so 5G technology has been designed to support connected device densities of up to 1 million devices per square kilometre.
- Network slicing – tailoring the network for specific uses. This is the ability to tailor the network in accordance with the performance requirements of a service by virtualising functions and moving them closer to the customer. The performance requirements of, say, a connected autonomous vehicle (ultra-reliable real-time connectivity 24/7) are very different to those of a smart parking sensor network (low power, non-real time connectivity of thousands of similar devices that will use very small amounts of network capacity infrequently and at random times). In the early stages of 5G, network slicing will be enabled by virtualising key network elements. But as it develops, the network functions themselves will be virtualised and located in the right place within the network for the performance demands of the customer's service.
- Edge Computing – Taking more of the network processing functions to the 'edges' of the network. This ensures network functions get the bandwidth and low latency required for key 5G services, by moving these functions closer to the cell sites supporting customer

devices. But it requires new network configurations including more high-quality transmission connections to these edge functions.

To a large extent, the mainstream consumer take-up of 5G in New Zealand will be influenced by consumers upgrading their wireless devices (smartphones, etc) to the latest 5G-capable models. These devices are set to operate within specific frequency bands, for example the 700 MHz band in the United States uses different frequencies to that used New Zealand, so a US-market handset may not initially work in NZ. Based on previous 4G devices, with time, new devices offer a wide range of frequency band support, so by 2020 there is a good prospect that 5G compatible handsets can be sourced for the NZ market [86].

3.7 Spectrum implications

To meet this demand for coverage and capacity there are several spectrum options available, including:

- Using the existing spectrum more efficiently i.e. increase spectral efficiency in bits per second per Hertz. For example, 5G is expected to incorporate link performance from massive MIMO (multiple-input multiple-output) and higher modulation rates that will increase spectral efficiency.
- Increasing the cell site density and increasing the frequency reuse between cell sites (bits per second per Hertz per unit area).
- Have more spectrum available – open more frequencies for use for cellular networks, to provide more spectrum in a way that maximises the value that society gains from the radio spectrum.

It is likely future wireless systems will combine all three of these techniques to use spectrum for cellular networks. As discussed, 5G is likely to have a higher site density and this will increase the frequency reuse through more sites in smaller areas to provide capacity. In addition, massive MIMO and higher modulation rates will increase spectral efficiency, but this thesis concentrates on the third option. That is methods to provide more spectrum for future wireless services in cellular networks.

This starts by investigating the use of Licensed Spectrum Parks.

Chapter 4. Licensed Spectrum Parks

This chapter introduces the first of the alternative spectrum allocation techniques described in this thesis, called a License Spectrum Park. This was presented at the TRPC conference in Washington DC by the author of this thesis in 2014.

4.1 Introduction

Traditionally spectrum for cellular or mobile radio use has been auctioned to cellular operators in discrete blocks as a management right over large geographical areas and for long timeframes. These auctions have been very profitable for governments around the world, for example generating $US19 billion in the United States in the 700 MHz spectrum auction alone [87].

However, such a large initial investment for spectrum has made it difficult for new entrants to competitively enter the mobile radio market. For example, in recent 700 MHz auctions in Australia parts of the 700 MHz band earmarked for LTE use have (initially) gone unsold as some existing cellular operators were unwilling or unable to meet the reserve price [88]

This chapter discusses how the auction process can be altered to allow more competition to enter the market. The idea is that the spectrum bands up for allocation be divided into two different licensed management right types. The first management right type would be for the traditional exclusive use, large geographic area, and long-term management right. This is the preferred management right traditionally desired by incumbent cellular operators. The licenses for this part of the band could be allocated by the traditional auction processes.

The second management right type would also be licensed but would be for a fixed location and for a short-term timeframe. This is defined as a Licensed Spectrum Park (LSP). This part of the band would not be auctioned. Operators would apply to use this band on a case by case basis. These LSP licenses could be assigned annually with the option to renew. This would be similar to the fixed licenses used for point-to-point radios in many countries, but in a point-to-multipoint configuration.

An LSP structure for part of the spectrum band would allow smaller and perhaps specialised cellular operators to enter the market. For example, it would be possible for a campus or academic network, or perhaps a government-only network, to operate in part of a city.

In addition to the existing spectrum and fixed licenses (as shown in Figure 9), a Licensed Spectrum Park (LSP) is:

- Licensed.
- Adjacent to spectrum assigned for cellular e.g. LTE use.
- In a fixed location and for a short-term timeframe.
- Not auctioned. Operators would apply to use this band on a case by case basis.
- Assigned yearly with the option to renew.

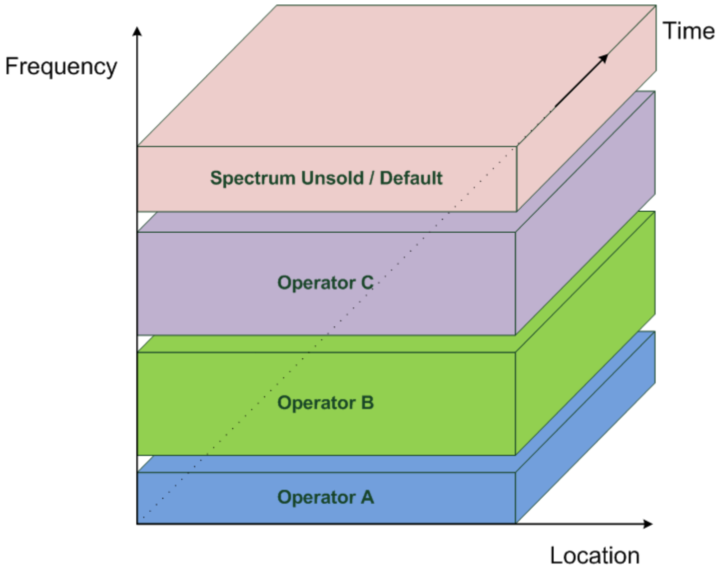

Figure 9. Standard method to assign frequency licenses for a large geographic location for a fixed term and exclusive use management right.

The licensed spectrum park spectrum allocation is shown in Figure 10.

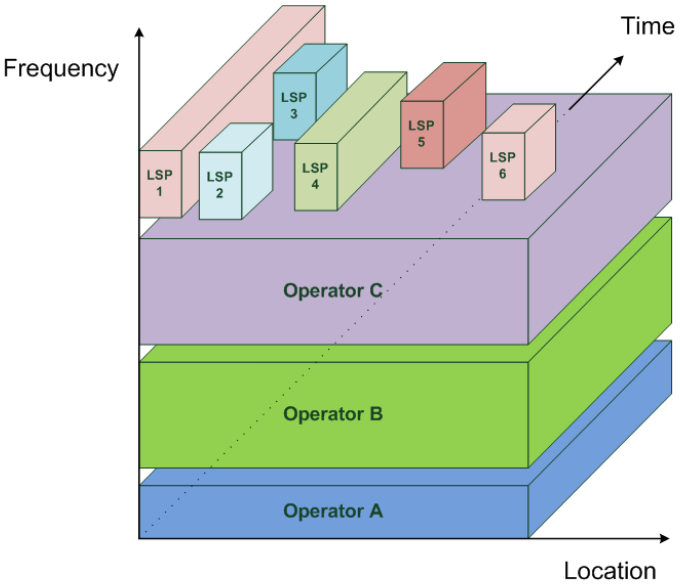

Figure 10. Licensed Spectrum Park spectrum allocation.

4.2 Spectrum sharing

A significant amount of the spectrum suitable for cellular radio use has already been assigned. This means that spectrum sharing is a likely solution to provide for the growing capacity required of incumbent cellular operators ([89] and [90]) but also allow smaller operators to build specialised networks. This section briefly summarises spectrum sharing methodologies.

4.2.1 Spectrum sharing models

There are many different models describing the best methods to share the spectrum ranging from:

- The use of unlicensed bands [49].
- Combining spectrum from licensed band operators to more efficiently use the resource [51].
- Cognitive radio approach, where underutilised spectrum can be used by other operators [52].
- Geographical databases used to track areas where spectrum is likely to be unused e.g. TV white spaces [55].

These spectrum sharing techniques and an LSP allocation model could be used in a complementary way to better utilise available spectrum. For example, increasing the use of unlicensed spectrum in alternative spectrum bands and using LSPs to allocate spectrum in adjacent sub-bands to the spectrum used for mobile radio.

4.2.2 **Spectrum commons vs. the spectrum property right**

The investment required to roll out the infrastructure of a cellular network is significant. Therefore, it is understandable that cellular operators want to be able to limit the interference from other radio systems. The idea of having a spectrum commons approach in sub-bands adjacent to licensed cellular systems was considered, but because these radios are likely to be unlicensed it would be more difficult to manage interference. For similar reasons cognitive radios operating in an unlicensed mode would make it difficult to find the source of interference in the event of equipment configuration errors or transmitters creating spurious emissions.

In addition, the idea of using geographical databases to identify areas where spectrum is currently unused is useful. However, given that cellular networks are almost continuously expanding and optimising frequency reuse, this database would only be useful in areas where there is little change to the configuration of the network, for example rural areas.

In this chapter we propose an LSP model, assigned by regulators, as a novel and improved method to assign adjacent sub-band spectrum for mobile radio use for specialised networks.

4.3 Spectrum allocation for cellular / mobile radio use

It is common for spectrum regulators to divide spectrum into different bands and suggest or mandate a use for these bands. For example, over the last few years many countries have had spectrum auctions in the 700 MHz band with the plan to use this spectrum for LTE (Long-Term Evolution or 4G). These auctions have designated the entire band as spectrum licenses (i.e. exclusive use management rights) to the winning bidders.

4.3.1 **Net Social Benefit**

It has been stated that "the key purpose of spectrum management is to maximise the value that society gains from the radio spectrum by allowing as many efficient users as possible while ensuring that the interference between different users remains manageable" [4]. This implies that spectrum auctions should not just be concerned with generating revenue for governments but that regulators should also have a mandate to provide a net social benefit.

The creation of LSP means there is a net social benefit for two reasons. The first is that the use of LSP allows specialist networks to be formed, effectively opening up the spectrum to more users and to potentially create more competition in the cellular market. The second is the fact that LSP is licensed which creates a method to control interference between different users and allows interference to be managed.

4.3.2 Dividing the spectrum

This section describes how future bands can be divided into the two licence types. Two options have been considered when evaluating how much spectrum should be available for LSPs. In the first instance only spectrum unsold in the traditional spectrum auctions is made available. For example, in Australia in a recent 700 MHz auction 15 MHz (paired) initially was unsold [88]. Australian regulators state this is to be sold in future auctions. However, we suggest that some of this spectrum be put aside for LSP use.

In the second instance an amount of spectrum should be put aside pre-auction, e.g. a minimum of 5 MHz (paired) in the 700 MHz band nationwide. The amount of spectrum to be allocated to LSPs depends on the amount of spectrum available in each country and/or region.

The APT (Asia-Pacific Telecommunity) band plan [91] together with a possible LSP allocation of a 5 MHz pair is shown in Figure 11. This consists of two paired blocks of spectrum, each 45 MHz wide and separated by a 10 MHz centre band gap.

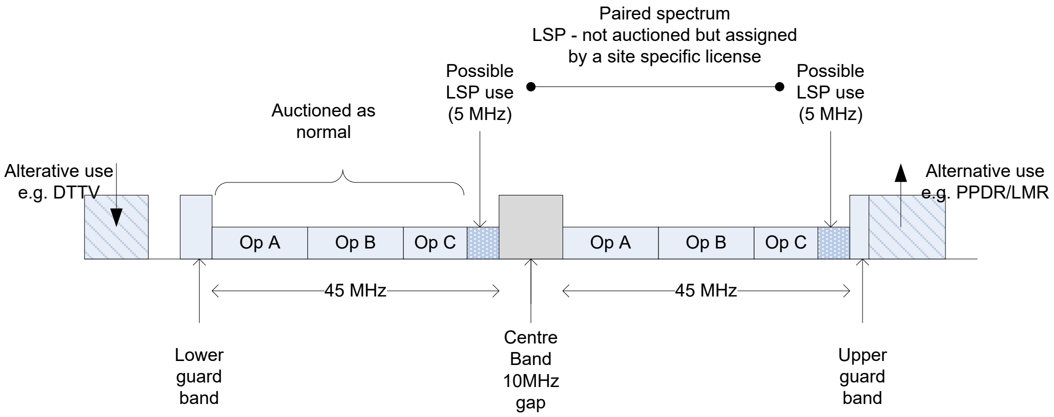

Figure 11. APT frequency band plan showing possible LSP allocations with 3 operators winning spectrum in adjacent sub-bands.

4.4 Introducing Licensed Spectrum Parks

This section introduces how LSPs could be managed, the target market for LSPs, interference issues, licence details, and the price of LSP licenses.

4.4.1 **Administration**

It is envisaged that LSP use be administered by existing radio spectrum management (RSM) organisations. The process would be very similar to fixed licenses currently supplied by RSM authorities today. The difference being this is a point-to-multipoint configuration with a fixed base station location.

It is envisaged that approved radio engineers review equipment configuration to ensure the transmitters stay within the designated LSP band and interference to other operators could also be managed by ensuring compliance with any existing licenses. Data to ensure compliance to a license would be kept on existing databases (similar to fixed licenses) managed by RSM groups who could also ensure installations and radio operation match the site specific license.

4.4.2 **Target market**

Ideally these site-by-site licenses would be assigned only to start-ups and specialised networks, thereby encouraging competition to enter the cellular market and to allow for small spectrum managed parks. The RSM groups would be mandated to deny licenses on a case-by-case to ensure that LSP use is for specialised networks only. This would prevent a single operator bulk buying licenses for a large scale roll out using LSP spectrum.

4.4.3 **Interference**

It is envisaged that approved radio engineers review equipment configuration to ensure the transmitters stay within the designated LSP band. Interference to other operators could also be managed by ensuring compliance with any existing licenses. This data would be kept on existing databases managed by RSM groups. The RSM groups could ensure that installations and radio operation match the site-specific licence. In this regard, a single, highly elevated transmitter with a very large coverage area effectively causing potential interference to future base stations over a large urban or suburban area would be unacceptable.

4.4.4 **Licence assignment**

It is proposed this LSP licence structure follows the structure of fixed licenses, where the licence is for one year, with the ability to rollover the licence on a yearly basis.

4.4.5 **Price of an LSP licence**

Our pricing analysis considers the population covered by the proposed base station, the amount of spectrum requested and length of the management right, against the normalised cost of the spectrum, for a given population and bandwidth, under the spectrum licence auctions. The resulting formula means that LSP licenses in urban environments with high spectrum requirements and populations, for example, would be more expensive as compared to smaller amounts of spectrum in rural environments.

For example, in the recent 700 MHz auction in New Zealand the reserve price (P_{RES}) was $NZ 22 million for each 5 MHz of paired spectrum (BW), covering an estimated 94% of the 4.43 million population (Pop, with the 700 MHz spectrum), on an 18-year management right (T). For LSP licenses sold beyond the first year (after auction) the price can be adjusted by an interest rate to take account of the time value of money (e.g. inflation).

Price of licence at LSP (per annum) =

$$P_{LSP} = \frac{P_{RES}}{BW * Pop} * \frac{BW_{LSP} * Pop_{LSP}}{T} + OH \tag{2}$$

In our first example, consider a small rural community with a population covered by a new cell site of 10,000 people (Pop_{LSP}), and a bandwidth requirement of 5 MHz (BW_{LSP}) and with overhead (OH) costs of $500 would cost $NZ 3,435 per year for a single licence.

In our second example, consider an urban cell site covering an academic campus with population 20,000 people (Pop_{LSP}), and a bandwidth requirement of 10 MHz (BW_{LSP}) and with overhead (OH) costs of $500 would cost $NZ 12,240 per year for a single licence.

4.4.6 Revenue from LSP licenses and spectrum auctions

The revenue generated from the sale of spectrum licenses including the reduced revenue if spectrum were apportioned for LSP, and the slowly increasing revenue from the sale of LSPs on a site-by-site basis, is illustrated in Figure 12.

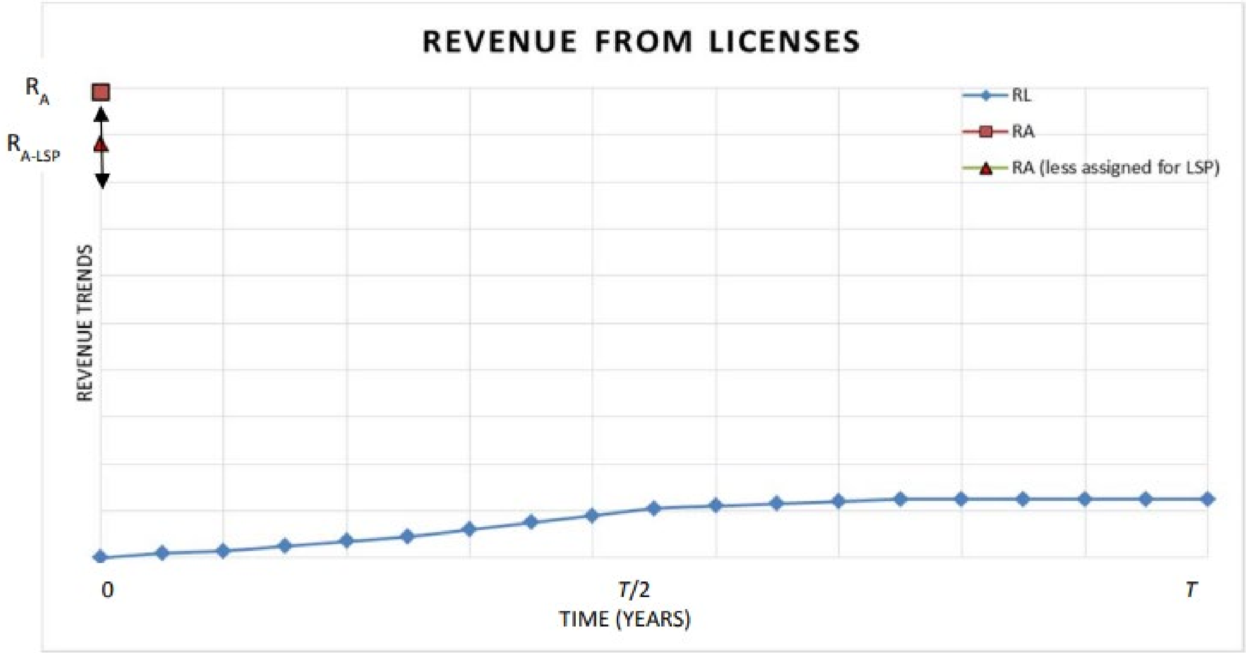

Figure 12. Revenue trends from the sale of spectrum licenses, showing that projected revenue from LSPs (R_L) increases as more specialised networks are rolled out but levels out with time. R_A is the revenue from spectrum licenses at auction.

This shows that by assigning spectrum for LSP use pre-auction may result in reduced auction revenue ($R_{A\text{-}LSP}$) as less spectrum is available for traditional spectrum licenses. However, this could be partially offset by the on-going licence fees from the sale of LSP licenses.

In addition, in certain circumstances the revenue from the spectrum licence auction may not decrease by assigning spectrum for LSP use. For example, operators may be willing to pay a higher price at auction for spectrum as there would be less spectrum available to buy as a management right, or all spectrum may not have sold at auction regardless of LSP allocation. This is discussed further in the next section.

4.5 Auction process and Licensed Spectrum Parks

The majority of spectrum for mobile radio use will still be auctioned, with the spectrum for LSP use either assigned pre-auction or assigned from any unsold spectrum.

In order to stimulate the creation of LSPs by new users, the regulator faces the issue of whether to allocate a fixed amount of spectrum for LSPs before auctioning the remaining spectrum, or alternatively auctioning the total spectrum and allocating any unsold spectrum to LSPs, if any is available. These options are shown in Figure 13.

If operators are aware that any unsold spectrum will be assigned for LSP use this could change their auction bidding strategies. Some operators could be concerned about possible new market entrants if spectrum is shared for example. They are certainly concerned about their reduced independence, autonomy and how much competitors pay for spectrum [92]. Therefore, demand for traditional spectrum could increase to block the creation of LSPs.

We have considered two models for the decision-making problems faced by regulators for LSP creation, namely model 1, where the regulator allocates a fixed amount of spectrum amongst new users for LSPs before auctioning the remaining spectrum, or alternatively model 2, where the regulator auctions the total spectrum and allocates any unsold spectrum to LSPs, if any is available. These are analysed in following sections.

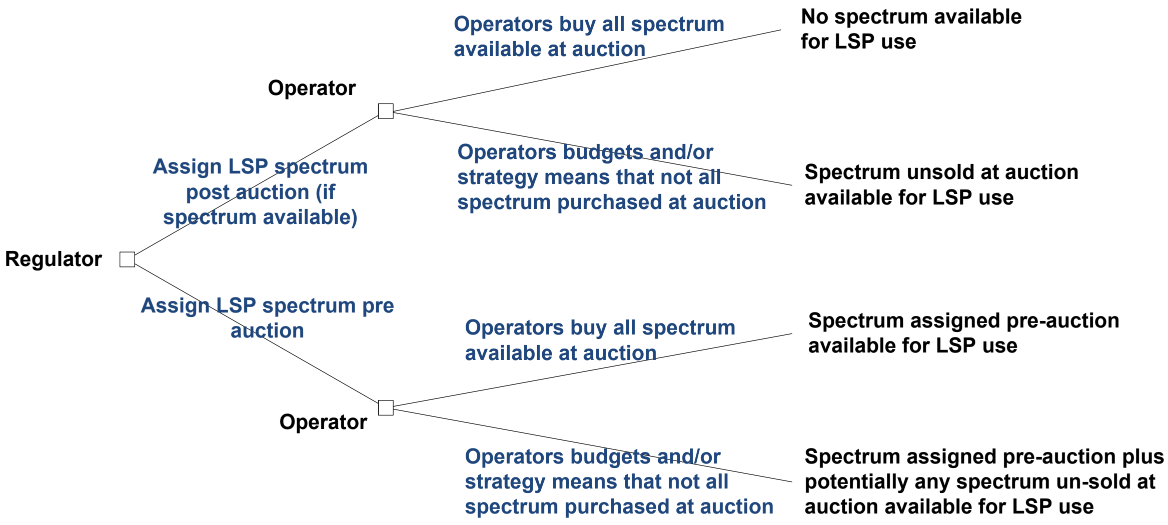

Figure 13. The challenges faced by both the regulators and the operators in the auction process.

4.5.1 **Problem re-stated using game theory**

Game theory is a useful tool to help radio spectrum management (or regulators) decide the best method to allocate spectrum for Licensed Spectrum Parks (LSPs). This is because game theory or interactive decision theory is a study of strategic decision making by mathematical models of 'conflict and cooperation between rational decision-makers" [93]. We can define how the spectrum is allocated as two models:

> (1) Operator's strategy in auction bidding in response to the regulator's announcement of allocating a pre-auction fixed amount of spectrum for LSP use.
>
> (2) Operator's strategy in auction bidding in response to the regulator's announcement of not allocating a pre-auction fixed amount of spectrum for LSP use but rather using any unsold spectrum for LSP use – if any is available.

4.5.2 **Game theory players: operators**

Operators seek profits through the sale of telecommunication services. Spectrum is an enabler of the technology required to sell telecommunication services. Operators want as much spectrum as possible for the cheapest price, where interference to other operators is manageable or negligible.

Regulators have interests to increase the net social benefit (as described earlier), but in addition the regulator has an interest to seek a fair and reasonable profit from the sale of spectrum to operators.

4.5.3 **Cooperative / non-cooperative model**

A game is cooperative if the players are able to form binding commitments normally enforced by a legal contract. In the spectrum auctions we are considering, we will assume the operators are bidding competitively for the available spectrum. This may not always be the case, in particular if operators share spectrum, for example as a pre-auction consortium to bid in auctions, or later as a means to share this resource post auction, as a means to improve coverage or capacity.

4.5.4 **Symmetric / asymmetric model**

A symmetric game is a game where the payoffs for playing a particular strategy depend only on the other strategies employed, not on who is playing them. If the identities of the players can be changed without changing the payoff to the strategies, then a game is symmetric.

4.5.5 **Simultaneous / sequential model**

Simultaneous games are games where both players move simultaneously, or if they do not move simultaneously, the later players are unaware of the earlier players' actions (making them effectively simultaneous). Sequential games (or dynamic games) are games where later players have some knowledge about earlier actions. This need not be perfect information about every action of earlier players; it might be very little knowledge. For instance, a player may know that an earlier player did not perform one particular action, while he does not know which of the other available actions the first player actually performed.

4.5.6 **Equilibrium (or Nash equilibrium)**

In game theory an equilibrium or Nash equilibrium[4] is a proposed solution of a non-cooperative game where each player has chosen a strategy such that no player can benefit by changing strategies while the other player keeps their strategy unchanged. Game theorists use the equilibrium to predict what will happen if 2 or more players are making decisions at the same time and the outcome for each player depends on the decisions of the others.

4.5.7 **Game theory analysis: pre or post auction spectrum allocation for LSPs in combinatorial clock auctions**

Recent spectrum auctions in several countries have used the combinatorial clock auction (CCA) e.g. [88] and [91] and we have concentrated on this auction method to analyse LSP allocation strategies. The CCA consists of an initial clock round in which prices ascend until there is no excess demand for spectrum. If supply exceeds demand the clock round can be followed by a supplementary round as discussed in the next section. Finally, the CCA auction consists of an assignment round in which specific spectrum blocks are allocated.

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[4] Named after the mathematician John Nash [54]

Work done by [94] showed that the CCA does have an equilibrium in which bidding is truthful and the outcome is efficient. But to achieve this equilibrium each bidder must restrict attention to proxy strategies in which bidders do not condition their bidding on rival behaviour.

However, we have seen that in spectrum auctions bidders are also interested in how much their competitors pay for their spectrum [92]. Work by [33] and [94] also showed that if bidders have a preference for raising rivals costs in a CCA auction, then bidding above (or below) the spectrums valuation can be optimal and furthermore CCA may lead to inefficient outcomes.

As previously stated, the use of LSP's can be divided into two different systems to be modelled. Model 1, the operator's strategy in auction bidding in response to the regulator's announcement of allocating a pre-auction fixed amount of spectrum for LSP use, can be modelled as a non-cooperative, symmetric and sequential game model if we assume a more tradition spectrum combinatorial clock auction with multiple rounds. Model 2, the operator's strategy in auction bidding in response to the regulator's announcement of not allocating a pre-auction fixed amount of spectrum for LSP use but rather using any unsold spectrum for LSP use – if any is available, can be also be modelled as non-cooperative and sequential but in this case asymmetric as bidders may change strategy if it looks like spectrum maybe available for LSP use.

It is easy to see that in model 1, if a regulator assigns spectrum pre-auction for LSP use, then this will not change the equilibria from the situation that no spectrum is assigned for LSP use at all. So, if bidders only attach value to their own interests then bidding truthfully in the clock round in CCA will remain an equilibrium. This is because bidders have no control over LSP creation if this is assigned pre-auction, and effectively the auction is the same as traditional CCA but for slightly less available spectrum.

Looking into model 2, we need to understand whether the incentive structure of the mechanism, that is, a CCA followed by an allocation of unsold spectrum to LSPs, admits truthful bidding as an equilibrium. If it does, we also need to ask whether there is a strictly better equilibrium, one in which all players use an alternative strategy that yields better payoffs.

One indication that an alternative to truthful bidding may exist in model 2 in equilibrium is the fact that all bidders face a collective action problem: they may find it attractive to exhaust the pool of offered lots in the action leaving none for LSPs. This of course would stop the formation of LSP's and stop the roll out of new specialised mobile radio networks on adjacent spectrum, thereby reducing the chance of more competition in the market.

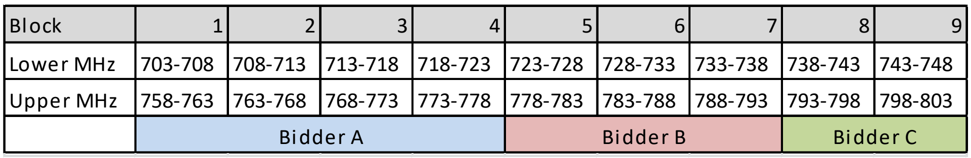
The fact that bidders may want or need to pre-empt blocking the entry of LSPs to the market becomes an important ingredient in the analysis. On the one hand we can argue that regulators would like to favour the process described in model 2 because the argument above suggests more revenue will be raised during that auction due to the sale of lots that otherwise would have remained unsold. On the other hand, bidders' behaviours would be affected because they now have to consider the need to hold on to more spectrum, and the resulting greater cost, than they would have to in the baseline scenario.

4.5.8 New Zealand's 700 MHz auction

In New Zealand's 700 MHz spectrum auction a total of 45 MHz paired (i.e. 703-748 MHz and 758-803 MHz) was available for auction in late 2013 / early 2014. Each 45 MHz pair was divided into 9 x 5 MHz blocks and the auction was for a spectrum management right for 18 years.

This 700 MHz auction was a combinatorial clock auction (CCA) comprising a clock round, supplementary round, and an assignment round. In the clock round a reserve price was set at $NZ 22 million (plus tax) per 5 MHz paired lot. In addition, in the clock round the auction was subject to an acquisition limit (or 'spectrum cap') of 15 MHz (paired) per bidder [91].

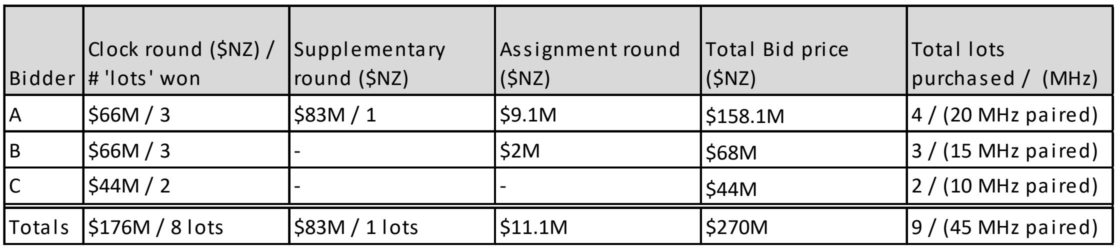
In the clock round there were three bidders (A, B, & C, the incumbent mobile radio operators). Bidder A and B bid the reserve for the maximum allowable 15 MHz in the clock round and Bidder C bid for 10 MHz, each paying the reserve price ($66M and $44M respectively). This left a 5 MHz pair available, unsold in the clock round. In the supplementary allocation round bidder A bid an additional $83M for this 5 MHz pair. In the assignment round bidder A bid an additional $9.1M and bidder B an additional $2M for the rights to be assigned the particular spectrum as shown in Table 2.



Block	1	2	3	4	5	6	7	8	9
Lower MHz	703-708	708-713	713-718	718-723	723-728	728-733	733-738	738-743	743-748
Upper MHz	758-763	763-768	768-773	773-778	778-783	783-788	788-793	793-798	798-803
	Bidder A				Bidder B			Bidder C	

Table 2. New Zealand assignment round in the 700 MHz combinatorial clock auction [34].

This resulted in the combined revenue of $270M for 45 MHz paired spectrum as shown in Table 3.



Bidder	Clock round ($NZ) / # 'lots' won	Supplementary round ($NZ)	Assignment round ($NZ)	Total Bid price ($NZ)	Total lots purchased / (MHz)
A	$66M / 3	$83M / 1	$9.1M	$158.1M	4 / (20 MHz paired)
B	$66M / 3	-	$2M	$68M	3 / (15 MHz paired)
C	$44M / 2	-	-	$44M	2 / (10 MHz paired)
Totals	$176M / 8 lots	$83M / 1 lots	$11.1M	$270M	9 / (45 MHz paired)

Table 3. New Zealand 700 MHz auction revenue [34].

4.5.9 Pre or post auction spectrum allocation for LSPs in the New Zealand 700 MHz auction

The discussions above on game theory can be applied to the New Zealand 700 MHz spectrum assignment. In it we can envisage that 5 MHz be assigned for LSP use. This could have been assigned pre-auction or from the spectrum that was unsold in the clock round. We can analyse this hypothetical example to see the result for New Zealand's 700 MHz spectrum auction.

4.5.10 Clock round

In the situation where the regulator could have allocated 5 MHz for LSP allocation pre-auction in the 700 MHz NZ auction example, this would have no effect on the auction revenue for the clock round. This is because achievable demand was less than supply in this case, mainly due to the spectrum cap limiting bidders to 15 MHz (maximum), and the third bidder and other interested parties either not wanting or unable to purchase the remaining spectrum.

In the hypothetical situation where the regulator could have allocated 5 MHz for LSP creation after the clock round, if any was available, then in this example, bidder C could have increased its bid to block this formation. This would have required an additional $22 million (and allowed the bidder another 5 MHz).

4.5.11 **Supplementary round**

The supplementary round would not have been required if 5 MHz of spectrum was allocated for LSP use, as all available spectrum would have been allocated as part of the clock round. Referring to Table 3 this would decrease the NZ 700 MHz auction revenue by $83 million.

4.5.12 **Assignment round**

In the hypothetical example where LSP spectrum was allocated at the top of the 700 MHz band then bidders may desire the lower band to reduce the chance of interference from LSP creation (even though LSP would be licensed and therefore the interference would be manageable).

This would result in the revenue from the 700 MHz in the hypothetical LSP creation to be the same or higher in the clock and assignment rounds but lower in the supplementary round. This is shown as the variable revenue for $R_{A\text{-}LSP}$ in Figure 12.

4.5.13 **New Zealand 700 MHz auction summary**

In the New Zealand 700MHz case there were 3 phases of the auction process i.e.

1. The Clock Allocation Phase (in which operators express interest in blocks of spectrum available, up to a maximum of 15 MHz).

2. Supplementary Allocation Phase (in the case where not all spectrum is wanted, operators bid on the available additional spectrum, in this case 5 MHz).

3. Combinatorial Assignment Phase (bidders know how much spectrum they will receive but may bid extra to gain their preferred “pole” position).

In practice there was less demand for spectrum from one operator than possibly anticipated. This meant that the initial demand for spectrum in the clock allocation phase produced only one round. The first and only round of the clock allocation phase was a non-cooperative, symmetric and simultaneous model, but if there were further rounds this would have been sequential.

The combinatorial assignment phase (the assignment round is a one-shot tender) is also simultaneous but in this case is asymmetric and bordering on co-operative (but still technically non-cooperative). This is because RSM limited which blocks one of the operators (Telecom) could be assigned. The practical effect of this is that Operator A will hold spectrum at one end of the band, with the other two operators (B and C) holding spectrum next to each other. This will allow Operator B and C (Two Degrees Mobile and Vodafone) to develop commercial arrangements if they wish, recognising that up to four contiguous lots can be deployed under current technology specifications.

4.5.14 **Work post publication of the licensed spectrum park model**

The work described in this chapter on Licensed Spectrum Parks was published at the Telecommunications Policy Research Conference held at the American University Washington College of Law in 2014. The paper was peer reviewed by an international group of researchers from academia, industry and US government. TPRC promotes interdisciplinary thinking on current and emerging issues in communications and the Internet by disseminating and discussing new research relevant to policy questions in the U.S. and around the world [95].

Since then there has been on-going work in the European Union and in the United States on Licensed Shared Access (LSA). Under the LSA regime, spectrum that is already occupied but underutilised would be shared, on a licensed basis, between incumbents and mobile operators, under agreed frequency, location and time-sharing conditions. LSA is a further development of Authorised Shared Access (ASA) which facilitates access for additional licenses in bands which are already used by one of more incumbents. ASA was introduced to enable access to additional frequency bands for mobile broadband which were identified for International Mobile Telecommunications (IMT) but is not available in some countries. The concept was extended as Licensed Shared Access, with the potential for application to other services in addition to mobile broadband.

The Radio Spectrum Policy Group Opinion on LSA [96], defines the LSA concept as a "regulatory approach aiming to facilitate the introduction of radio communication systems operated by a limited number of licensees under an individual licensing regime in a frequency band already assigned or expected to be assigned to one or more incumbent users". Under the Licensed Shared Access (LSA) approach, the additional users are authorised to use the spectrum (or part of the spectrum) in accordance with sharing rules included in their rights of use of spectrum, thereby allowing all the authorized users, including incumbents, to provide a certain Quality of Service (QoS)". Existing cellular operators, for example, would lease part of their spectrum to new users, for a certain period of time, while maintaining control over the radio spectrum in the long term. Radio spectrum would be shared in terms of time, location and/or frequency, in accordance with a set of sharing rules. These rules would include specific technical and operational requirements, for instance compatibility criteria, limitations of use, restriction/exclusion zones, and spectrum masks [21].

The LSA repository includes sharing rules and information on incumbent spectrum use. The existing cellular operators are responsible for providing the information to be included in the LSA repository, making sure that its information is up-to-date. The LSA controller retrieves information from the LSA repository and establishes spectrum availability for LSA licensees [21].

4.5.15 **Managed Spectrum Parks**

In New Zealand, a slightly different approach has been implemented, called Managed Spectrum Parks (MSPs). Rather than using adjacent spectrum or spectrum unused by incumbent cellular operators, a dedicated band at 2.5 GHz (2575 – 2620 MHz) was introduced. This nationwide band can be assigned to specific localised parks which are assigned to users on a first come first served basis. Rules to use MSPs in New Zealand were published in 2015 [6].

In is interesting to note how MSPs are charged and compare this to the proposed licensing fees introduced in this chapter and published paper. Along with any applicable licence administration fees (standard is $150), park licensees are also required to pay an annual charge consisting of a management charge and a resource rental, as follows:

1. An annual Managed Spectrum Park management charge, at the rate of $200 per base transmitter, to a maximum of $1,000; and

2. An annual resource rental (per MHz) = $a / b \times c / 20 \times d$

Where a is the population in the most recent census of each Territorial Local Authority in which the Licence has a Licence Area, b is the population of New Zealand in the most recent census, c is $20,346, being the average price per MHz for a 20-year right, paid in Auction No. 9 (of the 2.3 GHz and 2.5 GHz bands, held in December 2007) and d is the percentage increase in the Consumer Price Index since 1 January 2008 [11].

For users of managed spectrum parks, in areas of small population (by territorial local authority) the cost of this license is really just the administrative fees as the ($a / b \times c$)

component becomes negligible. The administrative fees are around $350 per year. This is significantly lower than the price per license recommended in this chapter in 4.4.5 ($NZ 3,435 to $NZ 12,240) suggesting that either: a dedicated spectrum band at 2.5 GHz is not desirable by cellular operators and that spectrum adjacent to that already used by cellular operators may be more desirable; or that operators using managed spectrum parks can't afford to pay higher rates; or that the rates suggested in this chapter are too high. We suggest that former reason as the most valid.

Both LSA and MSP have limitations when used to provide spectrum for future wireless services for cellular networks. With LSA, spectrum is shared to third parties from a spectrum band assigned or expected to be assigned to one or more incumbent users. This means if incumbents have some control over this spectrum and if they want to discourage competition then they have influence over how this spectrum can be shared. With the MSP approach spectrum is shared from a dedicated band at 2.5 GHz. This band is not currently used by cellular companies in New Zealand. This makes infrastructure sharing (e.g. antenna and RAN sharing) difficult with an incumbent cellular operators as this infrastructure will be operating on separate frequencies. In addition, MSP doesn't allow sharing of frequencies unused or unwanted from spectrum auctions. Therefore, LSP's seem to be a better approach to allocate spectrum for cellular networks as compared to these two alternative approaches.

4.6 Summary

A new method is proposed in this chapter to divide upcoming spectrum band allocations into two different spectrum licence / management right types. The first, a spectrum license, would allow successful auction bidders to roll out mobile radio networks on a long-term nationwide scale as normal. The second is a new concept called a licensed spectrum park (LSP) and would allow smaller operators to roll out specialized mobile radio networks on a short-term local site by site basis.

LSPs would be assigned by applying for a license based on a site specific, fixed base station location for a short timeframe that could be renewed periodically. It has been noted that the key purpose of spectrum management is to maximize the value that society gains from the radio spectrum by allowing as many efficient users as possible while ensuring that the interference between different users remains manageable. The creation of LSPs means there is a net social benefit or a fair allocation of spectrum for two reasons. The first is that the use of LSPs allows specialist networks to be formed, effectively opening up the spectrum to more users and to potentially create more competition in the mobile radio market. The second is the fact that an LSP is licensed which creates a method to control interference between different users and allows interference to be managed.

It is noted that administration of LSP use could be managed by existing radio spectrum management. The price of LSP licenses would be calculated on a site-by-site basis for short timeframes. The price of LSP licenses would be similar to the normalised price of adjacent sub-band spectrum licenses - calculated based on the spectrum available and population covered.

Regulators face the issue of whether to allocate a fixed amount of spectrum for LSP use before auctioning the remaining spectrum, or alternatively auctioning the total spectrum and allocating any unsold spectrum to LSPs, if any is available. In addition, operators have options in their bidding strategy to either help or hinder the creation of LSPs. These different scenarios were modelled to help regulators choose a scenario depending on the regions long term spectrum strategy plans.

In addition, the 700 MHz combinatorial clock auction in New Zealand was used as an example to show the hypothetical effect of assigning spectrum for LSP use. In this example spectrum unsold in the clock round of the auction could have been assigned for LSP use. The resulting change in auction revenue was presented and shown that had spectrum been assigned for LSP use then revenue would have been the same or higher in the clock and assignment rounds but lower in the supplementary round. It was also shown that any loss in auction revenue could be partially offset from the on-going licence fees from the sale of LSP licenses.

Recently similar methods to share spectrum have been proposed called Licensed Shared Access and Managed Spectrum Parks. LSA is different from LSPs in that with LSA a limited number of licensees under an individual licensing regime in a frequency band already assigned or expected to be assigned to one or more incumbent users. Also with MSPs a dedicated frequency band is assigned for local spectrum managed parks. Although different from the work presented in this chapter it is interesting to similar approaches being adopted by spectrum allocation regulators around the United States and the European Union.

Our analysis offers an important contribution for both spectrum regulators and private spectrum managers and provides the framework for spectrum allocation to new market entrants enabling more competition in the mobile radio market.

Chapter 5. Licensed Spectrum Sharing

This chapter introduces the second of the alternative spectrum allocation techniques described in this thesis, Licensed Spectrum Sharing. This chapter describes the effects of traffic profiles on spectrum sharing. In particular, it shows the effects of traffic profiles with asymmetric loads on the spectrum sharing dividends and quantifies the effects of sharing spectrum between two cellular network operators and its impact on the number of base stations required to meet capacity targets.

This work was presented at the IEEE 85th Vehicular Technology Conference (VTC) in Sydney by the author of this thesis in 2017. The paper was peer reviewed by an international group of researchers from academia and industry. The IEEE produces over 30% of the world's literature in the electrical and electronics engineering and computer science fields and the VTC conference specialises in wireless communications [97].

5.1 Introduction

Spectrum is a very valuable resource for mobile radio or cellular networks. The amount of spectrum and the frequency used determines both the capacity and coverage achievable. The result has been a huge demand to acquire spectrum management rights that are suitable for cellular networks. Forecasts continue to show increasing demand for capacity from cellular networks [98]. Traditionally spectrum is assigned in exclusive use management rights to meet this demand for capacity, but alternative methods to allocate spectrum have been considered. One possible alternative is the sharing of licensed spectrum between two or more operators.

The concept of sharing spectrum between cellular operators is not new. Theoretical studies have long shown the benefits of sharing spectrum, as shown in reviews [99] and [100]. Early work was based on simulations that showed that by sharing spectrum between two operators the spectral efficiency increased. Spectrum sharing efficiencies were shown, for example, by the reduced probability of cell blocking [89] or the reduction in frame delays [101] and more recently in the reduction of the number of cells required to meet specified throughput targets [102] and to achieve capacity gains [103].

Work has also been done showing the benefits of sharing spectrum with carrier aggregation in LTE-A or LTE Rel. 10 [104]. Carrier aggregation allows spectrum to be combined from different operators providing an overall greater transmission bandwidth [105]. Each operator has the ability to use the total combined spectrum if it is available. The spectrum does not need to be adjacent i.e. inter- or intra- band aggregation can be used. Hence carrier aggregation is well suited to allow spectrum to be shared amongst multiple operators even with a large separation in operating frequencies. Sharing of spectrum from two operators is shown in Figure 14.

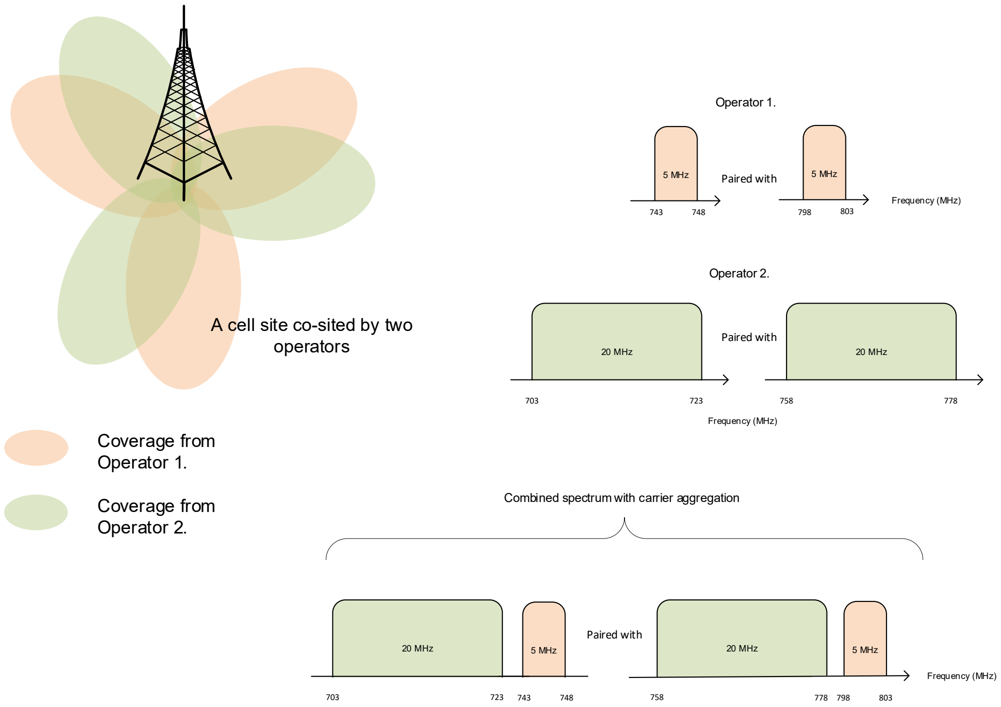


Figure 14. Spectrum sharing from two cellular operators.

Figure 14 is an example of spectrum sharing. In this example two operators share part of the spectrum they manage. In this example, an operator may own 5 - 20 MHz of paired spectrum in a particular band and they are considering the benefits to share this spectrum with another operator. This spectrum can be inter or intra band and operators can use carrier aggregation to share spectrum separated by frequency (for example separated by a guard band). In this example 5 MHz from operator 1 is shared with 20 MHz from operator 2, where both operators now can use the entire 25 MHz (paired).

Sharing of licensed spectrum as compared to using general radio user or unlicensed bands has advantages to cellular operators. Licensed spectrum is a management right to exclusively use spectrum for a fixed amount of time in a fixed geographical area. The exclusive use of this spectrum allows operators to manage interference from other users, because spectrum is shared only with other cellular operators. Also with licensed spectrum, this allows any instance of interference to be resolved between the limited numbers of operators.

A traffic profile from an urban (near CBD) site is shown in Figure 15. This shows the amount of downloaded data from this LTE base station over a day (averaged from data from Monday to Friday). From the hours of 00:00 to 06:00 the amount of traffic from this base station (eNodeB) is low but ramps up as more users enter the city from approximately 08:00 to 18:00. The traffic decreases as people leave the city to return home.

As the base station (and spectrum used) is only lightly loaded at night this spectrum could be used for other purposes at these times. Operators could offer cheaper access rates at night (as done by some electricity suppliers) to spread the load over the full 24-hour day or this spectrum could be shared with other cellular operators.

This chapter seeks to use traffic profiles from cellular operators to calculate the benefits of sharing spectrum. This research is unique in that it uses actual traffic profiles from two independent cellular operators. The hope is that there will be statistical multiplexing gains by sharing the spectrum. If traffic profiles from two different operators are asymmetric then the benefits of sharing spectrum will be greater as compared to the situation if the traffic from the two operators has similar profiles.

Section 5.2 of this chapter gives the methodology on how traffic profiles can be used to determine the benefits of sharing spectrum. In particular, it will show how traffic profiles can be used to calculate the spectrum sharing dividend (the reduced cell count to meet existing cell edge capacity). Section 5.3 will give our actual traffic profile results and based on these results calculate the benefits of sharing spectrum from these cellular networks. Section 5.4 will discuss the methods spectrum could be shared between operators and section 5.5 ends the chapter with some concluding remarks.

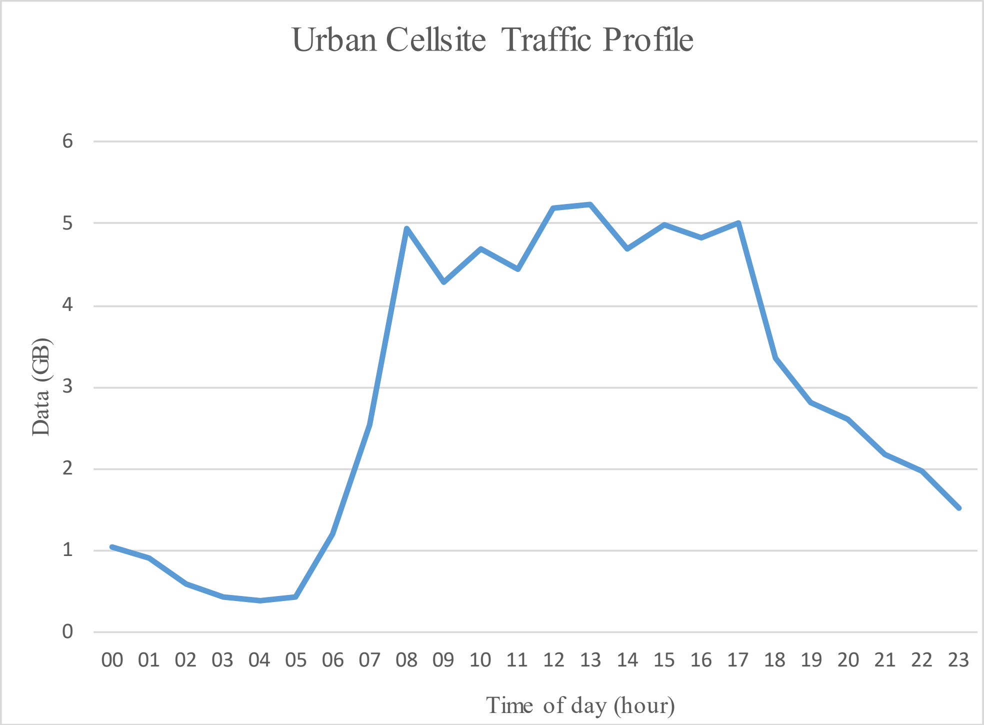


Figure 15. Traffic profile from an urban site. Data averaged over one work week (Monday to Friday).

5.2 Methodology

In sharing spectrum, operators hope to be able to increase the cell edge throughput to meet the forecasted demand in traffic growth. In addition, sharing spectrum in new markets may allow a lower number of base stations to be built to meet the forecasted growth in traffic. The latter is called the spectrum sharing dividend. The problem is how to calculate the benefit of asymmetric traffic profiles on both the cell edge throughput and the spectrum sharing dividend.

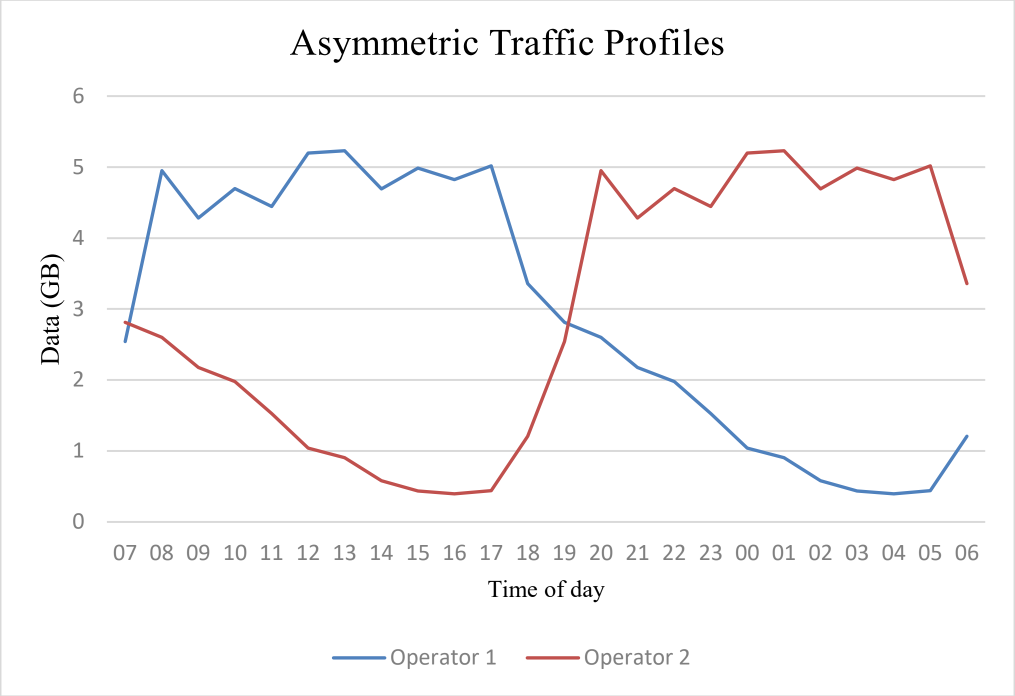


Figure 16. Asymmetric traffic profiles.

Figure 16 shows a hypothetical example of two operators with asymmetric traffic profiles. Although it is unlikely to occur in practice as most of the population use cellular networks during the day, traffic could be time of day limited if providing cellular services to a particular group of subscribers (for example students). In this example the traffic profiles are asymmetric – with little correlation between the two operators.

This chapter seeks to determine the relationship between asymmetry in traffic profiles and the spectrum sharing dividend. To calculate the spectrum sharing dividend, first a description of how propagation models are used in cellular networks is required.

5.2.1 **Propagation models**

A radio propagation model predicts the behaviour of the radio signal while it propagates from the transmitter (the base station) to the receiver (the mobile or UE device in cellular networks). Radio propagation describes the path loss which is the reduction or attenuation of signal strength due to propagation through space and terrain. Path loss may be due to many effects in the path itself, such as free-space loss, refraction, diffraction, reflection, and terrain or physical obstructions, but is also influenced by the transmitter and receiver design such as frequency, height, number and location of antennas.

Path loss models are important to predict the coverage area, interference, frequency assignments and cell parameters which define the network planning in cellular networks. Path loss models and the ability to predict coverage and capacity achievable from a given base station is crucial to design cellular networks and significantly effects how spectrum is used.

The free space path loss model is the most basic path loss prediction tool and is often used as a basis for other propagation prediction models. The free space path loss (in dB) is given as:

$$FSPL\ (dB) = 32.42 + 20log_{10}(d) + 20\ log_{10}(f) \tag{3}$$

Where *f* is the transmit frequency (in MHz) and *d* is the distance from the transmitter (in km). By the free space path loss model, the higher the frequency, the greater the path loss and the lower the coverage predicted. Note, this is opposite of capacity where the higher the frequency the more spectrum available and therefore the higher the maximum capacity achievable.

The Okumura-Hata model (also called the Hata model) is a common model used by cellular operators to predict the radio propagation used for cellular networks. This model is accurate for frequencies 150-1500 MHz and has a different model for urban, suburban and open areas. This is an empirical based model, based on the measured data and graphical information from the Okumura model and developed further to include modelling of diffraction, reflection and scattering from physical structures and obstructions based on work by Hata – therefore cumulating in the Okumura-Hata model [106].

The Okumura-Hata model expresses the basic propagation loss in urban areas as follows:

$$\begin{aligned} L_b = 69.55 + 26.16 \log f \\ - 13.82 \log h_b - a(h_m) + (44.9 - 6.55 \log h_b) \log d_m \end{aligned} \tag{4}$$

Where L_b is the path loss (in dB), *f* is the carrier frequency (150 to 1500 MHz), h_b is the height of the base station 30 to 200m, h_m is the height of the mobile (1 to 10m) *d* is the distance or path length (limited to 1 - 20km) and $a(h_m)$ is the correction factor for mobile antenna height and is computed differently for small and large cities and suburban and rural areas for example for a small to medium city. Here $a(h_m)$ is:

$$a(h_m) = (1.1\log f - 0.7)\,h_m - (1.56\log f - 0.8) \tag{5}$$

The COST-Hata model is another radio propagation model that extends the urban Hata model to cover a greater range of frequencies (up to 2 GHz). As such it is used by cellular operators when evaluating propagation using frequencies near 2 GHz e.g. 1800 MHz used in New Zealand. COST (Coopération européenne dans le domaine de la recherche Scientifique et Technique) is a European Union Forum for cooperative scientific research which has developed this model based on experimental measurements in multiple cities across Europe. COST 231 Hata [107] is modelled as:

$$\begin{aligned} L_b = 46.3 + 33.9\log f \\ - 13.82\log h_b - a(h_m) + (44.9 - 6.55\log h_b)\log d_m \\ + C_m \end{aligned} \tag{6}$$

Where again L_b is the path loss (in dB), f is the frequency (150 to 2000 MHz), h_b is the height of the base station 30 to 200m, h_m is the height of the mobile (1 to 10m) d is the distance or path length (limited to 1 - 20km), C_m is the constant offset (0 for medium cities and suburban areas, 3 for metropolitan areas) and $a(h_m)$ is the correction factor for mobile antenna height and is computed differently for small and large cities and suburban and rural areas as described in equation (5).

For higher frequencies, for example at 28 GHz, a 3GPP urban micro (UMi) path loss model has been used by some authors (e.g. [108] and [109]) given by:

$$L_b = 22.7 + 36.7\log_{10}(d) + 26\log_{10}(f) \tag{7}$$

Where L_b is the path loss, d is the distance from the base station and f is the carrier frequency. Note that equation (7) is a similar to the free space loss equation (3) suggesting that characteristics of refraction and diffraction are less prevalent at mm wavelength frequencies.

This thesis uses two of these propagation models in this and later chapters. This chapter uses the COST-Hata model to help calculate the spectrum sharing dividend as described below, and later chapters use the UMi path loss model.

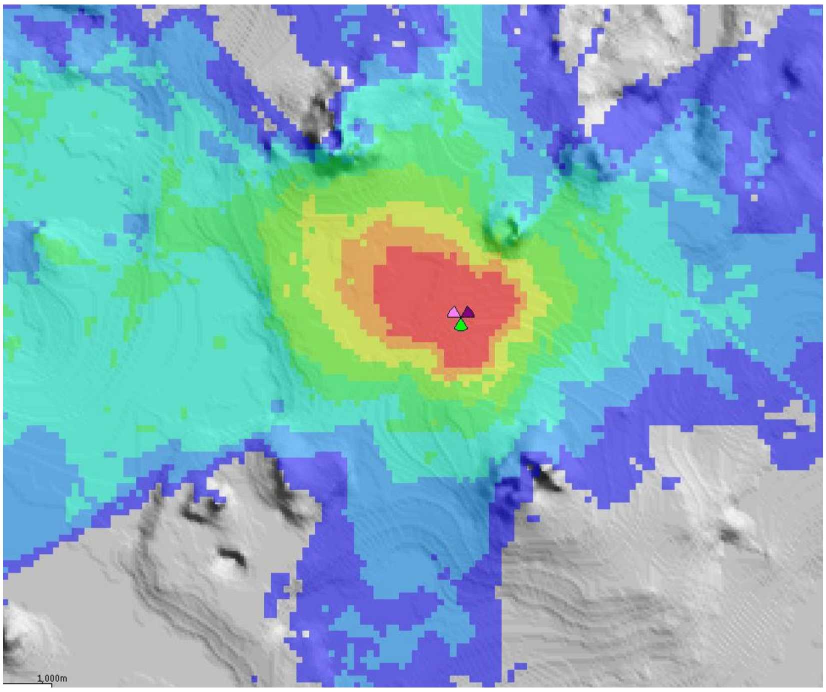


Figure 17. Coverage prediction based on COST-Hata model - propagation of UHF cellular networks with topographical background.

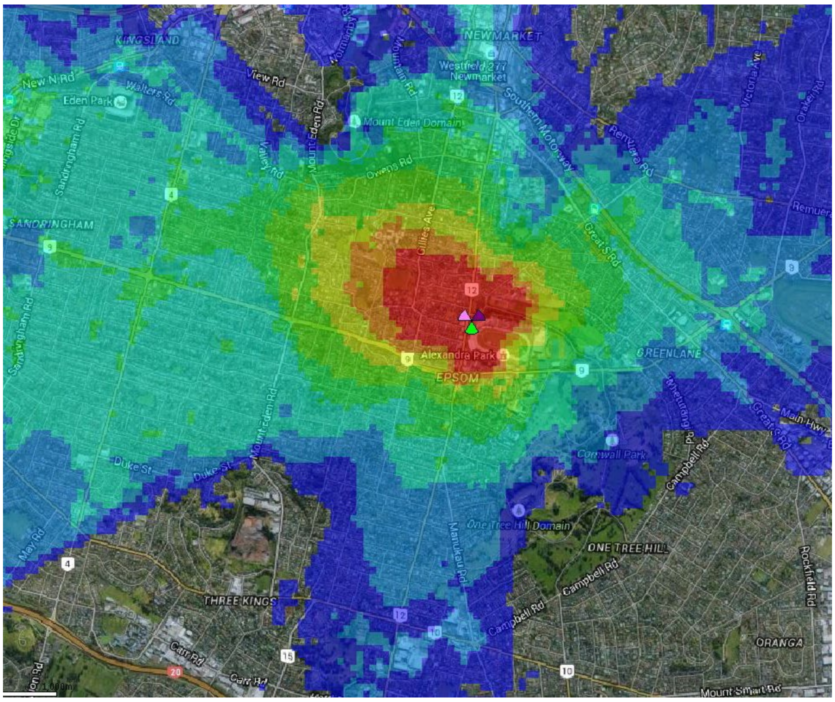


Figure 18. Coverage prediction based on COST-Hata model - propagation of UHF cellular network with road and clutter background.

These coverage predictions were created by the author using Atoll radio planning software (https://www.forsk.com/atoll-overview).

The red colour shows signal strength greater or equal to -70 dBm down to dark blue colour showing a signal strength of greater or equal to -105 dBm. Some cellular operators use -105 dBm or better to indicate the cell edge (the limit for acceptable cellular services).

The path loss models will show the relationship between frequency and distance (and other design factors such as transmitter and receiver heights) to the receive signal, but to change this to a propagation model requires implementing this path loss model with physical conditions. Physical conditions such as terrain obstructions (where obstructions such as hills will stop, scatter and diffract radio signals) as shown in Figure 17 and physical conditions such as buildings and foliage (known as clutter) will also reflect, diffract and scatter radio signals (consider the background of Figure 18). Note the signal is stopped by hills to the SW and SE of the base station, for example.

Propagation models are then used to predict the actual propagation characteristics from a particular base station and can be used to model base station placement to optimise signal strength and reduce inter cell interferance.

5.2.2 **Spectrum Sharing Dividends**

The spectrum sharing dividend is defined as a metric that shows the benefit to operators of sharing spectrum under peak load conditions. Previous work [102] has showed that the spectrum sharing dividend i.e. SSD^*_e, can be calculated by comparing the number of base stations required to serve a given area (A) with sharing ($N^*_{e,SH}$) and without spectrum sharing ($N^*_{e,NSH}$), where:

$$N^*_{e,(N)SH}= \frac{2}{3}A\sqrt{3}/(ISD^*_{e,(N)SH})^2 \tag{8}$$

$ISD^*_{e,NSH}$ and $ISD^*_{e,SH}$ donate the optimised inter-site distance for the case of non-sharing and sharing respectively. This can be shown as:

$$SSD^*_e = \frac{N^*_{e,NSH}-N^*_{e,SH}}{N^*_{e,NSH}} = \frac{\left(\frac{1}{ISD^*_{e,NSH}}\right)^2 - \left(\frac{1}{ISD^*_{e,SH}}\right)^2}{\left(\frac{1}{ISD^*_{e,NSH}}\right)^2} \tag{9}$$

The spectrum sharing dividend is optimized by calculating maximum allowed *ISD* that satisfies coverage and capacity requirements in environment *e*. The coverage *ISD* is calculated using the uplink budgets as shown in Table 4.

Item	LTE Value	Unit
Frequency band	1800	MHz
Max Tx power	23	dBm
Tx antenna gain	0	dBi
Body loss	0	dB
EIRP	23	dBm
Noise figure	2	dB
Thermal noise	-121.4	dBm
Rx noise	-119.4	dBm
SINR	3.9	dB
Rx sensitivity	-115.6	dBm
Interference margin	1	dB
Cable loss	3	dB
Rx antenna gain	18	dBi
Fast fading margin	0	dB
Soft handover gain	-	dB
Coverage reliability	90%	
Shadowing plus penetration loss:		
mean	10.6	dB
sigma	4.5	dB
margin	16.4	dB
Max. allowable path loss	136.2	dB
Path loss model (COST 231 Hata):		
fixed	134.8	dB
distance	35.2	dB
Max. allowable cell range	1.1	km

Table 4. Uplink budgets used to calculate the coverage inter-site distance.

The capacity *ISD* is calculated using the same (downlink) stochastic performance model as presented in [102]. Where the aim is to maximize the *ISD* such that the cell edge throughput target is still satisfied.

Here the throughput parameters used are:

Item	2015	2020	2025
Cell edge user throughput target (Mbit/s)	1	1.2	1.5
Average user throughput target (Mbit/s)	6	7.2	9

Table 5. Throughput parameters used to calculate the capacity inter-site distance.

The aim is then to calculate the minimum *ISD* from the coverage and capacity analysis i.e.

$$ISD_e^* = min\ [ISD_{cap,e}^*, ISD_{cov,e}^*] \tag{10}$$

Also from [102] we know that:

$$SSD = (1 - LSR) + LSR\ \times\ SSD_{sym} \tag{11}$$

Where *LSR* is the load symmetry ratio, a numerical description of the asymmetry of the traffic profiles. Here *LSR* is defined as the peak combined load of the sharing operators traffic divided by the sum of the individual peak loads of the sharing operators. Operators that have symmetric traffic profiles will have an *LSR* of 1 (with SSD_{sym} the *SSD* that would result if *LSR* = 1). *LSR* can be calculated by:

$$LSR = \frac{\max(D_{Op1} + D_{Op2})}{\max\left(D_{Op1}\right) + \max\left(D_{Op2}\right)} \tag{12}$$

Where $\max\left(D_{Op1}\right)$ is the maximum data (downlink) from Operator 1 and $\max(D_{Op1} + D_{Op2})$ is the maximum value of the sum of the data from each operator at any single sample point.

Using the results of equation (9) and the model result displayed by equation (10) and the definition of LSR by equations (11) and (12) we can plot the spectrum sharing dividend versus the LTE rollout (years) against various load symmetry ratios. This is shown in Figure 19 and more information, including the MATLAB program to calculate this plot is given in Appendix B. This shows for a particular load symmetry ratio the resulting spectrum sharing dividends for an LTE only network. For example, with a *LSR* of 0.7 in 2016 we would expect a spectrum sharing dividend of around 30%. This means 30% fewer sites would be required to meet the cell edge throughput forecasts, if spectrum between these two operators was shared.

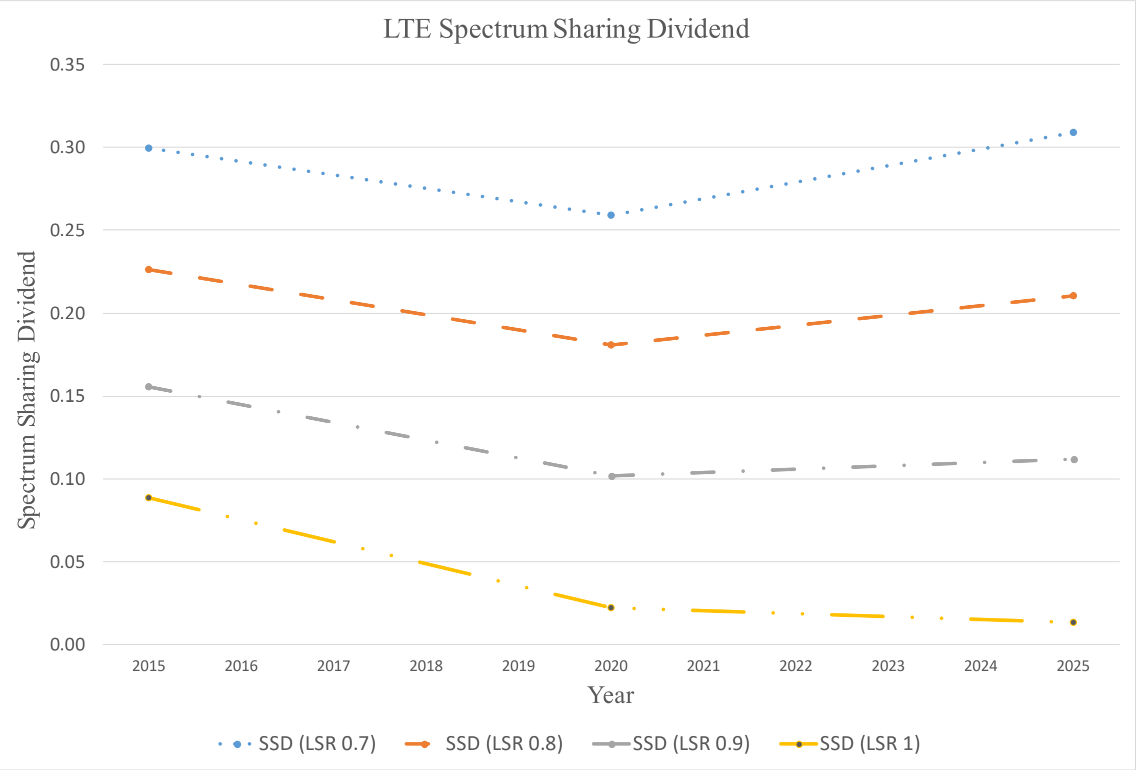


Figure 19. The LTE spectrum sharing dividend for specific load symmetry ratios.

5.3 Results

Traffic profiles from two independent cellular networks are shown in Figure 20 and Figure 21 below. These are from LTE networks using 1800 MHz and both use a bandwidth of 20 MHz of paired spectrum. The sites chosen are where the operators are co-sited – they share the same site for these particular base stations. The operators do have different equipment configurations, for example antenna types and azimuths and exhibit different coverage predictions from the same site. The operators obviously have different users on their networks, all resulting in different traffic profiles from each operator.

Figure 20 shows the resulting traffic profile from a suburban site. The traffic profile shows the same general profile as displayed in Figure 15, with low traffic at night. Figure 21 shows the resulting traffic profile from a rural site.

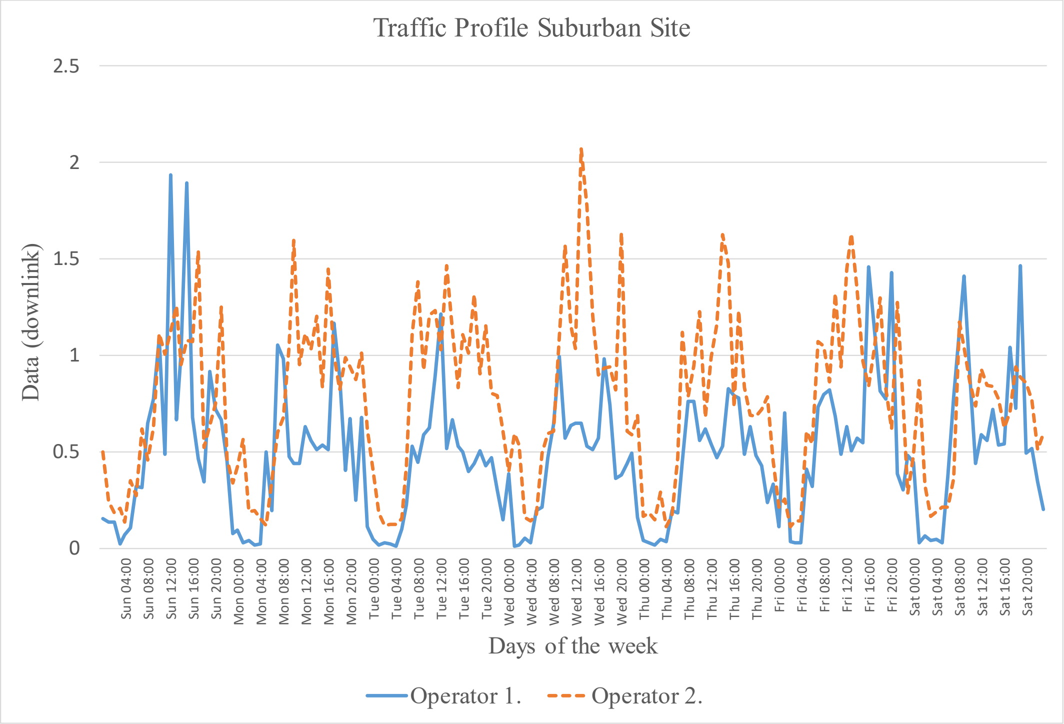


Figure 20. Traffic profile from a suburban LTE base station.
Shows data downlink (from base station to UE) in GB over a week.

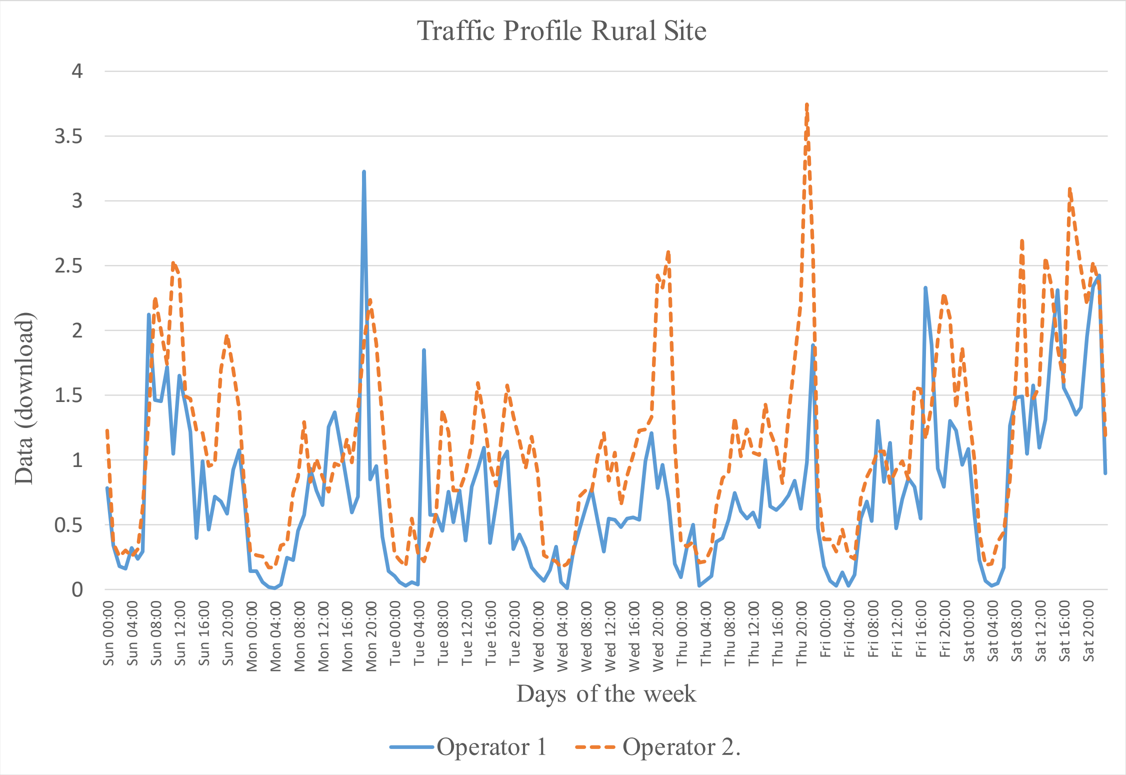


Figure 21. Traffic profile from a rural LTE base station.
Shows data downlink (from base station to UE) in GB over a week.

Using the methods shown in section 2 of this chapter we can calculate the load symmetry ratio of these two traffic profiles, as shown earlier in this chapter, as $\max(D_{Op1} + D_{Op2}) / (\max(D_{Op1}) + \max(D_{Op2}))$. For the suburban case the *LSR* is 3.06/4.01 = 0.76 and for the rural case the *LSR* is 5.14/6.97 = 0.74. Taking the average of these two sites we have an *LSR* of 0.75.

Based on the surveyed *LSR* of 0.75 we can now use Figure 19 to calculate the spectrum sharing divided for sharing spectrum across these LTE networks and the result is a *SSD* of 25 % in 2016. This result means that if these two networks shared spectrum then 25% less sites would be required to meet the capacity objectives.

5.4 Discussion

These results show that sharing spectrum is best done where there is a large difference in traffic profiles between operators i.e. the traffic profile asymmetry is high, or the load symmetry ratio is low. This is likely if the operators target markets with different user groups. An example would be an operator that targets business users, with a high data usage during business hours, sharing spectrum with an operator that targets the younger market (for example students) who are more likely to use the cellular network outside of business / school hours.

In addition, a large spectrum sharing dividend shows that spectrum sharing is beneficial, before building more base stations to meet the forecasted growth in capacity. Sharing spectrum may be most beneficial in urban settings where forecasted growth in capacity is expected to be high.

There are a number of options operators can use to share spectrum. This sharing could be site specific, sharing spectrum in a small geographical area for example in a sports stadium. The amount of spectrum shared could be pre-determined based on a traffic profile where the spectrum sharing is scheduled by each operator for a short timeframe. Spectrum sharing could also be dynamic (on-the-spot) sharing where an operator has an urgent need for more spectrum, for example in an emergency situation. Spectrum sharing could also be network wide where each operator shares all spectrum all the time.

There are also a number of options to calculate how each operator could charge for sharing spectrum. This could be cost based pricing where the amount of spectrum shared and the price is related to the cost initially paid for the spectrum, i.e.

$$Price = [Cost/(BW \times Pop)] \times [(BW_{SH} \times \ Pop_{cov})/T] + OH \tag{13}$$

Here *BW* is the amount of bandwidth (spectrum) shared, *Pop* is the population covered by the entire network, Pop_{cov} is the population covered by the shared spectrum, *T* is the amount of time the spectrum is required and *OH* is an overhead cost for administration. This is similar to the work done by [5]. Alternatively, the price of the shared spectrum could be calculated based on the value of spectrum to each operator i.e. based on the revenue generated by each operator by sharing spectrum. This is based on revenue information (payback) that is confidential to the operator. Finally, others, e.g. [48] have suggested an auction based method to share spectrum where operators bid for the rights to use available spectrum.

Licensed spectrum sharing will require co-ordination between the operators that wish to share spectrum. This will allow for frequency use optimisation across the radio access network (RAN). This means that operators will share information about frequency use potentially with a competitor i.e. the other operator. The level of coordination and information sharing will be high and may involve complete RAN sharing.

Based on the load symmetry ratio, spectrum sharing dividend, and capacity increase results, we showed earlier there are trunking and spectral efficiency gains to be made by sharing spectrum. Spectrum sharing perhaps works best when shared across the entire network or in large geographic areas and where all available spectrum in a particular frequency band is shared. This allows for each operator to accommodate unexpected peaks in data traffic and leads to less overheads to manage this resource.

5.4.1 **Work post publication of the traffic profiles and spectrum sharing model**

This chapter investigates a specific part of spectrum sharing, namely when two cellular operators share licensed spectrum in the same band with each other. Research continues to be published on other spectrum sharing techniques since this chapters work on spectrum sharing and asymmetric traffic profiles was published in 2017. Both industry and research communities have recognized the importance of network sharing in the evolution of cellular networks. Recent survey work in 2018 [110] showed the spectrum sharing technique proposed in this chapter is just one of many techniques used to share spectrum.

Other works state that next generation cellular networks will rely ever more heavily on resource sharing including the radio access network and spectrum sharing [111]. This particular paper concludes that performance gains brought about by spectrum sharing involve complex trade-offs that depend on how the spectrum is shared and on the nature of the cellular network deployments for example the location of base stations.

Other works [112] show the network capacity achievable by means of orthogonal sharing in the context of an unbalanced network scenario. This confirms that spectrum sharing gains are optimised when all spectrum is shared (sharing rate 100%). Referring to Figure 22 this shows the total capacity gains in sharing spectrum against the operator load ratio. Here the operator load ratio is not the same as the load symmetry ratio (which uses ratios of traffic) but in this case uses the ratio of the loading (users per cell), where the load of the first operator is kept at 40 users per cell and the load of the second operator is changed from almost no users to the same 40 users per cell as operator 1. This paper showed a 20% capacity gain at a 0.6 operator load ratio, from a sharing rate of 0% to a sharing rate of 100%.

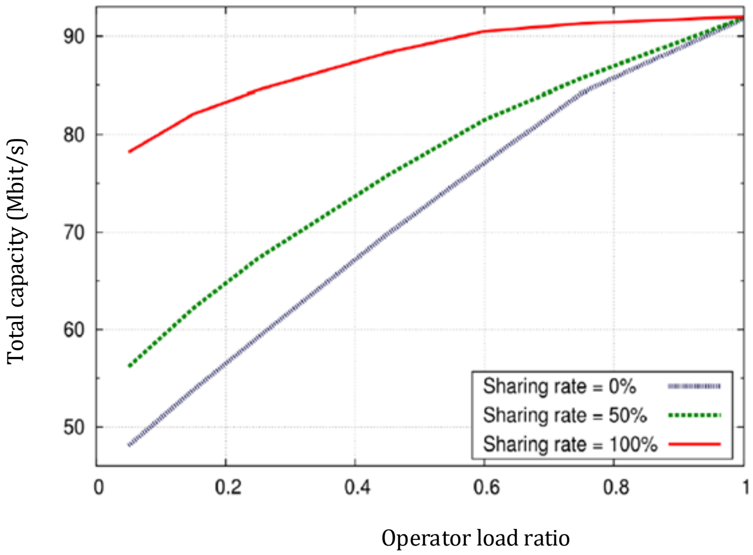


Figure 22. Performance evaluation of orthogonal sharing, for maximal throughput scheduling.

In practice, in cellular networks used today, spectrum sharing works similar to the method presented in this chapter. Recently the 3rd Generation Partnership Project (3GPP) has defined standards for network sharing [113]: namely the Multi-Operator Core Network (MOCN), and the Gateway Core Network (GWCN). The MOCN is a solution that provides a shared radio access network where multiple operators share the RAN and each base station is connected to multiple core networks. MOCN allows spectrum sharing – each operator sharing the spectrum at the base station, but traffic terminates at an independent Core. In the Gateway Core Network approach, the network operators share the RAN and spectrum but also share the Mobility Management Entity (MME) of the core network which is responsible for bearer and connection management.

This shows that cellular operators are interested in sharing critical spectrum (and other resources) with other cellular operators. At the moment cellular operators have two types of spectrum use: the use of licensed spectrum (used for voice, and on-net data) and the use of unlicensed spectrum (for Wi-Fi data offloading). In general, operators do not share licensed based spectrum except with other cellular operators. This matches the approach presented in this chapter, rather than many spectrum sharing techniques proposed in literature such as spectrum sensing or sharing spectrum unused and tracked by databases.

In the case presented in this chapter, both spectrum users are known to each other and any sources of interference between these two operators can be managed between professionals and quickly resolved. Both users will know and follow any technical limitations in using the spectrum keeping power and spurious emissions within the boundaries set by the regulator. Sharing of spectrum can also be organised via legal contracts that specify exactly how the spectrum will be shared between the parties limiting this to specific areas or sites when needed, although we have seen the benefits of sharing spectrum in the spectrum sharing dividend are greatest when sharing all spectrum used at all sites in the cellular network.

However cellular operators are commercial entities who desire to make profit from their networks and to gain competitive advantage over other cellular operators. Hence sharing of such a critical resource between operators is not a preferred method to manage spectrum for some. For example in New Zealand RAN sharing using MOCN is only used in very remote sites, funded by the Government to provide coverage where it is uneconomic for commercial cellular providers to provide the service [85].

5.5 Summary

This chapter presents the benefits of sharing licensed spectrum between two cellular network operators. This is motivated by the need by operators to meet the forecasted demand for capacity in cellular networks and also by the desire to reduce the number of base stations to serve this market.

This chapter shows that traffic profiles have a significant effect on the spectrum sharing gains. In particular, traffic profiles with asymmetric loads will show the greatest gains when sharing spectrum. To calculate these gains, we calculate the load spectrum ratio as the amount of asymmetry in traffic profiles to calculate the spectrum sharing dividend, which is the possible reduction in base stations to meet forecasted rise in capacity demands.

Also presented in this chapter are actual traffic profiles from two different cellular operators using LTE networks. We use this data to show that sharing spectrum from these two networks will result in a spectrum sharing dividend of 25% in 2016. This result means that if these two networks shared spectrum then 25% fewer sites would be required to meet the capacity forecasts.

Other works showed similar spectrum efficiency when sharing spectrum [112]. This paper shows the network capacity achievable by means of orthogonal sharing in the context of an unbalanced network scenario. This confirms that spectrum sharing gains are optimised when all spectrum is shared. Results from this paper showed a 20% capacity gain at a 0.6 operator load ratio, from a sharing rate of 0% to a sharing rate of 100%.

In discussing these results, we concluded that spectrum sharing is most efficient when all available spectrum is shared from a particular frequency band amongst cellular network operators. This allows for each operator to accommodate unexpected peaks in data traffic and leads to less overheads to manage this resource.

Chapter 6. The Use of Spectrum at Millimetre Wavelengths

This chapter introduces the third of the alternative spectrum allocation techniques described in this thesis. This chapter summarises the benefits and limitations of using spectrum at mm wavelengths for radio access in cellular networks. It discusses the engineering viability of using mm wavelengths for cellular use but focuses on the assignment of spectrum in this band from a regulation and policy use point of view. In particular, the analysis considers whether mm wavelength spectrum should be used as licensed or unlicensed bands, or a combination of both, when used for cellular networks.

This work was presented in a paper titled “The use of spectrum at mm wavelengths for cellular networks” at the Pacific Telecommunications Council (PTC) Conference in Honolulu, by the author of this thesis in 2016. The paper was peer reviewed by an international group of researchers from academia and industry at the PTC. PTC is the global non-profit membership organization promoting & advancing information and communication technologies in the Pacific Rim [114].

6.1 Introduction

Spectrum is a very valuable resource in cellular networks where the amount of spectrum and the frequency of use determine both the coverage and capacity achievable. Traditionally cellular networks use spectrum in the UHF band, which allows good radio propagation and meets most of the current demand for capacity. However the demand for capacity is increasing significantly, driven in part by the popularity of smart phones but also by the increase in wireless video content [115], [116] and the likely increase in machine to machine traffic. To meet the future demand for capacity a change in how spectrum is utilised needs to be considered. One possible solution is the use of millimetre (mm) wavelengths for cellular networks.

Millimetre wavelengths are defined as electromagnetic spectrum with wavelengths from 1 to 10 mm or 30 to 300 GHz – this is also known as the EHF or extremely high frequency band. Current cellular networks use frequencies in the UHF, or ultra high frequency band (300 MHz to 3 GHz). The UHF band has been used by first generation AMPS and DAMPS networks, second generation GSM and CDMA networks, third generation UMTS and even fourth generation LTE networks. More information of these technologies is given in Appendix A.

The main benefit of using mm wavelengths is the large bandwidths available for cellular network use. Cellular networks today typically use channel bandwidths of 5-20 MHz, whereas the channel bandwidths available at the mm wavelengths exceed 500 MHz [117]. The Shannon Hartley theorem [82] shows that the greater the bandwidth available then the greater the maximum capacity achievable i.e.

$$C = B \log_2 (1 + S/N) \tag{14}$$

Where C is the channel capacity, B is the bandwidth of the channel and S/N is the signal-to-noise ratio (SNR). Sometimes the SNR is expressed as the carrier to interference ratio. For the same signal to noise ratio an increase from channel bandwidth from 20 MHz to 500 MHz would allow at least a 25 times increase in the corresponding capacity.

The second main benefit of mm wavelengths is the fact that advanced beam forming techniques are possible with the use of these smaller wavelengths [118]. In particular the fact that a large number of antennas are achievable in a small space allows directional beam forming and greater use of MIMO to enhance spectral efficiency. MIMO (multiple-input and multiple-output) allows multiple transmit and receive antennas to increase capacity by allowing multipath propagation, and adaptive beam forming allows the signal strength to be increased by adaptive spatial signal processing in a specific direction, for example between a base station and a mobile device.

However, the use of mm wavelengths also has a downside. At these wavelengths there is very high attenuation (or blockage) of propagation through certain materials like concrete walls and foliage. At 28 GHz walls can cause 40-80 dB of attenuation, foliage up to 23 dB and the human body itself causes 20 to 35 dB of attenuation [119]. All these losses are dependent of the depth and construction of these materials. There is also higher air attenuation at these frequencies and higher outages due to rain. The high concrete, air and other material attenuation means that the coverage range of base stations would be much lower than the coverage range of base stations used in today's macro cell sites [120], and many more sites may be required when compared to the standard cell sites used today to give ubiquitous coverage.

The addition of more base stations implies higher cellular rollout costs. Additional base stations require more backhaul (fibre), site power, site acquisition and design, and planning and maintenance costs. Another challenge is that mm wavelength transceivers currently have high power consumption and high component cost [108], this affects both mobiles and base stations. This means that not only will more base stations be required, but each base station and the associated mobiles are likely to cost more.

Of particular relevance to cellular networks are frequencies located in the minima and maxima shown in Figure 23, which is a plot of air attenuation at sea level in dB/km versus frequency in GHz. The frequencies used by cellular networks in the UHF band (0.3 to 3 GHz) have very low air attenuation. The minima at approximately 28 GHz, for example, are the frequencies where air attenuation is relatively low but the bandwidth of available spectra is relatively high. Conversely, for the maxima, for example 60 GHz, the air attenuation is high, caused by the resonance of oxygen molecules at this frequency. This means propagation is particularly poor at this frequency even though available spectrum is high.

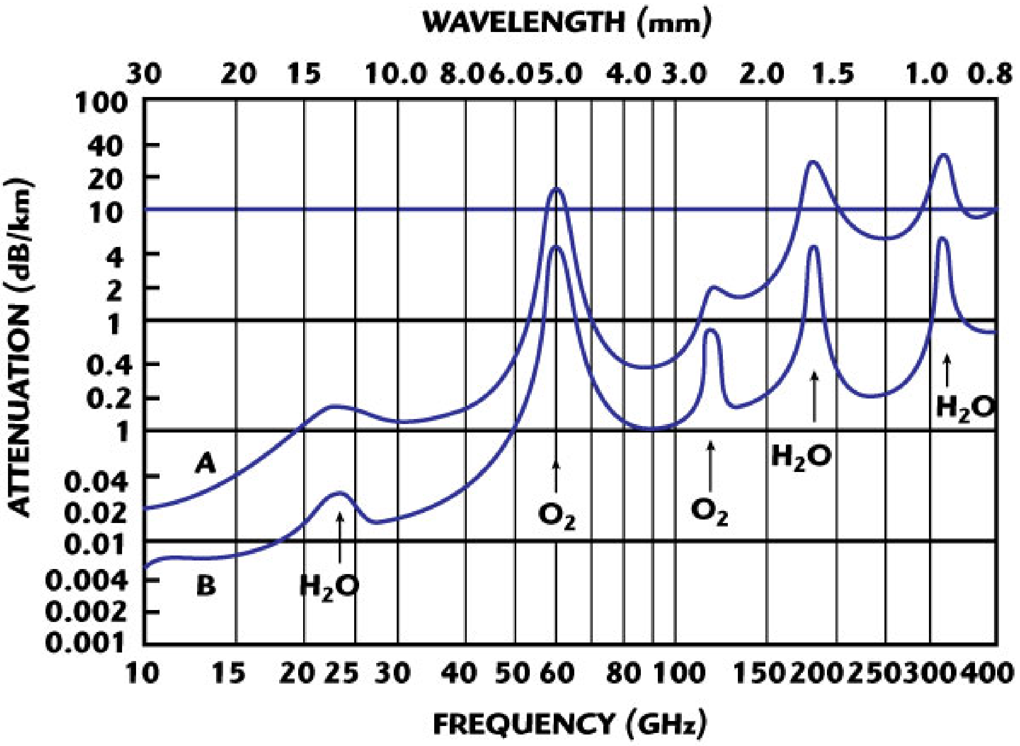


Figure 23. Attenuation (dB/km) versus frequency (GHz). Sourced from [121] **and** [122]**.**

In Figure 23 (A) is the average atmospheric absorption at sea level (Temp = 20 deg C, P=760mm, H_2O = 7.5 g/m^3) and (B) is average atmospheric absorption at 4 km altitude (Temp=0 deg C, H_2O=1 g/m^3).

Despite the challenges described above, research suggests that designing cellular networks using mm wavelengths is viable. Work reported in [120] on radio propagation path loss models showed a simulated effective cell radius of 220 m at 28 GHz, which agrees with measured data from [123]. The later paper concluded that since (mm wavelength) signals cannot readily propagate through outdoor building materials then indoor networks will be isolated from outdoor networks. They suggested that access points (base stations) may need to be installed for handoffs at entrances to commercial and residential buildings (to provide continuous coverage).

Note that 28 GHz is strictly not in the EHF or mm wavelength band i.e. 1 to 10 mm or 30 to 300 GHz but lies just outside this range. However, 28 GHz is important due to the location of the minima as shown in Figure 23 at this frequency.

Regulators will play an important role in determining policy for the use of mm wavelengths. The FCC has already submitted a notice of inquiry in the matter of ‘use of spectrum bands above 24 GHz for mobile radio services’ [124]. Certainly, the use of mm wavelengths in future generations of cellular networks seems likely given the large amounts of available spectrum. Whether this is for 5G or some later generation of cellular networks remains to be seen.

6.2 Millimetre wavelength propagation

Predicted LTE coverage areas using 28 GHz and 1800 MHz carriers are shown in Figure 24 and Figure 25, respectively. These figures show the significant coverage achievable using the UHF band (Figure 25) versus the coverage achievable using mm wavelengths (Figure 24).

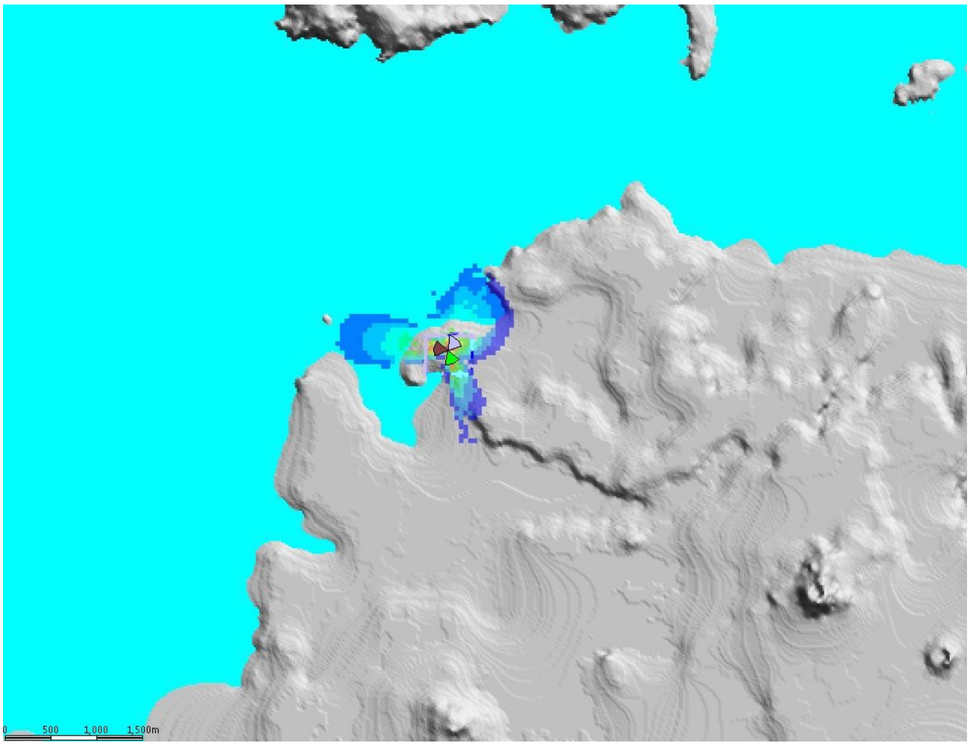


Figure 24. Simulated LTE coverage from a coastal cell site using mm wavelengths (28 GHz).

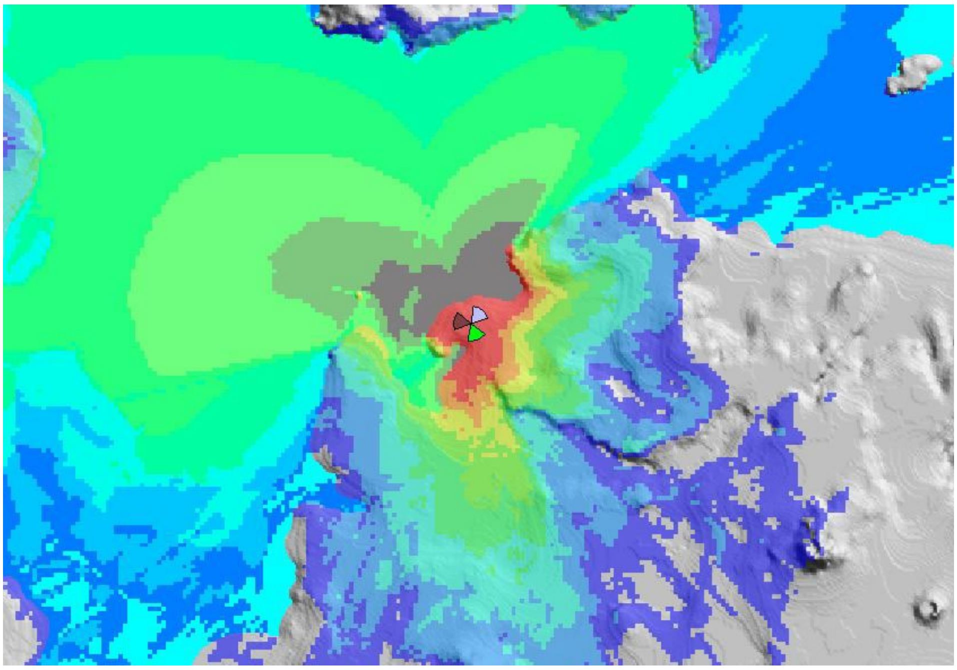
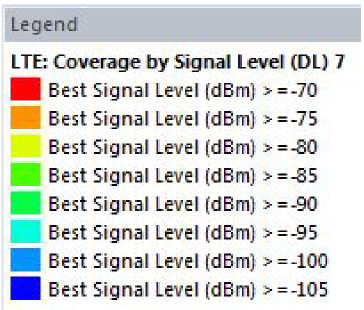


Figure 25. Actual LTE coverage from the same coastal site, using the UHF band (1800 MHz).

These coverage predictions were created by the author using Atoll radio planning software (https://www.forsk.com/atoll-overview).

Both these coverage plots have the following legend.



Legend

LTE: Coverage by Signal Level (DL) 7

🟥 Best Signal Level (dBm) >=-70

🟧 Best Signal Level (dBm) >=-75

🟨 Best Signal Level (dBm) >=-80

🟩 Best Signal Level (dBm) >=-85

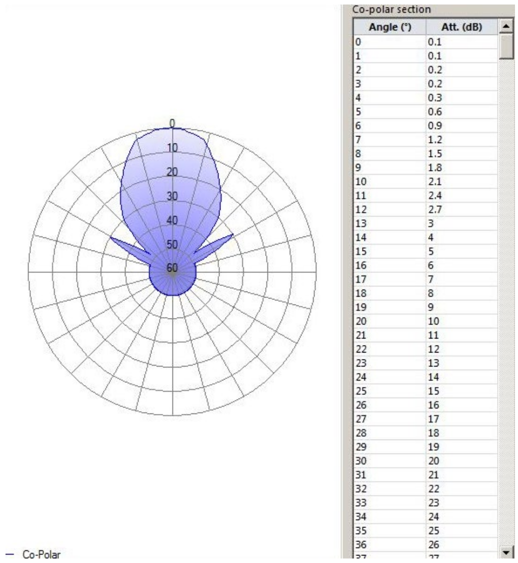
🟩 Best Signal Level (dBm) >=-90

🟦 Best Signal Level (dBm) >=-95

🟦 Best Signal Level (dBm) >=-100

🟦 Best Signal Level (dBm) >=-105

Figure 26. Legend for LTE coverage plots shown in Figure 24 and Figure 25.



Co-polar section

Angle (°)	Att. (dB)
0	0.1
1	0.1
2	0.2
3	0.2
4	0.3
5	0.6
6	0.9
7	1.2
8	1.5
9	1.8
10	2.1
11	2.4
12	2.7
13	3
14	4
15	5
16	6
17	7
18	8
19	9
20	10
21	11
22	12
23	13
24	14
25	15
26	16
27	17
28	18
29	19
30	20
31	21
32	22
33	23
34	24
35	25
36	26

Figure 27. Antenna radiation pattern used in mm wavelength propagation model.

The mm wavelength coverage prediction as shown in Figure 24 has a maximum transmit power of 30 dBm, a single horn antenna per sector with radiation pattern shown in Figure 27, with 17 dBi gain and a 3 dB beam width of 26.25 degrees. Figure 24 uses the 3GPP urban micro (UMi) path loss model [108] and [109] given by:

$$PL(d)\ [\mathrm{dB}] = 22.7 + 36.7 \log_{10}(d) + 26 \log_{10}(fc) \tag{15}$$

Where PL is the path loss, d is the distance from the base station and fc is the carrier frequency (28 GHz) in this case. The path length of Figure 24 matches that achieved in other published works [123].

The UHF coverage prediction as shown is Figure 25 shows the actual LTE coverage from a LTE 1800 MHz cell site in Auckland, New Zealand. This coverage has been confirmed by drive test results. This shows a large coverage area typical of a sub-urban cell site (near water). The coverage prediction as shown in Figure 25 has a maximum transmit power of 30 dBm, a single panel antenna per sector, with approximately 17 dBi gain and a 3 dB beam width of approximately 60 degrees.

A comparison of Figure 24 and Figure 25 shows that the coverage using UHF band in this example far exceeds the coverage using mm wavelengths. This is shown in the total coverage from each base station, in the coverage from each sector, and in the coverage achieved at high signal levels.

The greater coverage from each sector, in the UHF band example, is caused not only by the difference in propagation between mm wavelengths and the UHF band but is also due to the difference in beam widths of the antennas at these bands. The antennas currently available at higher frequencies generally have narrower beam widths. This could be partially overcome by having greater number of antennas at each base station i.e. increasing the number of sectors when using mm wavelengths with a corresponding increase in cost.

Figure 24 and Figure 25 also show that there is a greater amount of coverage in the UHF band example at higher signal levels. For example, a greater area covered where the signal level is -80 dBm or higher in the UHF band example. A high signal strength helps offset any losses caused by obstructions such as walls and foliage. A low signal strength (signal to noise ratio) can also negatively affect the capacity achieved, as shown earlier in this chapter in the Shannon Hartley theorem, equation (15).

Figure 24 and Figure 25 confirms the greater number of base stations required if using spectrum at mm wavelengths for cellular networks when compared to the use of spectrum in the UHF band.

6.3 Millimetre wavelengths – licensed spectrum

This section of this chapter considers assigning mm wavelength bands for cellular use as licensed spectrum. This means regulators would assign spectrum under an auction system such as the combinatorial clock auction [30] or other allocation methods [5]. The licenses would be for a fixed amount of spectrum, covering a large geographic area, for a large timeframe.

Licensed spectrum is desired by cellular operators as it allows the operators exclusive use to this spectrum with the ability to manage interference from third parties.

Historically licensed spectrum is sold for cellular use with a condition stating a high percentage of the population must be covered with this spectrum. For example, in the recent 700 MHz auction in New Zealand there was a requirement that operators achieve 75% national population coverage with this spectrum, including at least 50% population coverage within any given region, within five years [125].

The rollout of a licensed mm wavelength ubiquitous network would require a significant investment from cellular operators. Figure 28 shows the existing base station location of a cellular network in Auckland, New Zealand (a city of 1.4 million people). The sites located in the CBD are typically pico cells – with a distance between base stations ranging from 100-300 m. The sites in suburban locations are typically micro cells – with a distance between base stations ranging from 1-2 km. The sites located in rural areas are macro cells – with a distance between base stations typically 20 km+ (sometimes coverage is not continuous between rural sites in which case the distance between base stations is network specific). These distances match those in [126].

Figure 28. Existing base station locations for a single operator in Auckland, New Zealand.

Data for Figure 28 has been collected from public spectrum license information from Radio Spectrum Management [125]. The highest concentration of sites is in the city CBD, the other sites shown are in suburban areas.

If ubiquitous coverage is a requirement for a 'licensed' mm wavelength cellular network then having base stations at least every few hundred metres to cover 75% of the population (i.e. the requirement in New Zealand for operators to use 700 MHz) would be a very significant, if not prohibitive, cost. This means licensed band use of mm wavelengths for cellular use may not be able to follow standard regulatory conditions historically imposed on cellular rollouts. Therefore a heterogeneous network is a likely solution. This means a network where coverage to most of the population is via a UHF band providing voice and data but with a mm wavelength network providing localised high capacity data.

The most obvious place to use licensed mm wavelengths would be in the city CBD. This is where capacity demands are traditionally high and where the distance between existing cell sites of 200-300m, as shown in Figure 28, matches those required for a mm wavelength network [118]. As these are existing sites there will be existing backhaul (normally using optical fibre) and existing property lease and planning permission. However, most of these existing cell sites are located external to property. This means in-building coverage would require separate indoor base stations (also called access points).

Table **6** lists the cellular networks in use in New Zealand today. This table shows that existing cellular services all use the UHF band and that the existing services form a heterogeneous network – with 3G providing voice and data but roaming onto 2G services as required. 4G networks offering high capacity data are available in urban and some rural areas.

Generation	Cellular Network Examples	Frequency (NZ)	Areas used (NZ)	Density of cells
2G	GSM	900 and 1800 MHz	Nationwide (approx. 94% of population)	Macro – 20 km + Micro – 1-2 km Pico ~ 300 m
3G	UMTS	850 or 900 MHz, 2100 MHz	Nationwide (approx. 94% of population)	
4G	LTE	1800 MHz and 700 MHz	Urban and rural coverage met target of 75% national population within 5 years	
5G or later generations	TBA	UHF band and millimetre wavelengths e.g. 28000 MHz	Proposed to be used in CBD's or areas with high capacity requirements.	200-300 m

Table 6. Cellular services in New Zealand.

The areas used and density of cells shown in the table above shows that the addition of a mm wavelength network in the CBD and in some urban environments would only support the existing generations of cellular networks. This is because an LTE network would still be required to offer high speed data to suburban and rural areas with macro cells for example. The GSM network may become obsolete in the next 2-5 years, but this is still being used for voice roaming from UMTS when required and some M2M (machine to machine) communications. However, it is not the addition of mm wavelengths that would make a GSM network, or any other generation of cellular network, obsolete.

6.4 Millimetre wavelengths – unlicensed spectrum

The second section of this chapter considers assigning mm wavelength bands for cellular use as purely unlicensed spectrum. This would be similar to the ISM bands used for Wi-Fi today. ISM bands (also known as unlicensed or general user radio bands) are designated for industrial, scientific and medical applications. As these are unlicensed, the services operating within these bands are subject to interference from other applications using the same frequency band.

In this scenario a private individual would deploy their own mm wavelength base station or access point locally, thus meeting the installation costs themselves. The individual would pay for power and installation costs and provide backhaul via ADSL or optical fibre. Cellular operators could take advantage of this network using unlicensed spectrum in the mm wavelength band similar to how Wi-Fi is used today, keeping the UHF bands for spectrum licenses using mainly voice traffic, and data traffic where no mm wavelength network coverage is available.

As the public already use Wi-Fi hotspots on cellular phones they are more likely to be comfortable using a similar arrangement but with a mm wavelength network. This means that continuous coverage would not be expected, as compared to the expectation of continuous coverage if this service was offered as a 5G service by a cellular operator. This means a mm wavelength network could be used to provide coverage to cell phones only in certain areas of a city. Examples would be airports, business requiring high data services, in-door only hotspots, stadiums and some residential houses.

Millimetre wavelength ISM bands already exist in New Zealand and other countries that may be suitable for cellular or wireless LAN networks. In addition to the 2.4 and 5.8 GHz networks already used for Wireless LAN there are ISM bands designated from 24 to 24.25 GHz and from 61 to 61.5 GHz and higher frequencies. These are shown in Figure 29. Despite the fact that ISM bands at 2.4 GHz and 5.8 GHz are used for Wireless LAN, higher frequency bands may require spectrum regulator (local radio spectrum management) permission to use this for telecommunications.

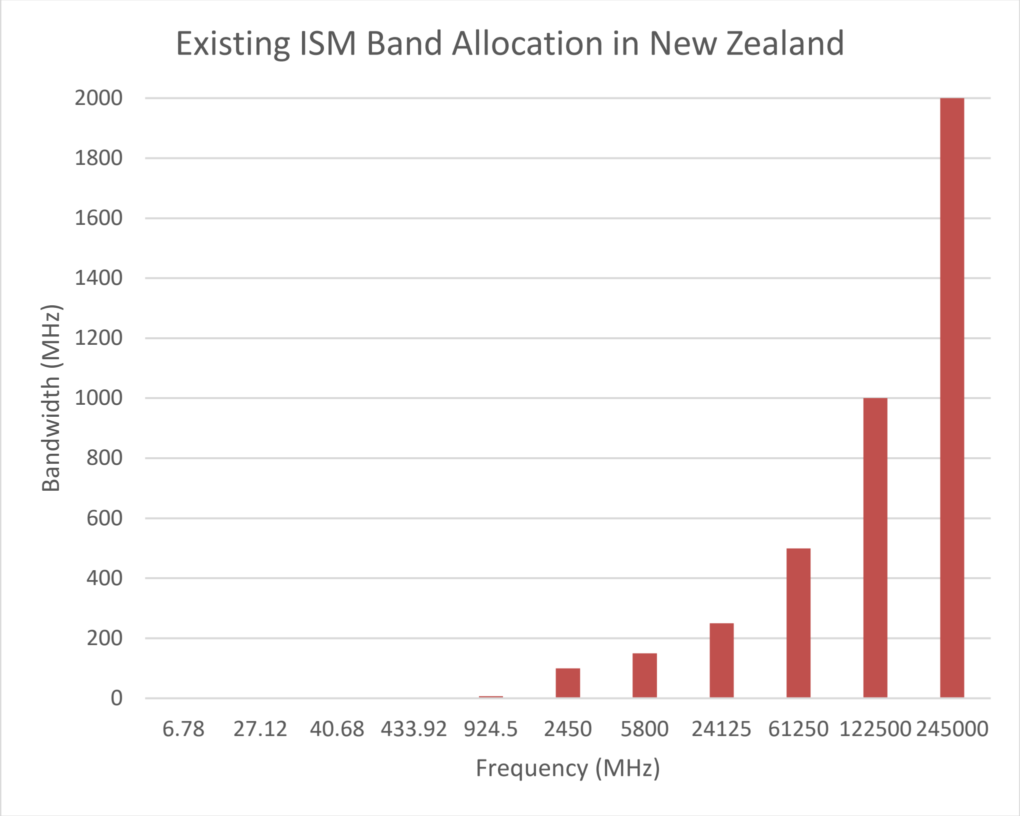


Figure 29. Unlicensed ISM bands designated in New Zealand. This shows the centre frequency in MHz of the ISM band and the amount of spectrum (bandwidth) currently available at that frequency.

Of particular interest is the 250 MHz of unlicensed spectrum available at 24 GHz, this is close to the local minima of air attenuation shown in Figure 23, but also close to existing licensed spectrum designated for LMDS (Local Multipoint Distribution Service) in New Zealand. LMDS is designated for point to multipoint services that are similar to the cellular services offered today.

6.5 Millimetre wavelengths – combined licensed and unlicensed spectrum

This section considers the allocation of both licensed and unlicensed spectrum in adjacent mm wavelength bands for cellular use. Part of the same band could be assigned for licensed use and part assigned for unlicensed use, with a guard band and rules defining transmitter conditions to reduce the chance of interference. In this scenario a single mobile device could cover the same band consisting of both licensed and unlicensed spectrum.

This would allow a licensed approach – allowing operators to manage interference with large amounts of spectrum available to provide capacity. Plus the option for a private individual (or smaller network operators) to have self-owned networks using the unlicensed part of this band. This scenario would effectively still be a heterogeneous network, keeping a UHF network for ubiquitous coverage, and a licensed mm wavelength to provide coverage in areas with high data demands, and an unlicensed mm wavelength network installed by third parties.

The benefits to operators using this approach would be the same as described earlier in this chapter. Operators would have a licensed band to provide additional capacity as required. But would also allow operators to offload to local unlicensed base stations (if available), when required by traffic demands.

The benefits to the public of having the unlicensed band would also be the same as described earlier in this chapter. However, because there is a licensed band adjacent to the unlicensed part of this band, potentially used by operators and the public then there will be some advantages due to the economies of scale in the availability of equipment from vendors. This means that vendors are more likely to offer handsets and base stations in a particular band if this band is used by many operators and the public – i.e. supply will match this high demand.

Figure 30 shows the radio spectrum assignment around 28 GHz in New Zealand which follows a similar assignment strategy as many other countries (based on the ITU (International Telecommunication Union) designation). This shows the existing ISM band (general license / unlicensed) designation and that assigned for LMDS (Local Multipoint Distribution Service) and DMR (Digital Microwave Radio) and is sourced from Radio Spectrum Management [127]. There are no New Zealand nationwide nor city-wide networks using this unlicensed spectrum (to date). In New Zealand the management rights to the LMDS spectrum are already owned by a cellular operator. This has not been used to date – i.e. there are no current nationwide or city-wide networks using this licensed spectrum.

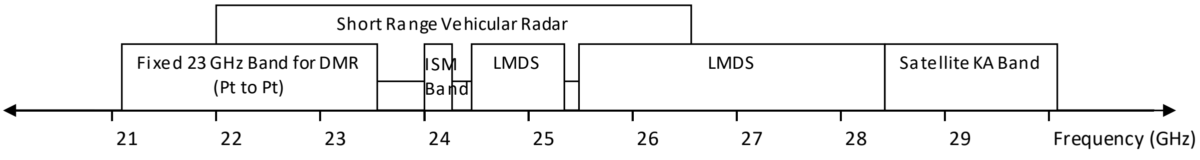


Figure 30. Radio spectrum usage in New Zealand – existing designation around 28 GHz.

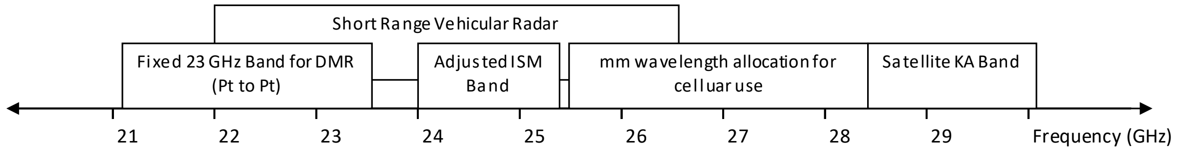


Figure 31. Possible adjustment of designations to increase ISM band allocation for unlicensed Wireless LAN use.

Figure 31 is a recommended alteration to the spectrum allocated around 28 GHz in New Zealand. The mm wavelength allocation here could be divided into and upper and lower band for frequency division duplex use. The ISM band is increased from a bandwidth of 250 MHz to a bandwidth of 1.392 GHz (compare this to the 100 MHz (0.1 GHz) currently available for Wireless LANs at 2.4 GHz). The LMDS band is reduced to the upper part of the band (25.557-28.35 GHz), still providing a 2.793 GHz bandwidth for licensed spectrum (compare this to 2 x 45 MHz currently (0.045 GHz) in use at 700 MHz for LTE). This increase in the amount of spectrum available allows a corresponding increase in capacity.

Having an unlicensed band adjacent to a licensed band for cellular networks also offers a unique opportunity, in the use of LTE-U (unlicensed) with LTE (or the 5G equivalent) and carrier aggregation. Carrier aggregation in LTE allows discontinuous channels to be used to provide greater capacity. These can be intra-band carrier aggregation with continuous or non-continuous component carriers or inter-band carrier aggregation such as in the example above where part of the licensed bands and part of the unlicensed band could be aggregated to carry traffic. This would require UE (user equipment) to have a transceiver capable of using a large bandwidth (in this example 24 to 28.4 GHz). This may have an impact on cost and power consumption and the performance of the device. But would allow significant amount of bandwidth and associated cellular capacity.

6.6 Work post publication of the mm wavelength paper

In 2016, the U.S. Federal Communication Commission (FCC) [124] allocated four new bands above 24 GHz towards 5G, among which the 27.5–28.35 GHz (28 GHz) band is considered one of the most promising candidates for the first 5G commercial products.

The FCC acknowledge that mm wavelengths have historically been considered unsuitable for mobile applications because of propagation losses at such high frequencies and the inability of mm wavelength signals to propagate around obstacles. The FCC also acknowledge that technological advances where very small antennas are able to concentrate signals into highly focused beams with enough gain to overcome propagation losses, will potentially unlock the mm wavelength bands for cellular use. In addition short transmission paths and high propagation losses can facilitate spectrum re-use, by limiting the amount of interference between adjacent cell sites.

The FCC propose to allocate spectrum in the 28 GHz band as a country wide, exclusive use licensing as two 425 MHz blocks. This would allow operators to coordinate interference from fixed and mobile uses within its geographic area and the FCC state that exclusive rights will promote investment and expedite the deployment of mobile and other advanced services.

In the same document [124] FCC propose to share spectrum in the 37 GHz band, by dividing the band into two segments (a lower and higher band) with different licensing rules and coordinated sharing of spectrum in the lower band. The lower band will share spectrum as Shared Access Licensees (SALs) that will be authorized by registering individual sites through a coordination mechanism. FCC state that “FCC staff will work with stakeholders, both Federal and non-Federal, to help develop the details of the coordination process”. This is similar to the licensed shared access paper and information presented in Chapter 4.

In 2017 Ofcom acknowledged that spectrum at high frequencies (above 24 GHz) are able to offer very large bandwidths, providing ultra-high capacity and support services requiring very low latency [128]. Ofcom specified the 26 GHz as a pioneer band for 5G across Europe (24.25 – 27.5 GHz). Ofcom also confirmed that mm wavelengths are subject to much higher signal losses due to obstacles such as walls, buildings, trees and terrain when compared to the lower frequency bands currently used for cellular networks. As such, 5G cell sites in built up areas will typically have a shorter range than traditional mobile macro sites and are therefore often referred to as ‘small cells’. It is likely that 26 GHz cells will typically have a radius ranging from 50 meters to a few hundred meters.

In New Zealand, RSM is following international practices in provisionally defining a 3.5 GHz band and a mm wavelength band for 5G (IMT) use. The range of 24.25 to 27.5 GHz is stated as RSM’s preliminary position for WRC-19 (matching Europe) [129]. This is to meet a requirement where spectrum bandwidth is required of at least 1 GHz to meet demand for network capacity, on the radio interface in frequency bands above 6 GHz.

This shows that regulators such as FCC, Ofcom and RSM are all considering mm wavelengths for at least part of the spectrum proposed for 5G. This is discussed in more detail in the next chapter of this thesis.

6.7 Summary

The main benefit of using mm wavelengths for cellular networks is the large bandwidth available which in turn allows a large increase in the capacity available in the radio access network. Cellular networks today typically use channel bandwidths of 5-20 MHz, whereas the channel bandwidths available at mm wavelengths can exceed 500 MHz. The second main benefit of mm wavelengths is the fact that advanced beam forming techniques are possible with the use of these smaller wavelengths. In particular the fact that a large number of antennas can co-exist in a small space allows directional beam forming and greater use of MIMO to enhance spectral efficiency.

However, the high air attenuation and high attenuation through concrete and foliage means the path length of mm wavelength base stations would be much lower than the path length of base stations used in today’s macro cell sites. In addition, as signals cannot readily propagate through outdoor building materials, many more indoor base stations will be required. LTE (4G) coverage predictions were presented in this chapter showing the coverage using 28 GHz and 1800 MHz using similar transmission parameters, except frequency. The resulting plots showed a base station path length of 200-300m when using mm wavelengths as compared to a base station path length of 2 km+ when using spectrum in the UHF band. This result showed that many more base stations would be required if using mm wavelengths to provide the same coverage as that achieved using spectrum in the UHF band.

This chapter first considers assigning mm wavelength bands for cellular use as licensed spectrum. Using licensed bands, a heterogeneous network is likely with UHF bands providing ubiquitous coverage and mm wavelengths covering areas with a high capacity demand. This may be a CBD only coverage but may need to be city wide if mm wavelengths are offered as a 5G or a later generation service. A nationwide rollout with a high density of mm wavelength base stations would be cost prohibitive. Since a heterogeneous solution is likely the use of mm wavelengths for cellular use would initially have little effect on the current demand for UHF bands.

The second section of this chapter considered assigning mm wavelength bands for cellular use as purely unlicensed spectrum. This would be similar to the ISM bands used for Wi-Fi today. In this scenario, private users would setup a mm wavelength base station locally, thus meeting the costs themselves. Operators could then off-load traffic to this private network using unlicensed spectrum, keeping the lower frequency (UHF) licensed bands for voice traffic and for data traffic where no mm wavelength network coverage is available. This means an unlicensed mm wavelength base station could be used at city hotspots with high demands for capacity.

The fact that operators in New Zealand already have a management right to use the LMDS bands for point to multipoint services around 25-28 GHz and the fact that there is an existing ISM band (unlicensed band) at 24 GHz, both unused for cellular networks, is indicative that cellular operators still perceive the UHF band as the most important band at this stage.

The third section of this chapter considers the allocation of both licensed and unlicensed spectrum in adjacent mm wavelength bands for cellular use. This scenario would effectively be a multi-band network, keeping a UHF network for ubiquitous coverage, and a licensed mm wavelength to provide additional coverage in areas with high data demands, and an unlicensed mm wavelength network installed by third parties. A possible spectrum allocation around 24-28 GHz was presented using ISM band spectrum at 24 GHz and adjacent spectrum at 27 GHz assigned for a LMDS service. This allocation of spectrum has the benefits of both the two scenarios described above, allowing both LTE and LTE-U traffic for example. This also has the benefit of allowing carrier aggregation – allowing both licensed and unlicensed band to carry traffic on the same device.

Given the fact that capacity demands are rising almost exponentially, it is highly likely that mm wavelengths will be used in some form to meet this demand. Whether this is for a worldwide 5G rollout or some later generation of cellular networks remains to be seen.

Chapter 7. Comparison of New Spectrum Allocation Techniques

This thesis has described three new techniques to allocate spectrum for future services in cellular networks. This chapter compares and discusses these new techniques and states why the use of the mm wavelength band is the preferred new spectrum utilisation method for future wireless services in cellular networks. The next chapter further discusses mm wavelengths and presents new spectrum valuation techniques for mm wavelengths to help regulators distribute this valuable spectrum resource for a fair market value.

7.1 Comparing the allocation techniques to maximise net social benefit

We earlier introduced the ‘spectrum net social benefit’, i.e. that “the key purpose of spectrum management is to maximise the value that society gains from the radio spectrum by allowing as many efficient users as possible while ensuring that the interference between different users remains manageable“ [4]. This definition is key to many of the principles used to determine and compare successful spectrum management techniques. Spectrum allocation methods must be useful to cellular operators, to provide both good coverage and capacity, but must also provide access to as many users as possible and manage interference between these users of spectrum.

The criteria used to compare spectrum allocation techniques against the definition of net social benefit is given below, in that techniques should:

- Allow many operators to use spectrum. This means that spectrum is available using this technique to many users.
- Allow the efficient use of spectrum. This means spectrum is used efficiently both in terms of geographic area and in terms of time, so the full range of frequencies are used over the largest possible geographic area.
- Keep interference to be manageable levels. This means that interference between users of spectrum is kept to a minimum.
- Allow good coverage. This is a subjective criteria and compares if spectrum available allows coverage more than, less than or the same as existing UHF based cellular coverage.

- Allow good capacity. This is also a subjective criteria and compares if the spectrum available allows data rates more than, less than or same as existing UHF based cellular coverage.
- Be currently in use, i.e. has the spectrum allocation technique been in use since publication of the papers presented as part of this research? This describes if the new spectrum allocation technique described has been used since this work was published.

The three spectrum allocation techniques presented in this thesis, namely Licensed Spectrum Parks, Licensed Spectrum Sharing and using spectrum at mm wavelengths are compared in this chapter against the criteria specified above. A summary of this comparison is given in Table 7. Section 7.2 evaluates Licensed Spectrum Parks, section 7.3 evaluates Licensed Spectrum Sharing and section 7.4 evaluates the use of mm wavelengths against these criteria.

	Licensed Spectrum Parks	Licensed Spectrum Sharing	The use of spectrum at mm wavelengths
Allows many operators to use spectrum	Yes	No	Yes
Efficient use of spectrum	No	Yes	Yes
Interference manageable	Limited	Yes	Yes
Provides good coverage	No	Yes	No
Provides good capacity	No	Yes	Yes
In use since publication	Limited	Limited	Limited, but proposed for 5G use.

Table 7. Comparison of spectrum allocation techniques presented in this thesis.

7.2 Comparative analysis - Licensed Spectrum Parks

The first technique presented in this thesis is a Licensed Spectrum Park, where spectrum is assigned on a site specific and fixed base station location for a short timeframe that could be renewed periodically. It was proposed that this technique is especially useful to assign spectrum unsold or not assigned from spectrum auctions and will be adjacent to spectrum allocated as a spectrum license.

The use of Licensed Spectrum Parks does in theory allow many different operators to use spectrum. This is because this allocation technique assigns spectrum on a special license in a small geographic area for a short timeframe. Examples of this potential use include a campus cellular network. As this is assigned to a park rather than a nationwide (or large area) rollout and for a lower spectrum cost than a nationwide management right, then this allocation method in theory would be used by more operators.

There are both positive and negative drivers to make this an efficient use of spectrum. In terms of geographic efficiency this allocation technique is not a very efficient use of spectrum. This is because these parks are separated by geographical areas where no spectrum has been assigned or being used. However, if this spectrum is only allocated from spectrum that is unsold or not assigned from spectrum auctions then this is efficient in that the alternative is that the spectrum would not be allocated at all. So, the efficiency depends on the demand for the spectrum to be allocated. This can be seen in similar spectrum allocation techniques that are starting to be used in Europe, the United States and New Zealand, for example Licensed Shared Access and Managed Spectrum Parks.

More recently in Europe and the United States we showed a Licensed Shared Access (LSA) approach is proposed. Under the LSA regime, spectrum that is already occupied but underutilised would be shared, on a licensed basis between incumbents and mobile operators, under agreed frequency, location and time-sharing conditions. We also showed that in New Zealand, a slightly different approach has been implemented, called Managed Spectrum Parks. Rather than using adjacent spectrum or spectrum unused by incumbent cellular operators, a dedicated band at 2.5GHz was introduced, in which a nationwide band can be assigned to specific localised parks which are assigned to users on a first come first served basis.

The allocation of spectrum in managed spectrum parks (MSP) for cellular networks has had limited success, to date. More commonly these small parks are used by wireless internet service providers [130] offering Internet access to fixed users rather than mobile voice, data, and messaging services. In comparing LSP's to other allocation techniques, it is likely this would also be true for Licensed Spectrum Parks for three main reasons. The first is that it would be more difficult to manage interference between users of spectrum, the second reason is more commercial where incumbent operators want to control new competition to the market and finally new operators may find it too expensive to rollout new cellular networks in limited geographic areas.

To manage interference, cellular operators want to limit other users using the same transmit or receive frequencies. Interference occurs when an unwanted frequency disrupts the use of the cellular (or radio) service. There are many types of interference but co-channel (where interference is caused by two different radio transmitters using the same channel) and adjacent channel (where interference caused by extraneous power from a signal in an adjacent channel) are common concerns. This interference can completely disrupt services or can lower the quality of service, of all services across a cellular network.

In practise, interference will be greater with LSPs as compared to the other techniques as the same spectrum is shared across many operators, even if this spectrum is used in a local area or park. This is because signals from base stations tend to propagate outside controlled areas such as spectrum parks and potentially cause interference to other users. In addition, if a frequency band is assigned to a device for use in a park and this device is moved outside this park and transmits on the same frequency band then this creates another source of interference beyond the base station and the spectrum park itself.

Licensed spectrum parks do not necessarily provide good coverage and good capacity in their own rights. These would provide good coverage and capacity if working with a roaming agreement with a nationwide operator, but due to the nature of confining coverage to a Park, this limits the out-of-park coverage and capacity using this allocation technique.

Most cellular networks are commercial entities that desire to make a return on investment (where the investment is building a cellular network). In Chapter 4 we showed that game theory can model this approach to spectrum allocation where a likely strategy is to limit competition from new entrants to this market. By limiting competition cellular operators are more likely to make a higher return on their investment, as more competition generally means less revenue for a specific cellular operator. Hence cellular companies are unlikely to help share a valuable resource like spectrum, if this could potentially create competition to themselves. This has contributed to limited use of licensed spectrum parks in the commercial sector.

In New Zealand, for example, we showed that even with dedicated spectrum in a managed spectrum park, new entrants have not used this resource to create small geographic cellular networks, for example in a campus or business park environment. It is perhaps too expensive for new operators to rollout a small park like cellular network (even with roaming outside this environment to other cellular networks). This may change in future if large international corporations gain access to spectrum in parks (for example Googles request for shared spectrum [131]) but this has not happened to date. This may also occur in the future if licensed shared access (LSA) is used to create spectrum availability in commercial parks in the United States and Europe.

LSA has been used in Europe and the US to share spectrum across large geographic areas. The availability of UHF spectrum from sharing the spectrum in the TV white spaces is a form of LSA [132]. The United States made a policy which advocated the sharing of unused federal radio spectrum and in line with this policy, the FCC is planning to extend the television band spectrum sharing (TV white space) into other bands, significantly into the 3.5 GHz band via a three-tier licensing model (incumbent, priority, and general access). However, to date, these are not on the small geographic scale proposed with licensed spectrum parks in this thesis.

Many cellular networks do however use radio access (RAN) and spectrum sharing between cellular operators. They often use dynamic spectrum sharing techniques that are close to licensed shared access approach. However, these operators often agree when and where to share spectrum between themselves. They will have agreed interference management techniques that can be managed between the operators. Any disputes are resolved internally or go to the court of law to be resolved. As this spectrum sharing is between incumbent cellular operators this does not encourage new entrants to enter this market. This means that spectrum sharing is more likely to be used between existing incumbent operators rather than new market entrants. This lead then to Chapter 5, quantifying the spectrum sharing gains and the effects of sharing spectrum between two cellular network operators and its impact on the number of base stations required to meet capacity targets.

7.3 Comparative analysis - Licensed Spectrum Sharing

Chapter 5 is of interest to operators as it shows the benefits of sharing spectrum between two operators. This was motivated by the need by operators to meet the forecasted demand for capacity in cellular networks and by the desire to reduce the number of base stations to serve this market. As spectrum is shared between only two cellular network operators, this means sources of interference will be known and can be managed between the two parties. Therefore, operators can work collaboratively to manage co-channel and adjacent channel interference, depending on how much and what frequencies are shared.

In discussing these results, we concluded that spectrum sharing is most efficient when all available spectrum is shared from a frequency band amongst two or more cellular network operators. This allows for each operator to accommodate unexpected peaks in data traffic and leads to less overheads to manage this resource.

Referring to Table 7 we see that Licensed Spectrum Sharing does not allow many users or operators to use spectrum. This is because this technique, as described in Chapter 5, is between two operators of spectrum, where each operator has an exclusive use of this spectrum. This techniques does however allow an efficient use of spectrum, where spectrum is used over large geographic areas and spectrum is shared to allow use by either party when demand for capacity cannot be meet by one operator's existing spectrum assets and if the second operator has available spectrum at that time.

As the spectrum is shared between two operators with known radio frequency propagation and known spectrum emissions, and is actively managed between these two operators, the interference is therefore manageable. It is also true that the coverage and capacity achieved using Licensed Spectrum Sharing is better or the same as that achieved using existing cellular networks, operated by independent operators. Comparing capacity for example, it was shown in Chapter 5 that a 20% capacity gain at a 0.6 operator load ratio, from a sharing rate of 0% to a sharing rate of 100% was possible.

The new spectrum sharing techniques presented in Chapter 5 presented a way to overcome two of the limitations of Licensed Spectrum Parks, namely management of interference and the coverage and capacity advantages of sharing spectrum. However, while it is true that in practise spectrum sharing by cellular operators is more common that the use of spectrum parks, ubiquitous spectrum sharing is still not used by many cellular operators.

This spectrum sharing technique does not allow one operator to have a capacity market differentiation – i.e. by having more spectrum and hence more capacity (data speeds) as compared to a competitor. Therefore, many operators still desire to have exclusive use spectrum management rights. Despite the spectrum sharing gains evident in licenced spectrum parks and by sharing spectrum with another operator, operators still want to have exclusive use management rights, with enough spectrum to meet the demands for future wireless services.

7.4 Comparative analysis - the use of spectrum at mm wavelengths

This lead then to Chapter 6 which presents the benefits and limitations of using spectrum at mm wavelengths for radio access in cellular networks. This chapter discusses the engineering viability of using mm wavelengths for cellular use but focuses on the assignment of spectrum in this band from a regulation and policy use point of view. This chapter shows that mm wavelengths for cellular use is best used where coverage is not expected to be continuous or ubiquitous, and used in areas where capacity demands cannot be met by using the UHF band. In addition, this chapter shows that there are benefits of assigning part of the mm wavelength band as unlicensed spectrum for private individuals or small networks, and part of the adjacent mm wavelength band as licensed spectrum for cellular operators.

The use of mm wavelengths for cellular networks opens up significantly more spectrum for more operators to use. Compare the hundreds of MHz of paired blocks commonly available in UHF band used today with the thousands of MHz available in the mm wavelength bands, as shown in Chapter 6. The more spectrum available increases the chance that this will be available for more operators. Although each cellular incumbent wants more of this spectrum, the techniques described in Chapter 6 do specify an unlicensed band component thereby ensuring this spectrum will be used by more users, if this follows the use of unlicensed access in other bands (e.g. Wi-Fi).

Referring to Table 7 the management of interference is similar to that experienced in the existing methods to allocate spectrum in the UHF band. Both exclusive use management rights for part of the frequency band and general access or unlicensed band use is recommended for part of the mm wavelength band, just like the use of Wi-Fi and cellular is used in the UHF band.

As discussed earlier, the increase in capacity using this band is offset against the coverage limitations inherent in using such a high frequency. Referring back to Table 7 this is shown as a negative comparison in coverage as compared to the use of UHF band networks, however mm wavelengths are unlikely to be used in a standalone network for cellular use and will be used in conjunction with other bands.

Since publishing material on mm wavelengths this spectrum allocation method has been more formally proposed for use for 5G to meet the future needs for spectrum for cellular networks [133]. The mm wavelength bands would be used in conjunction with another band (such as 600 MHz, 1.5 GHz or 3.5 GHz) each with different capabilities. The air interface defined by 3GPP for 5G is known as New Radio (NR), and the specification is subdivided into two frequency bands, FR1 (below 6 GHz) and FR2 (using mm wavelengths). This matches the recommendations in our published paper. This spectrum allocation method then overcomes many of the limitations of other techniques. Spectrum is allocated in an exclusive use management right which manages the interference issues and the use of mm wavelengths means that large amounts of spectrum is available meeting the forecasted capacity requirements.

The use of mm wavelengths seems popular in the United States with Verizon already providing some 5G home broadband services, pre 5G standardisation, in 28 GHz in several US cities [134]. In Europe however there are only 5G - mm wavelength trials, to date, with the only firm 5G deployment plans in the 3.5 GHz band. It was noted in [134] that propagation restrictions using mm wavelengths means it is suited for small areas requiring high capacity, this was also stated in our published paper. Certainly, in the United States regulation has been more open to the use of mm wavelengths where the FCC allows mobile usage of existing mm wavelength licenses [134] normally allocated for other use e.g. fixed license use.

However, there has been little evidence that regulators are planning to assign or extend spectrum in the mm wavelength band for general licence or unlicensed band use, which was also recommended in our paper and in Chapter 6. Assigning some spectrum for general license use in the mm wavelength band will allow more general use of this band for Wi-Fi, for example. This would be particularly useful once devices some as tablets and cell phones are designed to use this band which will happen if mm wavelengths are used for cellular networks.

In many ways there are many advantages to use mm wavelengths for Wi-Fi. The low propagation as shown in Chapter 6 will be less of an issue as Wi-Fi is generally used indoors reaching distances in the 100's of metres. Typically, base stations for Wi-Fi are indoors hence the high propagation losses through materials to gain indoor coverage is less of a concern, although the losses with indoor materials and walls will still be an issue. However, this can be overcome with multiple base stations for example a base station in every room.

7.5 Economic influence

The net social benefit definition as described in [4] is a useful tool to compare the different spectrum allocation techniques introduced in the thesis. However, this definition excludes a major influence in how successful spectrum allocation techniques can be, and that is the price of the spectrum.

Determining the value of spectrum is very important for both spectrum regulators and cellular network operators. Spectrum regulators need to determine the economic value of spectrum to set reasonable reserve prices for spectrum auctions or to set accurate fees for spectrum licenses. Similarly, network operators need to determine the value of spectrum specifically for their own networks, so that they don't over value spectrum to be purchased at auctions or spectrum purchased via secondary trading.

The success of spectrum allocation techniques is hugely influenced by the price of spectrum. If the spectrum is overvalued, then operators will not purchase spectrum and the allocation technique will fail. To help regulators decide the value of said spectrum we need to determine methods to value spectrum which is the subject of the next chapter.

7.6 Summary

In the comparison of these spectrum allocation techniques as shown in Table 7 there are a similar number of positive comparisons between the use of mm wavelengths and the use of Licensed Spectrum Sharing. The negative comparison is shown in the poor coverage using mm wavelengths and that Licensed Spectrum Sharing is between a limited number of operators and therefore does not open the spectrum for more users. We have also seen however the coverage limitations in the use of mm wavelengths is overcome by using this band for capacity in conjunction with another band like the UHF band for coverage.

The fact that capacity demands are raising with a compound annual growth rate of near 50% is the major driver for the need for more spectrum. It is likely therefore that the mm wavelengths will play a strong part in the allocation of the spectrum used for future generations of cellular networks. There are strong indications that the use of mm wavelengths will be used in part for 5G networks, but it is likely that for 6G and later generations of cellular networks, mm wavelengths will play an increasing part of the spectrum used to meet these future requirements. With the increased site densities and high attenuation discussed in these chapters it is possible that cellular base stations will reach a density where a base station is used in every building, much like Wi-Fi is used in many parts of the world today.

Chapter 8. Valuing Spectrum at mm Wavelengths

The previous chapter compared three new spectrum allocation techniques and concluded that the use of mm wavelengths is the most likely technique to meet the future needs of users on cellular networks. To allocate this resource to potential users of this spectrum, regulators and operators need to know how to calculate the economic value of this spectrum. This is useful to regulators as it offers insights into the economic value of mm wavelength spectrum which helps sets fees for spectrum licenses and to set reserve price and expected budgets for future spectrum auctions. To operators this information offers insights into spectrum valuation techniques and presents data on the value of mm wavelengths for cellular networks.

This chapter investigates the economic value of spectrum at mm wavelengths. The methods to calculate spectrum value presented in this chapter can be used for any spectrum band and in any country. However, to determine the value of mm wavelengths for cellular networks, we have used data from New Zealand, specifically for the existing 700 MHz LTE network and for a hypothetical 28 GHz LTE network.

The analysis uses four techniques to value spectrum, namely a benchmarking comparison, a discounted cash flow analysis, a real options approach and a deprival method. These models are based on geographic data, population, cellular traffic analysis and LTE network design from New Zealand.

This work was presented in a paper titled "Valuing spectrum at mm wavelengths for cellular networks” at the 15th International Telecommunications Society (ITS) Asia-Pacific Regional Conference, Japan, by the author of this thesis in 2017. This paper was peer reviewed by academics and specialists from governments and industry from ITS. ITS is an international forum for leading professionals, academics, business and government researchers, and policy makers in the information, communications, and technology sectors [135].

8.1 Introduction

Determining the value of spectrum is very important for both spectrum regulators and cellular network operators. Spectrum regulators need to determine the economic value of spectrum to set reasonable reserve prices for spectrum auctions or to set accurate fees for spectrum licenses. Similarly, network operators need to determine the value of spectrum specifically for their own networks, so that they don't over value spectrum to be purchased at auctions, or spectrum purchased via secondary trading.

The risks and reasons to value spectrum accurately are significant. If operators value spectrum too low they risk not acquiring necessary spectrum in a competitive market. If operators value spectrum too highly, and pay too much for spectrum, they become less profitable or risk defaulting on payments to regulators. If regulators value spectrum too highly they risk setting reserve prices too high and this situation may lead to no operator being willing to buy spectrum or operators defaulting on payments for spectrum. If regulators set the value of spectrum too low, they risk creating inefficiencies in spectrum use and allocation e.g. where operators buy spectrum and do not use it.

With the high demand for wireless traffic there is pressure for regulators to assign more spectrum for cellular networks. One likely answer to meet this demand for spectrum is to use mm wavelengths. Millimetre wavelengths are defined as electromagnetic spectrum with wavelengths from 1 to 10 mm or frequency from 30 to 300 GHz – this is also known as the EHF or extremely high frequency band. Current cellular networks use frequencies in the UHF, or ultra-high frequency band (300 MHz to 3 GHz). Although 28 GHz (as used in this chapter) is slightly outside the mm wavelength band, this frequency is desirable for cellular networks. This is because at this frequency the air attenuation is relatively low compared to higher frequencies (for example in the EHF band) but the bandwidth of available spectra is still relatively high compared to the UHF band [7].

The concept of using mm wavelengths for cellular networks is not new, e.g. [123]. The main benefit of using mm wavelengths is the large amount of spectrum available. Cellular networks today typically use channel bandwidths of 5-20 MHz, whereas the channel bandwidths available at the mm wavelengths exceed 500 MHz [7]. This additional bandwidth allows several orders of magnitude greater capacity than current cellular networks. However, the coverage achievable at these high frequencies is significantly less than that from existing base stations [117]. This means many more cellular base stations will be required to offer the same ubiquitous coverage as UHF band networks. Despite coverage limitations the use of mm wavelengths for cellular networks has been trialled by cellular network vendors [136] and proposed for investigation by spectrum regulators [124].

This chapter investigates the economic value of spectrum at mm wavelengths. The value of this spectrum is calculated using four models, namely:

- The *benchmarking* comparison - this investigates the value of mm wavelength spectrum based on a global search for recent spectrum valuation results in this band. The benchmarking approach has been studied in lower frequency bands and presented in [137].
- The *discounted cash flow* analysis - this is where the net present value (NPV) of the spectrum band to an operator is calculated by modelling cellular network costs and revenue. This is similar to the methods presented in [60].
- The *real options* approach – this expands from 'decision making under uncertainty' in that operators have flexibility in when spectrum is used for cellular networks. The real options approach has been used in papers [138] and [139].
- The *deprival method* or opportunity cost model – this is used to calculate the value of spectrum using the difference between two business cases, namely where a hypothetical business acquires new mm wavelength spectrum and where the business does not acquire new mm wavelength spectrum [140].

The methods to calculate spectrum value for cellular networks presented in this chapter can be used for any spectrum band and in any country. However, to evaluate the accuracy of the model and to calculate the value of mm wavelengths, we have used data from New Zealand. The models are based on both 700 MHz and 28 GHz LTE networks to calculate the value of mm wavelength spectrum.

This chapter starts by describing the LTE network cost model in section 8.2, and states why accurately costing this network is key to determining the value of spectrum. The four valuation models listed above are presented in sections 8.3 to 8.6. The results and comparative analysis are present in section 8.7. This includes the valuation of mm wavelengths under different scenarios.

8.2 Cost models

To value spectrum using the models described later in this chapter, it is necessary to accurately model the cellular network using this spectrum. This is because the cost component forms the basis for most of the spectrum valuation techniques used. For example, the discounted cash flow model uses the difference in revenue and the cost model to calculate the net present value of spectrum. Similarly, the deprival cost analysis uses the difference in cost models – the difference in having and not having mm wavelength spectrum. Therefore, the accuracy of the cost model for the network is very important to create accurate valuations for spectrum.

Modern cellular networks use LTE network design similar to that as shown in Figure 32. The cost model used in this chapter is a *scorched earth* or greenfields analysis. This means to calculate the network costs as though the network was being built today using modern equipment and technologies. This assumes no existing cellular network infrastructure. To accurately model the scorched earth LTE network, it is necessary to know the capacity requirements (the amount of traffic on the network) and the coverage requirements (the area 'covered' by the cellular network).

The capacity requirements are calculated by analysing the population and mobile device saturation together with the demand forecasts per devices used on the network. This is calculated based on voice, data and messaging traffic types. The coverage requirements are calculated by analysing the geographical area types of each country and the coverage typical from each base station or eNodeB type (e.g. Pico, Micro and Macro cells). The capacity of the network is heavily dependent on the channel bandwidth whereas the coverage achievable is heavily dependent on the frequency used.

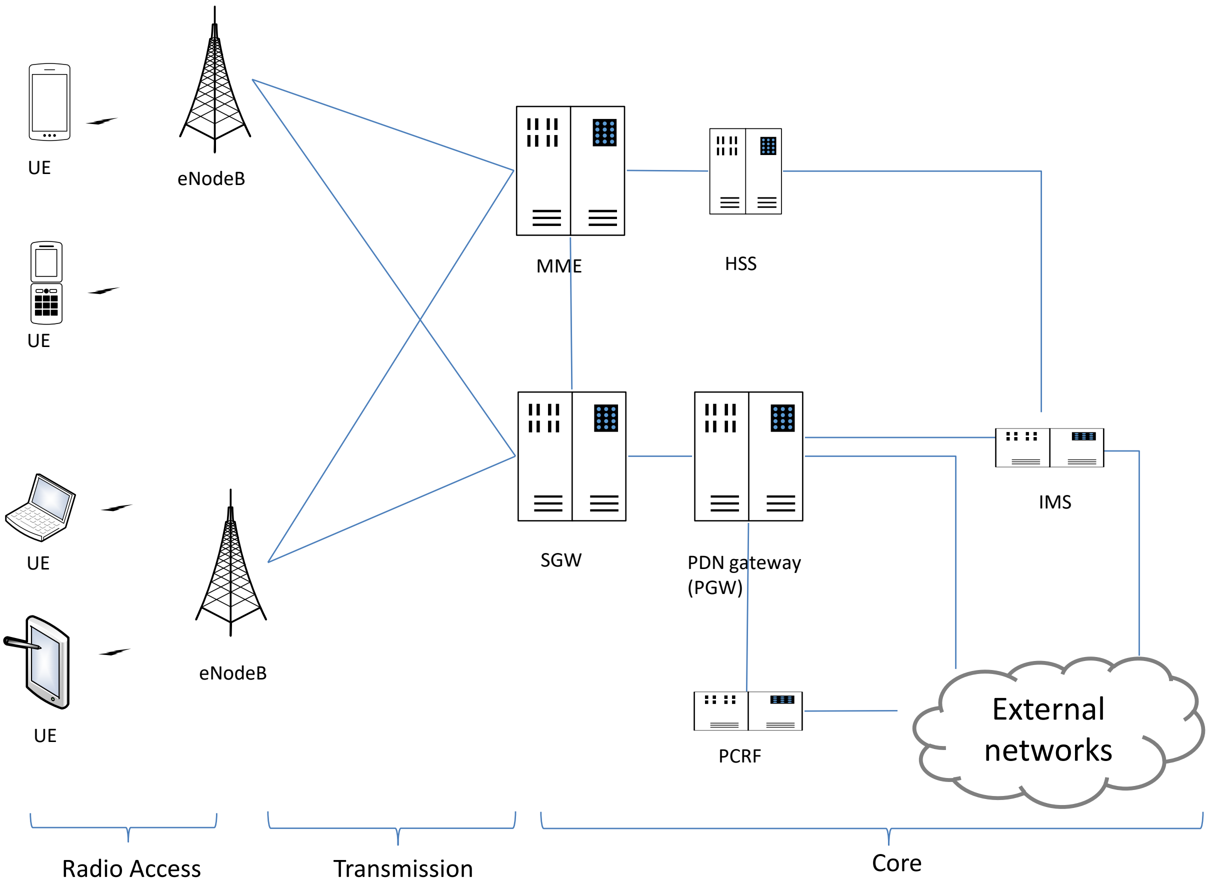


Figure 32. Scorched earth model of the LTE network used for cost analysis.

Once the coverage and capacity requirements are known this data can be used to calculate the LTE network equipment required. This is divided into equipment in the radio access network, equipment required for transmission, and equipment required in the core. In the radio access space, the UE (user equipment) can be divided into: low usage devices like (non-smartphones and machine to machine use); medium usage (such as smartphones); and high usage devices (like tablets and laptops). Based on the capacity requirements, the amount of traffic carried in the busy hour over each equipment type in the network is calculated and used to determine how much equipment is needed to meet this traffic demand. Similarly, the frequency and propagation model can be used to calculate the equipment required to meet the coverage demands.

The transmission and core components of the network are also defined by the amount of traffic and devices on the network. The transmission network can be divided into leased ethernet or digital microwave radio. Transmission hubs are used to collate this traffic in geographic areas before using high capacity fibre to backhaul this traffic to the core. Finally, the core can be simplified into the components shown in Figure 32. Here MME (mobility management entity), HSS (home subscriber server), PCRF (policy and charging rules function), SGW and PGW (serving gateway and packet data network gateway), form the basis of the evolved packet core with voice over LTE on the IMS (IP multimedia subsystem).

The overall cost of a cellular network is dominated by the cost of radio access, transmission and core equipment, but there are also significant costs of voicemail, management systems, billing systems, and other indirect costs. The costs of the equipment on LTE networks is very dependent on the vendor used to supply this equipment and is country and operator specific. For more information see Appendix C: Economic models.

8.3 Benchmarking

The first valuation model presented is the benchmarking approach. This seeks to establish a price for spectrum based on market prices in other countries in similar spectrum bands. The underlying assumption is that the prices will be comparable when market drivers, such as the specific application of the spectrum band, are the same. This information is sourced from spectrum auction results, spectrum trades between companies and from company financial returns.

In practice benchmarking has many challenges. Not all regulators publish data on spectrum allocation publicly. Sometimes only limited spectrum auction information is available with few suitable data points. For example, perhaps the total price paid for spectrum is presented but not the length of the management right for that spectrum. Sometimes there are limiting terms and conditions associated with the spectrum management right which could affect the price paid for the spectrum. Finally, the spectrum data available may only be from countries with very different cellular network markets to that of your target market. There may be a difference in market competition, revenue generated from that spectrum or the spectrum may be assigned to different technology applications.

Benchmarking the value of spectrum at mm wavelengths displays many of these challenges. Initially many countries assigned spectrum in this band not for cellular networks but for fixed licences used in point to point links, for example the use of 26 GHz for digital microwave radio. In the early 1990's spectrum around 28 GHz was assigned for LMDS (local multipoint distribution service) networks. However not many LMDS networks were implemented and competition for LMDS mm wavelength spectrum was limited.

The results of a benchmarking analysis for mm wavelengths is shown in Figure 33. This shows the value of spectrum identified by a price per MHz per population statistic ($ per MHz Pop). Note that the data shown in Figure 33 is in NZ dollars. The currency conversion used ‘purchasing power parities’ (PPPs) - the rates of currency conversion that equalise the purchasing power of different currencies by eliminating the differences in price levels between countries [141]. The population adjustment is at the population in that country in the year of the sale of spectrum.

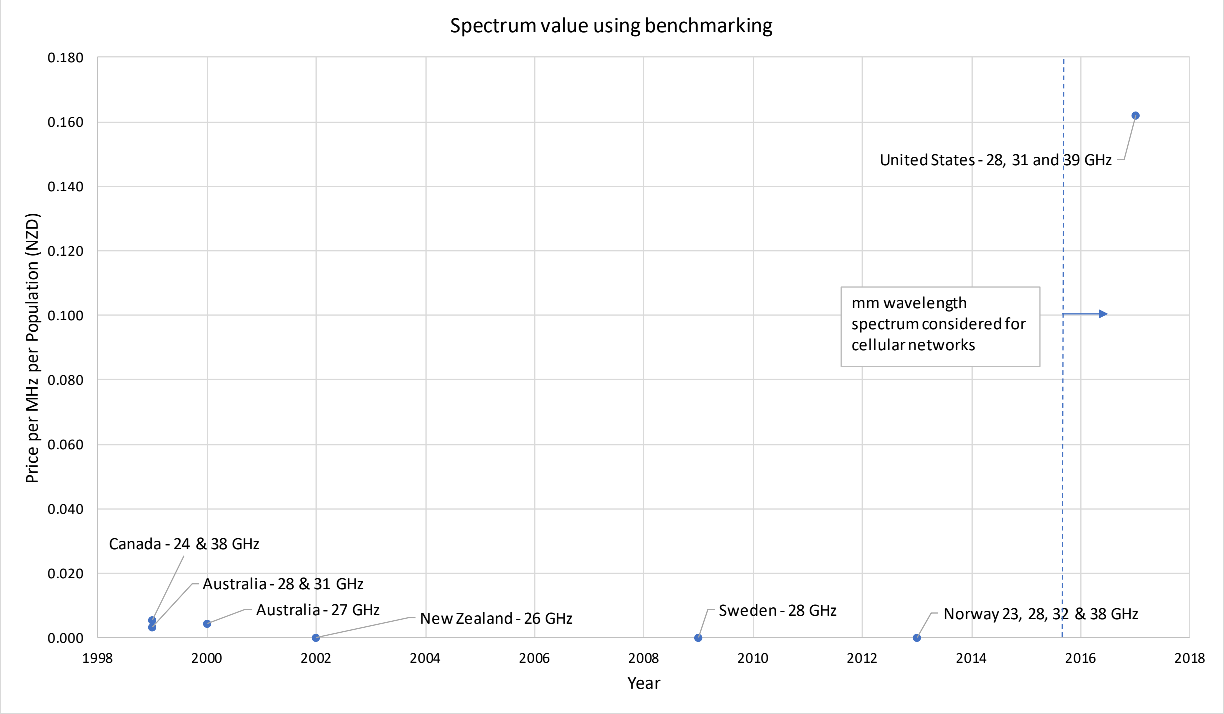


Figure 33. Millimetre wavelength spectrum value using benchmarking. Shown in price per MHz per population in NZD.

This graph shows the relatively low values of this spectrum in the last two decades when demand for this spectrum was low. However recent interest in this frequency band for cellular networks has led to a high benchmarking value for this spectrum in the United States. This was seen in the recent purchase of XO Communications by Verizon [142] showing the increasing $ per MHz Pop value as shown in Figure 33. This has also been shown in the share price of Straight Path Communications – a company with one of the largest spectrum assets in the US in 28 GHz and 39 GHz. The share price of this company has been reasonably static for over 3 years but by May 2017 had increased from a 52-week low of $US 15.06 to a high of $US 164.49.

The recent benchmark result from the United States show how the value of this mm wavelength spectrum is changing. Therefore, the US result should not be removed as an atypical data point. Using this information, we can estimate the value of spectrum in New Zealand using benchmarking as 0.09 $ per MHz Pop or $427 M based on NZ population and a spectrum bandwidth of 2 x 500 MHz.

8.4 Discounted cash flow

The second valuation model presented is the discounted cash flow analysis. This calculates the net present value of spectrum from forecasted future cash flows. The future cash flows are calculated from forecasted revenue less the forecasted costs, and a discounted rate is used to calculate this profit into a single present value. Expressed mathematically this is:

$$NPV = \sum_{t=0}^{N} \frac{R_t - C_t}{(1+i)^t} \tag{16}$$

where R_t is the revenue, C_t is the cost, discounted by a rate of return i, for time t.

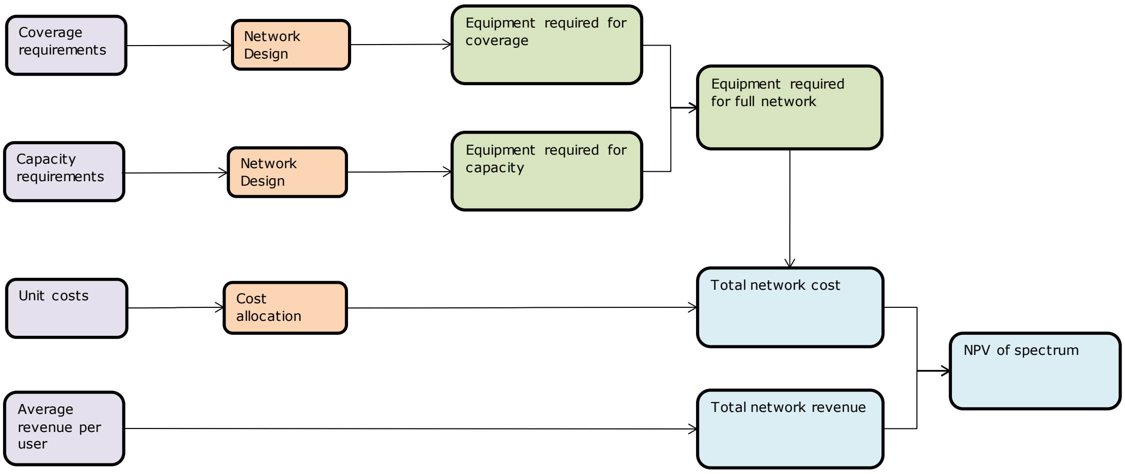


Figure 34. Spectrum valuation model using discounted cash flow.

Figure 34 shows the steps used to calculate the NPV of spectrum using discounted cash flow analysis. This chapter has already shown the method to calculate the total network cost of using spectrum. Revenue has a huge effect on the value of spectrum when using the discounted cash flow model. This revenue can be calculated based on the revenue generated per MB for data, per voice call and per SMS message. Using this forecast method revenue grows significantly with the forecast growth in traffic over cellular networks. The alternative is to calculate revenue based on an average revenue per user (ARPU) calculation. Using this forecast method, the revenue only grows with each additional user on the network rather than with the exponential growth of wireless traffic.

The results of an NPV analysis of spectrum valuation in New Zealand are shown in Table 8.

Model	Frequency	NPV Result	Lot Size	Present value. Price per MHz Pop (NZD)
NPV model – 700 MHz (ARPU model)	700 MHz	$304 M	2 x 20 MHz	1.60
NPV model – 28 GHz (ARPU model)	28 GHz & 700 MHz	-$251 M	2 x 500 MHz	-0.05
NPV model – 28 GHz (revenue based on traffic)	28 GHz & 700 MHz	$9,929 M	2 x 500 MHz	2.09

Table 8. Discounted cash flow analysis of spectrum in New Zealand. Based on a demand and revenue forecasts for 15 years from 2017.

The first result of Table 8 shows the NPV of spectrum at 700 MHz. This positive NPV result shows that it is currently economically viable to have a 700 MHz cellular network. The later results in Table 8 show the NPV of a combined 700 MHz and 28 GHz cellular network. This is using 700 MHz to provide coverage and a mm wavelength network to provide capacity in urban areas. This is a likely rollout scenario for cellular networks using these bands. Calculating the NPV of mm wavelength spectrum using the same revenue as the 700 MHz model creates a negative net present value for this spectrum, based on current capacity demands. This is to be expected. The capacity forecasts from [143] for New Zealand show a current demand of 2083 MB per Month per device in 2017 and 5217 MB per Month per device in 2021 with a compound interest growth rate of 31%. In the near future, it is not viable to rollout a mm wavelength network because the current UHF band network can meet this demand, and many more mm wavelength sites would be required to provide similar coverage, even in a purely urban setting.

A major assumption here is that the base station costs of mm wavelengths are similar to those using the UHF band. In fact, if the base station costs reduce by 38% and the demand increases beyond that forecasted in the next 5 years then using mm wavelengths becomes more viable in this scenario.

The final result of Table 8 shows the effect of revenue on NPV using the discounted cash flow model. If the revenue is based on the amount of traffic on the network (revenue based on traffic), rather than the amount of people using the network (ARPU), then using mm wavelength also becomes more profitable. However, with the average revenue per user from telecommunications networks remaining static this is a less likely forecast scenario.

The fact that mm wavelength spectrum valuation may increase with increasing network capacity demand, is the subject of the next section of this chapter.

8.5 Real options

The third valuation model presented is the real options approach. This expands from ‘decision making under uncertainty’ [138] in that operators have flexibility in how and when spectrum is used for cellular networks. The real options approach is particularly important in calculating the value of mm wavelength spectrum as it considers the option to delay using this spectrum until the capacity demands on the network require large channel bandwidths to meet this demand. As the amount of spectrum available at mm wavelengths is significantly more than that at lower frequency bands, this spectrum becomes more valuable as the capacity demands increase.

A real options analysis starts from the discounted cash flow model and net present value. In fact, the discounted cash flow model is a special case of real options analysis, calculating the net present value where no flexibility is available in the valuation model. Therefore, under real options valuation:

$$Project\ value = NPV + Options\ value \tag{17}$$

The options value can be defined by the Black Scholes equation as presented in [144]:

$$Option\ value = S \cdot N(d_1) - K \cdot e^{-r_f t} \cdot N(d_2) \tag{18}$$

Here S is current value of the underlying asset, K is the exercise price, t is the lifetime of the option, r_f is the risk-free interest rate, *N(d)* is a cumulative normal distribution. The first part of equation (18), *S N(d1),* returns the expected benefit of undertaking the investment as soon as possible, based on the present value of future cash flows, while the second term $K \cdot e^{-r_f t} \cdot N(d_2)$, is the exercise price or value of the investment cost, discounted back to present value, weighted by the probability of exercising the option. Here d_1 and d_2 are given in equations (19) and (20), and σ is the project uncertainty:

$$d_1 = \frac{\ln\frac{S}{K} + \left(r_f + \frac{\sigma^2}{2}\right) t}{\sigma\sqrt{t}} \tag{19}$$

$$d_2 = d_1 - \sigma\sqrt{t} \tag{20}$$

Option	Value	Description
t	5 years	Regulators typically require networks to be deployed before 5 years.
S	1,038 M	Present value of future cash flows using New Zealand mm wavelength cellular network.
K	1,289, M	Present value of investment cost using New Zealand mm wavelength cellular network.
σ	37.6 %	Can be calculated from historic price movements of company, here using 37.6 %.
r_f	3.64 %	Risk free rate consistent with bond rates.

Table 9. Values used in the real options calculation.

Using this data and the Black Scholes equations (18) and (19) we calculate $d_1 = 0.379$ and $d_2 = -0.461$ and the cumulative normal distribution, $N(d_1) = 0.648$ and $N(d_2) = 0.322$. This results in an options value of \$326 M.

This results in an overall project value of NPV + Options value = -\$251 M + \$326 M = \$75 M.

In this case, the network operator has an option to delay deploying a network using mm wavelengths. From section 8.4 in this chapter we saw that taking up this project today has a negative NPV. By exercising the option to defer by 5 years, the operators can utilise the spectrum at a time to make this more profitable, thereby increasing the value of this spectrum.

This result is heavily dependent on the volatility or project uncertainty (σ). As the volatility increases so too does the value of the option. For example, increasing σ to 50% increases the value of the option to \$429.6 M and the value of spectrum to \$178.6 M.

8.6 Deprival method

The final model to calculate spectrum value is the deprival method. This is where the value of spectrum is calculated using two business cases, namely:

- where the business acquires new mm wavelength spectrum, and
- where the business does not acquire new mm wavelength spectrum.

The difference in the value of the business with and without the spectrum is the theoretical maximum that the business would be prepared to pay for that spectrum. In this case, we compare the value of mm wavelength spectrum using two different LTE cellular network designs, both designed to meet the same forecasted coverage and capacity targets. The first using a heterogeneous network using both UHF and new mm wavelength bands, and the second a purely UHF band network.

Figure 35 shows the steps to calculate the value of spectrum using the deprival methodology. This uses the cost modelling techniques described earlier in this chapter.

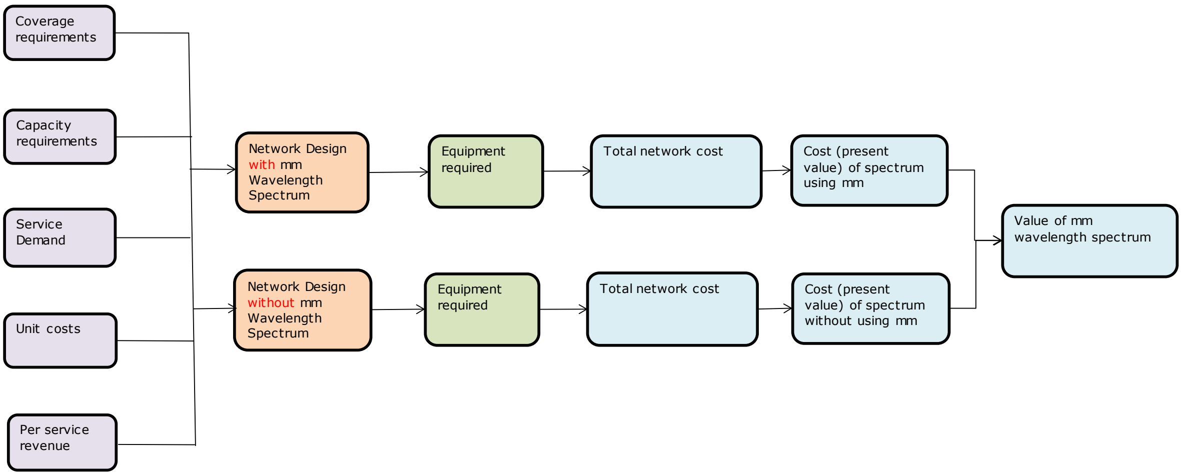


Figure 35. Deprival method to value spectrum.

In this case 28 GHz spectrum is used in an urban setting to provide coverage to areas with high capacity demands and 700 MHz spectrum is used to provide coverage to most of the rest of the population.

Table 10 presents network costs to calculate the value of mm wavelengths using the deprival method. The initial results show a deprival valuation based on Cisco VNI demand [143]. As expected the cost of a mm wavelength network to meet this demand is currently greater than that of a UHF network. Using the deprival value this spectrum is valued by the difference of $734 M - $1,289 M = -$555 M (or -0.11 $ per MHz Pop).

This result can also be confirmed looking at the difference in NPV values from Table 8 i.e. the difference in NPV of a combined 700 MHz and 28 GHz network, and a 700 MHz network. Using the results from Table 8 this is -$251 M - $304 M = - $555 M. This is the same result as above since the revenue is consistent across both business cases and is not needed in this deprival method calculation.

These results show that it is not economically viable to rollout a mm wavelength network to meet the 4G capacity demands of the near future. However, if we now set the forecasted demand to the elevated value of 10 x the current capacity demand, as advertised for 5G [136], then the results are significantly different. In this case, the value of this spectrum is $2,264 M - $1,980 M = $284 M or 0.06 $ per MHz Pop.

Model	Demand	Frequency	Lot Size	Cost present value
Cost model – 700 MHz	Cisco VNI	700 MHz	2 x 20 MHz	734 M
Cost model – 28 GHz & 700 MHz	Cisco VNI	28 GHz & 700 MHz	2 x 500 MHz & 2 x 20 MHz	1,289 M
Cost model – 700 MHz	10 x Cisco VNI	700 MHz	2 x 20 MHz	2,264 M
Cost model – 28 GHz & 700 MHz	10 x Cisco VNI	28 GHz & 700 MHz	2 x 500 MHz & 2 x 20 MHz	1,979 M

Table 10. Deprival method to calculate cost.

8.7 Results

The four valuation techniques investigated in this chapter can give quite different spectrum valuation results. This is because these valuation results are based on different methods to calculate spectrum with different inputs to each model. The initial valuation results based on current demand forecasts for New Zealand [143] are presented in Table 11.

The benchmarking results show a historic low value of mm wavelengths, used primarily for fixed networks, LMDS and satellite communications. The benchmarking value of $427 M is heavily weighted by recent high values of mm wavelength spectrum purchased in the United States. This shows the recent and increasing value and demand for this spectrum for cellular networks.

The discounted cash flow analysis, based on current capacity demand, shows a negative NPV for this spectrum. The NPV is calculated by the difference in forecasted revenues using this band and network costs to build a mm wavelength network. The negative NPV for mm wavelengths as compared to a positive NPV using the UHF band, shows that the costs are higher using mm wavelengths to meet this demand of capacity within the next 5 years, in New Zealand. This is also confirmed by the fact that management rights for mm wavelength spectrum are already owned by one of the leading cellular operators in this country and are not currently being used.

Model	Valuation of mm wavelength spectrum 2017 (NZD)	$ per MHZ Pop - 2017	Comment
Benchmarking	$427 M	0.09	This is weighted heavily by recent US results
Discounted Cash Flow	-$251 M	-0.05	Revenue based on ARPU
Real Options	$75 M	0.02	
Deprival	-$555 M	-0.11	

Table 11. mm wavelength valuation results. Based on demand and revenue forecasts for 15 years from 2017.

However, the value of this spectrum increases significantly once demand and revenue forecasts increase. Table 12 shows the model results by bringing forward the revenue and capacity forecasts by 5 years. This means both the demand and revenue have increased to 5G levels. We now have a positive NPV for this mm wavelength spectrum. This is driven primarily by the increased capacity forecast, requiring more spectrum, and the increase in revenues. This demand cannot be easily met using the limited amount of bandwidth available at 700 MHz.

Model	Valuation of spectrum 2017 (NZD)	$ per MHZ Pop - 2017	Comment
Discounted Cash Flow	$207.1 M	0.04	Revenue and capacity forecasts + 5 years
Real Options	$821.8 M	0.17	
Deprival	$33.9 M	0.01	

Table 12. mm wavelength valuation results. Based on bringing forward the forecasted revenue and capacity demands by 5 years.

The real options approach also confirmed the increase in value of spectrum by exercising the option to delay building the mm wavelength network. In this case, the option to delay building the network increased the value from a negative NPV of -$251 M to a positive NPV of $75 M.

Finally, the deprival method was used to calculate the value of spectrum by comparing the difference in the cost of networks from a network using, and a network not using, mm wavelengths. As shown in Table 11, again a negative valuation resulted when using the deprival method, for similar reasons, to meet the capacity demands of the near future. The cost to build a mm wavelength network to meet the forecasted capacity demands within the next 5 years, based on these models, was not economically viable. However, the data shown in Table 12 shows that when using the deprival method, the value of this spectrum also increases when the capacity demand and forecasted revenue are brought forward 5 years.

Both Table 11 and Table 12 show the same relationship between the valuation models, in that the deprival model showed a lower spectrum value than the discounted cash flow which showed a lower value than the real options approach.

There are positives and negatives associated with each of the valuation models presented in this chapter. The deprival method does not need revenue forecasts to calculate the value of spectrum. Therefore, there is less estimated or forecasted data used in this analysis. We have seen in the results above that the deprival method is significantly influenced by the capacity forecasts, with very different results depending on these values.

The discounted cash flow analysis uses both revenue and cost to determine the value of spectrum. We have seen in Table 8 the effect of increasing the revenue and how the revenue forecasts can significantly change the NPV result. However, the discounted cash flow cannot take into consideration the effect of timing on a project, in particular the effect of delaying the rollout of mm wavelengths until required by capacity demands.

The real options approach can take into consideration these project options, and we saw an increase in spectrum value using this valuation technique. However, the real options approach is dependent on σ , the project uncertainty. The project uncertainty is project specific and is difficult to accurately calculate. We saw that increasing σ by 12.4% resulted in an increased spectrum valuation by 138%.

The value of spectrum is likely bounded by the low value of the deprival method and the high value of the real options approach. The results presented by benchmarking are useful to show the historical change in value of spectrum from different markets. It is therefore recommended that these three approaches together be used to estimate the value of spectrum.

8.8 Summary

This chapter presents four models to value spectrum. We then use these models to value spectrum at mm wavelengths for cellular networks. To value spectrum accurately a thorough understanding of both the economic and engineering use of spectrum is required.

The foundation for the models presented in this chapter is an accurate model of the costs associated with the use of spectrum. In our case, we modelled an LTE network using the scorched earth approach using spectrum at both 700 MHz and 28 GHz.

In addition, the economic analysis determines how spectrum is valued. In the discounted cash flow analysis, we calculated the net present value of spectrum using network costs and revenue generated from that spectrum. The real options approach expanded from the NPV to value the option to delay building a network using mm wavelengths until the demand for capacity justified the network expenditure. In additional the deprival method was used because it excluded the need for revenue forecasts by evaluating the cost of spectrum between two cost models, one with and one without mm wavelength spectrum. Finally, a benchmarking analysis showed the historic value of mm wavelength spectrum based on previously published data.

All four models show that the value of mm wavelength spectrum for cellular networks increases with increasing demand for network capacity. Both the discounted cash flow and the deprival model showed a negative NPV when modelling demand forecasts pre 5G capacity values. However, the value becomes positive when the capacity demands use the high bandwidths of spectrum available at mm wavelengths.

In discussing these results, we showed that there are positives and negatives associated with each of the models. We concluded that the value of spectrum should be given as a range, bounded by the low value from the deprival method and the high value from the real options analysis. Benchmarking is also of interest showing the historical value of spectrum. This chapter showed the range of values for mm wavelengths is large i.e. 0.01 to 0.17 NZ $ per MHz per Pop based on initial 5G capacity forecasts in New Zealand. This is indicative of the change in value of this mm wavelength spectrum as it becomes more popular and in demand for cellular networks.

This work will be useful to both regulators and operators. To regulators it offers insights into the economic value of mm wavelength spectrum which helps sets fees for spectrum licenses and to set reserve price and expected budgets for future spectrum auctions. To operators this paper offers insights into spectrum valuation techniques and presents data on the value of mm wavelengths for cellular networks.

Chapter 9. Conclusions

This thesis introduces new spectrum allocation methods to meet the future needs of wireless services in cellular networks.

A literature review showed the existing spectrum allocation methods are allocated by either:

- administrative spectrum allocation,
- market-based spectrum allocation or
- technology-based spectrum allocation.

Administrative spectrum allocation, including comparative tenders and administrative regulation was the first method to allocate spectrum after regulation was first introduced in the 19th Century but is still used in some countries today.

Market-based spectrum allocation, including spectrum auctions and spectrum trading, is often used to allocate spectrum for cellular networks. In this case spectrum is often allocated via market-based spectrum auctions in the UHF band, for long term management rights and for large geographic areas.

Finally, technology-based spectrum allocation, including spectrum mobility, spectrum databases and equipment specific allocation techniques is often used for general user radio licenses or unlicensed band use such as the use of Wi-Fi and other industrial, scientific or medical uses.

This research also showed that the future demand for wireless services can be divided into three directions:

- enhanced mobile broadband services,
- ultra-reliable, low latency communications and
- massive machine type communications.

The enhanced mobile broadband services show the demand for higher capacity or data rates, such as the increasing use of ultra-high-definition video, data storage in cloud-based systems, and increasing use of augmented and virtual reality.

The ultra-reliable and low latency communications show the demand for services such as self-driving cars, and the reliability for emergency services and other mission critical services using cellular networks.

Finally, the massive machine type communications show the demand for IoT (Internet of Things) networks where IoT allows devices such as home appliances and devices in cities that contain electronics, software, sensors, and actuators to connect, interact and exchange data.

To meet these future needs for cellular networks three new spectrum allocation methods were proposed in this thesis. These include Licensed Spectrum Parks, Licensed Spectrum Sharing and the use of mm wavelengths to provide spectrum for cellular networks.

9.1 Chapter 4 summary – Licensed Spectrum Parks

A new method is proposed, in Chapter 4, to divide upcoming spectrum band allocations into two different spectrum licence / management right types. The first, a spectrum license, would allow successful auction bidders to roll out mobile radio networks on a long-term nationwide scale as normal. The second is a new concept called a Licensed Spectrum Park (LSP) and would allow smaller operators to roll out specialized mobile radio networks on a short-term local site by site basis. LSPs would be assigned by applying for a license based on a site specific, fixed base station location for a short timeframe that could be renewed periodically.

It is noted that administration of LSP use could be managed by existing regulators. The price of LSP licenses would be calculated on a site-by-site basis for short timeframes. The price of LSP licenses would be similar to the normalised price of adjacent sub-band spectrum licenses - calculated based on the spectrum available and population covered.

Regulators face the issue of whether to allocate a fixed amount of spectrum for LSP use before auctioning the remaining spectrum, or alternatively auctioning the total spectrum and allocating any unsold spectrum to LSPs, if any is available. In addition, operators have options in their bidding strategy to either help or hinder the creation of LSPs. These different scenarios were modelled to help regulators choose a scenario depending on the region's long-term spectrum strategy plans.

The 700MHz combinatorial clock auction in New Zealand was used as an example to show the hypothetical effect of assigning spectrum for LSP use. In this example, spectrum unsold in the clock round of the auction could have been assigned for LSP use. The resulting change in auction revenue was presented and showed that had spectrum been assigned for LSP use then revenue would have been the same or higher in the clock and assignment rounds but lower in the supplementary round. It was also shown that any loss in auction revenue could be partially offset from the on-going licence fees from the sale of LSP licenses.

Our analysis offers an important contribution for both spectrum regulators and private spectrum managers and provides the framework for spectrum allocation to new market entrants enabling more competition in the mobile radio market.

9.2 Chapter 5 summary – Licensed Spectrum Sharing

Chapter 5 presents the benefits of sharing licensed spectrum between two cellular network operators. This is motivated by the need by operators to meet the forecasted demand for capacity in cellular networks and by the desire to reduce the number of base stations to serve this market.

This chapter shows that traffic profiles have a significant effect on the spectrum sharing gains. In particular, traffic profiles with asymmetric loads will show the greatest gains when sharing spectrum. To calculate these gains, the load spectrum ratio was calculated as the amount of asymmetry in traffic profiles to calculate the spectrum sharing dividend, which is the possible reduction in base stations to meet forecasted rise in capacity demands.

Also presented in this chapter are actual traffic profiles from two different cellular operators using LTE networks. The data shows that sharing spectrum from these two networks will result in a spectrum sharing dividend of 25% in 2016. This result means that if these two networks shared spectrum then 25% fewer sites would be required to meet the capacity forecasts.

In discussing these results, it was concluded that spectrum sharing is most efficient when all available spectrum is shared from a particular frequency band amongst cellular network operators. This allows for each operator to accommodate unexpected peaks in data traffic and leads to less overheads to manage this resource.

9.3 Chapter 6 summary – the use of mm wavelengths

Chapter 6 showed that the main benefit of using mm wavelengths for cellular networks is the large bandwidth available which in turn allows a large increase in the capacity available in the radio access network. Cellular networks today typically use channel bandwidths of 5-20 MHz, whereas the channel bandwidths available at the mm wavelengths can exceed 500 MHz. The second main benefit of mm wavelengths is the fact that advanced beam forming techniques are possible with the use of these smaller wavelengths. In particular, the fact that a large number of antennas can co-exist in a small space allows directional beam forming and greater use of MIMO to enhance spectral efficiency.

However, the high air attenuation and high attenuation through concrete and foliage means the path length of mm wavelength base stations would be much lower than the path length of base stations used in today's macro cell sites. In addition, as signals cannot readily propagate through outdoor building materials, many more indoor base stations would be required. LTE (4G) coverage predictions were presented in this chapter showing the coverage using 28 GHz and 1800 MHz using similar transmission parameters (except frequency). The resulting plots showed a base station path length of 200-300m when using mm wavelengths as compared to a base station path length of 2 km+ when using spectrum in the UHF band. This result showed that many more base stations would be required if using mm wavelengths to provide the same coverage as that achieved using spectrum in the UHF band.

This chapter first considers assigning mm wavelength bands for cellular use as licensed spectrum. Using licensed bands, a heterogeneous network is likely with UHF bands providing ubiquitous coverage and mm wavelengths covering areas with a high capacity demand. This may be a CBD only coverage but may need to be city wide if mm wavelengths are offered as a 5G or a later generation service. A nationwide rollout with a high density of mm wavelength base stations would be cost prohibitive. Since a heterogeneous solution is likely the use of mm wavelengths for cellular use would initially have little effect on the current demand for UHF bands.

The second section of this chapter considered assigning mm wavelength bands for cellular use as purely unlicensed spectrum. This would be similar to the ISM bands used for Wi-Fi today. In this scenario private users would setup a mm wavelength base station locally, thus meeting the costs themselves. Operators could then take advantage of this private network using unlicensed spectrum, to carry some traffic, keeping the lower frequency (UHF) licensed bands for voice traffic and for data traffic where no mm wavelength network coverage is available. This means an unlicensed mm wavelength base station could be used at city hotspots with high demands for capacity.

The third section of this chapter considers the allocation of both licensed and unlicensed spectrum in adjacent mm wavelength bands for cellular use. This scenario would effectively be a multi-band network, keeping

- a UHF network for ubiquitous coverage,
- a licensed mm wavelength to provide additional coverage in areas with high data demands, and
- an unlicensed mm wavelength network installed by third parties.

A possible spectrum allocation around 24-28 GHz was presented using ISM band spectrum at 24 GHz and adjacent spectrum at 27 GHz assigned for a LMDS service. This allocation of spectrum has the benefits of both the two scenarios described above, allowing both LTE and LTE-U traffic for example. This also has the benefit of allowing carrier aggregation – allowing both licensed and unlicensed bands to carry traffic on the same device.

Given the fact that capacity demands are rising almost exponentially, it is highly likely that mm wavelengths will be used in some form to meet this demand. Whether this is for 5G or some later generation of cellular networks remains to be seen.

9.4 Chapter 7 summary – comparing the spectrum allocation methods

Chapter 7 uses the definition of the spectrum net social benefit for spectrum allocation to compare the three spectrum allocation techniques introduced in this thesis. Net social benefit states that the key purpose of spectrum management is to maximise the value that society gains from the radio spectrum by allowing as many efficient users as possible while ensuring that the interference between different users remains manageable [4]. This definition is key to many of the principles used to determine and compare successful spectrum management techniques. Spectrum allocation methods must be useful to cellular operators, to provide both good coverage and capacity, but it must also provide access to as many users as possible and manage interference between these users of spectrum.

In the comparison of these spectrum allocation techniques as shown in Chapter 7 there are a similar number of positive comparisons between the use of mm wavelengths and the use of Licensed Spectrum Sharing. The negative comparison is shown in the poor coverage using mm wavelengths and that Licensed Spectrum Sharing is between a limited number of operators and therefore does not open the spectrum for more users. We have also seen however the coverage limitations in the use of mm wavelengths is overcome by using this band for capacity in conjunction with another band like the UHF band for coverage.

We concluded in this comparison that it is likely that the mm wavelengths will play a strong part of the spectrum used for future generations of cellular networks.

However, it was noted that the definition of net social benefit excludes a major influence in how successful spectrum allocation techniques can be, and that is the price of the spectrum. This led to Chapter 8 – introducing methods to value spectrum.

9.5 Chapter 8 summary – valuing spectrum

Chapter 8 presents four models to value spectrum. We then use these models to value spectrum at mm wavelengths for cellular networks. To value spectrum accurately a thorough understanding of both the economic and engineering use of spectrum is required. The foundation for the models presented in this chapter is an accurate model of the costs associated with the use of spectrum. In this case, an LTE network was modelled using the scorched earth approach using spectrum at both 700 MHz and 28 GHz.

The economic analysis determines how spectrum is valued using four models:

- The discounted cash flow analysis calculates the net present value of spectrum using network costs and revenue generated from that spectrum.
- The real options approach expands from the NPV to value the option to delay building a network using mm wavelengths until the demand for capacity justified the network expenditure.
- The deprival method was used because it excluded the need for revenue forecasts by evaluating the cost of spectrum between two cost models, one with and one without mm wavelength spectrum.
- The benchmarking analysis showed the historic value of mm wavelength spectrum based on previously published data.

All four models show that the value of mm wavelength spectrum for cellular networks increases with increasing demand for network capacity. Both the discounted cash flow and the deprival model showed a negative NPV when modelling demand forecasts pre 5G capacity values. However, the value becomes positive when the capacity demands increase with time.

In discussing these results, it was shown that there are positives and negatives associated with each of the models. It was concluded that the value of spectrum should be given as a range, bounded by the low value from the deprival method and the high value from the real options analysis. Benchmarking is also of interest showing the historical value of spectrum. This chapter showed the range of values for mm wavelengths is large i.e. 0.01 to 0.17 NZ $ per MHz per Pop based on initial 5G capacity forecasts in New Zealand. This is indicative of the change in value of this mm wavelength spectrum as it becomes more popular, and in demand for cellular networks.

9.6 Future work

There are several avenues for future research that can be deduced from this thesis.

Firstly, an investigation into the combined use of mm wavelengths for part of a cellular network for example in the CBD and urban areas and the use of Licensed Spectrum Sharing for use in more remote areas could be the subject of future research.

The use of mm wavelengths for cellular networks is a research field in its own right and further work developing coverage predictions, the benefits of using MIMO and indoor and outdoor propagation testing could also be the subject of future research.

There is a changing need for more remote area cellular coverage, noting that most cellular operators target coverage to large population centres but frequently do not provide coverage to remote rural areas. A country like New Zealand may have 94% coverage by population but only 50% coverage by geographic area. Emergency services are starting to use cellular networks for communications and are driving the need for rural coverage [145]. How spectrum should be allocated to meet this need could be the subject of future research.

There is also potential to further develop the economic models presented in this thesis. For example, it is envisaged that base stations costs may change if (or when) base station density increases to meet the increasing demands for capacity. If the base station density continues to increase, there may be cellular networks that have base stations in every room (using mm wavelengths) much like the Wi-Fi networks today. This will significantly change how cellular networks are run and modelled.

9.7 Summary

This thesis has produced an important contribution to the field of spectrum allocation for cellular networks and has identified the use of mm wavelengths as a likely spectrum allocation method for future generations of cellular networks.

The research offers an important contribution for both spectrum operators and spectrum regulators.

To operators, this thesis presents methods for using measured data to calculate the benefits of sharing spectrum including capacity gains. This thesis also presents insights into spectrum valuation techniques useful to set maximum bids for future spectrum auctions. To operators this thesis also offers engineering and economic data on the use of mm wavelengths for cellular networks.

To regulators, this thesis offers the framework for spectrum allocation in spectrum parks for new market entrants enabling more competition in the mobile radio market. This thesis also presents data to show that sharing licensed spectrum between operators can reduce the total number of cell sites that are required to meet forecasted increases in capacity demand. To regulators this thesis also offers insights into the engineering and economic value of mm wavelength spectrum which helps sets policy, allocation rights and budgets for future spectrum auctions.

Chapter 10. Appendices

10.1 Appendix A: History of cellular network rollouts in New Zealand

10.1.1 Introduction

This appendix briefly describes the evolution of cellular networks in New Zealand

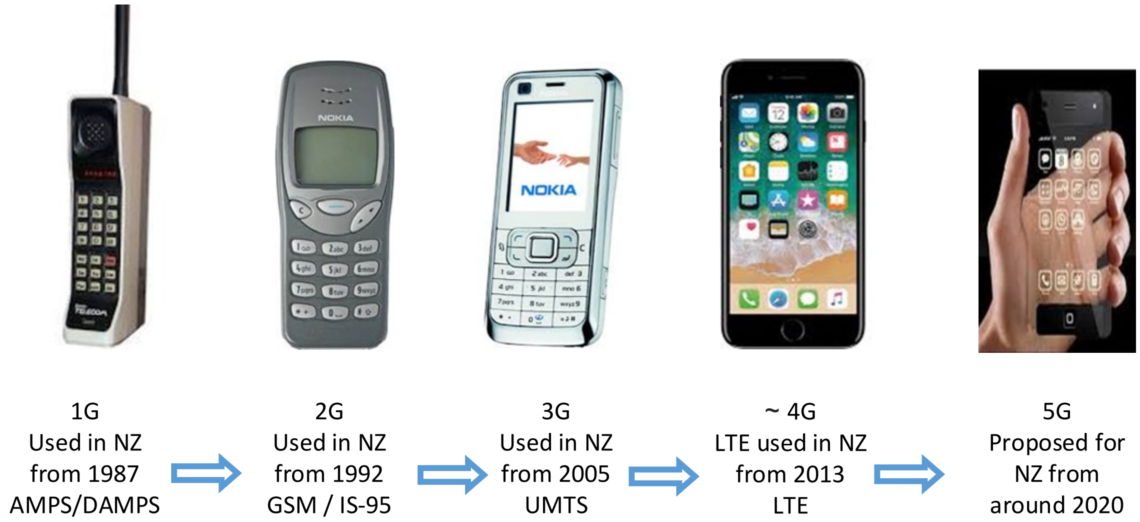


Figure 36. The evolution of technologies in the cellular industry.

1G (First Generation)		
Year	1987	1990’s
Technology	AMPS	DAMPS
Full Name	Advanced Mobile Phone System	Digital AMPS
Operator	Telecom	Telecom
Frequency	850 MHz (AMPS B)	850 MHz (AMPS A)
Access	FDMA	TDMA
Comments	Analogue scanners could listen in to conversations made using AMPS networks, phone cloning was also a problem.	

Table 13. The first generation of cellular networks in New Zealand.

2G (Second Generation)		
Year	1990’s	1990’s
Technology	GSM	CDMA 2000 (IS-95)
Full Name	Global System for Mobile Communication	Interim Standard 95 based on code division multiple access
Operator	BellSouth originally, later sold to Vodafone.	Telecom
Frequency	900 MHZ (TACS A) and 1800 MHz	850 MHz
Access	TDMA with FDD	CDMA with FDD
Evolution	GPRS	EV-DO
Comments	Nokia vendor.	Alcatel-Lucent vendor. Telecom actually started a GSM rollout in early 2000’s but delays caused a UMTS only rollout.

Table 14. The second generation of cellular networks in New Zealand.

Generation	3G (third generation)	4G (fourth generation) or LTE
Year	2005	2013
Technology	UMTS	LTE
Full Name	Universal Mobile Telecommunication System	Long Term Evolution
Operator	Vodafone, Telecom and Two Degrees Mobile	Vodafone, Telecom / Spark and Two Degrees Mobile
Frequency	U900/U2100 MHz (VF, 2D), U850 MHz (Telecom)	700 MHz primarily, 1800 MHz
Access	W-CDMA with FDD	OFDMA for download and SC_FDMA for upload
Evolution	HSPA	LTE - advanced
Comments	Nokia (Vodafone), Alcatel-Lucent (Telecom / Spark), Huawei (2 Degrees) vendors. 2-Degrees rolled out a GSM and UMTS network.	Huawei used by all three operators.

Table 15. The third and fourth generation of cellular networks in New Zealand.

10.2 Appendix B: Matlab to calculate Spectrum Sharing Dividends

10.2.1 **Introduction**

This appendix presents the Matlab code used to calculate the Spectrum Sharing Dividends.

10.2.2 **AnalyseParameters_PC_PropagationLimitedOnSSDividends**

```
% AnalyseParameters_PC_PropagationLimitedOnSSDividends m-file to plot
spectrum sharing dividends over time.
% For case where radio propagation limitations allow only a fraction of
each frequency
% band to be available in each zone (fraction can be 1)
% Each Parameter can assume a range of values.
% The SS dividends (and cell numbers) are stored in a multi-dimensional
% array (tensor)

% e.g.  cellnumber(i,j,k,l,m)
% 1st dimension (i) is for year (basic scenario)
% 2nd dimension (j) is for load variations
% 3rd dimension (k) is for (Spectrum Efficiency * Spectrum) variations
% 4th dimension (l) is for Throughput variations
% 5th dimension (m) is for load symmetry factor (e.g. complete load
% symmetry between operators mod_factor_load_symmetry = 1,
% for max total load = 90% of sum of operators max loads:
% mod_factor_load_symmetry = 0.9

% Note that Spectrum and Spectrum Efficiency have been combined into a
% single parameter because S*SE is always used in the model rather than S
% or SE individually


% To plot (2-dimensional) subsets of multidimensional array data it is
% necessary to use MatLabs SQUEEZE function to remove singleton dimensions
% e.g. squeeze(spectrum_sharing_dividend_MC_Edg_4G(:,1,1,:,:))

% to find the maximum value in a multidimensional array (A) use the
% command (for a 5 dimensional array)
% max(max(max(max(max(A)))) , otherwise the answer will be a (3-D) array


clear all


% Load scenario_matrix containing future technology/spectrum scenarios
scenario_matrix = SetScenarioMatrix_SpectrumDivisions; % function to load
scenario information
% This is a 27 by 15 matrix.
% Col 1  //  2 //  3 //     4       //      5       //   6     //         7
//     8            //      9                //     10
%   Year // 3G // 4G // DL Spectrum // DL Spect Eff // DL Load // #
Operators // # sharing spectrum // Edge Throughput Target // Avg
Throughput Target
% Plus spectrum within each band:
%                            800 / 900// 1800 //2100//2600 MHz
%                         Col 11// 12 //  13  // 14 // 15
```

```
% Set the rate in each of ten equal area zones in a cell (outermost last).
% rate = [3.2 2.37 1.62 1.04 0.65 0.39 0.29 0.19 0.15 0.10]; % data rates
(Mbits/s/MHz) in each zone 1..10
rate = SetFlowRate; % rate is a vector;  zones = length(rate)
zone_boundaries_fraction = SetZoneBoundaries; % set radius (as a fraction
of cell radius) of each zone boundary within cell

% 90%coverage_radius = [0.95      0.87       0.39       0.34       0.29];
coverage_environment = 'urban';% urban  coverage radius
% 90%coverage_radius = [4.15      3.89       1.08       0.94       0.79];
coverage_environment = 'suburban'; % suburban  coverage radius

coverage_environment_flag = 2;  % 1 = urban,   2 = suburban
[max_coverage_radius coverage_environment] =
SetCoverageRadius(coverage_environment_flag);
% Note that coverage_environment is a string


system_area = 1000; % system area in km^2

scenario_matrix3G = scenario_matrix((scenario_matrix(:,2)==1),:);  %
extract rows where 3G flag is true (=1)
scenario_matrix4G = scenario_matrix((scenario_matrix(:,3)==1),:);  %
extract rows where 4G flag is true (=1)
scenario_matrix_COMBINED = scenario_matrix((scenario_matrix(:,3)==2),:);  %
extract rows where COMBINED flag is true (=1)

% Include factors that modify the predictions of spectrum, throughput
% targets, spectral efficiency etc. to account for uncertainty in these
% predictions and show the sensitivity of the spectrum sharing dividend to
% these parameter values.

mod_factor = [1  1/2  1/1.5  1/1.25  1/1.1  1.1  1.25  1.5  2]; % factors
for scaling parameter estimates


% mod_factor_load = mod_factor;
% mod_factor_SSE = mod_factor;
% mod_factor_target_throughput = mod_factor;

% Can input different modification factors for each parameter
% mod_factor_load = [1 1/2 2];
% mod_factor_SSE = [1 1/(1.25^2) 1.25^2 1/1.25 1.25];
% mod_factor_target_throughput = [1 1/1.5 1.5];

% mod_factor_load = [1 1/2 2];
% mod_factor_SSE = [1 1/2 2];
% mod_factor_target_throughput = [1 1/2 2];
% mod_factor_load_symmetry = [1];

mod_factor_load = [1 ];
mod_factor_SSE = [1 ];
mod_factor_target_throughput = [1 ];
mod_factor_load_symmetry = [1 0.9 0.8 0.7];

% Note: modifying the load has no effect on the spectrum sharing dividend
% (only on the number of cells required to meet the load for both the NS
% and SH cases) Number of cells required is directly proportional to load.
```

```
% Consider non-sharing case first

for i = 1:length(scenario_matrix)   % for each year (2005, 2010, 2015,
2020, 2025)
    number_of_operators = scenario_matrix(i,7);
    spectrum_per_operator =
scenario_matrix(i,[11:15])./number_of_operators; % only downlink spectrum
is considered
    % spectrum_per_operator is a five element vector with the spectrum
    % available in each band (800  900 1800 2100 2600 MHz)

    load_km2 = (scenario_matrix(i,6)*mod_factor_load)/number_of_operators;
% in Mbit/s per km2   (per operator)

    SpectralEfficiency = scenario_matrix(i,5);      % in Mbit/s per MHz per
cell
    SE = SpectralEfficiency*mod_factor_SSE;


    TargetThroughputEdg =
scenario_matrix(i,9)*mod_factor_target_throughput;     % in Mbit/s

    operator_load = system_area * load_km2;  % area (in km^2) * load per
km^2 per operator

    for j =1:length(mod_factor_load)               % Load variations
       for k = 1:length(mod_factor_SSE)           % Spectrum Efficiency *
Spectrum variations
            for l = 1:length(mod_factor_target_throughput)      %
Throughput Target variations
                for m = 1:length(mod_factor_load_symmetry)      % OPerator
load symmetry variations
   %     [cell_radius cell_area] = Radius_To_Meet_Edge_Throughput(
spectrum_available_per_band, SE, ...
   % zone_boundaries_fraction, max_coverage_radius, load_per_km2, rate,
edg_throughput_target )
   [cell_radius cell_area] = Radius_To_Meet_Edge_Throughput_PC(
spectrum_per_operator, SE(k), ...
    zone_boundaries_fraction, coverage_environment_flag, load_km2(j), rate,
TargetThroughputEdg(l) );
      cells_required_for_MC_Edg_NS(i,j,k,l,m) = system_area/cell_area;
      % Note that mod_factor_load_symmetry has no effect on non-sharing
      % calculations i.e. during the innermost (m) loop the [cell_radius
      % cell_area]values will not change. However the dimension is required
      % later because sharing and non-sharing matrices must be the same
      % size
                end
            end
       end
    end

end


% Consider Spectrum Sharing Case

for i = 1:length(scenario_matrix)   % for each year (2005, 2010, 2015,
2020, 2025)
    number_of_operators = scenario_matrix(i,7);
    number_of_operators_sharing = scenario_matrix(i,8);
```

```
    spectrum_per_operator = scenario_matrix(i,[11:15])/number_of_operators;
% only downlink spectrum is considered

    load_km2 = (scenario_matrix(i,6)*mod_factor_load)/number_of_operators;
% in Mbit/s per km2   (per operator)

    SpectralEfficiency = scenario_matrix(i,5);      % in Mbit/s per MHz per
cell
    SE = SpectralEfficiency*mod_factor_SSE;

    TargetThroughputEdg =
scenario_matrix(i,9)*mod_factor_target_throughput;     % in Mbit/s

    operator_load = system_area * load_km2;  % area (in km^2) * load per
km^2 per operator

    for j =1:length(mod_factor_load)               % Load variations
       for k = 1:length(mod_factor_SSE)           % Spectrum Efficiency *
Spectrum variations
            for l = 1:length(mod_factor_target_throughput)      %
Throughput Target variations
                for m = 1:length(mod_factor_load_symmetry)      % OPerator
load symmetry variations
   %     [cell_radius cell_area] = Radius_To_Meet_Edge_Throughput(
spectrum_available_per_band, SE, ...
   % zone_boundaries_fraction, max_coverage_radius, load_per_km2, rate,
edg_throughput_target )
   [cell_radius cell_area] = Radius_To_Meet_Edge_Throughput_PC(
spectrum_per_operator.*number_of_operators_sharing, SE(k), ...
    zone_boundaries_fraction, coverage_environment_flag,
load_km2(j)*number_of_operators_sharing*mod_factor_load_symmetry(m), rate,
TargetThroughputEdg(l) );
      cells_required_for_MC_Edg_SH(i,j,k,l,m) = system_area/cell_area;
                end
             end
         end
     end



end


scenario_matrix3G = scenario_matrix((scenario_matrix(:,2)==1),:);  %
extract rows where 3G flag is true (=1)
scenario_matrix4G = scenario_matrix((scenario_matrix(:,3)==1),:);  %
extract rows where 4G flag is true (=1)
scenario_matrix_COMBINED = scenario_matrix((scenario_matrix(:,3)==2),:);  %
extract rows where COMBINED flag is true (=2)

spectrum_sharing_dividend_MC_Edg = (cells_required_for_MC_Edg_NS -
cells_required_for_MC_Edg_SH)./cells_required_for_MC_Edg_NS;

spectrum_sharing_dividend_MC_Edg_3G =
spectrum_sharing_dividend_MC_Edg((scenario_matrix(:,2)==1),:,:,:,:); %
extract only 3G data

spectrum_sharing_dividend_MC_Edg_4G =
spectrum_sharing_dividend_MC_Edg((scenario_matrix(:,3)==1),:,:,:,:); %
extract only 4G data
```

```
spectrum_sharing_dividend_MC_Edg_COMBINED =
spectrum_sharing_dividend_MC_Edg((scenario_matrix(:,3)==2),:,:,:,:); %
extract only COMBINED data

% Sort cell numbers required into sharing/nonsharing and 3G/4G/Combined
% Calculated here only for MC_Edg (but could also be included for SC and
% MC_Avg
cells_required_for_MC_Edg_SH_3G =
cells_required_for_MC_Edg_SH((scenario_matrix(:,2)==1),:,:,:,:);
cells_required_for_MC_Edg_SH_4G =
cells_required_for_MC_Edg_SH((scenario_matrix(:,3)==1),:,:,:,:);
cells_required_for_MC_Edg_SH_COMBINED =
cells_required_for_MC_Edg_SH((scenario_matrix(:,3)==2),:,:,:,:);
cells_required_for_MC_Edg_NS_3G =
cells_required_for_MC_Edg_NS((scenario_matrix(:,2)==1),:,:,:,:);
cells_required_for_MC_Edg_NS_4G =
cells_required_for_MC_Edg_NS((scenario_matrix(:,3)==1),:,:,:,:);
cells_required_for_MC_Edg_NS_COMBINED =
cells_required_for_MC_Edg_NS((scenario_matrix(:,3)==2),:,:,:,:);

% Use these comands to plot array of required cell numbers for NS and SH
case for
% 3G, 4G and COMBINED
% [squeeze(cells_required_for_MC_Edg_NS_3G(:,1,1,1,1))
squeeze(cells_required_for_MC_Edg_NS_4G(:,1,1,1,1))
squeeze(cells_required_for_MC_Edg_NS_COMBINED(:,1,1,1,1))]
% [squeeze(cells_required_for_MC_Edg_SH_3G(:,1,1,1,1))
squeeze(cells_required_for_MC_Edg_SH_4G(:,1,1,1,1))
squeeze(cells_required_for_MC_Edg_SH_COMBINED(:,1,1,1,1))]



% Need to check whether cell densities are sufficiently high to allow a
% reduction in cell sites.

%       coverage radius (km):  800 MHz   900 MHz    1800 MHz   2100 MHz
2600 MHz
%            urban              0.95      0.87       0.39       0.34
0.29
%          suburban             4.15      3.89       1.08       0.94
0.79
%
%
% (120 degree sector Cell Area = radius^2 * sqrt(3)/2  (km^2) % Use a
% slightly different definition of cell coverage area i.e. a hexagon with
% diameter (radius) rather than two equilateral triangles of side length
% radius
% Instead use  Cell Area = radius^2 * 3 * sqrt(3)/8  (km^2)

% max_coverage_radius = [0.95      0.87       0.39       0.34       0.29];
coverage_environment = 'urban';% urban  coverage radius
% max_coverage_radius = [4.15      3.89       1.08       0.94       0.79];
coverage_environment = 'suburban'; % suburban  coverage radius

% Called earlier % [max_coverage_radius coverage_environment] =
SetCoverageRadius(2);  % 1 = urban,   2 = suburban

minimum_required_cell_density = 8./((max_coverage_radius.^2)*sqrt(3)*3);  %
This is a vector with (5) element values corresponding to the minimum
% required density for coverage for each of the frequencies considered for
% the coverage radius data
```

```
cell_density_for_MC_Edg_NS = cells_required_for_MC_Edg_NS./system_area; %
cell density based in calculated cell numbers

cell_density_for_MC_Edg_SH = cells_required_for_MC_Edg_SH./system_area;  %
cell density based in calculated cell numbers


% Now determine which results meet the required coverage criteria
% Create multidimensional arrays (corresponding to every result) that give
% an integer that indicates which coverage criteria are satisfied:
%
% 0 = no coverage criteria met
% 2 = 900 MHz coverage criteria met
% 3 = 1800 MHz coverage criteria met
% 4 = 2100 MHz coverage criteria met
% 5 = 2600 MHz coverage criteria met
%
% Note that if a higher frequency coverage criterion is met then the lower
% frequencies will also be covered.


coverage_criteria_met_MC_Edg_NS = 0.*cell_density_for_MC_Edg_NS;

coverage_criteria_met_MC_Edg_SH = 0.*cell_density_for_MC_Edg_SH;

for jj=1:length(minimum_required_cell_density)

    coverage_criteria_met_MC_Edg_NS = coverage_criteria_met_MC_Edg_NS +
(cell_density_for_MC_Edg_NS>=minimum_required_cell_density(jj));

    coverage_criteria_met_MC_Edg_SH = coverage_criteria_met_MC_Edg_SH +
(cell_density_for_MC_Edg_SH>=minimum_required_cell_density(jj));
end

% % Now replace zeros with NaNs so that the zero points won't be plotted
% (at zero) with a marker later:  THIS ISN'T REQUIRED

% coverage_criteria_met_MC_Edg_NS(coverage_criteria_met_MC_Edg_NS==0) =
NaN;
% coverage_criteria_met_MC_Edg_SH(coverage_criteria_met_MC_Edg_SH==0) =
NaN;



coverage_criteria_met_MC_Edg_NS_3G =
coverage_criteria_met_MC_Edg_NS((scenario_matrix(:,2)==1),:,:,:,:);%
extract only 3G data for non sharing case

coverage_criteria_met_MC_Edg_NS_4G =
coverage_criteria_met_MC_Edg_NS((scenario_matrix(:,3)==1),:,:,:,:); %
extract only 4G data for non sharing case

coverage_criteria_met_MC_Edg_NS_COMBINED =
coverage_criteria_met_MC_Edg_NS((scenario_matrix(:,3)==2),:,:,:,:);  %
extract only COMBINED data for non sharing case

coverage_criteria_met_MC_Edg_SH_3G =
coverage_criteria_met_MC_Edg_SH((scenario_matrix(:,2)==1),:,:,:,:);  %
extract only 3G data for sharing case
```

```
coverage_criteria_met_MC_Edg_SH_4G =
coverage_criteria_met_MC_Edg_SH((scenario_matrix(:,3)==1),:,:,:,:); %
extract only 4G data for sharing case

coverage_criteria_met_MC_Edg_SH_COMBINED =
coverage_criteria_met_MC_Edg_SH((scenario_matrix(:,3)==2),:,:,:,:);%
extract only COMBINED data for sharing case
```

```
% ************************************************************************
%
% Plot Graphs:
```

```
% plot(scenario_matrix3G(:,1), spectrum_sharing_dividend_MC_Edg_3G, ...
%     scenario_matrix3G(:,1), spectrum_sharing_dividend_MC_Avg_3G, ...
%     scenario_matrix3G(:,1), spectrum_sharing_dividend_SC_3G)
%
% hold on
%
% plot(scenario_matrix3G(:,1), spectrum_sharing_dividend_MC_Edg_4G, ...
%     scenario_matrix3G(:,1), spectrum_sharing_dividend_MC_Avg_4G, ...
%     scenario_matrix3G(:,1), spectrum_sharing_dividend_SC_4G)
%
% title('Spectrum Sharing Dividend','FontName','Times');
% xlabel('Year','FontName','Times');
% ylabel('Sharing Dividend','FontName','Times');
%
% legend('Multiclass (Edg)','Multiclass (Avg)', 'Single Class',0)
%
% hold off

% plot(scenario_matrix(:,1), cells_required_for_SC_SH)
Undefined function or variable 'SetScenarioMatrix_SpectrumDivisions'.

Error in AnalyseParameters_PC_PropagationLimitedOnSSDividends (line 36)
scenario_matrix = SetScenarioMatrix_SpectrumDivisions; % function to load
scenario information
```

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10.2.3 **Function scenario_matrix = SetScenarioMatrix**

```
function scenario_matrix = SetScenarioMatrix
%SetScenarioMatrix creates a matrix with data indicating future spectrum,
%loads, operator shares in future 3G and 4G networks
%
%   The Scenario matrix has multiple columns. These are
% Year // 3G Flag // 4G Flag // DL Spectrum (MHz)// DL Spectrum Efficiency
// DL
% Load (Mbs/km2)// Number of Operators // Number of operators sharing
spectrum //
% Cell Edge Throuput Target // Average Cell Throughput Target
%
scenario_matrix = zeros(5,10); % Set Matrix Dimensions and erase previous
data
% Col 1  //   2    //    3    //     4       //      5       //   6     //
7    //     8             //      9                //     10
%  Year // 3G // 4G // DL Spectrum // DL Spect Eff // DL Load // #
Operators // # sharing spectrum // Edge Throughput Target // Avg
Throughput Target
scenario_matrix(1,:)  = [2005 1 0 60     0.15   0.8*0.230961 4 2 0.15 0.9];
scenario_matrix(2,:)  = [2005 0 1 0      0      0            4 2 0.15 0.9];
% No 4G operation

scenario_matrix(3,:)  = [2010 1 0 60     0.53   2.4          4 2 0.3  1.8];
scenario_matrix(4,:)  = [2010 0 1 0      0      0            4 2 0.3  1.8];
% No 4G operation

scenario_matrix(5,:)  = [2015 1 0 77.5   0.815  23.692       4 2 0.4  2.4];
scenario_matrix(6,:)  = [2015 0 1 137.5  1.87   7.7935       4 2 1.0  6.0];

scenario_matrix(7,:)  = [2020 1 0 75.5   1.1    80.985       4 2 0.5  3.0];
scenario_matrix(8,:)  = [2020 0 1 177    2.098  323.941      4 2 1.2  7.2];

scenario_matrix(9,:)  = [2025 1 0 0      0      0            4 2 0.5  3.0];
% 3G phased out by 2025
scenario_matrix(10,:) = [2025 0 1 270    2.6    4207.734     4 2 1.5  9.0];

% Set mixed scenario (combine 3G and 4G data) use load weighted throughput
% targets
for ii=1:5
    scenario_matrix(10+ii,[1 7 8])  = scenario_matrix(2*ii,[1 7 8]); % set
year,  # operators, number sharing
    scenario_matrix(10+ii,[2 3])  = [2 2]; % set flags 2 2 indicates
combined 3G and 4G case
    scenario_matrix(10+ii,4)  = scenario_matrix((2*ii-1),4)+
scenario_matrix(2*ii,4); % Combine spectrum
    load_3G = scenario_matrix((2*ii-1),6);
    load_4G = scenario_matrix((2*ii),6);
    weight_3G = load_3G/(load_3G + load_4G); % weighting for 3G
contribution to SE and throughput target
    weight_4G = load_4G/(load_3G + load_4G); % weighting for 4G
contribution to SE and throughput target
    scenario_matrix(10+ii,5) = weight_3G*scenario_matrix((2*ii-1),5)+
weight_4G*scenario_matrix(2*ii,5); % Combine Spectral Efficiencies
    scenario_matrix(10+ii,6) = load_3G + load_4G; % Combine loads (per unit
area)
    scenario_matrix(10+ii,9) = weight_3G*scenario_matrix((2*ii-1),9)+
weight_4G*scenario_matrix(2*ii,9); % Combine Edge Throughput Targets
```

```
    scenario_matrix(10+ii,10) = weight_3G*scenario_matrix((2*ii-1),10)+
weight_4G*scenario_matrix(2*ii,10); % Combine Avg Throughput Targets
end

    %


end
ans =

   1.0e+03 *

  Columns 1 through 7

    2.0050    0.0010         0    0.0600    0.0001    0.0002    0.0040
    2.0050         0    0.0010         0         0         0    0.0040
    2.0100    0.0010         0    0.0600    0.0005    0.0024    0.0040
    2.0100         0    0.0010         0         0         0    0.0040
    2.0150    0.0010         0    0.0775    0.0008    0.0237    0.0040
    2.0150         0    0.0010    0.1375    0.0019    0.0078    0.0040
    2.0200    0.0010         0    0.0755    0.0011    0.0810    0.0040
    2.0200         0    0.0010    0.1770    0.0021    0.3239    0.0040
    2.0250    0.0010         0         0         0         0    0.0040
    2.0250         0    0.0010    0.2700    0.0026    4.2077    0.0040
    2.0050    0.0020    0.0020    0.0600    0.0001    0.0002    0.0040
    2.0100    0.0020    0.0020    0.0600    0.0005    0.0024    0.0040
    2.0150    0.0020    0.0020    0.2150    0.0011    0.0315    0.0040
    2.0200    0.0020    0.0020    0.2525    0.0019    0.4049    0.0040
    2.0250    0.0020    0.0020    0.2700    0.0026    4.2077    0.0040

  Columns 8 through 10

    0.0020    0.0001    0.0009
    0.0020    0.0001    0.0009
    0.0020    0.0003    0.0018
    0.0020    0.0003    0.0018
    0.0020    0.0004    0.0024
    0.0020    0.0010    0.0060
    0.0020    0.0005    0.0030
    0.0020    0.0012    0.0072
    0.0020    0.0005    0.0030
    0.0020    0.0015    0.0090
    0.0020    0.0001    0.0009
    0.0020    0.0003    0.0018
    0.0020    0.0005    0.0033
    0.0020    0.0011    0.0064
    0.0020    0.0015    0.0090
```

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10.2.4 Plot Spectrum Sharing Dividends for IEEE 85th Vehicular Technology Conference

```
% PlotSpectrumSharingDividends_for_ IEEE 85th Vehicular Technology
Conference m-file to plot graphs of spectrum sharing dividend, number of
cells
% required, etc for AnalyseParametersOnSSDividends m-file

% Run AnalyseParametersOnSSDividends  before running this script

% Each matrix of results has five dimensions e.g.
% e.g.  cellnumber(i,j,k,l,m)
% 1st dimension (i) is for year (basic scenario)
% 2nd dimension (j) is for load variations
% 3rd dimension (k) is for (Spectrum Efficiency * Spectrum) variations
% 4th dimension (l) is for Throughput variations
% 5th dimension (m) is for load symmetry factor (e.g. complete load
% symmetry between operators mod_factor_load_symmetry = 1,
% for max total load = 90% of sum of operators max loads:
% mod_factor_load_symmetry = 0.9

%
% i = 1:length(scenario_matrix)   % for each year (2005, 2010, 2015, 2020,
2025)
%     for j =1:length(mod_factor)               % Load variations
%        for k = 1:length(mod_factor)           % Spectrum Efficiency *
Spectrum variations
%             for l = 1:length(mod_factor)      % Throughput Target
variations
%                 for m = 1:length(mod_factor)  % Load symmetry ratio
%
%    cells_required_for_SC_NS(i,j,k,l,m) =
Calculate_Cells_Required_SingleClass(operator_load(j),
TargetThroughputAvg(l), SSE(k));
%    cells_required_for_MC_Avg_NS(i,j,k,l,m) =
Calculate_Cells_Required_MultiClass_Avg(operator_load(j),
TargetThroughputAvg(l), SSE(k), rate);
%    cells_required_for_MC_Edg_NS(i,j,k,l,m) =
Calculate_Cells_Required_MultiClass_Edg(operator_load(j),
TargetThroughputEdg(l), SSE(k), rate);
%             end
%        end
%     end
% end
%

% Matrices available are:

%    cells_required_for_SC_NS(i,j,k,l,m) =
Calculate_Cells_Required_SingleClass(operator_load(j),
TargetThroughputAvg(l), SSE(k));
%    cells_required_for_MC_Avg_NS(i,j,k,l,m) =
Calculate_Cells_Required_MultiClass_Avg(operator_load(j),
TargetThroughputAvg(l), SSE(k), rate);
%    cells_required_for_MC_Edg_NS(i,j,k,l,m) =
Calculate_Cells_Required_MultiClass_Edg(operator_load(j),
TargetThroughputEdg(l), SSE(k), rate);
%
```

```
%    cells_required_for_SC_SH(i,j,k,l,m) =
Calculate_Cells_Required_SingleClass(operator_load(j),
TargetThroughputAvg(l), SSE(k));
%    cells_required_for_MC_Avg_SH(i,j,k,l,m) =
Calculate_Cells_Required_MultiClass_Avg(operator_load(j),
TargetThroughputAvg(l), SSE(k), rate);
%    cells_required_for_MC_Edg_SH(i,j,k,l,m) =
Calculate_Cells_Required_MultiClass_Edg(operator_load(j),
TargetThroughputEdg(l), SSE(k), rate);
%
% spectrum_sharing_dividend_SC = (cells_required_for_SC_NS -
cells_required_for_SC_SH)./cells_required_for_SC_NS; % calculate spectrum
sharing dividend
% spectrum_sharing_dividend_MC_Avg = (cells_required_for_MC_Avg_NS -
cells_required_for_MC_Avg_SH)./cells_required_for_MC_Avg_NS;
% spectrum_sharing_dividend_MC_Edg = (cells_required_for_MC_Edg_NS -
cells_required_for_MC_Edg_SH)./cells_required_for_MC_Edg_NS;
%
% spectrum_sharing_dividend_SC_3G =
spectrum_sharing_dividend_SC((scenario_matrix(:,2)==1),:,:,:,:);   %
extract only 3G data
% spectrum_sharing_dividend_MC_Avg_3G =
spectrum_sharing_dividend_MC_Avg((scenario_matrix(:,2)==1),:,:,:,:);
% spectrum_sharing_dividend_MC_Edg_3G =
spectrum_sharing_dividend_MC_Edg((scenario_matrix(:,2)==1),:,:,:,:);
%
% spectrum_sharing_dividend_SC_4G =
spectrum_sharing_dividend_SC((scenario_matrix(:,3)==1),:,:,:,:);   %
extract only 4G data
% spectrum_sharing_dividend_MC_Avg_4G =
spectrum_sharing_dividend_MC_Avg((scenario_matrix(:,3)==1),:,:,:,:);
% spectrum_sharing_dividend_MC_Edg_4G =
spectrum_sharing_dividend_MC_Edg((scenario_matrix(:,3)==1),:,:,:,:);
%
% minimum_required_cell_density = 8./((max_coverage_radius.^2)*sqrt(3)*3);
%
% cell_density_for_SC_NS = cells_required_for_SC_NS./system_area;   % cell
density based in calculated cell numbers
% cell_density_for_MC_Avg_NS = cells_required_for_MC_Avg_NS./system_area;
% cell_density_for_MC_Edg_NS = cells_required_for_MC_Edg_NS./system_area;
%
% cell_density_for_SC_SH = cells_required_for_SC_SH./system_area;   % cell
density based in calculated cell numbers
% cell_density_for_MC_Avg_SH = cells_required_for_MC_Avg_SH./system_area;
% cell_density_for_MC_Edg_SH = cells_required_for_MC_Edg_SH./system_area;

% Example of plotting from a multidimensional array:
%
plot(scenario_matrix4G(:,1),squeeze(spectrum_sharing_dividend_MC_Edg_4G(:,1
,1,:,1)))
% plots SS_dividend for x = years   y = SS_dividend   curves for different
% throughput targets (lth dimension)

% We require a set of 5 distinct markers to indicate when coverage
criterion
% are met. Define these markers:
markernumber = cellstr(['ko'; 'bx'; 'gs'; 'mv'; 'rp']);
set(0,'DefaultLineMarkerSize', 10);
% set(0,'DefaultLineMarkerFaceColor', 'auto'); % Use this to make markers
% opaque
% set(0,'DefaultLineMarkerFaceColor', 'remove');
```

```
%            b     blue          .     point              -     solid
%            g     green         o     circle             :     dotted
%            r     red           x     x-mark             -.    dashdot
%            c     cyan          +     plus               --    dashed
%            m     magenta       *     star             (none)  no line
%            y     yellow        s     square
%            k     black         d     diamond
%            w     white         v     triangle (down)
%                                ^     triangle (up)
%                                <     triangle (left)
%                                >     triangle (right)
%                                p     pentagram
%                                h     hexagram


% Also require a set of nine different line types for the variation plots
LineDensity_array = {3;2;1;1;1;1;1;1;1;2};
LineStyle_array = {'-'; ':'; '--'; '-.'; ':'; ':'; '-.'; '--';':';'-'};
LineColor_array = {'k'; 'b'; 'g' ; 'c' ; 'g'; 'm'; 'm' ; 'm' ;'r';'r'};


set(gca,'LineStyleOrder',{'-k', ':b', '--g', '-.c', ':g', ':m', '-.y', '--
m',':r'}); set(gca,'LineStyleOrder',{'-', ':', '--', '-.', ':', ':', '-.',
'--',':'}); set(0,'DefaultAxesLineStyleOrder',{'-', ':', '--', '-.', ':',
':', '-.', '--',':'}); set(0,'DefaultAxesLineStyleOrder','remove'); sets
the LineStyleOrder back to '-' for all line

% set axes range
axesrange = [2005 2025 0 35]; %[startyear endyear thruputmin thruputmax]
% create a string_matrix to label the lines in a legend
clear legend_labels_load;
for ii = 1:length(mod_factor_load)  % mod_factor is what changes for each
graph line plotted
    if mod_factor_load(ii)<10
    legend_labels_load(ii,:) = ['load mod.  ',num2str(mod_factor_load(ii),
'%4.2f')] ;
    else
        if mod_factor_load(ii)<100
        legend_labels_load(ii,:) = ['load mod.
',num2str(mod_factor_load(ii), '%5.2f')] ;
        else
            legend_labels_load(ii,:) = ['load mod.
',num2str(mod_factor_load(ii), '%5.1f')] ;
        end
    end
end
legend_labels_load(ii+1,:) = ['cov. @  800 MHz'] ;
legend_labels_load(ii+2,:) = ['cov. @  900 MHz'] ;
legend_labels_load(ii+3,:) = ['cov. @ 1800 MHz'] ;
legend_labels_load(ii+4,:) = ['cov. @ 2100 MHz'] ;
legend_labels_load(ii+5,:) = ['cov. @ 2600 MHz'] ;

clear legend_labels_SSE;
for ii = 1:length(mod_factor_SSE)  % mod_factor is what changes for each
graph line plotted
    legend_labels_SSE(ii,:) = ['S*SE mod.  ',num2str(mod_factor_SSE(ii),
'%4.2f')] ;
end
legend_labels_SSE(ii+1,:) = ['cov. @  800 MHz'] ;
legend_labels_SSE(ii+2,:) = ['cov. @  900 MHz'] ;
```

```
legend_labels_SSE(ii+3,:) = ['cov. @ 1800 MHz'] ;
legend_labels_SSE(ii+4,:) = ['cov. @ 2100 MHz'] ;
legend_labels_SSE(ii+5,:) = ['cov. @ 2600 MHz'] ;

clear clear legend_labels_target_throughput;
for ii = 1:length(mod_factor_target_throughput)  % mod_factor is what
changes for each graph line plotted
    legend_labels_target_throughput(ii,:) = ['Thrput
mod.',num2str(mod_factor_target_throughput(ii), '%4.2f')] ;
end
legend_labels_target_throughput(ii+1,:) = ['cov. @  800 MHz'] ;
legend_labels_target_throughput(ii+2,:) = ['cov. @  900 MHz'] ;
legend_labels_target_throughput(ii+3,:) = ['cov. @ 1800 MHz'] ;
legend_labels_target_throughput(ii+4,:) = ['cov. @ 2100 MHz'] ;
legend_labels_target_throughput(ii+5,:) = ['cov. @ 2600 MHz'] ;

clear clear legend_labels_LSR;
for ii = 1:length(mod_factor_load_symmetry)  % mod_factor is what changes
for each graph line plotted
    legend_labels_LSR(ii,:) = ['LSR mod.
',num2str(mod_factor_load_symmetry(ii), '%4.2f')] ;
end
legend_labels_LSR(ii+1,:) = ['cov. @  800 MHz'] ;
legend_labels_LSR(ii+2,:) = ['cov. @  900 MHz'] ;
legend_labels_LSR(ii+3,:) = ['cov. @ 1800 MHz'] ;
legend_labels_LSR(ii+4,:) = ['cov. @ 2100 MHz'] ;
legend_labels_LSR(ii+5,:) = ['cov. @ 2600 MHz'] ;

% Dimensions of data arrays:
% (year, Load, Spectrum(&Efficiency), Throughput Target, Load Symmetry
Ratio)
Undefined function or variable 'mod_factor_load'.

***********************************************************************
fig_SSD_= figure('Name','SS Dividends', 'NumberTitle', 'off');

% subplot(3,1,1) % First subplot  3G
plot_title = ['Spectrum Sharing Dividend (Coverage Environment:'
coverage_environment ')'];
% Specify which of the modified value lines are to be plotted
modifer_values = [1:length(mod_factor_target_throughput)]; % all values is
[1:length(mod_factor)]
% first value [1] is the unmodified value
AA_3G = squeeze(spectrum_sharing_dividend_MC_Edg_3G(:,1,1,1,:));
CC_3G = squeeze(coverage_criteria_met_MC_Edg_SH_3G(:,1,1,1,:));

 % SSD_3G = AA_3G.*(CC_3G >= [4 4 4 2 2 2 2 2 2]'); % Puts zeros when
coverage requirement is not achieved
                                                 % lowest available
                                                 % spectrum does not
                                                 % provide coverage
 SSD_3G = AA_3G.*(CC_3G >= kron([4 4 4 2 2 2 2 2 2],ones(4,1))');


AA_4G = squeeze(spectrum_sharing_dividend_MC_Edg_4G(:,1,1,1,:));
CC_4G = squeeze(coverage_criteria_met_MC_Edg_SH_4G(:,1,1,1,:));
% SSD_4G = AA_4G.*(CC_4G >= [6 6 6 6 6 1 1 1 1]');
SSD_4G = AA_4G.*(CC_4G >= kron([6 6 6 6 6 1 1 1 1],ones(4,1))');

SSD_singleRAT = 100* min(SSD_3G,SSD_4G); % When users are either 3G or 4G
(but not both)
```

```
AA_COMBINED =
squeeze(spectrum_sharing_dividend_MC_Edg_COMBINED(:,1,1,1,:));
CC_COMBINED = squeeze(coverage_criteria_met_MC_Edg_SH_COMBINED(:,1,1,1,:));
% SSD_COMBINED = AA_COMBINED.*(CC_COMBINED >= [4 4 4 2 2 1 1 1 1]');
 SSD_COMBINED = 100*AA_COMBINED.*(CC_COMBINED >= kron([4 4 4 2 2 1 1 1
1],ones(4,1))');

years = scenario_matrix3G(:,1);

h = plot(years,SSD_COMBINED,'r-s' );
% h = plot(years,SSD_singleRAT, 'b-d',years,SSD_COMBINED,'r-s' );
% Now adjust line styles, colours and widths (as specified above)
% set( h(1:length(AA(1,:))),
{'LineWidth'},LineDensity_array(modifer_values), ...
%     {'LineStyle'},LineStyle_array(modifer_values), ...
%     {'Color'},LineColor_array(modifer_values));

set( h(:), 'LineWidth',2 , ...
   {'LineStyle'},LineStyle_array(1:4)); %, ...
 %  {'Color'},LineColor_array(modifer_values));

hold on
% clear hPoints hPGroup;
% for kk = 1:length(markernumber)
%     DD = +(CC==kk); % the "+" is required to make DD numeric rather than
logical
%     DD(DD==0)= NaN;  % Replaces "0s" in DD with NaNs, so the point won't
plot at y=0
%     hPoints(kk,:) = plot(scenario_matrix3G(:,1),DD.*AA,
char(markernumber(kk)) );
%     hPGroup(kk) = hggroup;  % The group the plots for each marker type
together
%     set(hPoints(kk,:),'Parent',hPGroup(kk))
%     set(get(get(hPGroup(kk), 'Annotation'), 'LegendInformation'),
'IconDisplayStyle','on'); % Only show one legend line for each marker type
% end

% title(plot_title,'FontName','Times');
% xlabel('Year','FontName','Times','FontSize',10);
ylabel('SSD^*_{suburban}  (%)','FontName','Times','FontSize',12);
axis(axesrange)  % years 2005-2025 and SS_dividend up to 20%
set(gca,'FontName','Times New Roman','FontSize',10);
grid on
% legend(h,'Single RAT terminals','Multi RAT terminals')
% legend(legend_labels_target_throughput([modifer_values
(length(mod_factor_target_throughput)+1):(length(mod_factor_target_throughp
ut)+5)],:),...
%     'Location','EastOutside') % Requires an string_matrix to label each
line in the graph
% % Note that the complicated indexing of legend_labels is to allow for
% % plotting fewer lines than in the full length of the mod_factor array
% % legend('off')% To turn the legend off, if required

text(2025-0.3,SSD_COMBINED(end,1)+1.7,'symmetric loads (LSR =
1)','HorizontalAlignment','right','FontName','Times','FontSize',10);
text(2025-0.3,SSD_COMBINED(end,2)+1,'LSR =
0.9','HorizontalAlignment','right','FontName','Times','FontSize',10);
text(2025-0.3,SSD_COMBINED(end,3)+1,'LSR =
0.8','HorizontalAlignment','right','FontName','Times','FontSize',10);
```

```
text(2025-0.3,SSD_COMBINED(end,4)+1,'LSR =
0.7','HorizontalAlignment','right','FontName','Times','FontSize',10);
hold off
**********************************************************************
```

Published with MATLAB® R2013a

10.3 Appendix C: Economic models

10.3.1 Introduction

This appendix shows details of the economic models used in Chapter 8 – Valuing spectrum at mm wavelengths. These models were written in Microsoft Excel.

To value spectrum using the models described in Chapter 8, it is necessary to accurately model and cost the cellular network using spectrum. This is because the cost component forms the basis for most of the spectrum valuation techniques used. For example, the discounted cash flow model uses the difference in revenue and the cost model to calculate the net present value of spectrum. Similarly, the deprival cost analysis uses the difference in cost models – the difference in having and not having mm wavelength spectrum. Therefore, the accuracy of the cost model for the network is very important to create accurate valuations for spectrum.

The capital costs used in the published paper and presented in this thesis have been provided by cellular equipment vendors, with the proviso this information be kept confidential. Some of the values presented in Appendix C have been changed with a randomised value to keep this confidentiality.

Figure 37 shows the method used to calculate the cost of the cellular network. In this case a hypothetical cellular network based on New Zealand topology and traffic profiles.

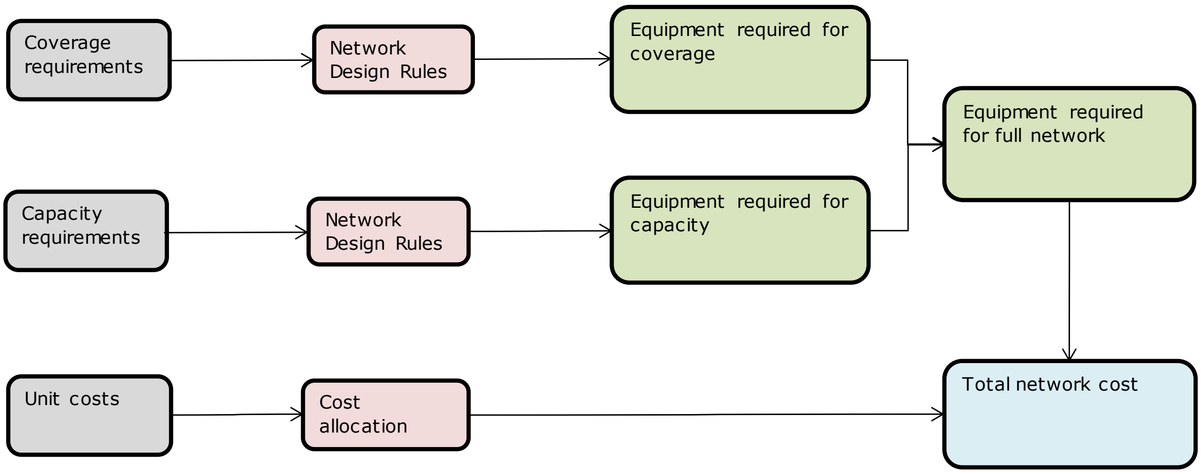

Figure 37. Method used to calculate the cost of a cellular network.

The model uses projected data from 2017 to 2031, however only 2017 to 2023 is shown in this appendix to make this data easier to read.[5]

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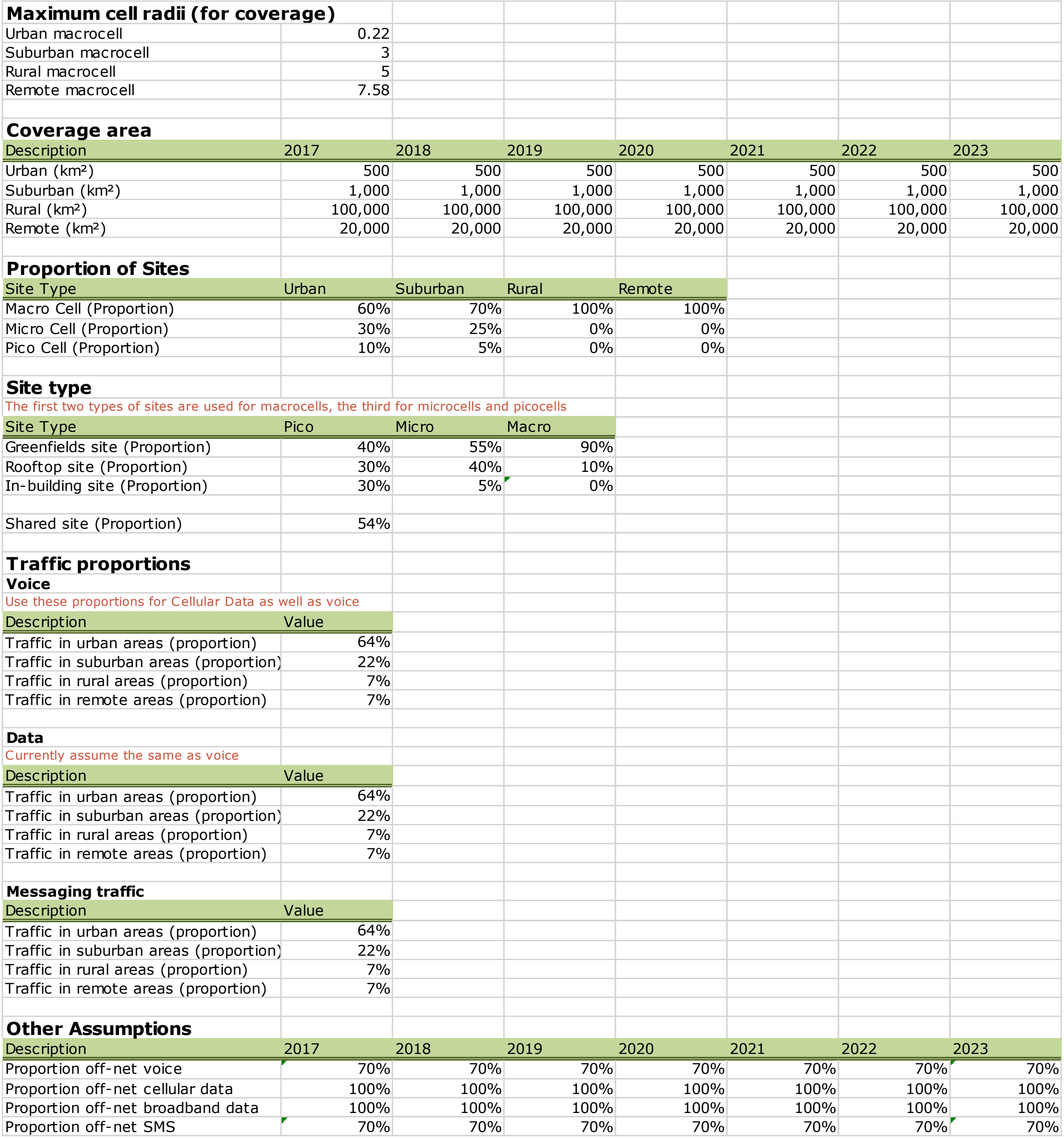
[5] The layout of the discounted cash flow Microsoft Excel spreadsheet is similar to other unpublished work, by the author of this thesis, as part of consulting work in Auckland, New Zealand. The data, methodology and research on mm wavelengths is original for this thesis.

10.3.2 **Coverage requirements**

This section describes the coverage requirements based on New Zealand topology, the coverage area achieved from each base station type, and the percentage of traffic in each area (urban, suburban, rural and remote).



Maximum cell radii (for coverage)

Urban macrocell	0.22
Suburban macrocell	3
Rural macrocell	5
Remote macrocell	7.58

Coverage area

Description	2017	2018	2019	2020	2021	2022	2023
Urban (km²)	500	500	500	500	500	500	500
Suburban (km²)	1,000	1,000	1,000	1,000	1,000	1,000	1,000
Rural (km²)	100,000	100,000	100,000	100,000	100,000	100,000	100,000
Remote (km²)	20,000	20,000	20,000	20,000	20,000	20,000	20,000

Proportion of Sites

Site Type	Urban	Suburban	Rural	Remote
Macro Cell (Proportion)	60%	70%	100%	100%
Micro Cell (Proportion)	30%	25%	0%	0%
Pico Cell (Proportion)	10%	5%	0%	0%

Site type

The first two types of sites are used for macrocells, the third for microcells and picocells

Site Type	Pico	Micro	Macro
Greenfields site (Proportion)	40%	55%	90%
Rooftop site (Proportion)	30%	40%	10%
In-building site (Proportion)	30%	5%	0%
Shared site (Proportion)	54%		

Traffic proportions

Voice

Use these proportions for Cellular Data as well as voice

Description	Value
Traffic in urban areas (proportion)	64%
Traffic in suburban areas (proportion)	22%
Traffic in rural areas (proportion)	7%
Traffic in remote areas (proportion)	7%

Data

Currently assume the same as voice

Description	Value
Traffic in urban areas (proportion)	64%
Traffic in suburban areas (proportion)	22%
Traffic in rural areas (proportion)	7%
Traffic in remote areas (proportion)	7%

Messaging traffic

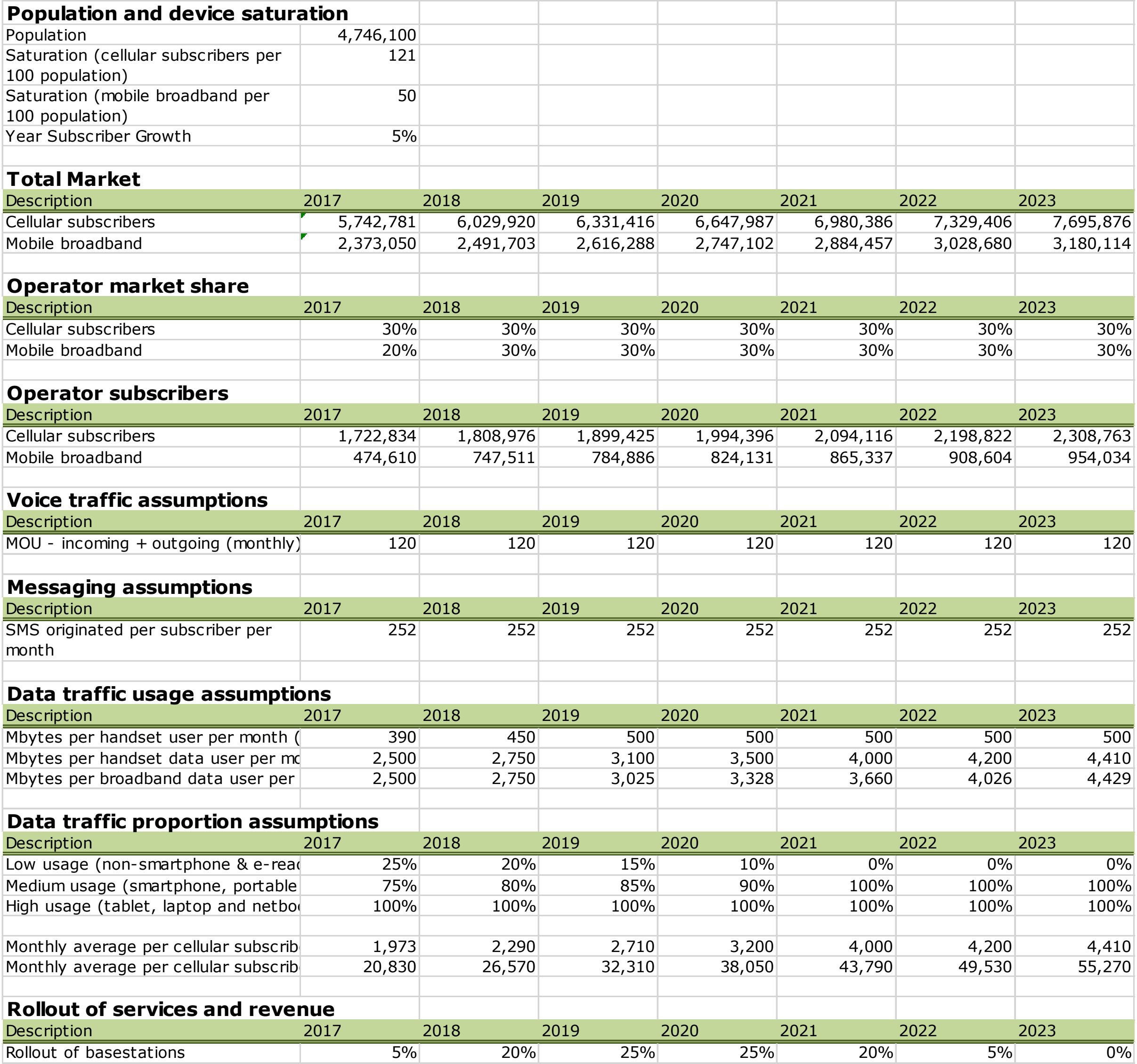
Description	Value
Traffic in urban areas (proportion)	64%
Traffic in suburban areas (proportion)	22%
Traffic in rural areas (proportion)	7%
Traffic in remote areas (proportion)	7%

Other Assumptions

Description	2017	2018	2019	2020	2021	2022	2023
Proportion off-net voice	70%	70%	70%	70%	70%	70%	70%
Proportion off-net cellular data	100%	100%	100%	100%	100%	100%	100%
Proportion off-net broadband data	100%	100%	100%	100%	100%	100%	100%
Proportion off-net SMS	70%	70%	70%	70%	70%	70%	70%

10.3.3 **Capacity requirements**

This section describes the capacity requirements based on New Zealand population and device use statistics.



Population and device saturation							
Population	4,746,100						
Saturation (cellular subscribers per 100 population)	121						
Saturation (mobile broadband per 100 population)	50						
Year Subscriber Growth	5%						
Total Market							
Description	2017	2018	2019	2020	2021	2022	2023
Cellular subscribers	5,742,781	6,029,920	6,331,416	6,647,987	6,980,386	7,329,406	7,695,876
Mobile broadband	2,373,050	2,491,703	2,616,288	2,747,102	2,884,457	3,028,680	3,180,114
Operator market share							
Description	2017	2018	2019	2020	2021	2022	2023
Cellular subscribers	30%	30%	30%	30%	30%	30%	30%
Mobile broadband	20%	30%	30%	30%	30%	30%	30%
Operator subscribers							
Description	2017	2018	2019	2020	2021	2022	2023
Cellular subscribers	1,722,834	1,808,976	1,899,425	1,994,396	2,094,116	2,198,822	2,308,763
Mobile broadband	474,610	747,511	784,886	824,131	865,337	908,604	954,034
Voice traffic assumptions							
Description	2017	2018	2019	2020	2021	2022	2023
MOU - incoming + outgoing (monthly)	120	120	120	120	120	120	120
Messaging assumptions							
Description	2017	2018	2019	2020	2021	2022	2023
SMS originated per subscriber per month	252	252	252	252	252	252	252
Data traffic usage assumptions							
Description	2017	2018	2019	2020	2021	2022	2023
Mbytes per handset user per month (	390	450	500	500	500	500	500
Mbytes per handset data user per mo	2,500	2,750	3,100	3,500	4,000	4,200	4,410
Mbytes per broadband data user per	2,500	2,750	3,025	3,328	3,660	4,026	4,429
Data traffic proportion assumptions							
Description	2017	2018	2019	2020	2021	2022	2023
Low usage (non-smartphone & e-read	25%	20%	15%	10%	0%	0%	0%
Medium usage (smartphone, portable	75%	80%	85%	90%	100%	100%	100%
High usage (tablet, laptop and netbo	100%	100%	100%	100%	100%	100%	100%
Monthly average per cellular subscrib	1,973	2,290	2,710	3,200	4,000	4,200	4,410
Monthly average per cellular subscrib	20,830	26,570	32,310	38,050	43,790	49,530	55,270
Rollout of services and revenue							
Description	2017	2018	2019	2020	2021	2022	2023
Rollout of basestations	5%	20%	25%	25%	20%	5%	0%

10.3.4 **Demand forecasts**

This section describes the different traffic demand forecasts. As described in Chapter 8 this has a large effect on the network required to serve this demand for capacity and will ultimately have a large effect on the value of spectrum. These different demand scenarios are presented graphically in Figure 38.

Year	2017	2018	2019	2020	2021	2022	2023
Based on aggressive forecast	1,337	1,912	2,734	3,910	5,591	7,995	11,433
Linear - Based on Cisco VNI for 2015	2,083	2,657	3,231	3,805	4,379	4,953	5,527
10 x linear	20,830	26,570	32,310	38,050	43,790	49,530	55,270
Demand based on usage	1,900	2,185	2,513	2,890	3,323	3,822	4,395

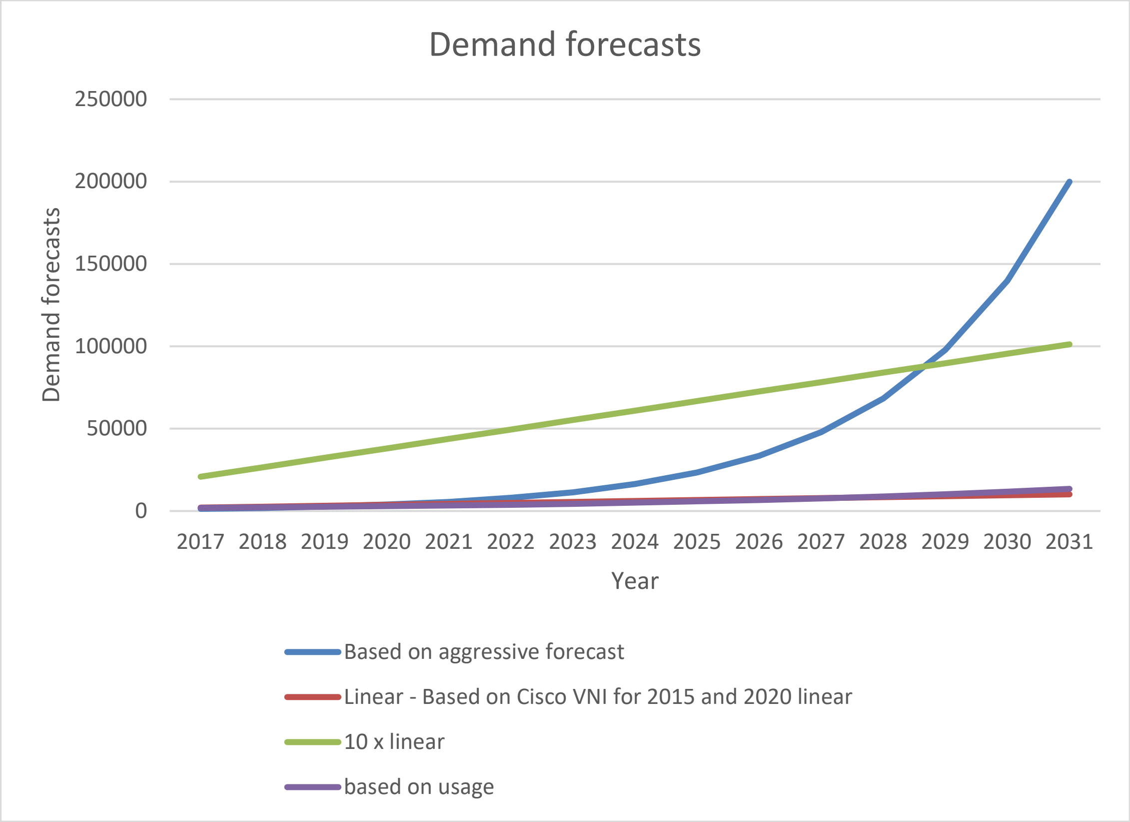
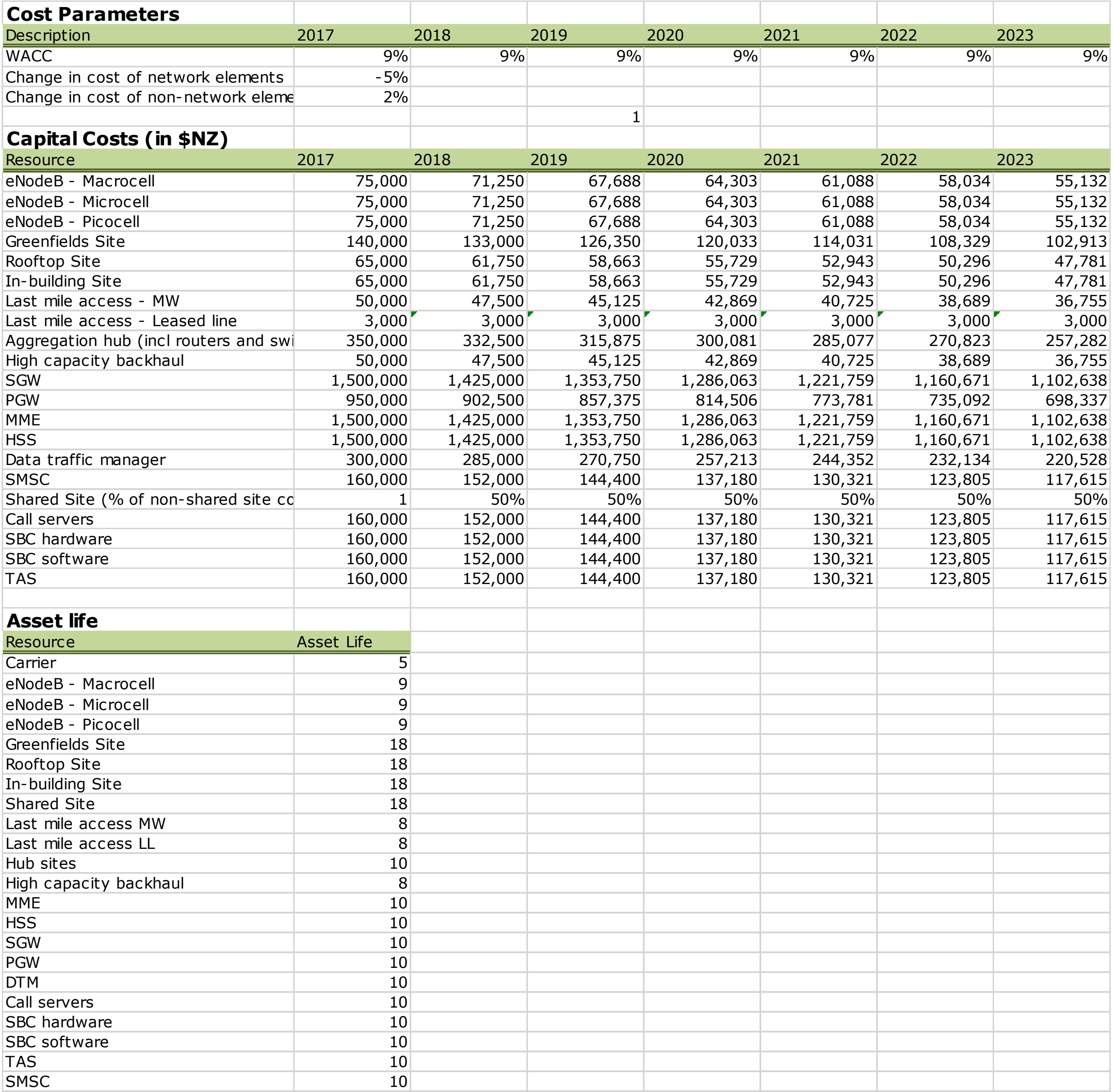


Figure 38. Demand forecasts.

10.3.5 **Unit costs**

This section describes the equipment costs, asset life, fixed and indirect costs of equipment and assets used in cellular networks. A reminder that some of these costs and other data has been altered to keep this information confidential.



Cost Parameters

Description	2017	2018	2019	2020	2021	2022	2023
WACC	9%	9%	9%	9%	9%	9%	9%
Change in cost of network elements	-5%						
Change in cost of non-network eleme	2%						
			1				

Capital Costs (in $NZ)

Resource	2017	2018	2019	2020	2021	2022	2023
eNodeB - Macrocell	75,000	71,250	67,688	64,303	61,088	58,034	55,132
eNodeB - Microcell	75,000	71,250	67,688	64,303	61,088	58,034	55,132
eNodeB - Picocell	75,000	71,250	67,688	64,303	61,088	58,034	55,132
Greenfields Site	140,000	133,000	126,350	120,033	114,031	108,329	102,913
Rooftop Site	65,000	61,750	58,663	55,729	52,943	50,296	47,781
In-building Site	65,000	61,750	58,663	55,729	52,943	50,296	47,781
Last mile access - MW	50,000	47,500	45,125	42,869	40,725	38,689	36,755
Last mile access - Leased line	3,000	3,000	3,000	3,000	3,000	3,000	3,000
Aggregation hub (incl routers and swi	350,000	332,500	315,875	300,081	285,077	270,823	257,282
High capacity backhaul	50,000	47,500	45,125	42,869	40,725	38,689	36,755
SGW	1,500,000	1,425,000	1,353,750	1,286,063	1,221,759	1,160,671	1,102,638
PGW	950,000	902,500	857,375	814,506	773,781	735,092	698,337
MME	1,500,000	1,425,000	1,353,750	1,286,063	1,221,759	1,160,671	1,102,638
HSS	1,500,000	1,425,000	1,353,750	1,286,063	1,221,759	1,160,671	1,102,638
Data traffic manager	300,000	285,000	270,750	257,213	244,352	232,134	220,528
SMSC	160,000	152,000	144,400	137,180	130,321	123,805	117,615
Shared Site (% of non-shared site cc	1	50%	50%	50%	50%	50%	50%
Call servers	160,000	152,000	144,400	137,180	130,321	123,805	117,615
SBC hardware	160,000	152,000	144,400	137,180	130,321	123,805	117,615
SBC software	160,000	152,000	144,400	137,180	130,321	123,805	117,615
TAS	160,000	152,000	144,400	137,180	130,321	123,805	117,615

Asset life

Resource	Asset Life
Carrier	5
eNodeB - Macrocell	9
eNodeB - Microcell	9
eNodeB - Picocell	9
Greenfields Site	18
Rooftop Site	18
In-building Site	18
Shared Site	18
Last mile access MW	8
Last mile access LL	8
Hub sites	10
High capacity backhaul	8
MME	10
HSS	10
SGW	10
PGW	10
DTM	10
Call servers	10
SBC hardware	10
SBC software	10
TAS	10
SMSC	10

Noting the asset life will be used to determine future replacement costs and timeframes for equipment replacement.

Fixed Costs

Description	Cost	Asset Life
Spectrum	0	15
OMC / NMC	14,239,232	20
Voicemail System	5,000,000	7
Billing System	10,000,000	5

Indirect Costs

Description	Value
Operating Costs	5%
Corporate overhead	30%
Indirect costs	35%

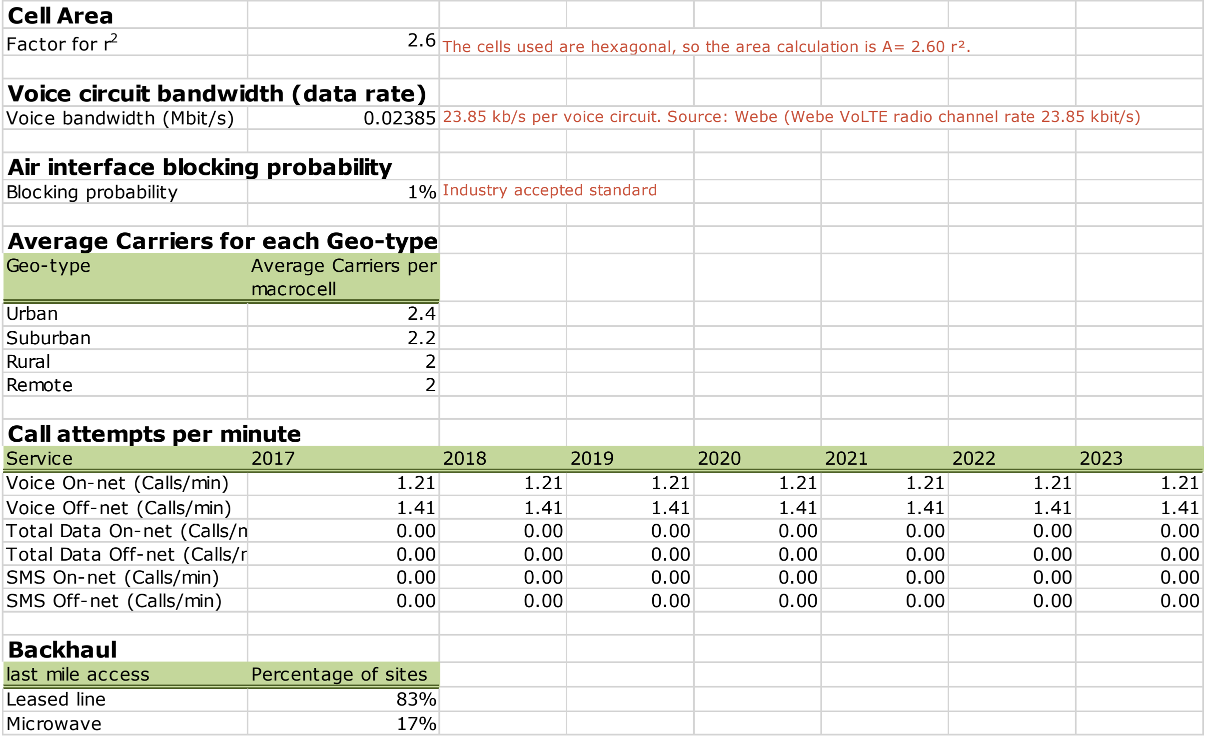
10.3.6 **Network design - conversions**

This section describes the busy hour traffic and the conversion ratios used.

Voice		
Use this to convert annual traffic to busy-hour traffic		
Description	Value	Source/Notes
Proportion of annual traffic in busy hour	0.000547945	Based on 365 busy days and 20% of daily traffic in busy hour
Packet Switched Data		
Use this to convert nominal bandwidth to annual traffic		
Description	Value	Source/Notes
Proportion of annual traffic in busy hour	0.000547945	Based on 365 busy days and 20% of daily traffic in busy hour
Messaging		
Use this to convert annual traffic to busy-hour traffic		
Description	Value	Source/Notes
Proportion of annual messages in busy hour	0.000547945	Based on 365 busy days and 20% of daily traffic in busy hour
Traffic		
Description	Value	Notes
Non-conversation holding time (min)	0.1	Source: Industry accepted standard
Average call length (min)	2	Source: Industry accepted standard
Conversions		
For voice: convert minutes to MB and BHE to Mb/s		
For data: convert user MB to (transport) MB and user Mb/s to (transport) Mb/s		
For messaging: convert messagaes to MB and messages/hour to Mb/s		
Description	Value	Notes
MB per hour to Mbit/sec	0.0022	8 (bits per byte) / 3600 (sec per hour)
Mb/s per BHE	0.012	12 kb/s per voice circuit
MB per minute	0.09	12 kb/s * 60 (sec per min) / 8 (bits/byte)
IP overhead	0.12	
MB per SMS	0.000238419	250 bytes per average message. 250/(1024 (B/KB)*1024 (KB/MB)).
Mbit/s per message/hour	5.17401E-10	length of message (kB) / 1024 (kB/MB) * 8 (b/B) / 3600 (sec/hour)

10.3.7 Network design - architecture

This section describes the architecture assumptions including the cell areas and carriers used in each geo type, call attempts, and backhaul (transmission) information.



Cell Area

Factor for r^2	2.6	The cells used are hexagonal, so the area calculation is A= 2.60 r².

Voice circuit bandwidth (data rate)

Voice bandwidth (Mbit/s)	0.02385	23.85 kb/s per voice circuit. Source: Webe (Webe VoLTE radio channel rate 23.85 kbit/s)

Air interface blocking probability

Blocking probability	1%	Industry accepted standard

Average Carriers for each Geo-type

Geo-type	Average Carriers per macrocell
Urban	2.4
Suburban	2.2
Rural	2
Remote	2

Call attempts per minute

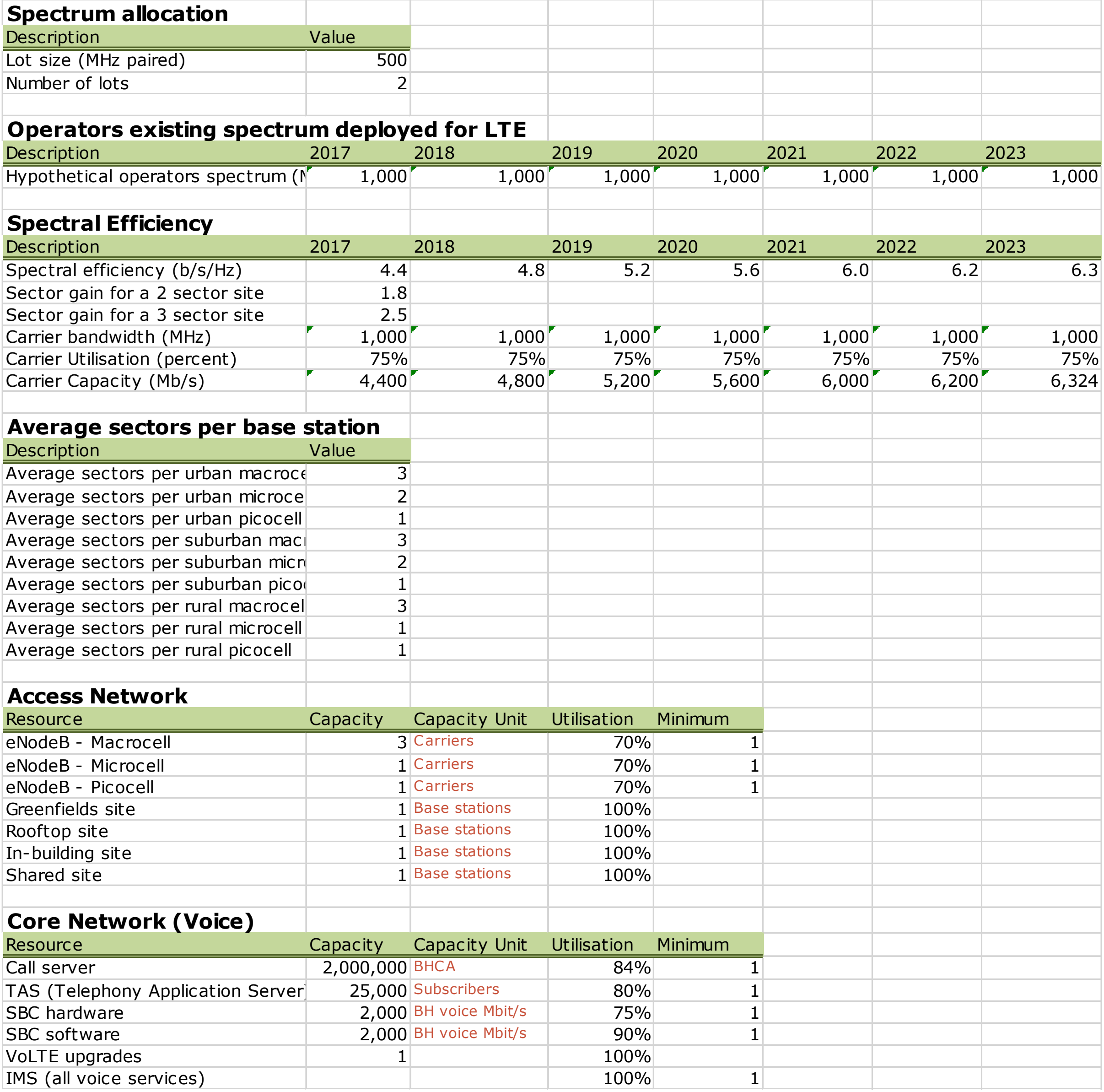
Service	2017	2018	2019	2020	2021	2022	2023
Voice On-net (Calls/min)	1.21	1.21	1.21	1.21	1.21	1.21	1.21
Voice Off-net (Calls/min)	1.41	1.41	1.41	1.41	1.41	1.41	1.41
Total Data On-net (Calls/n	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total Data Off-net (Calls/r	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SMS On-net (Calls/min)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SMS Off-net (Calls/min)	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Backhaul

last mile access	Percentage of sites
Leased line	83%
Microwave	17%

10.3.8 Network design - resource capacities

This section describes the resource capabilities, including spectrum allocation and spectral efficiency, the access (RAN) capability, and the Core and Transmission capabilities.



Spectrum allocation

Description	Value
Lot size (MHz paired)	500
Number of lots	2

Operators existing spectrum deployed for LTE

Description	2017	2018	2019	2020	2021	2022	2023
Hypothetical operators spectrum (	1,000	1,000	1,000	1,000	1,000	1,000	1,000

Spectral Efficiency

Description	2017	2018	2019	2020	2021	2022	2023
Spectral efficiency (b/s/Hz)	4.4	4.8	5.2	5.6	6.0	6.2	6.3
Sector gain for a 2 sector site	1.8						
Sector gain for a 3 sector site	2.5						
Carrier bandwidth (MHz)	1,000	1,000	1,000	1,000	1,000	1,000	1,000
Carrier Utilisation (percent)	75%	75%	75%	75%	75%	75%	75%
Carrier Capacity (Mb/s)	4,400	4,800	5,200	5,600	6,000	6,200	6,324

Average sectors per base station

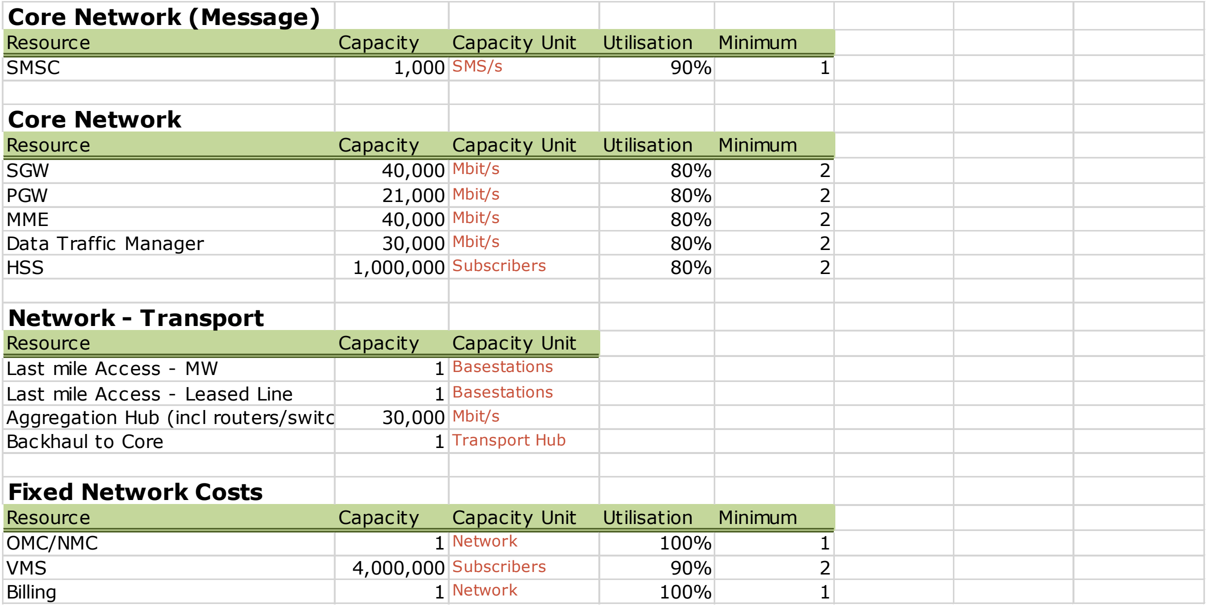
Description	Value
Average sectors per urban macroce	3
Average sectors per urban microce	2
Average sectors per urban picocell	1
Average sectors per suburban mac	3
Average sectors per suburban micr	2
Average sectors per suburban pico	1
Average sectors per rural macrocel	3
Average sectors per rural microcell	1
Average sectors per rural picocell	1

Access Network

Resource	Capacity	Capacity Unit	Utilisation	Minimum
eNodeB - Macrocell	3	Carriers	70%	1
eNodeB - Microcell	1	Carriers	70%	1
eNodeB - Picocell	1	Carriers	70%	1
Greenfields site	1	Base stations	100%	
Rooftop site	1	Base stations	100%	
In-building site	1	Base stations	100%	
Shared site	1	Base stations	100%	

Core Network (Voice)

Resource	Capacity	Capacity Unit	Utilisation	Minimum
Call server	2,000,000	BHCA	84%	1
TAS (Telephony Application Server	25,000	Subscribers	80%	1
SBC hardware	2,000	BH voice Mbit/s	75%	1
SBC software	2,000	BH voice Mbit/s	90%	1
VoLTE upgrades	1		100%	
IMS (all voice services)			100%	1



Core Network (Message)

Resource	Capacity	Capacity Unit	Utilisation	Minimum
SMSC	1,000	SMS/s	90%	1

Core Network

Resource	Capacity	Capacity Unit	Utilisation	Minimum
SGW	40,000	Mbit/s	80%	2
PGW	21,000	Mbit/s	80%	2
MME	40,000	Mbit/s	80%	2
Data Traffic Manager	30,000	Mbit/s	80%	2
HSS	1,000,000	Subscribers	80%	2

Network - Transport

Resource	Capacity	Capacity Unit
Last mile Access - MW	1	Basestations
Last mile Access - Leased Line	1	Basestations
Aggregation Hub (incl routers/switc	30,000	Mbit/s
Backhaul to Core	1	Transport Hub

Fixed Network Costs

Resource	Capacity	Capacity Unit	Utilisation	Minimum
OMC/NMC	1	Network	100%	1
VMS	4,000,000	Subscribers	90%	2
Billing	1	Network	100%	1

10.3.8.1 Routing factors

This section adjusts the traffic totals on the network depending on the traffic destination. On-net refers to traffic that stays on the cellular network and off-net refers to traffic that terminates off the cellular network.

Access Network

Element	Unit	Voice On-net	Voice Off-net	Data On-net	Data Off-net	SMS On-net	SMS Off-net
Carrier	Mb/s ("Erlang Mb/s")	2	1	2	1	2	1
Base Station (eNodeB)	Mb/s ("Erlang Mb/s")	2	1	2	1	2	1

Transmission Network

Element	Unit	Voice On-net	Voice Off-net	Data On-net	Data Off-net	SMS On-net	SMS Off-net
Last mile access	Mb/s	2	1	2	1	2	1
Backhaul	Mb/s ("Erlang Mb/s")	2	1	2	1	2	1
Hub	Mb/s ("Erlang Mb/s")	2	1	2	1	2	1

Core Network - Voice + SMS

Element	Unit	Voice On-net	Voice Off-net	Data On-net	Data Off-net	SMS On-net	SMS Off-net
IMS	Subscribers	2	1	0	0	0	0
SMSC	Messages	0	0	0	0	2	1

Core Network - All traffic

Element	Unit	Voice On-net	Voice Off-net	Data On-net	Data Off-net	SMS On-net	SMS Off-net
SGW	Mb/s	2	1	2	1	2	1
PGW	Mb/s	2	1	2	1	2	1
MME	Mb/s	2	1	2	1	2	1
HSS	Subscribers	2	1	2	1	2	1
DTM	Mb/s	2	1	2	1	2	1

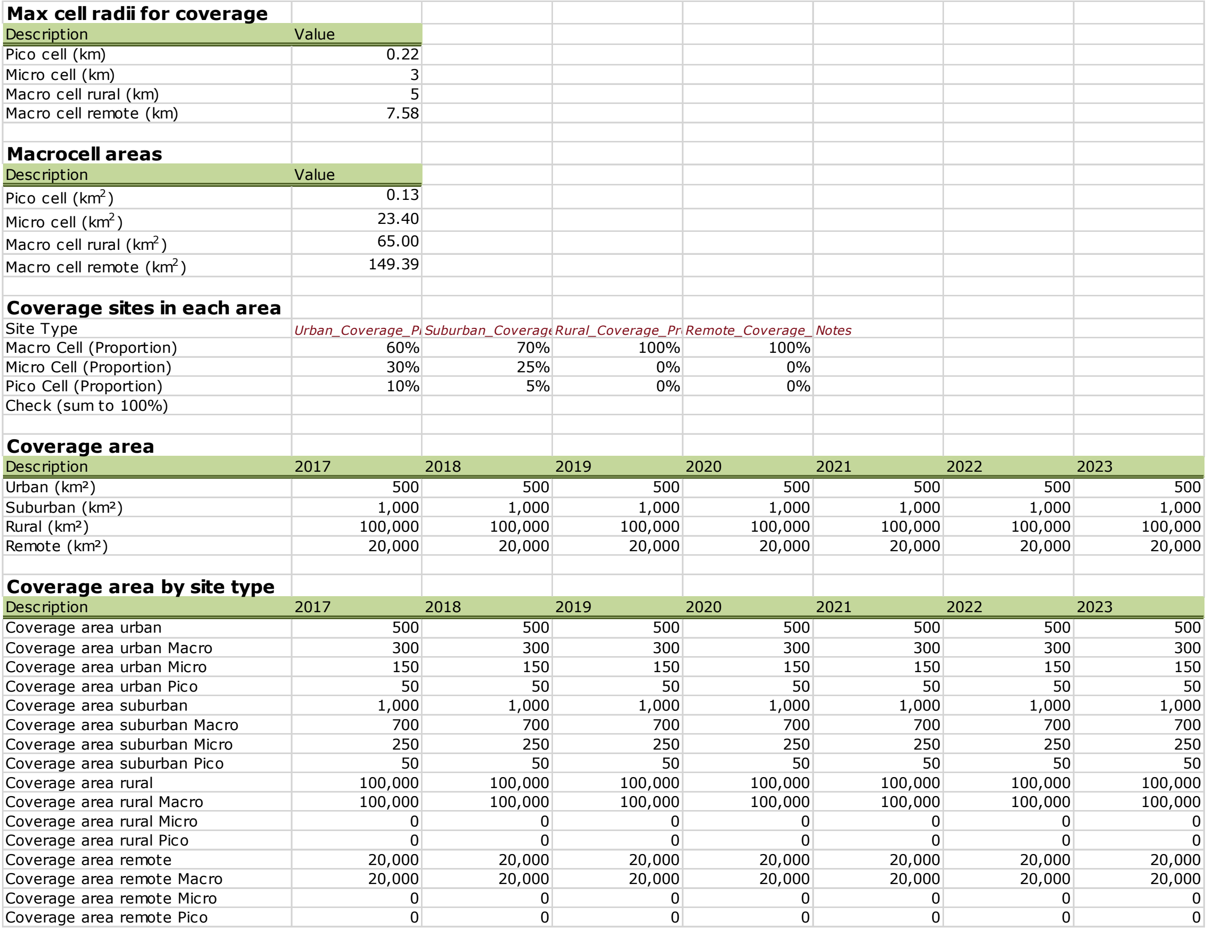
Fixed Network Costs

Routing factors do not have effect on fixed network costs. Fixed network costs to not influence incremental cost at all

Element	Unit	Value	Notes
OMC/NMC	Network	1	One required for entire network
VMS	Network	1	One Voice Mail Server required for entire network
Billing	Network	1	One required for entire network
4G licence	Network	1	One required for entire network

10.3.8.2 Coverage network – equipment required

This section describes the minimum coverage network required to serve the target coverage area. This is adjusted for the different coverage achieved from different base station types (Macro, Micro and Pico).



Max cell radii for coverage

Description	Value
Pico cell (km)	0.22
Micro cell (km)	3
Macro cell rural (km)	5
Macro cell remote (km)	7.58

Macrocell areas

Description	Value
Pico cell (km^2)	0.13
Micro cell (km^2)	23.40
Macro cell rural (km^2)	65.00
Macro cell remote (km^2)	149.39

Coverage sites in each area

Site Type	*Urban_Coverage_P*	*Suburban_Coverage*	*Rural_Coverage_Pr*	*Remote_Coverage_*	*Notes*
Macro Cell (Proportion)	60%	70%	100%	100%	
Micro Cell (Proportion)	30%	25%	0%	0%	
Pico Cell (Proportion)	10%	5%	0%	0%	
Check (sum to 100%)					

Coverage area

Description	2017	2018	2019	2020	2021	2022	2023
Urban (km^2)	500	500	500	500	500	500	500
Suburban (km^2)	1,000	1,000	1,000	1,000	1,000	1,000	1,000
Rural (km^2)	100,000	100,000	100,000	100,000	100,000	100,000	100,000
Remote (km^2)	20,000	20,000	20,000	20,000	20,000	20,000	20,000

Coverage area by site type

Description	2017	2018	2019	2020	2021	2022	2023
Coverage area urban	500	500	500	500	500	500	500
Coverage area urban Macro	300	300	300	300	300	300	300
Coverage area urban Micro	150	150	150	150	150	150	150
Coverage area urban Pico	50	50	50	50	50	50	50
Coverage area suburban	1,000	1,000	1,000	1,000	1,000	1,000	1,000
Coverage area suburban Macro	700	700	700	700	700	700	700
Coverage area suburban Micro	250	250	250	250	250	250	250
Coverage area suburban Pico	50	50	50	50	50	50	50
Coverage area rural	100,000	100,000	100,000	100,000	100,000	100,000	100,000
Coverage area rural Macro	100,000	100,000	100,000	100,000	100,000	100,000	100,000
Coverage area rural Micro	0	0	0	0	0	0	0
Coverage area rural Pico	0	0	0	0	0	0	0
Coverage area remote	20,000	20,000	20,000	20,000	20,000	20,000	20,000
Coverage area remote Macro	20,000	20,000	20,000	20,000	20,000	20,000	20,000
Coverage area remote Micro	0	0	0	0	0	0	0
Coverage area remote Pico	0	0	0	0	0	0	0

Coverage area by site type (totals)

Description	2017	2018	2019	2020	2021	2022	2023
Macro Coverage Area (rural)	101,000	101,000	101,000	101,000	101,000	101,000	101,000
Macro Coverage Area (remote)	20,000	20,000	20,000	20,000	20,000	20,000	20,000
Micro Coverage Area	400	400	400	400	400	400	400
Pico Coverage Area	100	100	100	100	100	100	100

Number of sites

Description	2017	2018	2019	2020	2021	2022	2023
eNodeB - Macrocell	1,688	1,688	1,688	1,688	1,688	1,688	1,688
eNodeB - Microcell	17	17	17	17	17	17	17
eNodeB - Picocell	795	795	795	795	795	795	795
Total Coverage Sites	2,499	2,499	2,499	2,499	2,499	2,499	2,499
Urban Sites	408	408	408	408	408	408	408
Suburban Sites	419	419	419	419	419	419	419
Rural Sites	1,538	1,538	1,538	1,538	1,538	1,538	1,538
Remote Sites	134	134	134	134	134	134	134
Total Coverage Sites (check)	2,499						
Greenfields Site	1,846	1,846	1,846	1,846	1,846	1,846	1,846
Rooftop Site	414	414	414	414	414	414	414
In-building Site	239	239	239	239	239	239	239
Shared Site	997	997	997	997	997	997	997

Backhaul requirements for Coverage

Description	2017	2018	2019	2020	2021	2022	2023
Maximum Mbit/s of Carriers	10,997,716	11,997,508	12,997,300	13,997,093	14,996,885	15,496,781	15,806,717

Last Mile Access for Coverage

Description	2017	2018	2019	2020	2021	2022	2023
Last mile access MW	425	425	425	425	425	425	425
Last mile access LL	2,075	2,075	2,075	2,075	2,075	2,075	2,075
Total last mile access	2,499	2,499	2,499	2,499	2,499	2,499	2,499

Hub / Aggregation Sites for coverage

Description	2017	2018	2019	2020	2021	2022	2023
Total Hub sites for Coverage Network	367	400	434	467	500	517	527

Core Network for Coverage

Description	2017	2018	2019	2020	2021	2022	2023
Total MME for Coverage Network	2	2	2	2	2	2	2
Total IMS for Coverage Network	1	1	1	1	1	1	1
Total HSS for Coverage Network	2	2	2	2	2	2	2
Total SGW for Coverage Network	2	2	2	2	2	2	2
Total PGW for Coverage Network	2	2	2	2	2	2	2
Total DTM for Coverage Network	2	2	2	2	2	2	2
Total SMSC for Coverage Network	1	1	1	1	1	1	1

Core Network Transport for Coverage

Total Element Traffic

Description	2017	2018	2019	2020	2021	2022	2023
Number of Hub to Core Links required	734	800	868	934	1,000	1,034	1,054

10.3.8.3 Capacity network – equipment required

This section describes the minimum capacity network required to serve the demand for voice and data traffic at the busy hour. This is adjusted for the different base station types, routing factors, and geographical location types.

Site Capacity

Description	2017	2018	2019	2020	2021	2022	2023
Capacity of urban macrocell (Mbit	13,200	14,400	15,600	16,800	18,000	18,600	18,972
Capacity of urban microcell (Mbit/	8,800	9,600	10,400	11,200	12,000	12,400	12,648
Capacity of urban picocell (Mbit/s	4,400	4,800	5,200	5,600	6,000	6,200	6,324
Capacity of suburban macrocell (	13,200	14,400	15,600	16,800	18,000	18,600	18,972
Capacity of suburban microcell (M	8,800	9,600	10,400	11,200	12,000	12,400	12,648
Capacity of suburban picocell (Mb	4,400	4,800	5,200	5,600	6,000	6,200	6,324
Capacity of rural macrocell (Mbit/	13,200	14,400	15,600	16,800	18,000	18,600	18,972
Capacity of rural microcell (Mbit/s	4,400	4,800	5,200	5,600	6,000	6,200	6,324
Capacity of rural picocell (Mbit/s)	4,400	4,800	5,200	5,600	6,000	6,200	6,324

Total element traffic

Urban - Busy Hour (BHE and MB)

Description	2017	2018	2019	2020	2021	2022	2023	Routing Multiplier	Notes
Voice On-net	9,135	9,592	10,071	10,575	11,104	11,659	12,242	2	BHE
Voice Off-net	10,658	11,190	11,750	12,337	12,954	13,602	14,282	1	BHE
Data On-net	0	0	0	0	0	0	0	2	MB
Data Off-net	174,733,437	232,996,979	296,711,696	366,286,605	442,159,476	524,798,916	614,706,624	1	MB
SMS On-net	1,096,210	1,151,020	1,208,571	1,269,000	1,332,450	1,399,072	1,469,026	2	MB
SMS Off-net	1,278,911	1,342,857	1,410,000	1,480,500	1,554,525	1,632,251	1,713,864	1	MB

Urban - Busy Hour (Mb/s)

Description	2017	2018	2019	2020	2021	2022	2023	Routing Multiplier	Notes
Voice On-net	110	115	121	127	133	140	147	2	Mbit/s
Voice Off-net	128	134	141	148	155	163	171	1	Mbit/s
Data On-net	0	0	0	0	0	0	0	2	Mbit/s
Data Off-net	388,297	517,771	659,359	813,970	982,577	1,166,220	1,366,015	1	Mbit/s
SMS On-net	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2	Mbit/s
SMS Off-net	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1	Mbit/s

Suburban - Busy Hour (BHE and MB)

Description	2017	2018	2019	2020	2021	2022	2023	Routing Multiplier	Notes
Voice On-net	3,140	3,297	3,462	3,635	3,817	4,008	4,208	2	BHE
Voice Off-net	3,664	3,847	4,039	4,241	4,453	4,676	4,910	1	BHE
Data On-net	0	0	0	0	0	0	0	2	MB
Data Off-net	60,064,619	80,092,711	101,994,646	125,911,021	151,992,320	180,399,627	211,305,402	1	MB
SMS On-net	376,822	395,663	415,446	436,219	458,030	480,931	504,978	2	MB
SMS Off-net	439,626	461,607	484,687	508,922	534,368	561,086	589,141	1	MB

Suburban - Busy Hour (Mb/s)

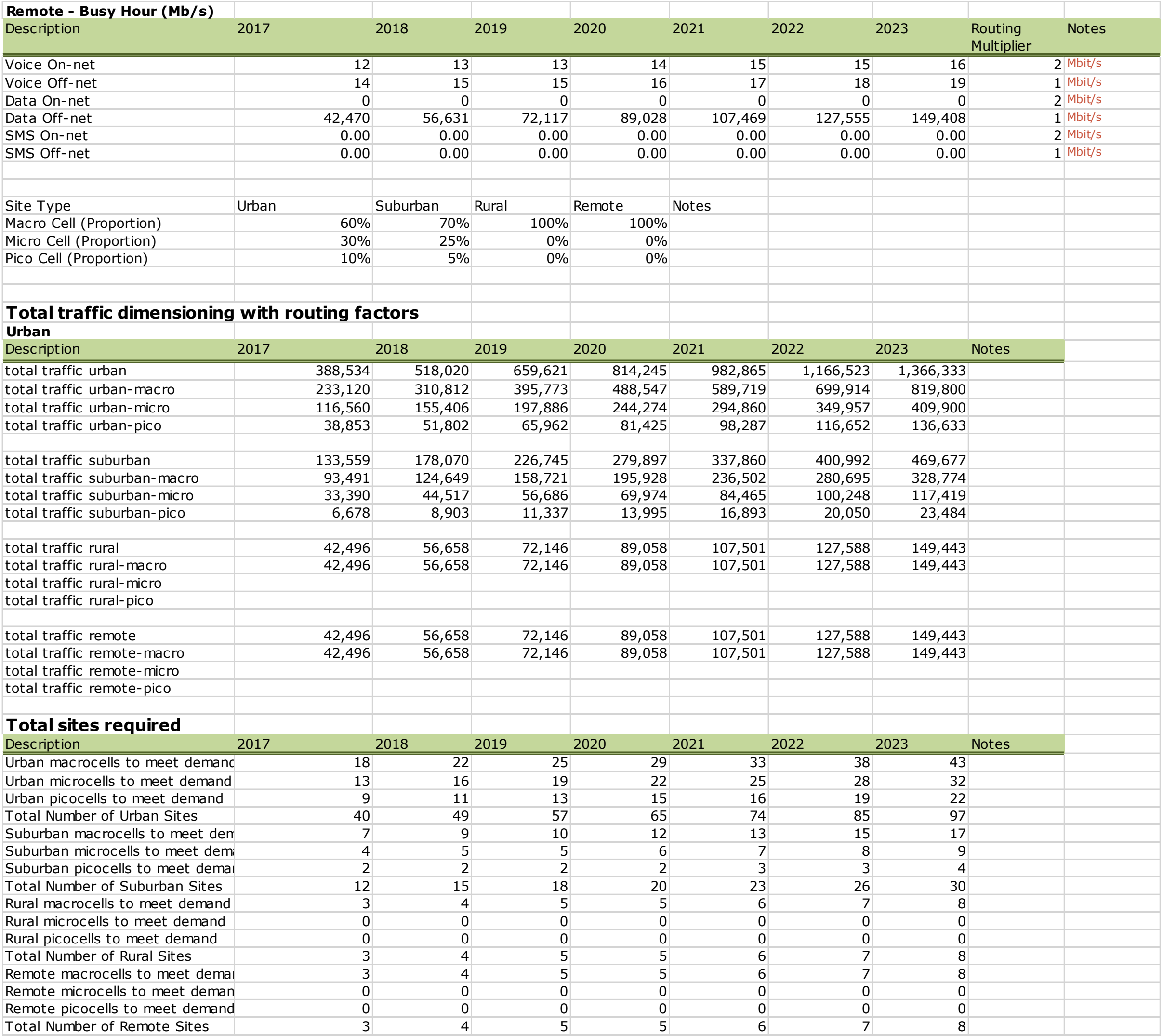
Description	2017	2018	2019	2020	2021	2022	2023	Routing Multiplier	Notes
Voice On-net	38	40	42	44	46	48	50	2	Mbit/s
Voice Off-net	44	46	48	51	53	56	59	1	Mbit/s
Data On-net	0	0	0	0	0	0	0	2	Mbit/s
Data Off-net	133,477	177,984	226,655	279,802	337,761	400,888	469,568	1	Mbit/s
SMS On-net	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2	Mbit/s
SMS Off-net	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1	Mbit/s

Rural - Busy Hour (BHE and MB)

Description	2017	2018	2019	2020	2021	2022	2023	Routing Multiplier	Notes
Voice On-net	999	1,049	1,102	1,157	1,214	1,275	1,339	2	BHE
Voice Off-net	1,166	1,224	1,285	1,349	1,417	1,488	1,562	1	BHE
Data On-net	0	0	0	0	0	0	0	2	MB
Data Off-net	19,111,470	25,484,045	32,452,842	40,062,597	48,361,193	57,399,881	67,233,537	1	MB
SMS On-net	119,898	125,893	132,187	138,797	145,737	153,024	160,675	2	MB
SMS Off-net	139,881	146,875	154,219	161,930	170,026	178,527	187,454	1	MB

Rural - Busy Hour (Mb/s)

Description	2017	2018	2019	2020	2021	2022	2023	Routing Multiplier	Notes
Voice On-net	12	13	13	14	15	15	16	2	Mbit/s
Voice Off-net	14	15	15	16	17	18	19	1	Mbit/s
Data On-net	0	0	0	0	0	0	0	2	Mbit/s
Data Off-net	42,470	56,631	72,117	89,028	107,469	127,555	149,408	1	Mbit/s
SMS On-net	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2	Mbit/s
SMS Off-net	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1	Mbit/s



Remote - Busy Hour (Mb/s)

Description	2017	2018	2019	2020	2021	2022	2023	Routing Multiplier	Notes
Voice On-net	12	13	13	14	15	15	16	2	Mbit/s
Voice Off-net	14	15	15	16	17	18	19	1	Mbit/s
Data On-net	0	0	0	0	0	0	0	2	Mbit/s
Data Off-net	42,470	56,631	72,117	89,028	107,469	127,555	149,408	1	Mbit/s
SMS On-net	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2	Mbit/s
SMS Off-net	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1	Mbit/s

Site Type	Urban	Suburban	Rural	Remote	Notes
Macro Cell (Proportion)	60%	70%	100%	100%	
Micro Cell (Proportion)	30%	25%	0%	0%	
Pico Cell (Proportion)	10%	5%	0%	0%	

Total traffic dimensioning with routing factors

Urban

Description	2017	2018	2019	2020	2021	2022	2023	Notes
total traffic urban	388,534	518,020	659,621	814,245	982,865	1,166,523	1,366,333	
total traffic urban-macro	233,120	310,812	395,773	488,547	589,719	699,914	819,800	
total traffic urban-micro	116,560	155,406	197,886	244,274	294,860	349,957	409,900	
total traffic urban-pico	38,853	51,802	65,962	81,425	98,287	116,652	136,633	
total traffic suburban	133,559	178,070	226,745	279,897	337,860	400,992	469,677	
total traffic suburban-macro	93,491	124,649	158,721	195,928	236,502	280,695	328,774	
total traffic suburban-micro	33,390	44,517	56,686	69,974	84,465	100,248	117,419	
total traffic suburban-pico	6,678	8,903	11,337	13,995	16,893	20,050	23,484	
total traffic rural	42,496	56,658	72,146	89,058	107,501	127,588	149,443	
total traffic rural-macro	42,496	56,658	72,146	89,058	107,501	127,588	149,443	
total traffic rural-micro								
total traffic rural-pico								
total traffic remote	42,496	56,658	72,146	89,058	107,501	127,588	149,443	
total traffic remote-macro	42,496	56,658	72,146	89,058	107,501	127,588	149,443	
total traffic remote-micro								
total traffic remote-pico								

Total sites required

Description	2017	2018	2019	2020	2021	2022	2023	Notes
Urban macrocells to meet deman	18	22	25	29	33	38	43	
Urban microcells to meet demand	13	16	19	22	25	28	32	
Urban picocells to meet demand	9	11	13	15	16	19	22	
Total Number of Urban Sites	40	49	57	65	74	85	97	
Suburban macrocells to meet de	7	9	10	12	13	15	17	
Suburban microcells to meet dem	4	5	5	6	7	8	9	
Suburban picocells to meet dema	2	2	2	2	3	3	4	
Total Number of Suburban Sites	12	15	18	20	23	26	30	
Rural macrocells to meet demand	3	4	5	5	6	7	8	
Rural microcells to meet demand	0	0	0	0	0	0	0	
Rural picocells to meet demand	0	0	0	0	0	0	0	
Total Number of Rural Sites	3	4	5	5	6	7	8	
Remote macrocells to meet dema	3	4	5	5	6	7	8	
Remote microcells to meet deman	0	0	0	0	0	0	0	
Remote picocells to meet demand	0	0	0	0	0	0	0	
Total Number of Remote Sites	3	4	5	5	6	7	8	

eNodeB Types

Description	2017	2018	2019	2020	2021	2022	2023	Notes
Urban Macrocell Sites	18	22	25	29	33	38	43	
Suburban Macrocell Sites	7	9	10	12	13	15	17	
Rural Macrocell Sites	3	4	5	5	6	7	8	
Remote Macrocell Sites	3	4	5	5	6	7	8	
Total Number of Macrocell Sites	31	38	45	51	58	66	76	
Urban Microcell Sites	13	16	19	22	25	28	32	
Suburban Microcell Sites	4	5	5	6	7	8	9	
Rural Microcell Sites	0	0	0	0	0	0	0	
Remote Microcell Sites	0	0	0	0	0	0	0	
Total Number of Microcell Sites	17	21	24	28	32	36	42	
Urban Picocell Sites	9	11	13	15	16	19	22	
Suburban Picocell Sites	2	2	2	2	3	3	4	
Rural Picocell Sites	0	0	0	0	0	0	0	
Remote Picocell Sites	0	0	0	0	0	0	0	
Total Number of Picocell Sites	10	13	15	17	19	22	25	
Number of eNodeB Sites	59	72	84	96	109	125	143	

Site Types

Description	2017	2018	2019	2020	2021	2022	2023		Notes
Pico Greenfield Sites	4	5	6	7	8	9	10	40%	
Micro Greenfield Sites	9	11	13	15	17	20	23	55%	
Macro Rural Greenfield Sites	25	31	36	41	47	54	62	90%	
Macro Remote Greenfield Sites	0	0	0	0	0	0	0	0%	
Total Number of Greenfields Sites	39	47	56	64	72	82	95		Sites calculated
Pico Rooftop Sites	3	4	4	5	6	7	8	30%	
Micro Rooftop Sites	7	8	10	11	13	15	17	40%	
Macro Rural Rooftop Sites	3	3	4	5	5	6	7	10%	
Macro Remote Rooftop Sites	0	0	0	0	0	0	0	0%	
Total Number of Rooftop Sites	13	16	18	21	24	27	31		Sites calculated
Pico Inbuilding Sites	3	4	4	5	6	7	8	30%	
Micro Inbuilding Sites	1	1	1	1	2	2	2	5%	
Macro Rural Inbuilding Sites	0	0	0	0	0	0	0	0%	
Macro Remote Inbuilding Sites	0	0	0	0	0	0	0	0%	
Total Number of In-building Sites	4	5	6	7	7	8	10		Sites calculated
Total number of sites	55	68	80	91	103	118	135		
Check number of sites									Cross check

Shared Sites

Description	2017	2018	2019	2020	2021	2022	2023	Notes
Total number of Greenfields Sites	39	47	56	64	72	82	95	Only Greenfield sites can be sha
Maximum number of shared sites	30	37	43	50	56	64	74	Total sites multiplied by the site
Actual number of shared sites	30	37	43	50	56	64	74	Minimum of Greenfield sites and
Shared site proportion	54%	55%	54%	55%	55%	54%	55%	Actual proportion of shared sites

Last Mile Access for Capacity

Description	2017	2018	2019	2020	2021	2022	2023	Notes
Last mile access MW	9	12	14	15	17	20	23	
Last mile access LL	46	56	66	76	85	98	112	
Total last mile access	55	68	80	91	103	118	135	

Total Hub sites (traffic aggregation)

Description	2017	2018	2019	2020	2021	2022	2023	Notes
Urban Hubs	13	18	22	28	33	39	46	
Suburban Router	5	6	8	10	12	14	16	
Rural Router	2	2	3	3	4	5	5	
Remote Router	2	2	3	3	4	5	5	
Hubs needed for access dimensio	22	28	36	44	53	63	72	

10.3.8.4 Core dimensioning – equipment required

This section describes the minimum Core network required to serve the demand for voice and data traffic. This is adjusted for the Core components as described in Chapter 3 (section 3.5.4).

SGW Dimensioning

Total Element Traffic

Multiply service traffic by service routing factors to get total element traffic

Service	2017	2018	2019	2020	2021	2022	2023	Notes
Voice On-net	171	180	189	198	208	219	230	Mbit/s
Voice Off-net	200	210	220	231	243	255	268	Mbit/s
Data On-net	0	0	0	0	0	0	0	Mbit/s
Data Off-net	606,713	809,017	1,030,249	1,271,828	1,535,276	1,822,218	2,134,398	Mbit/s
SMS On-net	0	0	0	0	0	0	0	Mbit/s
SMS Off-net	0	0	0	0	0	0	0	Mbit/s

Dimension Calculations

Description	2017	2018	2019	2020	2021	2022	2023
Total Traffic Carried on SGW	607,084	809,407	1,030,658	1,272,258	1,535,727	1,822,692	2,134,895
Capacity of SGW	32,000	32,000	32,000	32,000	32,000	32,000	32,000
Number of SGWs required	19	26	33	40	48	57	67

PGW Dimensioning

Total Element Traffic

Multiply service traffic by service routing factors to get total element traffic

Service	2017	2018	2019	2020	2021	2022	2023	Notes
Voice On-net	171	180	189	198	208	219	230	Mbit/s
Voice Off-net	200	210	220	231	243	255	268	Mbit/s
Data On-net	0	0	0	0	0	0	0	Mbit/s
Data Off-net	606,713	809,017	1,030,249	1,271,828	1,535,276	1,822,218	2,134,398	Mbit/s
SMS On-net	0	0	0	0	0	0	0	Mbit/s
SMS Off-net	0	0	0	0	0	0	0	Mbit/s

Dimension Calculations

Description	2017	2018	2019	2020	2021	2022	2023
Total Traffic Carried on PGW	607,084	809,407	1,030,658	1,272,258	1,535,727	1,822,692	2,134,895
Capacity of PGW	16,800	16,800	16,800	16,800	16,800	16,800	16,800
Number of PGWs required	37	49	62	76	92	109	128

HSS Dimensioning

Total Element Traffic

Multiply service traffic by service routing factors to get total element traffic

Service	2017	2018	2019	2020	2021	2022	2023	Notes
Voice On-net	171	180	189	198	208	219	230	Mbit/s
Voice Off-net	200	210	220	231	243	255	268	Mbit/s
Data On-net	0	0	0	0	0	0	0	Mbit/s
Data Off-net	606,713	809,017	1,030,249	1,271,828	1,535,276	1,822,218	2,134,398	Mbit/s
SMS On-net	0	0	0	0	0	0	0	Mbit/s
SMS Off-net	0	0	0	0	0	0	0	Mbit/s

Dimension Calculations

Description	2017	2018	2019	2020	2021	2022	2023
Total Traffic Carried on HSS	607,084	809,407	1,030,658	1,272,258	1,535,727	1,822,692	2,134,895
Capacity of HSS	800,000	800,000	800,000	800,000	800,000	800,000	800,000
Number of HSSs required	2	2	2	2	2	3	3

MME Dimensioning

Total Element Traffic

Multiply service traffic by service routing factors to get total element traffic

Service	2017	2018	2019	2020	2021	2022	2023	Notes
Voice On-net	171	180	189	198	208	219	230	Mbit/s
Voice Off-net	200	210	220	231	243	255	268	Mbit/s
Data On-net	0	0	0	0	0	0	0	Mbit/s
Data Off-net	606,713	809,017	1,030,249	1,271,828	1,535,276	1,822,218	2,134,398	Mbit/s
SMS On-net	0	0	0	0	0	0	0	Mbit/s
SMS Off-net	0	0	0	0	0	0	0	Mbit/s

Dimension Calculations

Description	2017	2018	2019	2020	2021	2022	2023
Total Traffic Carried on MME	607,084	809,407	1,030,658	1,272,258	1,535,727	1,822,692	2,134,895
Capacity of MME	32,000	32,000	32,000	32,000	32,000	32,000	32,000
Number of PGWs required	19	26	33	40	48	57	67

DTM Dimensioning

Total Element Traffic

Multiply service traffic by service routing factors to get total element traffic

Service	2017	2018	2019	2020	2021	2022	2023	Notes
Voice On-net	171	180	189	198	208	219	230	Mbit/s
Voice Off-net	200	210	220	231	243	255	268	Mbit/s
Data On-net	0	0	0	0	0	0	0	Mbit/s
Data Off-net	606,713	809,017	1,030,249	1,271,828	1,535,276	1,822,218	2,134,398	Mbit/s
SMS On-net	0	0	0	0	0	0	0	Mbit/s
SMS Off-net	0	0	0	0	0	0	0	Mbit/s

Dimension Calculations

Description	2017	2018	2019	2020	2021	2022	2023
Total Traffic Carried on DTM	607,084	809,407	1,030,658	1,272,258	1,535,727	1,822,692	2,134,895
Capacity of DTM	24,000	24,000	24,000	24,000	24,000	24,000	24,000
Number of DTMs required	26	34	43	54	64	76	89

Voice

Busy Hour Demand (BHE and MB)

Multiply service traffic by service routing factors to get total element traffic

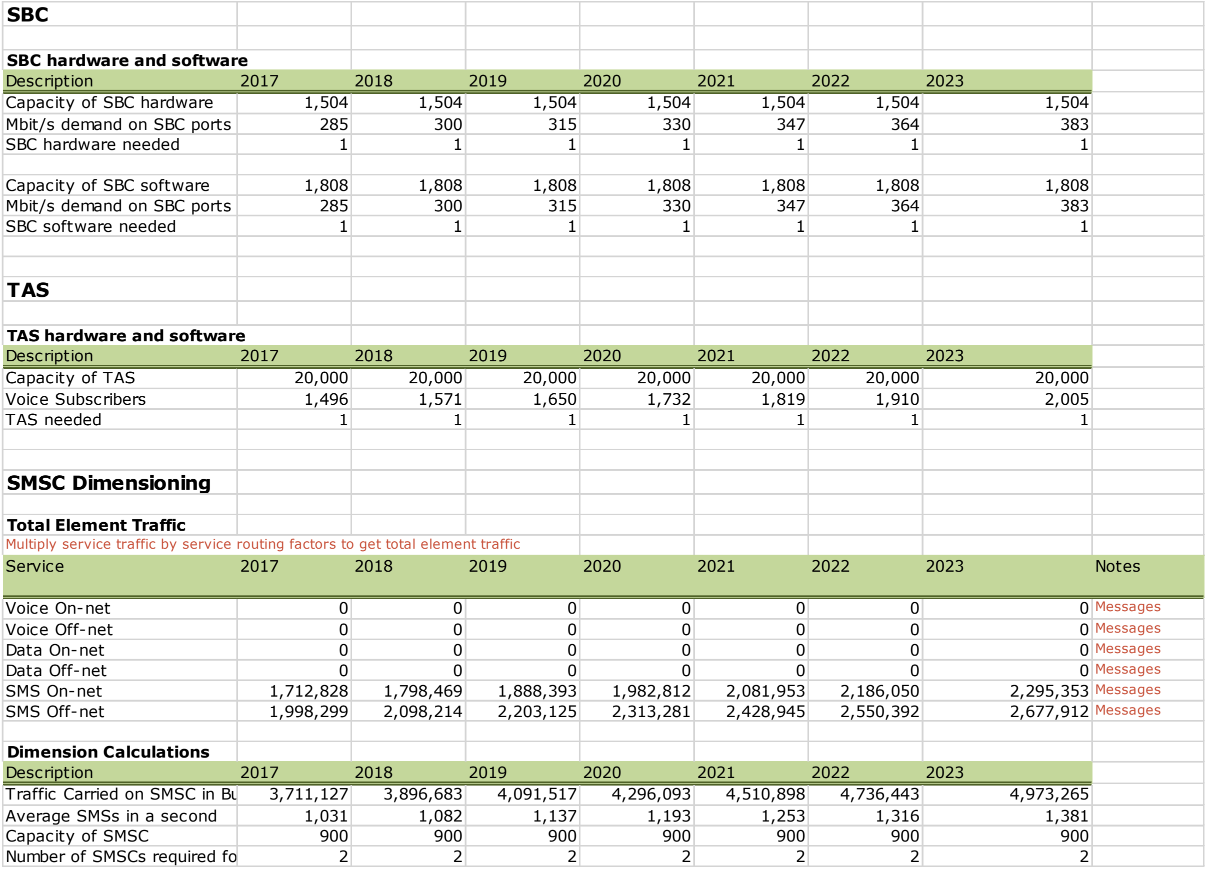
Description	2017	2018	2019	2020	2021	2022	2023	Notes
Voice On-net	14,274	14,987	15,737	16,523	17,350	18,217	19,128	BHE
Voice Off-net	16,652	17,485	18,359	19,277	20,241	21,253	22,316	BHE
Data On-net	0	0	0	0	0	0	0	MB
Data Off-net	0	0	0	0	0	0	0	MB
SMS On-net	0	0	0	0	0	0	0	Messages
SMS Off-net	0	0	0	0	0	0	0	Messages

Call Attempts (BHCA)

Description	2017	2018	2019	2020	2021	2022	2023
Voice On-net (BHCA)	17,321	18,187	19,096	20,051	21,053	22,106	23,211
Voice Off-net (BHCA)	23,509	24,685	25,919	27,215	28,576	30,005	31,505
Data On-net (BHCA)	0	0	0	0	0	0	0
Data Off-net (BHCA)	0	0	0	0	0	0	0
SMS On-net (BHCA)	0	0	0	0	0	0	0
SMS Off-net (BHCA)	0	0	0	0	0	0	0
Total Call Attempts	40,830	42,872	45,015	47,266	49,629	52,111	54,716

Call server hardware

Description	2017	2018	2019	2020	2021	2022	2023
Capacity of call server (BHCA	1,680,000	1,680,000	1,680,000	1,680,000	1,680,000	1,680,000	1,680,000
Call servers needed	1	1	1	1	1	1	1



SBC

SBC hardware and software

Description	2017	2018	2019	2020	2021	2022	2023
Capacity of SBC hardware	1,504	1,504	1,504	1,504	1,504	1,504	1,504
Mbit/s demand on SBC ports	285	300	315	330	347	364	383
SBC hardware needed	1	1	1	1	1	1	1
Capacity of SBC software	1,808	1,808	1,808	1,808	1,808	1,808	1,808
Mbit/s demand on SBC ports	285	300	315	330	347	364	383
SBC software needed	1	1	1	1	1	1	1

TAS

TAS hardware and software

Description	2017	2018	2019	2020	2021	2022	2023
Capacity of TAS	20,000	20,000	20,000	20,000	20,000	20,000	20,000
Voice Subscribers	1,496	1,571	1,650	1,732	1,819	1,910	2,005
TAS needed	1	1	1	1	1	1	1

SMSC Dimensioning

Total Element Traffic

Multiply service traffic by service routing factors to get total element traffic

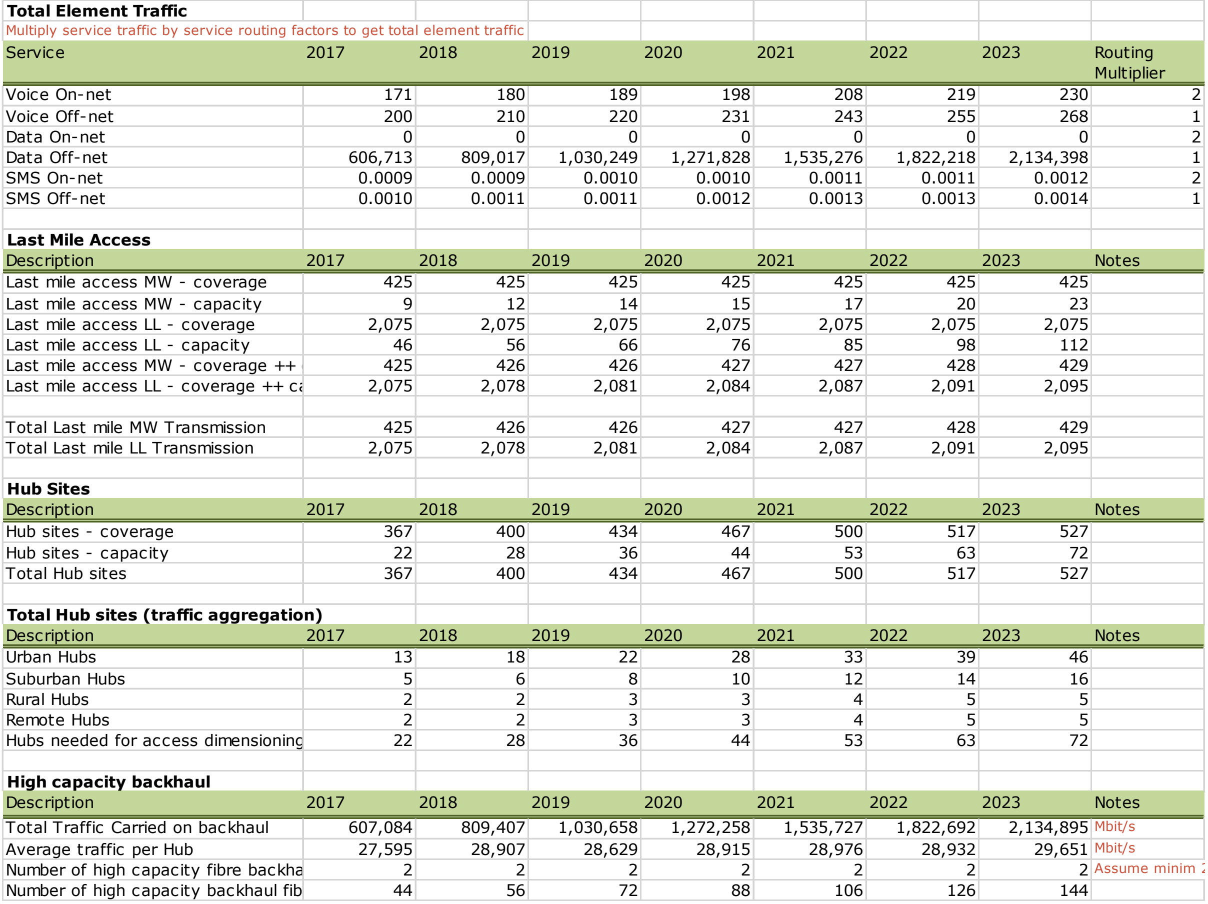
Service	2017	2018	2019	2020	2021	2022	2023	Notes
Voice On-net	0	0	0	0	0	0	0	Messages
Voice Off-net	0	0	0	0	0	0	0	Messages
Data On-net	0	0	0	0	0	0	0	Messages
Data Off-net	0	0	0	0	0	0	0	Messages
SMS On-net	1,712,828	1,798,469	1,888,393	1,982,812	2,081,953	2,186,050	2,295,353	Messages
SMS Off-net	1,998,299	2,098,214	2,203,125	2,313,281	2,428,945	2,550,392	2,677,912	Messages

Dimension Calculations

Description	2017	2018	2019	2020	2021	2022	2023
Traffic Carried on SMSC in Bu	3,711,127	3,896,683	4,091,517	4,296,093	4,510,898	4,736,443	4,973,265
Average SMSs in a second	1,031	1,082	1,137	1,193	1,253	1,316	1,381
Capacity of SMSC	900	900	900	900	900	900	900
Number of SMSCs required fo	2	2	2	2	2	2	2

10.3.8.5 Transmission dimensioning – equipment required

This section describes the minimum Transmission network required to serve the demand for voice and data traffic. This is adjusted for the Transmission components as described in Chapter 3 (section 3.5.3).



Total Element Traffic

Multiply service traffic by service routing factors to get total element traffic

Service	2017	2018	2019	2020	2021	2022	2023	Routing Multiplier
Voice On-net	171	180	189	198	208	219	230	2
Voice Off-net	200	210	220	231	243	255	268	1
Data On-net	0	0	0	0	0	0	0	2
Data Off-net	606,713	809,017	1,030,249	1,271,828	1,535,276	1,822,218	2,134,398	1
SMS On-net	0.0009	0.0009	0.0010	0.0010	0.0011	0.0011	0.0012	2
SMS Off-net	0.0010	0.0011	0.0011	0.0012	0.0013	0.0013	0.0014	1

Last Mile Access

Description	2017	2018	2019	2020	2021	2022	2023	Notes
Last mile access MW - coverage	425	425	425	425	425	425	425	
Last mile access MW - capacity	9	12	14	15	17	20	23	
Last mile access LL - coverage	2,075	2,075	2,075	2,075	2,075	2,075	2,075	
Last mile access LL - capacity	46	56	66	76	85	98	112	
Last mile access MW - coverage ++	425	426	426	427	427	428	429	
Last mile access LL - coverage ++ ca	2,075	2,078	2,081	2,084	2,087	2,091	2,095	
Total Last mile MW Transmission	425	426	426	427	427	428	429	
Total Last mile LL Transmission	2,075	2,078	2,081	2,084	2,087	2,091	2,095	

Hub Sites

Description	2017	2018	2019	2020	2021	2022	2023	Notes
Hub sites - coverage	367	400	434	467	500	517	527	
Hub sites - capacity	22	28	36	44	53	63	72	
Total Hub sites	367	400	434	467	500	517	527	

Total Hub sites (traffic aggregation)

Description	2017	2018	2019	2020	2021	2022	2023	Notes
Urban Hubs	13	18	22	28	33	39	46	
Suburban Hubs	5	6	8	10	12	14	16	
Rural Hubs	2	2	3	3	4	5	5	
Remote Hubs	2	2	3	3	4	5	5	
Hubs needed for access dimensioning	22	28	36	44	53	63	72	

High capacity backhaul

Description	2017	2018	2019	2020	2021	2022	2023	Notes
Total Traffic Carried on backhaul	607,084	809,407	1,030,658	1,272,258	1,535,727	1,822,692	2,134,895	Mbit/s
Average traffic per Hub	27,595	28,907	28,629	28,915	28,976	28,932	29,651	Mbit/s
Number of high capacity fibre backha	2	2	2	2	2	2	2	Assume minim
Number of high capacity backhaul fib	44	56	72	88	106	126	144	

10.3.8.6 Cost analysis

This section takes the equipment and services specified in the Coverage, Capacity, Core and Transmission sections to meet the demand for voice and data traffic. Then multiples the minimum equipment requirements against the capital costs of this equipment. Costs are adjusted by replacement and depreciation costs. The operational and other fixed costs are added to the sub-total to give the total LTE network cost.

Capital Costs

Resource	2017	2018	2019	2020	2021	2022	2023	Notes
Sites								
eNodeB - Macrocell	6,328,976	24,050,109	28,559,504	27,131,529	20,619,962	4,897,241	-	
eNodeB - Microcell	64,103	509,448	536,509	504,986	425,866	322,154	296,888	
eNodeB - Picocell	2,979,975	11,323,903	13,447,135	12,774,778	9,708,832	2,305,848	-	
Greenfields Site	12,923,539	49,382,398	58,571,311	55,637,922	42,328,019	10,279,809	304,805	
Rooftop Site	1,345,527	5,205,166	6,157,402	5,847,903	4,458,993	1,135,628	102,921	
In-building Site	777,571	2,966,291	3,519,504	3,343,325	2,542,750	613,480	12,865	
Shared Site								
Last mile access M	1,062,279	4,066,792	4,821,557	4,579,947	3,485,528	852,861	33,647	
Last mile access LL	311,185	1,254,033	1,565,022	1,564,840	1,253,587	322,880	13,409	
Hub sites	128,450,000	10,972,500	10,739,750	9,902,681	9,407,547	4,603,997	2,572,822	
High capacity back	36,700,000	3,135,000	3,068,500	2,829,338	2,687,871	1,315,428	735,092	
MME	28,500,000	9,975,000	9,476,250	9,002,438	9,774,075	10,446,043	11,026,378	
HSS	3,000,000	-	-	-	-	1,160,671	-	
SGW	28,500,000	9,975,000	9,476,250	9,002,438	9,774,075	10,446,043	11,026,378	
PGW	35,150,000	10,830,000	11,145,875	11,403,088	12,380,495	12,496,562	13,268,409	
DTM	7,800,000	2,280,000	2,436,750	2,829,338	2,443,519	2,785,611	2,866,858	
Call servers	160,000	-	-	-	-	-	-	
SBC hardware	160,000	-	-	-	-	-	-	
SBC software	160,000	-	-	-	-	-	-	
TAS	160,000	-	-	-	-	-	-	
SMSC	320,000	-	-	-	-	-	-	
Total Capital Costs	294,853,155	145,925,640	163,521,320	156,354,550	131,291,119	63,984,255	42,260,472	

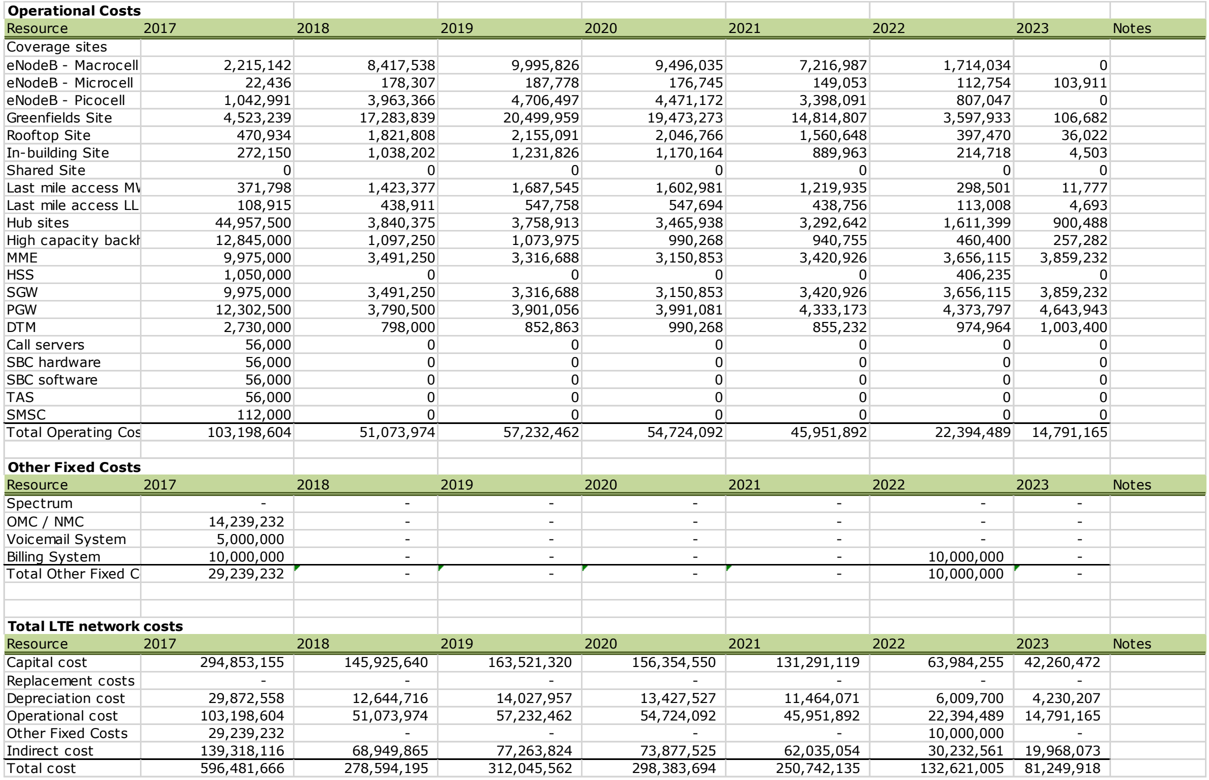
Replacement Costs

Note that no replacement costs are shown 2017-2023 as the first asset that needs replacing is in 2026 (9 year asset life)

Resource	2017	2018	2019	2020	2021	2022	2023	Asset Life
Sites								
eNodeB - Macrocell								9
eNodeB - Microcell								9
eNodeB - Picocell								9
Greenfields Site								18
Rooftop Site								18
In-building Site								18
Shared Site								18
Last mile access MW								8
Last mile access LL								8
Hub sites								10
High capacity backhaul								8
MME								10
HSS								10
SGW								10
PGW								10
DTM								10
Call servers								10
SBC hardware								10
SBC software								10
TAS								10
SMSC								10
Total Replacement	-	-	-	-	-	-	-	

Depreciation Costs

Resource	2017	2018	2019	2020	2021	2022	2023	Asset Life
eNodeB - Macrocell	703,220	2,672,234	3,173,278	3,014,614	2,291,107	544,138	0	9
eNodeB - Microcell	7,123	56,605	59,612	56,110	47,318	35,795	32,988	9
eNodeB - Picocell	331,108	1,258,211	1,494,126	1,419,420	1,078,759	256,205	0	9
Greenfields Site	717,974	2,743,467	3,253,962	3,090,996	2,351,557	571,101	16,934	18
Rooftop Site	74,751	289,176	342,078	324,884	247,722	63,090	5,718	18
In-building Site	43,198	164,794	195,528	185,740	141,264	34,082	715	18
Shared Site	0	0	0	0	0	0	0	18
Last mile access M	132,785	508,349	602,695	572,493	435,691	106,608	4,206	8
Last mile access LL	38,898	156,754	195,628	195,605	156,698	40,360	1,676	8
Hub sites	12,845,000	1,097,250	1,073,975	990,268	940,755	460,400	257,282	10
High capacity back	4,587,500	391,875	383,563	353,667	335,984	164,428	91,886	8
MME	2,850,000	997,500	947,625	900,244	977,408	1,044,604	1,102,638	10
HSS	300,000	0	0	0	0	116,067	0	10
SGW	2,850,000	997,500	947,625	900,244	977,408	1,044,604	1,102,638	10
PGW	3,515,000	1,083,000	1,114,588	1,140,309	1,238,050	1,249,656	1,326,841	10
DTM	780,000	228,000	243,675	282,934	244,352	278,561	286,686	10
Call servers	16,000	0	0	0	0	0	0	10
SBC hardware	16,000	0	0	0	0	0	0	10
SBC software	16,000	0	0	0	0	0	0	10
TAS	16,000	0	0	0	0	0	0	10
SMSC	32,000	0	0	0	0	0	0	10
Total Capital Costs	29,872,558	12,644,716	14,027,957	13,427,527	11,464,071	6,009,700	4,230,207	



Operational Costs

Resource	2017	2018	2019	2020	2021	2022	2023	Notes
Coverage sites								
eNodeB - Macrocell	2,215,142	8,417,538	9,995,826	9,496,035	7,216,987	1,714,034	0	
eNodeB - Microcell	22,436	178,307	187,778	176,745	149,053	112,754	103,911	
eNodeB - Picocell	1,042,991	3,963,366	4,706,497	4,471,172	3,398,091	807,047	0	
Greenfields Site	4,523,239	17,283,839	20,499,959	19,473,273	14,814,807	3,597,933	106,682	
Rooftop Site	470,934	1,821,808	2,155,091	2,046,766	1,560,648	397,470	36,022	
In-building Site	272,150	1,038,202	1,231,826	1,170,164	889,963	214,718	4,503	
Shared Site	0	0	0	0	0	0	0	
Last mile access MV	371,798	1,423,377	1,687,545	1,602,981	1,219,935	298,501	11,777	
Last mile access LL	108,915	438,911	547,758	547,694	438,756	113,008	4,693	
Hub sites	44,957,500	3,840,375	3,758,913	3,465,938	3,292,642	1,611,399	900,488	
High capacity backh	12,845,000	1,097,250	1,073,975	990,268	940,755	460,400	257,282	
MME	9,975,000	3,491,250	3,316,688	3,150,853	3,420,926	3,656,115	3,859,232	
HSS	1,050,000	0	0	0	0	406,235	0	
SGW	9,975,000	3,491,250	3,316,688	3,150,853	3,420,926	3,656,115	3,859,232	
PGW	12,302,500	3,790,500	3,901,056	3,991,081	4,333,173	4,373,797	4,643,943	
DTM	2,730,000	798,000	852,863	990,268	855,232	974,964	1,003,400	
Call servers	56,000	0	0	0	0	0	0	
SBC hardware	56,000	0	0	0	0	0	0	
SBC software	56,000	0	0	0	0	0	0	
TAS	56,000	0	0	0	0	0	0	
SMSC	112,000	0	0	0	0	0	0	
Total Operating Cos	103,198,604	51,073,974	57,232,462	54,724,092	45,951,892	22,394,489	14,791,165	

Other Fixed Costs

Resource	2017	2018	2019	2020	2021	2022	2023	Notes
Spectrum	-	-	-	-	-	-	-	
OMC / NMC	14,239,232	-	-	-	-	-	-	
Voicemail System	5,000,000	-	-	-	-	-	-	
Billing System	10,000,000	-	-	-	-	10,000,000	-	
Total Other Fixed C	29,239,232	-	-	-	-	10,000,000	-	

Total LTE network costs

Resource	2017	2018	2019	2020	2021	2022	2023	Notes
Capital cost	294,853,155	145,925,640	163,521,320	156,354,550	131,291,119	63,984,255	42,260,472	
Replacement costs	-	-	-	-	-	-	-	
Depreciation cost	29,872,558	12,644,716	14,027,957	13,427,527	11,464,071	6,009,700	4,230,207	
Operational cost	103,198,604	51,073,974	57,232,462	54,724,092	45,951,892	22,394,489	14,791,165	
Other Fixed Costs	29,239,232	-	-	-	-	10,000,000	-	
Indirect cost	139,318,116	68,949,865	77,263,824	73,877,525	62,035,054	30,232,561	19,968,073	
Total cost	596,481,666	278,594,195	312,045,562	298,383,694	250,742,135	132,621,005	81,249,918	

The total LTE network costs can then be used by the different valuation techniques as described in Chapter 8 to calculate the value of spectrum.

Chapter 11. References

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