The Economic Significance of Licence-Exempt Spectrum to the Future of the Internet

Richard Thanki

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About the Author

Richard Thanki was the lead author of the 2009 Perspective Associates study 'The economic value generated by current and future allocations of unlicensed spectrum'

He is currently the economic advisor at Real Wireless and is completing a PhD at the Institute for Complex Systems Simulation at the University of Southampton.

Previously he was a senior consultant at Perspective Associates and acted as the deputy for Kip Meek, the UK's government-appointed Independent Spectrum Broker. Richard was a Senior Associate economist at Ofcom, the UK telecommunications regulator, where he specialised in economic modelling, spectrum valuation and competition issues across the sector.

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richardthanki@gmail.com

Contents

1 Introduction and Overview 6

1.1 Connecting all the people 7

1.2 Connecting all the things 10

1.3 Building resilient and flexible networks 12

1.4 Implications for policy 13

2 A brief introduction to the radio spectrum and its management 16

2.1 The nature of radio communications 16

2.2 The methods of spectrum management 18

3 Connecting all the people 23

3.1 The reach and economic significance of the internet 23

3.2 Costly existing delivery methods and the underserved billions 26

3.3 Licence-exempt technologies decrease the costs of delivering broadband and increase the quality of the product 31

3.4 Future changes concerning licence-exempt technologies 44

3.5 The evolving model of broadband delivery 47

4 Connecting everything else 49

4.1 What is the internet of things? 49

4.2 The applications and economic potential of the internet of things 56

4.3 The role being played by licence-exempt spectrum 59

4.4 The role that could be played by new licence-exempt technologies 64

4.5 The economic repercussions of spectrum unavailability – the example of Europe's smart grid 65

5 Creating robust and adaptable networks – the benefits of user configurable wireless spectrum 74

5.1 The importance of robustness and flexibility in our global communications systems 74

5.2 The robustness of individual licence-exempt links 75

5.3 The robustness and adaptability of networks built with licence exempt links 80

5.4 The role of upcoming licence-exempt technologies 87

6 Policy implications and directions for further work 89

6.1 The overwhelming case for licence-exempt access to TV white spaces 89

6.2 Finding an efficient balance of new licensed and licence-exempt allocations to meet the world's growing demand for data 90

6.3 Building economic theory around a better understanding of 'spectrum' 91

References 95

Annex 1 – Broadband affordability data by continent and country 101

Annex 2 – Value of Wi-Fi to fixed broadband by country 107

Annex 3 – Value of Wi-Fi to mobile operators 112

Table of figures

Figure 1 - Fixed broadband unaffordability by country 7
Figure 2 - Traffic carried by different channels for different types of device (PB per month) 8
Figure 3 – The traffic generated by UK smartphones on an average weekday split between Wi-Fi and 3G data 8
Figure 4 – The allocation of spectrum in the USA 17
Figure 5 – The differing propagation of radio signals in high and low frequency spectrum 18
Figure 6 – The utilisation of spectrum over a 24-hour period in Brno, Czech Republic 19
Figure 7 – The ISM bands available in ITU Region 2 21
Figure 8 – Take up of key communications technologies since 1900 24
Figure 9 – internet usage frequency in the developed and developing world 26
Figure 10 – The proportion of people who would find fixed broadband unaffordable by country 28
Figure 11 - Traffic carried by different channels for different types of device (PB per month) 34
Figure 12 – Comparing the capacity of the Wi-Fi and cellular networks in selected countries 35
Figure 13 – Economic value generated by Wi-Fi through fixed broadband value enhancement 36
Figure 14 – Balance of cellular data traffic and Wi-Fi for selected countries 37
Figure 15 - Total weekday smartphone traffic split by means of transport and time of day. 37
Figure 16 - Extra cell sites required in the absence of Wi-Fi by continent 38
Figure 17 – Cell sites required globally in the presence and in the absence of Wi-Fi 39
Figure 18 – The TV white spaces, exiting licence-exempt bands and global mobile allocations 44
Figure 19 – The increase in Wi-Fi speed over time 46
Figure 20 – Sales of internet capable devices since 1990 50
Figure 21 - Sales of microcontrollers over time 52
Figure 22- Devices containing microcontrollers 53
Figure 23 - Machine terminals on the internet of things 54
Figure 24 – Comparison of projections for the size and scale of possibilities of the internet of things 57
Figure 25 – An illustration of human and machine interactions over the internet 58
Figure 26 – The varied attributes of licence-exempt technologies suitable for machine to machine connections 61
Figure 27 – The transition to the smart grid 66
Figure 28 – The links between the components and benefits of the Smart Grid 68
Figure 29 – The balance of technologies used in smart meter shipments in Q1 2011 69
Figure 30 – The organisation of a mesh network for smart metering 70
Figure 31 - Advantages and disadvantages of PLC and cellular systems in smart metering application 71
Figure 32 - The economic costs from delaying the benefits of the smart grid 72
Figure 33 – The years of introduction of various radio technologies into Wi-Fi and cellular 78
Figure 34 – Comparison of a densely interconnected and a tree-like road system 83
Figure 35 – A fixed communications network possessing a tree-like structure and therefore many points for failure 84
Figure 36 – The diversity and robustness enhancing effects of licence-exempt spectrum 85
Figure 37 - The fallacy of spectrum as a finite resource 92

1 Introduction and Overview

Over the last decade the internet has become the world's pre-eminent communications system. It delivers enhanced versions of services that once necessitated dedicated networks and infrastructures, such as news, telephony and television. More significantly it has enabled entirely new applications, from the world wide web to platforms for social networking, ecommerce and real-time collaboration. The economic and social impact of the internet has already been tremendous.

The next decade offers consumers the prospect of even greater benefits – if certain connectivity challenges can be overcome. This paper focuses on three of these challenges: (1) Delivering universal and affordable broadband access; (2) Enabling the machine-to-machine networks of the future; and (3) Ensuring that communications networks are resilient, particularly in the face of natural and manmade disasters. This paper argues that the unique technical and commercial innovation found in licence-exempt (or unlicensed) spectrum has the potential to play a vital, if not predominant, role in meeting each of these connectivity challenges. More to the point, these challenges will not be met without an increased, globally harmonized supply of licence-exempt spectrum. Any approach that relies principally on licensed spectrum to address these challenges will needlessly impose great additional costs on society and on consumers.

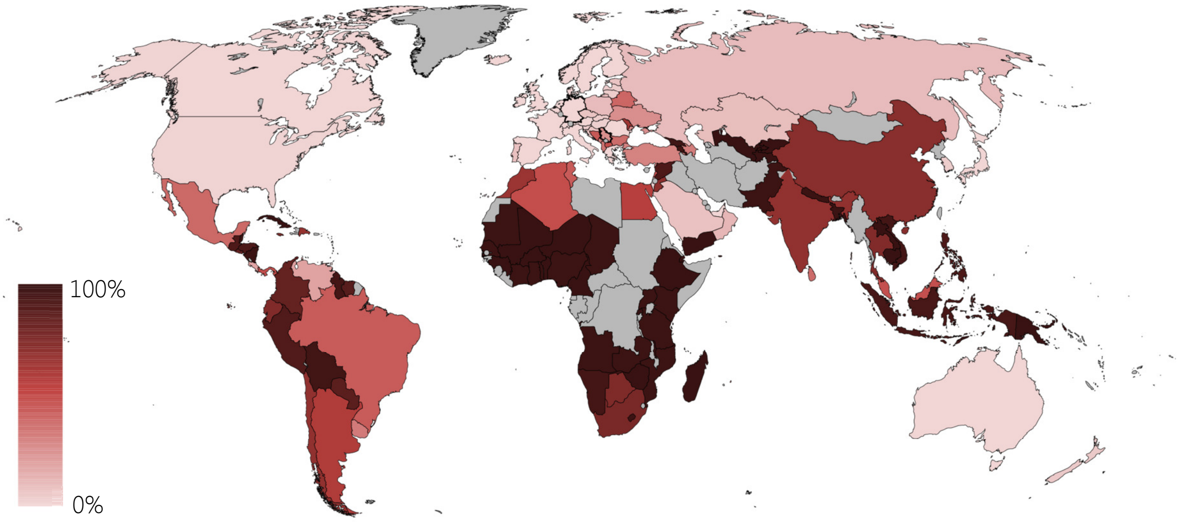
To ensure that these substantial benefits can be realised, policy makers and regulators have an important role to play.

- Many countries are in the process of enabling licence-exempt use of the unused gaps in the terrestrial television spectrum bands below 1GHz, the TV white spaces. The unique characteristics of this spectrum have the potential to improve radically the benefits of licence-exempt technologies. As explained below, TV white spaces could be used to connect many of the billions of people currently without affordable access to the internet, enable a global market in machine-to-machine communications, and increase the resilience of networks in the face of natural and manmade disasters.
- Cellular operators are calling for ever more exclusive-use spectrum, in some cases up to 1,000MHz of additional bandwidth. Fulfilling these requests will lead to a substantial concentration in the ownership of the most valuable spectrum, risking both decreased competition and innovation. As part of a balanced approach to meeting the growing demands for data, policy makers should also enable more dynamic spectrum sharing and licence-exempt access across the spectrum. As shown in this report, licence-exemption promotes methods of broadband delivery that are overwhelmingly more efficient in their use of spectrum than their licensed counterparts. In addition, the licence-exempt ecosystem has been notable for creating contestable and competitive markets, characterised by disruptive innovation.

1.1 Connecting all the people

For over 3.9 billion people, around 61% of the world's population, the price of fixed broadband is unaffordable. By continent this ranges from 8% of the population of Europe, to 90% of the population of Africa. Likewise, basic mobile broadband is unaffordable for over 2.6 billion of the world's population as shown below in Figure 1.

Figure 1 - Fixed broadband unaffordability by country



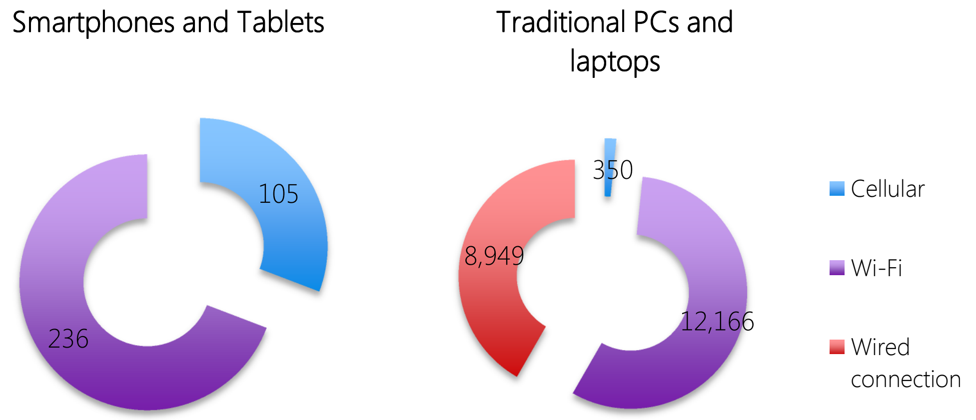
In addition, the coverage of the major broadband networks is lacking. There are fewer than 1.2 billion telephone lines in the world, and a large proportion will not be capable of delivering broadband. Mobile broadband covers only around 45% of the world's population.

At the root of the world's broadband availability and affordability gap are the high costs and high barriers to entry characteristic of the world's fixed and mobile telecoms industries. However, in contrast technologies that use licence-exempt spectrum are cost-effective and can be deployed by any person or entity. These technologies are already being deployed by established operators, new entrants and individuals to increase the quality, decrease the cost and extend the reach of broadband networks.

1.1.1 The role being played by licence-exempt spectrum

Already Wi-Fi is carrying the majority of the world's data traffic, as shown in Figure 2 below.

Figure 2 - Traffic carried by different channels for different types of device (PB per month)[1]



In the case of smartphones and tablets, Wi-Fi carries 69% of total traffic generated. For traditional PCs and laptops, Wi-Fi is responsible for carrying 57% of total traffic, greater than the share of Ethernet connections and 3G data combined. As explained more in Chapter 3, the aggregate capacity of the world's Wi-Fi networks dwarfs the total capacity of the world's 3G and 4G networks.

Wi-Fi substantially enhances the value of fixed broadband, increasing take-up and allowing connections to be effectively shared between multiple individuals. 439 million households – 25% of all households worldwide – have home Wi-Fi networks. Each household may derive a yearly benefit from Wi-Fi of $118 to $225 resulting in a total economic gain for all households of around $52 to $99 billion annually. Without Wi-Fi the value of fixed broadband would be lower and would result in the disconnection of perhaps 50 to 114 million fixed broadband connections around the world.

In addition, Wi-Fi substantially decreases the costs of cellular data networks. Comprehensive recent research finds that Wi-Fi is responsible for carrying the large majority of data used by smartphone users in most countries surveyed. For example, Figure 3 shows the split of smartphone traffic between Wi-Fi and 3G for an average weekday in the UK.

Figure 3 – The traffic generated by UK smartphones on an average weekday split between Wi-Fi and 3G data

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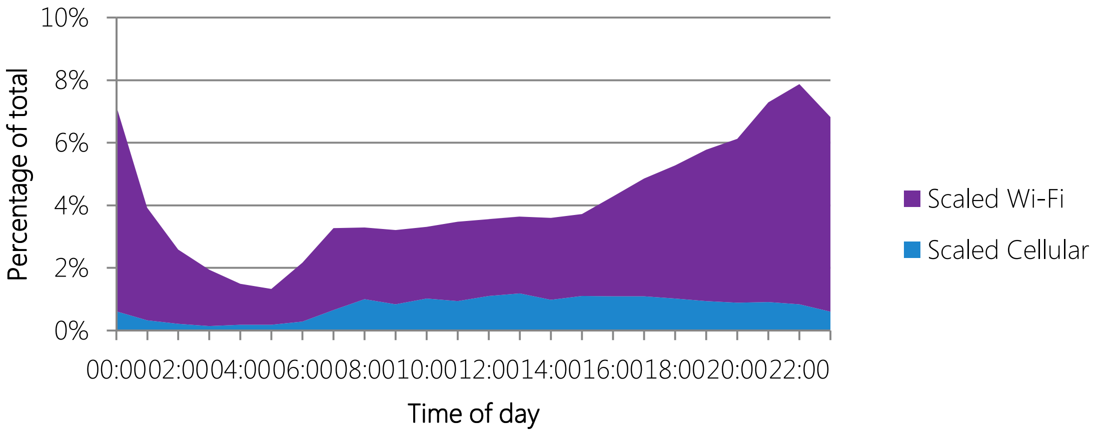
[1] These numbers have been derived from data from the Cisco VNI, Strategy Analytics and the ITU. They are likely to be a substantial underestimate of the true role of Wi-Fi. For smartphones and tablets we have assumed no Wi-Fi offload at all for Africa, the Middle East and Latin America (as there is a lack of dependable data). For PCs and laptops we have assumed that all business data traffic is carried by wired connections.



In the absence of Wi-Fi mobile operators would be forced to invest large sums in their networks or strictly curtail their users' usage. Worldwide, approximately 150,000 to 450,000 new radio base stations would be needed to cope with world smartphone traffic in the absence of Wi-Fi. Wi-Fi networks are saving mobile operators from needing to make an investment of $30 - $93 billion this year alone.

A 40% yearly growth of data traffic to 2016 will require mobile operators to deploy an additional 115,000 extra sites, an increase of around 4% from today's numbers. However, in the absence of Wi-Fi an additional 1.4 million macrocell sites, or 43% of the current total would be required. The difference in costs between the two scenarios is extremely large, $250 billion (NPV) – comparable to around one third of the total annual revenue of the telecommunications industry. Even the least expensive solutions involving femtocells or picocells would require an investment of $45 - $60 billion.

It is clear that in the absence of Wi-Fi smartphones and tablets could not be used to their full potential.

In addition to the obvious importance of Wi-Fi, tens of thousands of businesses and organisations are using a range of licence-exempt spectrum technologies to extend broadband to many millions of people that are not covered by fixed and mobile networks, from numerous small projects in the favelas of Rio de Janeiro to large scale networks that span rural Catalonia or provide access to 150,000 people in rural Nigeria.

1.1.2 The future potential of licence-exempt spectrum

The future of the cellular industry lies in moving away from an architecture consisting mainly of large neighbourhood sized base stations to one of smaller cells. Each of the small cell solutions proposed by the major manufacturers in 2012 integrates Wi-Fi as a core data delivery method. Wi-Fi is also the leading contender in providing backhaul from these small cells. Furthermore, a number of efforts are underway to automate user connections to Wi-Fi networks. These schemes are likely to lead to a further surge in the usage of Wi-Fi as a primary delivery method by mobile operators.

Existing licence-exempt spectrum suitable for broadband delivery is located at higher frequencies which have poor propagation characteristics; they are blocked by obstructions such as walls and foliage. This limits the ability of licence-exempt technologies to provide broadband in many urban and rural use cases. The TV white space spectrum has the potential to be the world’s first globally available, broadband-capable licence-exempt band in the optimal sub-1GHz spectrum. In unconnected urban and rural areas, entrepreneurs could use inexpensive, but reliable, Wi-Fi and other types of radio equipment capable of operating on TV band white spaces spectrum to deliver cost-effective broadband services.

1.2 Connecting all the things

To date, activity on the internet has primarily consisted of communication between people. However, the internet is also increasingly used for communication between a wide variety of sensors and control mechanisms supporting a variety of applications, including delivery trucks reporting their location, wireless sensor networks in forests primed to detect fires and smart meters reporting on a household’s usage and generation of electricity. These new uses are collectively termed ‘the internet of things’.

Already there are more machine users than human users connected to the internet and in the coming years this disparity is likely to grow as a greater range of devices are embedded with intelligence and connectivity.

The economic benefits from the internet of things will be as varied as the uses to which it is put. Many uses will generate only incremental economic value, such as connected interactive children’s toys, or an irrigation controller monitoring and watering an olive tree. The potential value from some uses may be extraordinarily high, such as smart pacemakers able to monitor abnormalities and bridge integrity systems able to instantaneously detect structural problems and raise an alarm. The combined value of these applications may be revolutionary.

For the reasons provided in Chapter 4, the number of intelligent connected devices is likely to exceed 100 billion by 2020[2]. Metcalfe's law proposes that the value of a network is proportional not to the number of users but to the number of possible connections. The growth of the internet from 4 billion human and intelligent machine users today to potentially 100 billion by 2020 represents a 25-fold increase in the number of users but 625-fold increase in the number of possible connections. Therefore, even if each of the new machine interconnections on the internet could generate only one one-hundredth of the economic value of today's human connections their combined economic contribution by 2020 could reach $1.4 to $2.2 trillion per year – around five times that of the internet today.

1.2.1 The role being played by licence-exempt spectrum

Almost all of the connections to the IOT will be made through licence-exempt spectrum – significantly increasing demand across the licence-exempt spectrum bands. It is forecast that there may be 1 to 2.5 billion cellular machine connections operating on licensed spectrum by 2020. Whilst that is a large number in its own right, the remainder, at least 95% to 97.5% of all connections, will use licence-exempt technologies. It is not difficult to see why this is the case. Licence-exempt technologies are cost-effective, power-efficient and provide users a range of technologies and fine control over the networks and infrastructure they deploy, whether it is a hospital in-patient cardiac monitoring system or a multi-million node smart metering mesh network.

If licence-exempt spectrum were not available it is reasonable to expect the internet of things would not reach the scale that is widely expected. Simply assuming that the least-valuable 50% of devices would not be connected, around $560 to $870 billion a year of economic value could be foregone in 2020. This loss is equivalent to around one-third of the total value that might be generated by the internet of things.

1.2.2 The potential importance of licence-exempt TV white space spectrum

The importance of the licence-exempt TV white spaces in realising the full benefits of the internet of things cannot be understated. The propagation characteristics of sub-1GHz spectrum, such as the TV white spaces, provide excellent coverage at low power requirements; ideal for a number of machine uses of the internet. A wide variety of licence-exempt spectrum will be used to extend and enhance possibilities for machine-to-machine communications, but none of these possess the economic potential of the TV white spaces.

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[2] According to IBM, the number of simpler connected devices, such as shipping containers and smartcards may well number over 1 trillion.

The scale of the costs for not having available sub-1GHz licence-exempt spectrum can be seen in Europe's experience in deploying smart electricity meters. In the United States operators have had access to a usable licence-exempt band of spectrum at 900MHz, and the vast majority of meters deployed have used mesh architectures based in this band. In Europe this spectrum has not been available and European operators have had to resort to less capable or more costly technologies such as power-line communications and cellular systems. Many operators in Europe have expressed dissatisfaction with both of these substitutes. For example, even if Europe's lack of suitable licence-exempt spectrum delayed the full benefits of the smart grid by only 6 months the cost to its economy could reach a cumulative $37 – 56 billion by 2020.

1.3 Building resilient and flexible networks

In the future we will face the twin challenges of ensuring that our communications networks remain reliable, as they host increasingly important applications, as well as adapting them to incorporate new technologies and accommodate new demands. Devices and networks utilising licence-exempt spectrum are significantly contributing to the overall reliability and adaptability of communications networks. Indeed, communications networks and the consumers who rely upon them would be significantly more vulnerable in the absence of licence-exempt spectrum access.

The wide deployment of networks consisting of technologies using licence-exempt spectrum has served to create a denser more diverse broadband data architecture. For example, many new networks delivering Wi-Fi broadband have been launched, and any entity is free to launch such a service. In addition many specialised networks are being built, such as home networks for entertainment or automation, businesses networks for control and monitoring purposes, and city-wide networks built by local governments. Many of the functions of each of these licence-exempt networks would be immune to the failure of our traditional wide area networks using fixed infrastructure or licensed spectrum.

The lack of barriers faced when deploying licence-exempt technologies encourages the creation of bottom-up networks, greatly aiding the adaptability of our communications networks. As new challenges requiring data connectivity and networking emerge it is likely that hundreds or thousands of entities will attempt to develop solutions using licence-exempt technologies. This dynamism stands in contrast to fixed and licensed cellular industries where only a handful of firms may be in a position to provide a solution.

In emergency situations, such as the aftermath of a natural disaster or violent attack, telecommunications networks often fail. Specialised personnel or replacement equipment are often required to restore connectivity and these may not be forthcoming. The deployment of a licence-exempt network, however, does not require any specialised equipment. Off-the-shelf components or repurposed home and office Wi-Fi access points can be stitched together by any entity to create broadband networks. This approach has been used in a number of instances where telecommunications services have been lost, from the aftermath of the Haiti earthquake to areas affected by the Indian Ocean tsunami.

The introduction of technology using the TV white spaces will also extend the possibilities of licence-exempt operation, permitting broadband links that span hundreds of metres and lower speed machine-to-machine links that span many kilometres. However, they can also be used at shorter distances to create highly reliable connections that can penetrate obstacles (intended or otherwise). White spaces will also provide a substantial boost to adaptability by enabling the creation of near ubiquitous networks very quickly in the case of disaster. It is not too surprising then that major white space technology trials are investigating disaster recovery capabilities.

1.4 Implications for policy

Already today technologies using licence-exempt spectrum are delivering the majority of internet traffic to end users, connecting the vast majority of end points to the internet of things and creating diverse networks that boost the resilience and responsiveness of our overall communications infrastructure. As is demonstrated in this report, these licence-exempt technologies are likely to play an increasingly important role in each of these areas in the years to come.

The overall success and broad applicability of technologies using licence-exempt spectrum presents a number of opportunities for policy-makers as well as challenges for overall telecommunications policy.

1.4.1 Taking advantage of the unique opportunity afforded by the TV white spaces

An important thread running through the findings of this report has been the identification of the substantial benefits that a globally harmonised licence-exempt band of sub-1GHz spectrum has the potential to provide. It will be a powerful tool for connecting the underserved billions in the world's rural areas, for establishing layers of high quality connectivity in cities, for building a global platform for machine-to-machine communications and the ideal spectrum for use in establishing emergency broadband networks in dire disaster recovery situations.

The United States has enabled the use of the white spaces, a number of nations are pressing ahead with authorising the use of this band and many more are running trials.

1.4.2 Finding the right balance between licences and licence-exempt spectrum to serve the ever-growing demands for data

As the demand for wireless data connectivity continues to rise, many cellular operators are predicting a shortfall in available radio spectrum, a "spectrum crunch". However, the capacity of a network is directly proportional to two variables: the quantity of spectrum available and the number of sites deployed. It is therefore equally valid to say that mobile operators are suffering an "infrastructure crunch" as they attempt to serve a growing volume of traffic using networks originally designed to provide outdoor voice services and not ubiquitous, largely indoor, data.

However, the market reality is increasingly a move towards small cells and dense networks. Indeed, it is notable that a large majority of smartphone traffic is currently carried using Wi-Fi, the exemplary small-cell network. As explained in this report, such a small-cell architecture is remarkably spectrally efficient; the aggregate spectral efficiency of the 2.4GHz band is at least 30 times greater than the overall efficiency of any cellular band.

To increase capacity whilst maintaining their sparse architecture, mobile networks will require increasingly large quantities of spectrum. Policy makers and regulators will need to assess whether this approach to meeting the data demands of the future justifies the substantial risks of increasing the concentration of spectrum ownership and the relatively inefficient use that it will entail. As insurance against this risk, policy makers should also enable increased use of dynamic spectrum sharing and make more licence-exempt spectrum available across a variety of bands.

1.4.3 Revisiting fundamental notions about spectrum and its management

It is often claimed that spectrum is "a finite natural resource", such as land, or oil, or fish stocks[3]. However, an analogy is only useful if it is accurate and allows for a nuanced understanding of the subject to which it is applied. The idea of spectrum as a finite natural resource is failing increasingly to fulfil either aim[4].

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[3] For instance, the search term 'spectrum-is-a-finite radio' on Google yields over 5 million matches.

[4] For example, the capacity of a network can be doubled by doubling the number of base stations whilst using the same range of frequencies. This would be akin to a parcel of land that could double

The notion of spectrum as a finite natural resource like land stems from the early days of spectrum usage when frequency separation was the only method of management that could be imagined. Today, in a world of increasingly interference tolerant systems employing spread spectrum technology, diverse network architectures and adaptive beamforming antenna arrays this notion is clearly of limited value, possibly even absurd. However, this idea has been taken to heart by many economists and is central to seriously held notions such as liquid secondary markets in spectrum rights, “spectrum crunches” and even “spectrum congestion”. It is time for regulators and policy-makers to work towards a more nuanced model of the radio spectrum and an honest appraisal of the real-world successes and limitations of the regulatory approaches that have been in use.

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its output of food for each doubling of the number of tractors employed, or an oil field that would double its output of oil if the number of well were doubled. In neither case would we be willing to refer to the resource in question as ‘finite’.

2 A brief introduction to the radio spectrum and its management

The impact of the internet may exceed that of all of the other phases of telecommunications that have gone before it. Already, the industries related to the internet – telecoms, IT and electronics – are undergoing rapid change, and their products are contributing to transformations taking place in almost every other sector.

Access to the internet will be demanded ever more ubiquitously, and there will be significant pressure to ensure that universal and affordable access is a reality. Meanwhile, the services that run over the internet will continue to innovate, mature and increase in value. We are also seeing the beginnings of a great trend to expand connectivity into new hitherto unconnected devices. Already wireless sensors and control mechanisms are being embedded into objects ranging from streetlights and pacemakers to forest fire detectors and grain harvesters. Both of these trends are explored in greater detail in the following chapters.

Although there is much about future technological change that is uncertain and debateable, the importance of wireless technology is a near certainty. In twenty years wireless connectivity has gone from being a high priced novelty to the default mode of connection to the phone network and the internet. Indeed, the vast majority of devices today use exclusively wireless connections, a trend that will only increase over time.

The radio spectrum is a subject of seemingly limitless complexity. This section endeavours to provide a quick and non-technical introduction.

2.1 The nature of radio communications

The aim of a radio transmission, exactly like that of a spoken word, is to convey information from a transmitter (speaker) to a receiver (listener)[5]. However, instead of issuing sound energy of varying pitch (frequency) and volumes (amplitude), as is the case in human speech, a radio uses electromagnetic energy of varying frequency and amplitude. Early radio experience showed that if two nearby receivers were attempting to receive transmissions using the same frequency at the same time neither would be able to correctly discern the information being communicated. This is essentially the concept of “harmful” or “destructive” interference. It is important to note that neither transmission is actually being

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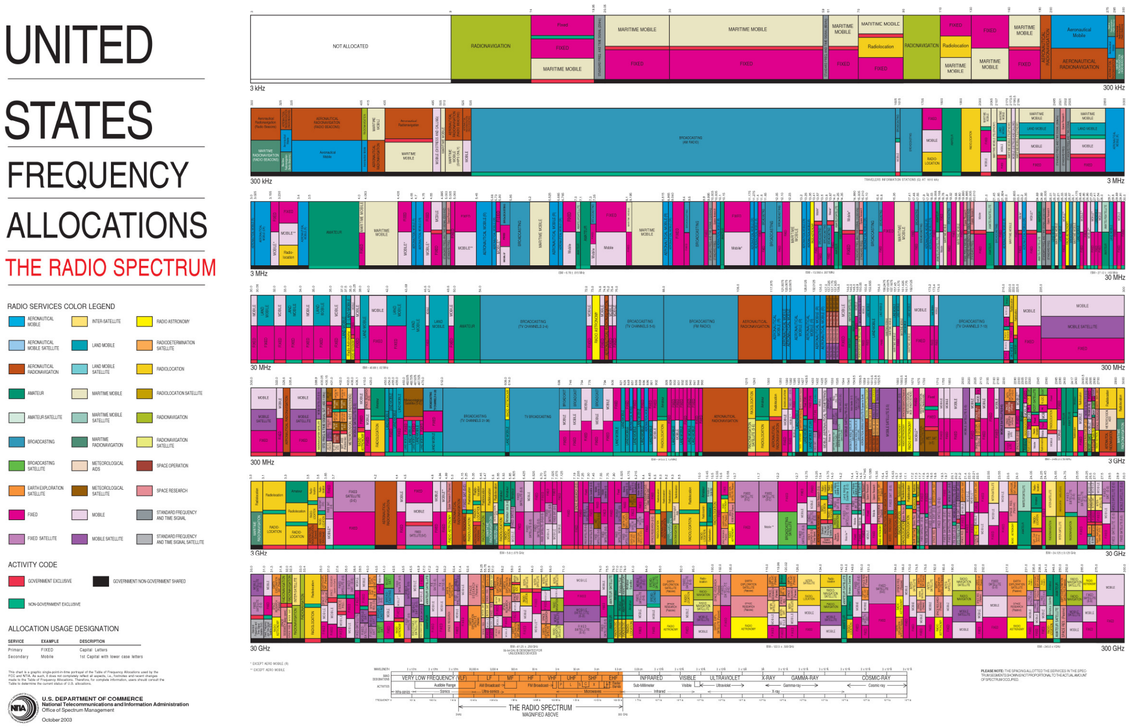
[5] In a TV or radio broadcast, much like a one sided conversation, the information flows entirely in one direction. In a two-way voice or data transmission information flows in both directions, either by both devices taking turns to use one particular band of spectrum or both devices simultaneously using different bands of spectrum.

"harmed" or "destroyed" – it is just that neither receiver can pick out the intended signal from the total amount of energy.

A number of methods are now known to be able to prevent this interference[6]. However, these require technologies that were not available to the early radio pioneers. Therefore, users were assigned specific frequency ranges (spectrum bands) for their exclusive use. These early radios were only capable of transmitting at very low frequencies (which easily propagate thousands of kilometres) and so the licences were largely granted on at least a regional basis. As technology improved and higher frequencies became possible these too were licensed on a frequency basis, giving rise to the familiar striated pattern of a national spectrum allocation map.

Figure 4 – The allocation of spectrum in the USA



The properties of spectrum vary at different frequencies. At lower frequencies, especially below 1GHz, radio waves are capable of moving past obstructions such as walls and foliage and can deliver non-line-of-sight coverage (like the effective propagation of a booming bass

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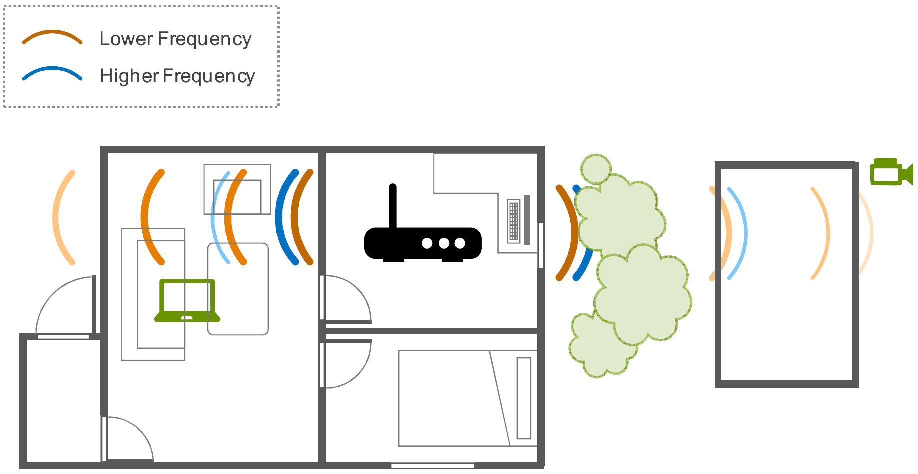
[6] There are some cases where the analogy with conversation is near perfect, such as coordinating transmissions in time (taking turns to speak) or beamforming (cupping hands around a mouth or an ear). There are other cases where the analogy becomes less clear, such as the exploitation of radio properties such as polarisation, spread spectrum techniques or most recently orbital angular momentum.

drum). At much higher frequencies, waves are more easily stopped by obstructions, limiting their usefulness to mostly line of sight applications, as shown below in Figure 5.

Figure 5 – The differing propagation of radio signals in high and low frequency spectrum



Although properties vary by frequency, the capacity of a band does not. A 5MHz wide channel of spectrum at a low frequency has the same potential capacity as a 5MHz wide channel at a high frequency. However, it should be noted that the amount of spectrum available does not limit the capacity of a network; it merely limits the capacity of a single radio base station. By doubling the number of base stations the capacity of the network can also be doubled.

2.2 The methods of spectrum management

Spectrum licensed by frequency for exclusive-use has been the primary mode of spectrum management for over a century. However, more recently regulators have opened a very small part of the radio spectrum for licence-exempt access.

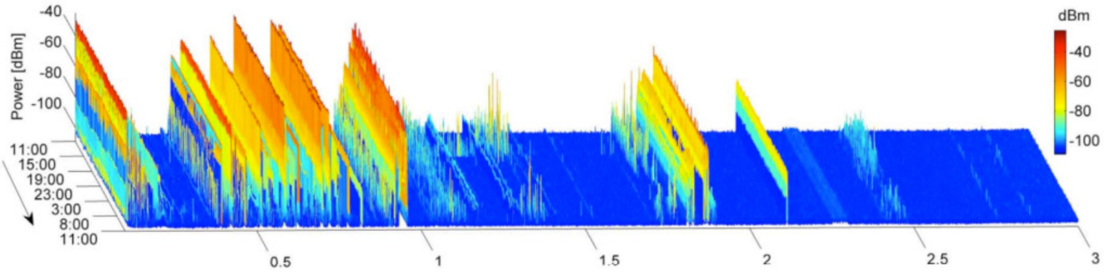
2.2.1 Spectrum licences

The overwhelming majority of spectrum not in government hands is provided through exclusive-use frequency licences, which specify a range of frequencies, or ‘band’, within which a licensee must limit their transmissions.

This system of spectrum management has a number of advantages. It is easy to administer, as the frequency of a transmission is an easier variable to coordinate than its time, location or directionality. It has also allowed some new services to gain unused, or quiet, spectrum and so deploy networks more cheaply than would be the case were the spectrum noisy. Many economically valuable services have been developed using the licensed bands of spectrum, including mobile telephony, television and satellite services.

However, exclusive-use licensing has many disadvantages. Primarily, it leads to a gross underutilisation of spectrum. The licensed bands are full of unused 'white space': periods of time or geographic areas or frequency sub sets in which licence-holders do not transmit and in which the law permits no other party to do so. In fact, the vast majority of the radio spectrum is unused, as shown in a number of studies[7], such as the one from Brno in the Czech Republic[8] shown in Figure 6 below.

Figure 6 – The utilisation of spectrum over a 24-hour period in Brno, Czech Republic



In addition, in most cases exclusive use rights have not encouraged efficiency. There is very little incentive for licence-holders that face little competition to move to newer more efficient technologies. Finally, the preponderance of pre-existing narrowband assignments (as shown in Figure 4 above) create inflexibility which makes it difficult to accommodate new wide band users[9].

Ronald Coase famously noted the inflexibility of spectrum allocation and the near-certainty of suboptimal allocation in 1959[10]. His solution was not to move away from exclusive-use licensing but to extend it further and treat these licences as property rights that could be bought and sold. Coase claimed that no matter how these rights were initially allocated, mutually beneficial trades would lead to an economically efficient allocation. Coase's ideas

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[7] See, for example Harrold, et al (2011), Islam et al (2006) and McHenry (2006). Microsoft recently unveiled a spectrum observatory tool accessible publicly http://spectrum-observatory.cloudapp.net/

[8] Forge, Simon, Robert Horvitz, and Colin Blackman. *Perspectives on the value of shared spectrum*, 2012.

[9] This can perhaps best be seen by the world's disparate global bands for mobile telecommunications. Manufacturers would have saved billions in costs had there been global harmonization. Instead, even with the latest LTE allocations frequency harmonization has not been achieved.

[10] Coase, R. H. "The federal communications commission." *Journal of Law and Economics* (1959).

have gained fairly broad acceptance over the previous 50 years. Auctions have become the most common way in which spectrum rights have been assigned and many countries have permitted the trading of spectrum licences.

Markets in exclusive use spectrum licences have been virtually non-existent, however. In many of the countries that have implemented tradable regimes the limited trades that have occurred have been largely the results of large operators buying up regionally issued licences or takeovers of firms. Some of the larger trades that have been proposed have had the appearance of somewhat blatant attempts to exploit regulatory rules for expanding ownership of spectrum for their arbitrage opportunities[11]. Perhaps most disappointingly, the ability to buy and sell exclusive-use licences has not allowed innovative operators or services to emerge. In contrast, they have largely enabled the largest operators in established industries to consolidate their position.

Peter Stanforth, the CTO of Spectrum Bridge – one of the US's biggest spectrum exchanges, expressed his disappointment in a presentation entitled "Why Haven't Secondary Markets Been Successful?" According to Yochai Benkler, Berkman Professor of Entrepreneurial Legal Studies at Harvard University, "Stanforth identified lack of education, fear of interference, lack of incentives against hoarding, and high transactions costs as the primary reasons for the disappointing performance of secondary markets."[12]

2.2.2 Licence-exempt spectrum

In 1985 the FCC authorised the use of the ISM (Industrial, Scientific and Medicine) bands for low powered communications devices on a 'licence-exempt', or 'unlicensed', basis. These were relatively wide frequency bands but were used for high powered non-communications applications such as industrial heating, microwave ovens, and medical diathermy machines. The power output of these applications was so high that these bands had long been considered useless for communications. The ISM bands for ITU region 2 are shown in Figure 7 below.

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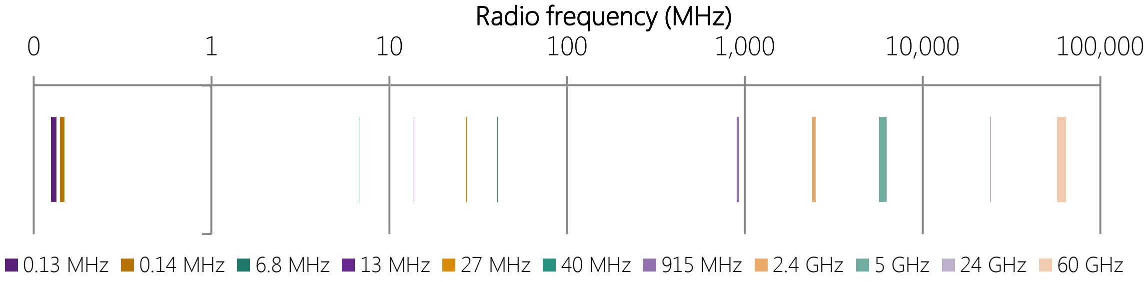
[11] For example the proposed transfer of spectrum from a consortium of cable operators to Verizon Wireless has become mired in competition law controversy, see http://thehill.com/blogs/hillicon-valley/technology/203879-fcc-commissioner-questions-whether-comcast-misled-regulators

[12] Benkler, Yochai. "Open Wireless vs. Licensed Spectrum: Evidence from Market Adoption" (2011).

Figure 7 – The ISM bands available in ITU Region 2



The FCC's rulings did not specify too many details of operation but instead merely set limits on the maximum power output of each device in the band. Importantly, this was the limit of the protection afforded to any user of the band. For potential operators this minimal set of rules presented numerous challenges as well as substantial benefits.

The main challenge was that the new licence-exempt bands were already subject to interference from industrial applications such as microwave heaters. Moreover, as the number of communications devices increased they would also face interference from each other. Furthermore there would be no official coordination or dispute resolution in these bands beyond the minimal rules set by regulators.

However, licence-exempt spectrum also presented opportunities. It provided the first instance in which any entity could set up a broadband data network, anywhere they wished and for any purpose. The desire to unleash the potential for such uses was the driving force behind the move to licence-exemption.

The first 25 years of licence-exempt spectrum have been marked by dramatic growth, innovation and diversity. By 2008 devices operating in licence-exempt spectrum were outselling those using licensed spectrum, including the totality of televisions, radios and cellular phones. The innovation in these bands had been marked – a number of technologies that are now being introduced into licensed applications were developed and first introduced in licence-exempt bands. These bands were also home to a large number of competing and complementary standards such as Wi-Fi, Bluetooth and RFID as well as a bewildering variety of applications – a number of which will be introduced in this report.

Vital to the success of licence-exempt spectrum has been the interplay between technologies and market forces. The technological standards that have been best able to avoid interfering with their neighbours have been the ones selected by end-users. This has driven up the scale of these 'good' technologies, driven down their prices and made them even more attractive to the market, in a process of positive feedback. An opposite contractionary force is at play on 'bad' technologies that are unreliable or cause interference. Crucially, this process of market selection is unmediated by large network operators and so happens at the speed of the consumer market, which is very fast indeed.

The following three chapters focus on the benefits that are being delivered by licence-exempt technologies: in the delivery of broadband internet access, in creating the internet of things and in creating robust and adaptable communications networks.

The final chapter returns to the critical question of policy. Given the leading role that licence-exempt spectrum is playing in meeting the challenges described above, what immediate and near-term actions can policy makers and regulators take to amplify its positive effects? And, perhaps most profoundly, how must we modify our broader understanding of spectrum and its management in light of the plentiful evidence at hand?

3 Connecting all the people

The people of the world are increasingly interconnected through the action of technology. Communications technologies play an essential role in facilitating the economic and social interactions of an increasingly mobile global populace. Indeed, for many of us, that connectivity has become an essential part of our daily lives. Universal broadband access to the internet carries the promise of rich economic benefits as well as a level of social interconnection between people that has not been seen since the emergence of humanity.

However, broadband remains unavailable to billions of people around the world. Many live in areas which are not covered by fixed or mobile broadband networks. For many others, broadband access is unaffordable. Both issues stem from the same root cause: the provision of fixed and mobile broadband relies on costly networks and creates markets contested by only a few large operators with near identical business models. These economics result in high prices and limited geographic roll-outs.

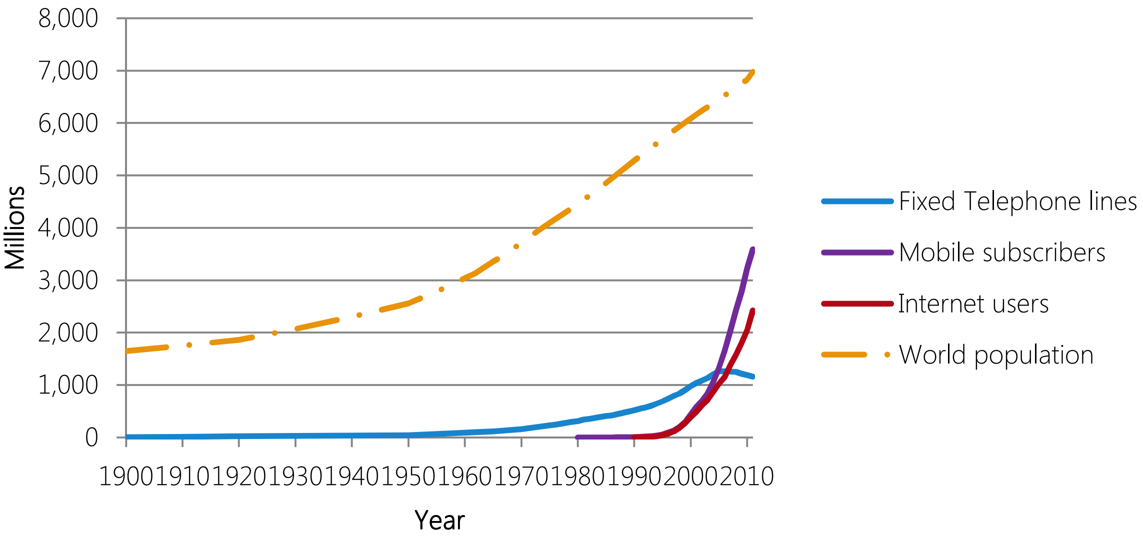
Unlike fixed or cellular networks, technologies that use licence-exempt spectrum are cost-effective and can be deployed by any person or entity. Wi-Fi has been deployed in hundreds of millions of homes and workplaces, and in tens of millions of retail premises and public places. It enhances substantially the economic value of fixed broadband and provides cost-effective public broadband access. Wi-Fi carries the majority of the world's smartphone traffic, saving mobile operators many billions of dollars annually in infrastructure costs. In addition, tens of thousands of businesses and organisations are using licence-exempt technologies, including Wi-Fi, to extend broadband to places that are not covered by fixed and mobile networks, from small projects in the favelas of Rio de Janeiro to large scale networks that span rural Catalonia.

The existing broadband capable licence-exempt spectrum bands are located at higher frequencies. This limits their range to tens of metres indoors and potentially a hundred metres outdoors. Licence-exempt use of the sub-1GHz spectrum in the TV white spaces could permit broadband links for hundreds of metres in cities and for many kilometres outdoors, even without a clear line of sight. Combined with the vibrancy and entrepreneurship already shown in licence-exempt spectrum the TV white spaces have the potential to extend broadband to hundreds of millions more people.

3.1 The reach and economic significance of the internet

Figure 8 below shows the take-up of some important communications technologies since 1900.

Figure 8 – Take up of key communications technologies since 1900



The growth of mobile voice subscribers and internet users is astonishing. There are 3.6 billion mobile voice users and 2.4 billion users of the internet, both now exceed the number of fixed telephone lines, whose numbers stand at around 1.1 billion[13]. The delivery of broadband internet requires a greater bandwidth and so more expensive infrastructure than mobile voice services.

In a number of spheres the impact of the internet has already been immense.

3.1.1 Commercial impacts of the internet

The internet has affected the commercial world in multiple ways.

The value of the global ecommerce market is $8 trillion a year and this sum is growing at a rate of over 50% each year[14]. The use of online selling platforms such as eBay and Amazon marketplace has generated a substantial increase in the number of small businesses who use the internet to sell goods. Other portals such as alibaba.com do not deal with consumers but instead facilitate trade between businesses.

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[13] The underlying data is from www.areppim.com. The mobile subscription number has been adjusted by the ratio provided at http://www.mobileworldcongress.com/articles/mobile-world-congress-press-releases/connected-economy.html

[14] Rausas, D, J Manyika, E Hazan, J Bughin, and M Chui. "Internet matters: The Net's sweeping impact on growth, jobs, and prosperity." *McKinsey Global Institute,* May (2011).

The internet has also had a substantial effect on our industrial organisation. Broadband allows workers to work increasingly from home, often resulting in higher productivity and lower costs. There has also been a substantial rise in freelancing, sometimes termed the ‘gig’ economy[15]. Some forecasts estimate that almost half of the US workforce might be self-employed by 2020.[16]

A number of developments suggest that the stream of commercial innovation online is far from over. The phenomena of crowd funding, including sites such as Kickstarter and AngelList appears to be providing new sources of capital for start-up businesses and other non-commercial projects. Ideas such as the Lending Club appear to be extending the forces of disintermediation in the hitherto resilient financial services industry.

3.1.2 Social impact of the internet

For the majority of internet users its social aspect is perhaps most prominent. Globally, the use of social networking is the most popular activity using the internet. Facebook has over 845 million registered users, Qzone over 480 million and Twitter over 300 million[17]. There are over 3.1 billion email accounts worldwide[18]. Access to broadband internet also allows access to other communications platforms such as the global telephone network and SMS messaging through services such as Skype and Rebtel.

The internet is home to a vast repository of knowledge and information, much of it accessible at no cost. It is also increasingly the arena in which scientific research and academic debate occurs. Sites such as Wikipedia have become the de facto primary destination for introductory knowledge. The internet has become the primary source of news in many countries around the world and various forums are also used to organise social and political action. Governments are increasingly delivering services and information to their citizens using the internet.

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[15] Stillman, Jessica. “Yup, Britain is a freelance nation too.” *GigaOM*, 2012.

[16] Kim, Ryan. “By 2020, independent workers will be the majority.” *GigaOM*, 2011.

[17] “http://en.wikipedia.org/wiki/List_of_social_networking_websites.” *Wikipedia*

[18] Radicati, Sara, Principal Analyst, and Quoc Hoang. “Email Statistics Report , 2011-2015.” *Reproduction* 44, no. 0 (2011): 0-3.

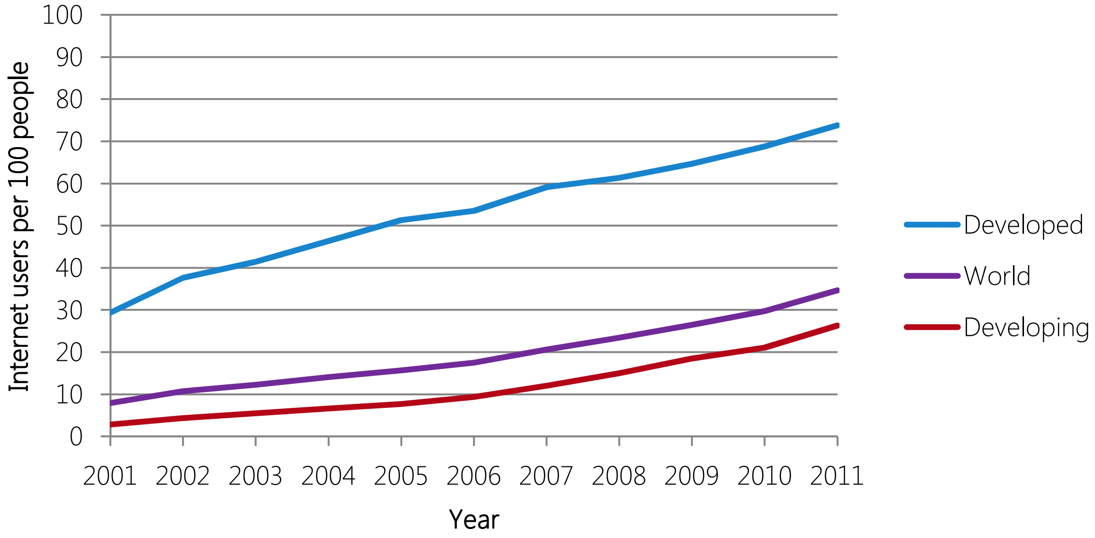
3.1.3 The economic value of the internet

The combined economic value generated by these activities on the internet is likely to be vast. A number of studies have attempted to measure aspects of the value generated[19] but none has yet provided a comprehensive assessment; the ubiquitous impacts of the internet may even preclude such an analysis. Perhaps the most ambitious quantification comes from a 2011 study performed by the McKinsey Global Institute[20]. The researchers find that the average contribution of internet related industries was 3.4% of GDP in the 13 countries studied. In aggregate this suggests that the internet is contributing over $1.5 trillion to global GDP. However, GDP is merely an accounting measure; McKinsey's estimate of the true economic value provided to the end user is $240 to $370 billion a year.

3.2 Costly existing delivery methods and the underserved billions

In spite of the great gains made by the internet economy, only one third of the world's population are internet users. There is already a striking disparity between developed and developing countries in internet take-up as depicted below in Figure 9.

Figure 9 – internet usage frequency in the developed and developing world[21]



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[19] See Williamson, Brian, and Phillipa Marks (2008), Goolsbee, Austan, and Peter J Klenow (2006) and Dutz, M, and J Orszag. (2009).

[20] Rausas et al (2011)

[21] Ibid.

The current wave of growth in the usage of fixed and, especially, mobile broadband will certainly introduce a large number to the internet. However, our existing methods of broadband delivery are costly, limiting their take-up in densely populated areas and preventing roll-out altogether in more sparsely populated areas.

3.2.1 Limited affordability of broadband

The cost of broadband access is a major factor limiting its uptake. The International Telecoms Union (ITU) has set a target for 2015 that broadband access should cost no more than 5% of income[22]. Achieving this goal would help to stimulate the take-up of broadband and the economic benefits that would ensue.

Unfortunately the ITU's methodology for measuring the unaffordability of broadband only compares the costs of basic packages with the average level of income per country. This does not take account of income variations that should also be of interest to policy-makers.

My analysis below uses the ITU's data to examine the worldwide affordability of fixed and mobile broadband. However, it offers an important enhancement. Instead of comparing costs with average monthly income it compares the cost of the package to the entire distribution of incomes within each country[23]. This provides a more nuanced understanding of affordability, as within poorer countries there will be some for whom services are affordable and vice versa.

For fixed broadband, the extent of unaffordability by country is shown in Figure 10 below.

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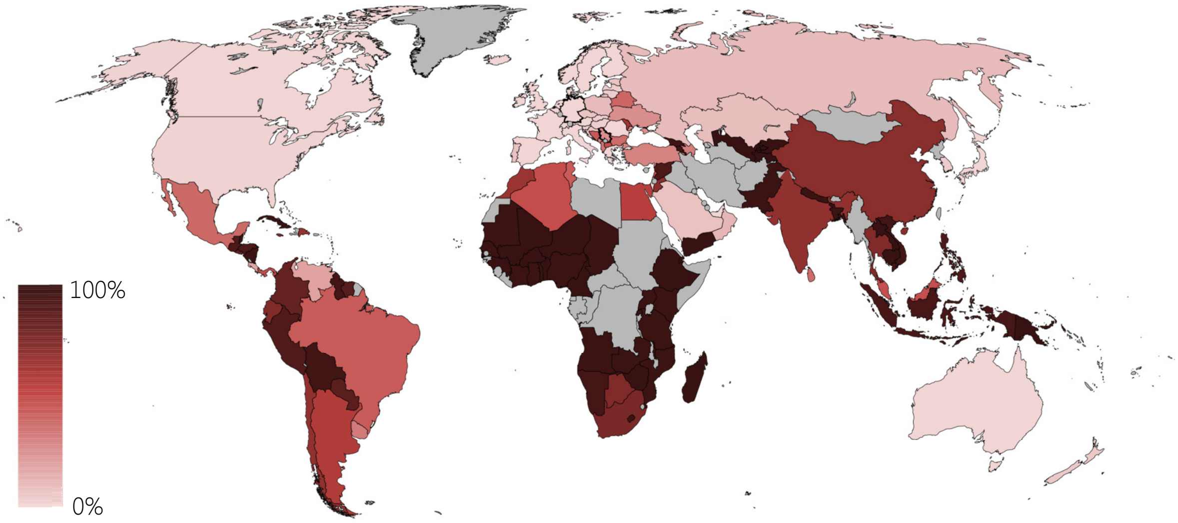
[22] ITU. "Measuring the information society, 2011" (2011).

[23] To achieve this I have used Gini coefficient data from The World Bank and The CIA World Factbook to derive a lognormal estimation of the Lorenz Curve detailing income distribution. Although this is an approximation it has been shown to be a highly accurate one. See Kemp-Benedict, Eric. "Income Distribution and Poverty Methods for Using Available Data in Global Analysis" (2001). The resultant distributions of income per country were compared to the data from ITU "Measuring the information society, 2011"

Figure 10 – The proportion of people who would find fixed broadband unaffordable by country



For over 3.9 billion people, around 61% of the world's population, the cost of fixed broadband is more than 5% of their income and so deemed unaffordable. By continent this ranges from 8% of the population of Europe, to 90% of the population of Africa.

Unfortunately, the ITU did not compile a comprehensive study of prices for mobile broadband in 2011. However, it did perform a more limited survey for a number of selected countries and finds that the average cost of 1GB of mobile broadband service is 81% of the cost of its fixed broadband counterpart. Therefore, if an approximation that mobile broadband is 50 to 80% of the cost of fixed broadband is applied generally, mobile broadband is likely to be unaffordable for 2.6 to 3.5 billion people.

A breakdown of this analysis by country and continent is provided in Annex 1 of this document, which also details the effects of changing the threshold for affordability.

3.2.2 Limited roll-out of broadband

There are only a handful of countries in which universal availability of fixed and mobile broadband is a practical reality. This includes a number of wealthy densely populated nations, such as Luxembourg, Denmark and Singapore[24]. Some larger nations, such as South Korea and Japan have achieved near ubiquity, but only with substantial public subsidy.

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[24] From the relevant Point Topic country profiles, see http://point-topic.com

Even in the relatively developed markets of Europe and North America broadband is not universally available. For example, in Europe fixed broadband is not available to 4.7% of the population, around 23.5 million people, of whom 18 million are in rural areas. 90% of Europe's citizens can receive an outdoor 3G signal, but usable indoor coverage is likely to be substantially lower. In the USA, 4% of the population, 11 million people, cannot access fixed broadband.[25]

In much of the developing world there is very little broadband coverage. There were 1.2 billion telephone lines in use in 2010[26], and even if it is assumed that only 80% of householders with lines available take them up this would suggest around 1.5 billion telephone lines available worldwide. A substantial proportion of these lines would not be capable of delivering broadband access. With mobile broadband, the ITU estimates that 3 and 3.5G networks provide outdoor coverage to only 45% of the world population[27].

3.2.3 The high costs of existing models of broadband delivery

The vast majority of subscriptions for broadband services use either fixed line (such as fibre, cable, ADSL) or mobile broadband options (delivered using 3G and 4G mobile technologies). Both these delivery methods are costly.

3.2.3.1 Fixed networks

In most nations, the fixed broadband infrastructure is an upgrade of previously deployed fixed networks, such as the copper based phone and cable TV networks, providing ADSL and DOCCIS respectively. New fixed networks based on optical fibre are being deployed in limited quantities in parts of the world.

The construction of fixed networks is a supremely costly proposition. The most expensive element is that of providing the last mile, or the final connection to the consumer. Laying cables in the ground costs anywhere from $7.5 to $150 per metre[28]. Other high costs include the installation of customer premises interfaces, the cabling to be laid and the construction of sub-stations to aggregate the cable ends. Even fully depreciated networks have high costs of maintenance and repair.

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[25] European Commission. "Digital Agenda Scoreboard 2011" (2011).

[26] Central Intelligence Agency. "Telephone - main lines in use." *The World Factbook*, 2010.

[27] ITU. "ICT Facts and FIgures" (2011).

[28] Bradley, Neil. "Installing fibre-optic cables underground." *Beyond Broadband*, 2012.

These substantial sunk costs – so-called because they cannot be recovered – render fixed networks natural monopolies. In many countries a single state-run monopoly was historically the sole provider of telecommunications services. Although most of these operations have now been privatised it is still the norm that they are closely price regulated, due to the lack of effective competition.

3.2.3.2 Mobile networks

Mobile broadband is delivered over 3G networks (using technologies such as HSPA and EVDO) and increasingly pre-4G networks (such as LTE and WiMAX). The costs of building a mobile network are substantially lower than those of a fixed network. Indeed, entry-level mobile broadband packages have played an important role in extending mobile broadband coverage to market segments that have not traditionally been able to afford fixed broadband[29].

However, there are a number of factors that limit the potential of the mobile industry from reaching lower price points and expanding deeper into rural areas.

Mobile networks are still characterised by high costs. National networks are required of highly specialised equipment that must sometimes support many layers of legacy operation. This encourages the formation of large national or international companies with the attendant costs.

Perhaps more importantly, there is a trend towards diminished competitiveness with these markets. In nations with developed mobile markets the industry now attracts little interest from potential new entrants. This is the result of ever increasing barriers to entry, due to a number of underlying causes:

- High spectrum and site barriers – existing operators possess increasingly extensive spectrum assets as well as the best physical sites for their equipment, providing a substantial competitive advantage over newcomers
- Customer acquisition difficulty – building a customer base has proven difficult in the mobile industry for a number of new entrants.
- The needs for scale and rapid technology upgrades – in most markets operators are national entities, the possibilities for success for a regional or metropolitan operator seem limited.

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[29] For 3G options. The price for a high-end LTE mobile broadband tariff is over $50 per month, see Tariff Consultancy Ltd. *LTE Mobile Broadband Pricing 2012*, (2011).

It is not difficult to see why any entity faced with the task of building a competitive national mobile broadband network with spectrum resources that are not supported by the majority of existing handsets could not hope to reach profitability. The lack of new entrants also works to diminish the levels of competition between existing operators. Consolidation has been ongoing in this industry for a decade and has intensified since 2010, suggesting that the advantages of scale are beginning to tell ever more greatly in this market. This has the prospects of further reducing competition[30].

3.3 Licence-exempt technologies decrease the costs of delivering broadband and increase the quality of the product

As discussed above, the deployment of fixed and cellular networks requires highly expensive equipment and is limited to a few large organisations. By contrast, technologies that use licence-exempt spectrum are cost-effective and can be deployed by any person or entity. Licence-exempt technologies are already widely deployed, carrying the majority of the world's data traffic and acting to increase the quality and decrease the costs of broadband access. In addition, licence-exempt networks are being used to extend cost-effective broadband to places that are not covered by fixed and mobile networks.

3.3.1 The properties of technologies using the licence-exempt spectrum

Technologies using licence-exempt spectrum possess three characteristics that differentiate them from technologies designed for licensed spectrum. They are accessible for deployment by anyone, the cost of the equipment is much lower and the capabilities of the equipment used advances at a quicker rate.

The key principle of licence-exemption is the regulation of devices rather than the regulation of users. As such any individual or organisation is free to purchase compliant equipment from manufacturers and deploy their own networks.

Due to this permissive regulation, licence-exempt operation has been adopted by a huge number of users worldwide. This has resulted in large volumes of equipment being sold and

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[30] Indeed, it was on the risk of decreased competition in the US market that AT&T was prevented from acquiring T-Mobile US, and why the merger of T-Mobile and Orange in the UK was permitted by the European Commission only due to concessions given to protect the future of the smallest player, H3G.

driven down the prices. For example a cellular picocell costs from $7,500 to $15,000[31] whereas a much higher capacity carrier-grade Wi-Fi access point costs around $2,000[32]. The cost of a Wi-Fi chipset for a consumer device is around $5, whereas 3G cellular chipsets costs around $30[33].

As a direct to consumer channel, new innovations in technology can rapidly be brought to market by manufacturers. In licensed markets manufacturers sell network equipment to network operators, and so are dependent on their upgrade plans. This bias is evident if Wi-Fi equipment is compared to cellular equipment. Innovations are often brought to cellular systems a number of years after they first appear in Wi-Fi[34].

These characteristics suggest that licence-exempt technologies may have an important role to play in both reducing the costs of broadband connectivity as well as expanding its reach. In fact, they are already playing this role to an extent that many may not realise.

3.3.2 Wi-Fi is central to our broadband networks

The licence-exempt technology that has most greatly affected the delivery of broadband is Wi-Fi. Its capabilities and cost-effectiveness are playing an important role in enhancing the quality and lowering the costs of existing broadband products, as well as allowing a huge diversity of new networks to be built; many in areas where fixed and cellular networks are not available. Wi-Fi perhaps also offers an example of how future technologies based on upcoming licence-exempt spectrum, such as the TV white spaces, might be used.

3.3.2.1 Wi-Fi is ubiquitous and delivers most of the world's data

The growth of Wi-Fi in the home since its introduction around a decade ago has been exceedingly rapid. Strategy Analytics, a research consultancy, reports that by the end of 2011, 439 million households worldwide had installed home Wi-Fi networks, representing around 85% of all fixed broadband connections and 25% of all households worldwide[35]. The

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[31] PA Consulting Group. *Not-spots research*, 2010.

[32] A typical price seen for the following Ruckus Zoneflex 7762-ac product

[33] Lawson, Stephen. "AT&T sees an end to Wi-Fi-only tablets." *PC Advisor*, May 2012.

[34] Thanki, R. *The economic value generated by current and future allocations of unlicensed spectrum. Final report, Perspective Associates*, 2009.

[35] Burger, Andrew. "Report: Wi-Fi Households to Approach 800 million by 2016." *Telecompetitor*, n.d. http://www.telecompetitor.com/report-wi-fi-households-to-approach-800-million-by-2016/.

company expects this number to grow to nearly 800 million by 2016 or around 45% of all global households.

Wi-Fi is also common in businesses, used to provide wireless access across an office or campus or through an industrial or retail area. There are likely to be 14 million Wi-Fi access points deployed in offices in the OECD alone[36].

There are 4.5 million "community" hotspots owned privately but shared publically through schemes such as FON. A further 1.3 million public Wi-Fi spots have been deployed by mobile network operators or stand-alone Wi-Fi providers. Informa, a research consultancy, expects this number to grow to 5.8 million by 2015[37]. In addition, there are networks of access points deployed by municipal authorities and many tens of millions more made available by entities such as coffee shops, bars, hotels and museums amongst others[38].

Wi-Fi carries more internet traffic to end users' terminals than cellular or wired connections combined. In the case of smartphones and tablets Wi-Fi carries 69% of total traffic generated. For traditional PCs and laptops Wi-Fi is responsible for carrying 57% of total traffic, greater than wired connections or connections over licensed cellular spectrum combined. This is depicted in **Error! Reference source not found.** below.

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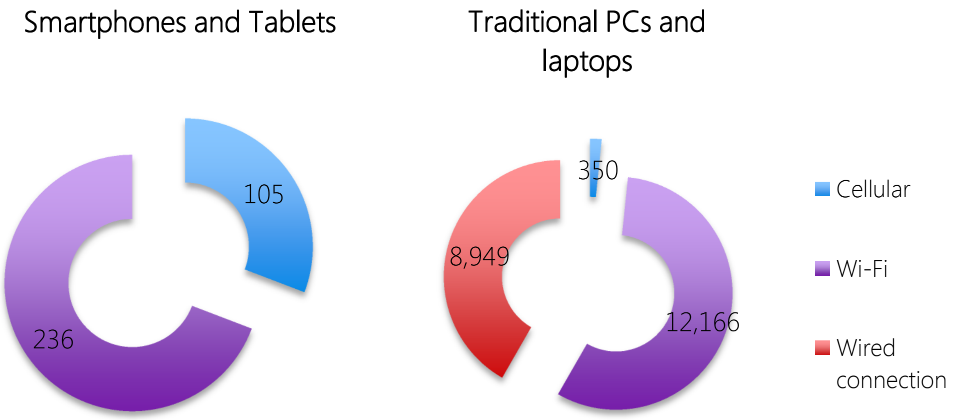
[36] Assuming that the amount of office space across the OECD is proportional by population to that in the US (Linneman 1997) and that one access point is needed to cover each 2000 sq ft (Florwick 2011) and that 70% of all space is covered.

[37] WBA. *Global Developments in Public Wi-Fi*, 2011.

[38] This number has never been accurately tallied, but considering that there STR Global reports that there are 13 million hotels rooms in the world, even if only 8% of the rooms had Wi-Fi there would be over 1 million hotspots in the hotel industry alone.

Figure 11 - Traffic carried by different channels for different types of device (PB per month)[39]



Another way of understanding the scale of global Wi-Fi deployments is to compare the aggregate capacity of Wi-Fi networks to global cellular networks. The aggregate capacity of the world's Wi-Fi networks can be conservatively estimated to be well over 16,500 terabits per second. In comparison, the total capacity of the world's 3G and 4G radio networks is probably no more 600 terabits per second. Below, in Figure 12, I show comparisons estimated on a country-by-country basis.[40]

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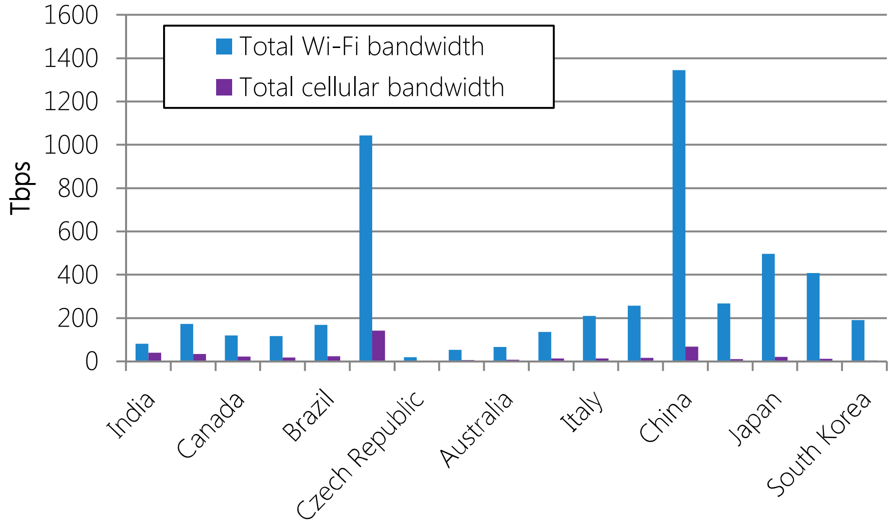
[39] These numbers have been derived from data from the Cisco (2011), Strategy Analytics (2012), and the ITU (2011). They are likely to be a substantial underestimate of the true role of Wi-Fi. For smartphones and tablets I have assumed no Wi-Fi offload at all for Africa, the Middle East and Latin America (as there is a lack of dependable data). For PCs and laptops I have assumed that all business data traffic is carried by wired connections.

[40] This analysis makes a number of broad approximations. Firstly, Wi-Fi routers are assumed to be 85% 802.11g, 10% 802.11n operating in the 2.4GHz band and 5% 802.11n operating in the 5GHz band, with average throughputs of 27, 72 and 150 Mbps respectively. For cellular I assume that there are 4 operators per country each with 2 x 35MHz of spectrum devoted to data, achieving a spectral efficiency of 2.5 b/Hz. These assumptions are likely to significantly overstate the capacity of most cellular networks.

Figure 12 – Comparing the capacity of the Wi-Fi and cellular networks in selected countries



3.3.2.2 Wi-Fi greatly increases the value of fixed broadband

Over 85% of broadband using homes now have Wi-Fi; it enhances the value of a fixed broadband connection by allowing ubiquitous and simultaneous access throughout a home. A 2009 study by Perspective Associates estimated the economic value generated through this use for the US economy.

Using the more detailed data now available I have extended this work on a global basis[41].

The results of the analysis indicate that by enhancing the value of fixed home broadband Wi-Fi generates approximately $52 to $99 billion of consumer surplus each year. Without this effect the value of fixed broadband would be lower and would result in the disconnection of perhaps 50 to 114 million fixed broadband connections around the world.

In the Figure 13 below these effects are disaggregated by continent.

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[41] These global figures were derived by estimating the home Wi-Fi users per country, using UN population data, ITU data on the incidence of fixed broadband connections and Strategy Analytic determination of a Wi-Fi penetration of 85% of all fixed users. For the low end of the value range I assumed that each Wi-Fi user's consumer surplus was equal to that of a US user scaled by the relative GNI difference between the nations in question and the US. For the high end of the range I did not scale the number. There are a number of reasons to believe that the higher end number is more appropriate: in lower income countries it is likely to be only those with higher incomes who have access to fixed broadband and these users' valuations are likely to be closer to the valuation of an average US user.

Figure 13 – Economic value generated by Wi-Fi through fixed broadband value enhancement

	Low value ($m per year)	High Value ($m per year)	Connections generated by Wi-Fi (million)
Africa	69	901	0.5 - 1
Asia	10,820	41,516	21.2 - 48.2
Europe	21,657	30,164	15.4 - 35
North America	17,769	19,952	10.2 - 23.2
Oceania	1,049	1,217	0.6 - 1.4
South America	782	4,772	2.4 - 5.5

A breakdown of this value by country can be found in Annex 2.

It should be noted that this valuation does not include many sources of value that stem from Wi-Fi usage in the home[42], such as easy networking between devices, the sharing and streaming of media and future uses such as being the hub for home automation and the interface of the smart grid[43].

3.3.2.3 Wi-Fi provides substantial cost-savings for cellular operators

In addition to 3G data capability almost every smartphone sold today has the ability to communicate over Wi-Fi. This happens at users' homes, in their offices and in other locations where they have the credentials to access Wi-Fi. Until recently, the balance of usage between smartphone users using mobile data networks and using Wi-Fi was not known. Estimates ranged from a 2:1 balance between mobile data and Wi-Fi networks[44] to parity[45].

However, in 2012 the research firm Mobidia released substantial data from its 600,000 strong panel of smartphone app users. In eight[46] of the twelve countries for which data has been released 94% of smartphone users are also Wi-Fi users. Even in China and India, where Wi-Fi penetration is low over 70% of smartphone users also use Wi-Fi[47].

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[42] The numbers have not been uprated from 2009 – this has been done on purpose so as not to include the benefits from large scale mobile offload, which is considered in the following section.

[43] The smart grid is discussed in greater detail in Chapter 1.

[44] Cisco (2011)

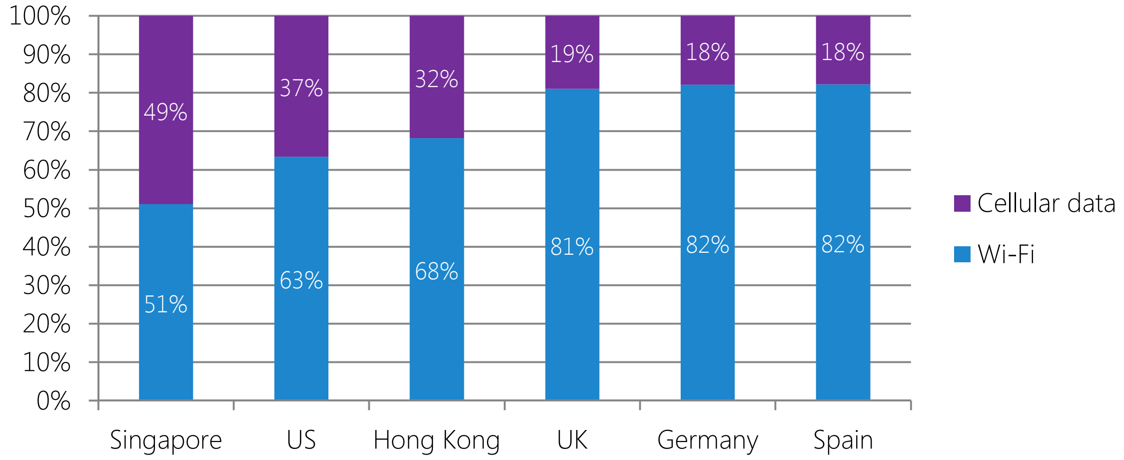
[45] Milgrom, P, and J Levin. "The case for unlicensed spectrum." *Policy Analysis* (2011).

[46] Netherlands, Hong Kong, UK, Spain, Germany, Canada, Malaysia, and France.

[47] This is particularly fascinating in the case of India, which according to strategy analytics has only 2.5% of households possessing Wi-Fi, suggesting a strong correlation between fixed broadband and mobile broadband usage.

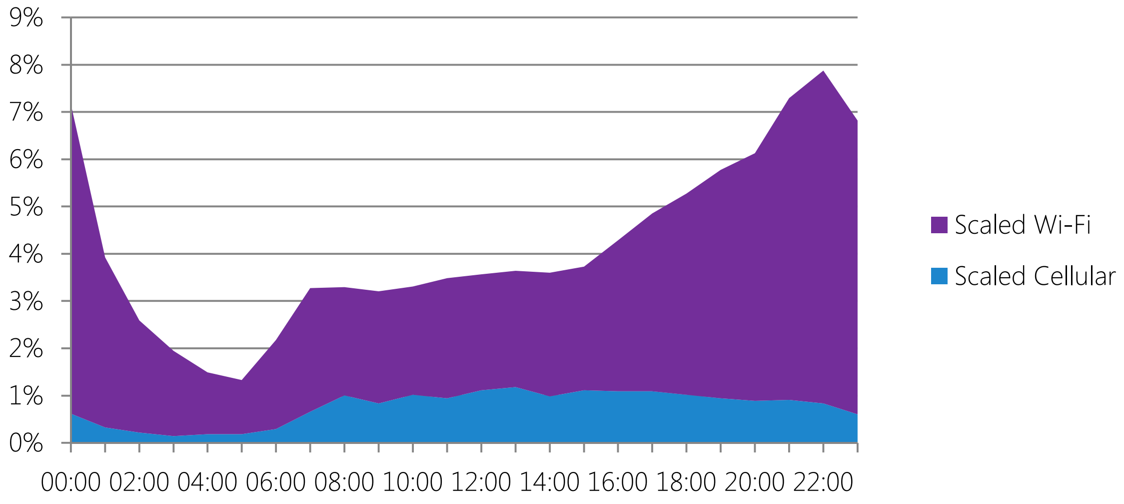
The balance of traffic between the mobile network and Wi-Fi is also revealed for 6 countries, and in the majority the data show a preponderance of Wi-Fi traffic. Figure 14 below details the ratios by country.

Figure 14 – Balance of cellular data traffic and Wi-Fi for selected countries



Mobidia provides a detailed hourly breakdown for the traffic only for the UK, which is accurately scaled and shown in Figure 2Figure 15 below.

Figure 15 - Total weekday smartphone traffic split by means of transport and time of day.



As can be seen the vast majority of smartphone use takes place across Wi-Fi networks. At no point does the total smartphone traffic on the cellular network come to even one third of the corresponding Wi-Fi traffic. At its most extreme, smartphone data carried over Wi-Fi exceeds cellular by a factor of 15.

In the absence of Wi-Fi mobile operators would have to carry substantially more traffic on their networks. This would entail substantial network costs should the new level of traffic exceed the current capacity of the network. Assessing these increased costs is a coherent first approximation of the economic value of Wi-Fi to the cellular industry.

A series of models have been applied to arrive at a broad estimate of the additional number of sites that would have to be deployed around the world to cope with traffic were Wi-Fi unavailable[48]. The results are shown by continent below in Figure 16.

Figure 16 - Extra cell sites required in the absence of Wi-Fi by continent

	Extra sites required (4x traffic)	Extra sites required (8x traffic)	4x costs ($mn)	8x costs ($mn)
Asia	85,500	306,400	17,600	63,100
Europe	31,600	82,000	6,500	16,900
North America	22,100	39,900	4,500	8,200
South America	4,600	8,400	900	1,700
Africa	3,400	7,400	700	1,500
Oceania	2,600	8,200	500	1,700
Total	149,800	452,300	30,700	93,100

Approximately 149,000 to 452,000 new radio base stations would be needed immediately to cope with worldwide smartphone traffic in the absence of Wi-Fi, representing a cost to mobile operators of $30 – 93 billion.

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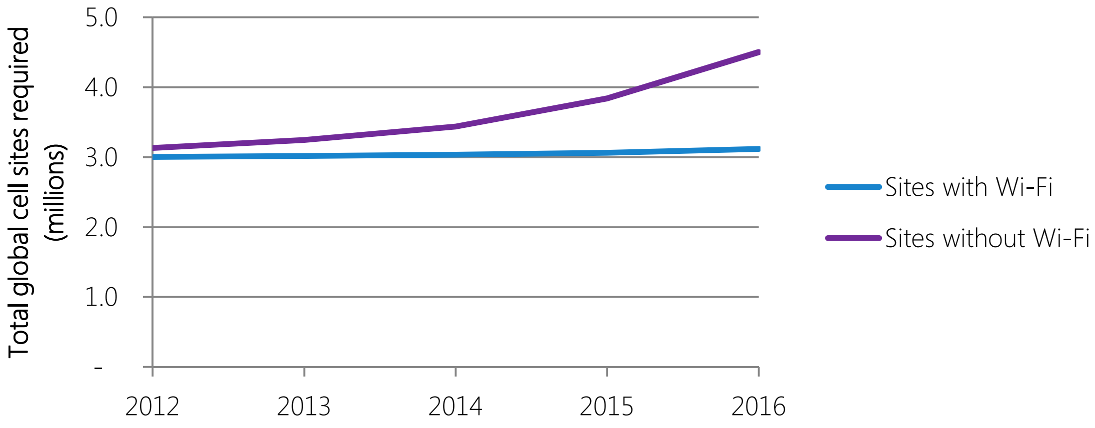
[48] At the core of my modelling is a model created by Ofcom, the UK regulator, to assess the effect of differing traffic levels on cell site numbers in urban areas in its consultation "Application of spectrum liberalisation and trading to the mobile sector" (Ofcom, 2009). To establish smartphone usage and traffic by country, I used ITU data on mobile broadband subscribers per country and estimates from TeliaSonera on the average data usage per user. To establish the urban population of each country, I used data from the UN's World Urbanization Prospects 2011. For the urban area of each country I used data from the Global Rural-Urban Mapping Project, version 1 (GRUMPv1) at Columbia University, normalising it using assumptions taken from Ofcom's work. Ofcom's model splits the total urban population and areas by a number of categories (Suburban, Open in urban, Urban and Dense urban) and I assumed that the *split* of each countries *urban* area and population is proportional to that in the UK. I assumed that each country has 4 mobile operators, each with equal market share and using 2 x 15 MHz of 2.1GHz spectrum to provide coverage throughout the urban area. This is actually a conservative assumption, as although the initial number of sites in each country will be higher than the real figure (for operators using sub-2.1GHz spectrum), the delta from absorbing Wi-Fi usage will in fact be lower, and it is this delta that gives rise to our cost estimations. Ofcom estimated that the initial costs of building a new site were on the order of £80,000, with on-going operating costs of £8,000. An NPV of 10 years of operation is taken as the cost per site.

It is important to note that this broad estimate is likely to be an understatement of the true benefits of Wi-Fi. First, this includes only a very standard cost for sites. It does not include the costs for backhaul or core network upgrades. It also does not account for increasing marginal costs for site acquisition in densely used areas. Second, the Mobidia data above suggests that absorbing Wi-Fi could shift the peak hour of traffic away from the middle of the day and into the evening hours. This could mean a substantial network reconfiguration and the need to find extra sites in residential areas[49]. Perhaps most significant is that our estimates are for a single point in time. TeliaSonera predicts that mobile data usage will grow tenfold over the next five years[50].

Using the same modelling framework I have extended the analysis to investigate how the number of sites required globally would change over the next four years with and without the availability of Wi-Fi. This scenario assumes the lower end base case: that peak time traffic would rise by fourfold without Wi-Fi, it also assumes that data growth from smartphones rises 40% per year over this period[51]. The results are presented in Figure 17, below.

Figure 17 – Cell sites required globally in the presence and in the absence of Wi-Fi



With Wi-Fi available – absorbing 75% of users' additional data demand – around 115,000 extra sites would be needed over this period, a modest increase of around 4%. However, in the absence of Wi-Fi the required number of sites required would rise dramatically; an extra 1.4 million macrocell sites, or 43% of the total. The difference in costs between the two

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[49] This has often proved difficult for operators. http://stakeholders.ofcom.org.uk/binaries/research/telecoms-research/not-spots/not-spots.pdf

[50] TeliaSonera. "TeliaSonera predicts tenfold increase in mobile data usage", 2012.

[51] This is much less than TeliaSonera's estimate and is in line with the growth that AT&T in the US reported in users' data usage in 2012.

scenarios is extremely large, $250 billion (NPV) – comparable to around one third of the total annual revenue of the telecommunications industry.

Macrocells may not be the most efficient way to deal with this traffic. It is conceivable that all the new sites could be smaller cells, known as microcells; this might reduce the cost by around 75%, to $60 billion. Or operators could install femtocells in customers' houses. However, to replace 75% the world's Wi-Fi access points with femtocells would cost over $45 billion. In any case, the costs to the industry would be severe.

It would probably not be feasible for network operators to maintain the density of sites needed in the absence of Wi-Fi. A more cost-effective response might be to dampen demand by raising prices. This might prevent the operators from incurring the costs estimated above but would place severe restrictions on the usage of smartphones, reducing the value that consumers derive and potentially stifling the innovation that has characterised this sector. It also would place mobile broadband out of the reach of billions more users.

Our work suggests that the fixed network through Wi-Fi underpins the majority of the usage of smartphones, and that these devices may never provide their full potential benefits in its absence.

Detailed breakdowns of this analysis by country can be found in Annex 3.

3.3.3 A range of licence-exempt technologies are being used to deliver broadband

Substantial economic benefits are being delivered by Wi-Fi and due to its sheer ubiquity this is possibly the most familiar usage of licence-exempt spectrum. However, Wi-Fi and licence-exempt technologies are being used in other innovative ways to deliver broadband.

3.3.3.1 Rural wireless internet service providers (WISPs)

Licence-exempt technologies have played a fundamental role in the growth of wireless internet service providers. These companies often provide broadband to remote areas that would be without service. The world's largest market for WISPs is in the US, where there are over a thousand predominantly small firms providing access to around 3 million users. The majority of these firms use licence-exempt or light-licensed spectrum[52]. Brian Webster, a

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[52] This consists of a number of bands where users have to notify the regulator of the use of spectrum and pay a small annual fee.

mapping and radio systems consultant, who has long experience with this industry writes the following:

> "WISPs do this without subsidy…and grew using money generated from the actual business. They don't have 6 figure base salaries and they don't burn through stockholder money to create their golden parachute. Being small business owners they also have a keen sense of the market space and they can react quickly to changes. Their equipment has advanced much more rapidly than other broadband technologies. Today they are capable of delivering 5, 10, 15 and even 20 meg connections to the consumer. They have the lowest cost per home passed of any broadband technology. It's a novel approach to the Telecom business model."[53]

WISPs are not only present in developed nations. Indeed the cost effectiveness of licence-exempt equipment and the liberalised access to spectrum have encouraged a huge number of projects[54]. Most of these projects rely on Wi-Fi and operate in areas far beyond the reach of wired or wireless data services. Notable examples include ZittNet in Nigeria, which serves 150,000 people[55], LinkNet Zambia which uses a licence-exempt mesh network to connect 150 rural communities to the internet[56] and Air Jaldi which uses Wi-Fi to distribute connectivity in the challenging terrain of the Himalayas[57].

3.3.3.2 Urban broadband provision

The previous section examined the benefits that Wi-Fi provides in combination with a fixed broadband subscription or a mobile broadband subscription. However, Wi-Fi is increasingly feasible as a primary method of internet access. As described above there are many tens of millions of public Wi-Fi hotspots. These are being deployed by many different entities and the flexibility of Wi-Fi thus permits many different business models for providing access:

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[53] Webster, Brian. "Wireless ISP's (WISP) – the other white meat of the broadband world.", 2011.

[54] For the beginnings of a list please see: http://wiki.villagetelco.org/index.php?title=Wireless_Networks_in_the_South

[55] See http://zittnet.net/

[56] Oxford, Adam. "How Linux is changing lives in Zambia", 2012.

[57] See http://drupal.airjaldi.com/

- deployments by stand-alone Wi-Fi providers providing service through subscriptions (examples include The Cloud in the UK, WaziWiFi in Nairobi, Kenya[58] and Parque Online in Rio de Janeiro[59])
- deployments by mobile network operators seeking the most cost-effective way to serve traffic[60]. Access to these is available at no cost to subscribers and a small charge for non-subscribers
- networks and access points operated by businesses such as shopping centres, coffee shops and restaurants as an inducement to customers
- networks run by public bodies such as local governments, museums and transport hubs, often offering free or subsidised access

These access points provide a major source of connectivity for users who are unable to afford a fixed or mobile subscription. In addition this may act as a competitive force acting to lower the costs of both fixed and mobile broadband.

In some cases there are also businesses that are seeking to deliver comprehensive broadband delivery networks based on licence-exempt spectrum. Perhaps one of the most ambitious examples is Tikona – an Indian ISP, which is currently delivering broadband using only Wi-Fi and other licence-exempt technologies. It covers a large population in India and has amassed 220,000 customers, and is valued at $1 bn.

Some operators are also using other licence-exempt spectrum to deliver cost-effective superfast broadband in urban areas.[61]

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[58] See http://waziwifi.co.ke/faqs.html

[59] See http://www.youtube.com/watch?v=8nAHQ-5u-Y4

[60] Wang Jianzhou, CEO of China Mobile, told an audience at the Mobile World Congress 2012 that Wi-Fi should be the default mode of connection to the internet for smartphones and that his company intends to roll out 1 million Wi-Fi access points by 2014. Japan's KDDI is intending to build out 100,000 access points in the same time frame.

[61] An excellent example of this is the firm Webpass, which provides fast Ethernet Internet connections to buildings in the San Francisco Bay Area, US. Its network is based around leased fibre that runs to various points in the city. From these it uses licence-exempt point-to-point links operating in the high frequency 24GHz band to connect together buildings in the area in a mesh network. Using this infrastructure Webpass is able to provide high speed Ethernet connections at 45, 100 or 200 Mbps to residential customers and speeds of up to 1000 Mbps to business customers at a very low cost. Webpass also appears to achieve a very high price/reliability/performance balance as evidenced by its excellent customer satisfaction on third party sites. See http://www.yelp.co.uk/biz/webpass-san-francisco

3.3.3.3 Bottom-up community built mesh networks

The licence-exempt networks described so far have been either the networks built by WISPs, the larger deployments of Wi-Fi by mobile operators, city authorities and hotels or the atomised Wi-Fi access points used by households and small businesses to extend their broadband. However, another class of network exists which provides interconnection and also broadband access, the bottom-up community mesh network.

These networks are based on infrastructure sharing by participants, granting access to each of the participants, and often the broader public, to the combined resources shared with the network. Each participant contributes with resources, usually fixed broadband and/or access points, and adheres to a set of rules or charter governing the infrastructure sharing. In a non-exhaustive list Wikipedia notes the existence of over 300 such groups worldwide.

As noted by Oliver et al[62] most of these networks have remained small and have failed to reach those users lacking access to broadband in the first place. However, there are other instances where these bottom-up networks have achieved just this, with the best example possibly being Guifi in the Catalan region of Spain.

Beginning as an effort to connect underserved rural areas near the town of Gurb using low-cost off-the-shelf Wi-Fi equipment, the network quickly grew and attracted the support of local authorities, businesses and individuals who provided the necessary resources to expand the network to further unserved areas. From its inception in 2004, it reached 1000 nodes in early 2006, 9,000 nodes by the end of 2009 and currently stands at over 25,000 nodes with almost 30,000 km of wireless links, serving over 50,000 people. Oliver et al. put the success of the effort down to a number of factors, most importantly its well-articulated rules about participation in and management of the network, its formation of a legal foundation to speak for the interests of the network and buy in from local organisations and authorities.

The strong organisation of the network is evident in its latest undertaking, FFTF (fibre from the farm), which seeks to build a full regional fibre ring with peering to international networks in both Barcelona and Girona, thus providing a ready supply of internet bandwidth from which to further expand the network.[63] It is a stated aim of this project to remain financially self-sustaining and not depend on grants or intermediaries.

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[62] Oliver, Miquel, Johan Zuidweg, and Michail Batikas. "Wireless Commons against the digital divide." *2010 IEEE International Symposium on Technology and Society* (June 2010): 457-465.

[63] Guifi.net. "The FFTF initiative" (2011).

3.4 Future changes concerning licence-exempt technologies

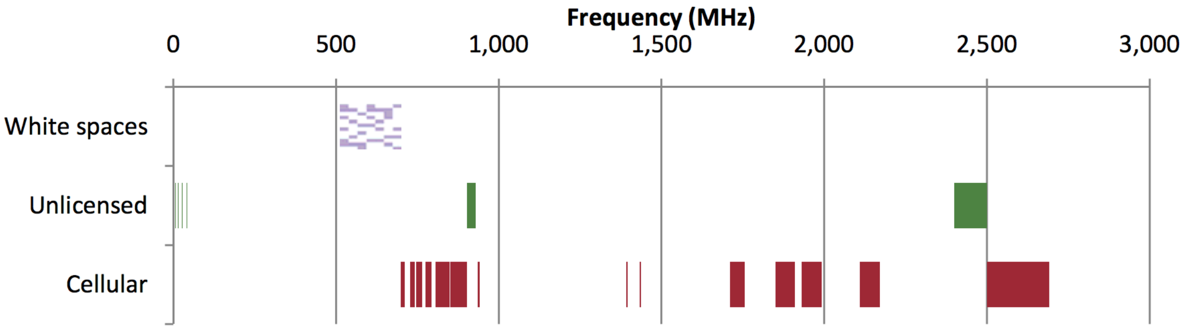
There are a number of changes either taking place or on the horizon that will affect how licence-exempt spectrum is used to deliver broadband.

3.4.1 The addition of the television white spaces

As described in Chapter 1, a number of bands of licence exempt bands of spectrum are available worldwide. However, these bands are all in frequencies above 1GHz, limiting their ability to propagate through foliage, walls or over the crest of a hill. This physical constraint has limited the deployments of licence-exempt technologies.

The TV white spaces are locally unused frequency ranges of spectrum that exist within the frequencies that are used for terrestrial television transmission, as depicted in Figure 18 below.

Figure 18 – The TV white spaces, exiting licence-exempt bands and global mobile allocations



Source: Perspective analysis

The spectrum in these bands has the potential to become the world's first globally harmonised spectrum below 1GHz. They have already been authorised for licence-exempt use in the US and a number of other countries are at various stages of the process of enabling their use. Although the amount of TV white space available will vary by area, it has been estimated in a number of studies to average 100MHz in each location, a greater capacity than the 2.4GHz band.

The opening up globally of a band of spectrum with excellent range and penetration characteristics on a licence-exempt basis will create the possibilities for a multitude of new applications. As was the case when the first bands for licence-exempt usage were authorised in the mid-1980s, it is impossible to foresee the totality of applications that this spectrum will enable. However, the enhanced delivery of broadband is likely to be amongst the first[64]. Indeed technology trials and commercial pilots for the delivery of broadband using the TV white spaces are underway in the US and UK and are planned to begin in Singapore, South Africa, the Philippines, and many other countries. Spectrum Bridge and KTS have recently launched the world's first commercial radio system using the white spaces in Wilmington, North Carolina, USA. Likewise, Telcordia and Adaptrum have announced plans for a commercial network in rural Nottaway County in Virginia.

The white spaces are likely to be put to different uses in rural and urban settings.

In rural settings the white spaces are likely to become an effective additional tool available to WISPs and other entities seeking to provide broadband.

For areas that are shielded by foliage or terrain, the excellent propagation characteristics of white spaces can be used to create a non-line-of-sight link and with 100MHz of spectrum available this link could have a capacity of up to 250Mbps[65]. Even in less than ideal conditions, were only half this capacity available, this single link could support 500 5Mbps broadband connections[66]. In a case where less spectrum were available the white space capacity could be combined with another source such a satellite in which the white space spectrum could be prioritised for those applications which depend on low latency like VOIP, secure transactions and gaming – services which are close to unusable on satellite connections alone.

In rural areas that already receive good coverage, either through fixed or wireless broadband, white space spectrum could be used to spread coverage over an entire area, such as large farm or a village centre, using only a single access point. Users could then connect to this using an appropriate wireless device.

In an urban setting, white space spectrum is likely to prove very useful in the delivery of connectivity in specific contexts. For example, a large organisation, which already has densely deployed Wi-Fi, such as a school, university or hospital, could overlay one or two white space access points onto their existing networks. By doing so they would be able to extend coverage into places that their existing networks may not be able to reach. A white

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[64] In the next chapter I look at some of the possibilities for machine-to-machine communication, whose value may even outstrip that of the human internet today.

[65] Based on extrapolating the capacity that the Neul-Carlson RuralConnect product can achieve with a 6 MHz channel (Lung (2012)).

[66] Given a link capacity of 125Mbps and a contention ratio of 20:1, better than the common ADSL ratios.

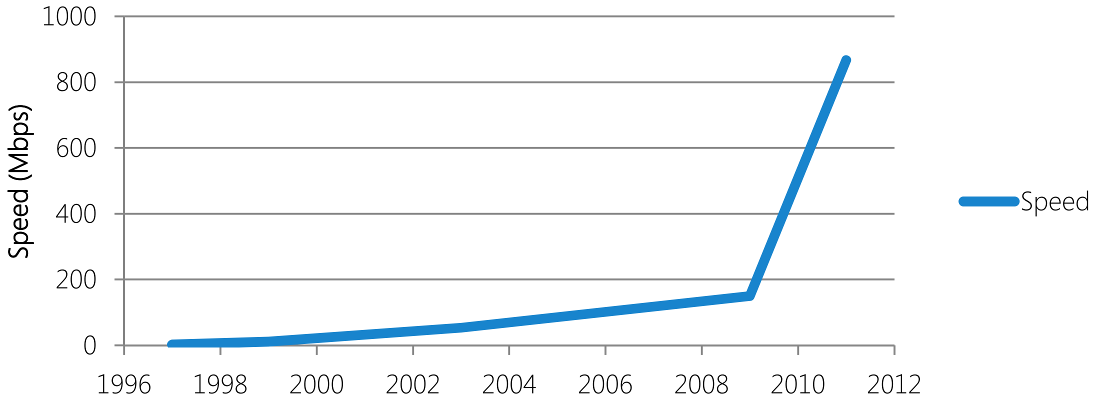
space network could also be used to quickly and easily create a private network designated for particular users. This could be useful for provisioning staff access at a public facility, or security use at an outdoor event. Finally, Wi-Fi routers incorporating the technology may prove particularly useful in providing connectivity in buildings where 2.4GHz or 5GHz signals cannot propagate well enough.

3.4.2 Trends in licence-exempt technology

While white space spectrum will prove a highly useful addition to the raw spectrum resources available, the technologies that work to deliver broadband are also advancing.

The capacity and capability of Wi-Fi have increased dramatically since its introduction in 2001, as shown below in Figure 19.

Figure 19 – The increase in Wi-Fi speed over time



In recent years, the advances in speed have been made possible through the use of wider channels of spectrum in the 5GHz band and smarter antenna techniques such as MIMO (to create multiple spatial streams between the receiver and antenna) and beamforming (to direct radio energy from the receiver to the antenna). Whilst increasing the speed of throughput to the end terminal these techniques also increase the reliability and provide the possibility of even denser deployments of Wi-Fi.

One of the most significant changes may come in the field of Wi-Fi authentication. Although the use of Wi-Fi to carry traffic generated by smartphone users has proven successful in certain environments, a typical user is likely to connect to very few of the large number of Wi-Fi networks that she encounters each day. Some of these networks will be private, belonging to businesses or individuals who do not wish to share access. Some others will be commercial and available for use but will require the user to manually provide credentials.

This limits the ability of mobile operators to reduce traffic on their network as well as the ability of new firms like Republic Wireless to use for their Wi-Fi dependent services.

However, two new initiatives with Wi-Fi are taking shape that could change this situation. Both the Wi-Fi Passpoint[67] will and the Next Generation Hotspot standard[68] will allow users to automatically log into hotspots using SIM card identification, device identification or the use of a one-time password and roam between enabled hotspots with no further intervention. One of the goals of both of these schemes is to achieve smoother cellular to Wi-Fi network transition and authentication where both data and voice sessions continue seamlessly. Both of these initiatives are scheduled to reach the market in 2012.

3.5 The evolving model of broadband delivery

Licence-exempt technologies already play a major role in increasing the value and decreasing the costs of broadband deployment, in some cases bringing broadband to areas that would otherwise be entirely unconnected. In addition, licence-exempt technologies are improving in speed, decreasing in cost and soon will permit automatic authentication. These changes may have a substantial impact on the business and technical models used to deploy broadband in the years to come.

Existing mobile operators are increasingly using Wi-Fi to deliver data traffic to their users. The advent of automatic user authentication will make this an even more effective tool to ease capacity concerns on their networks. Indeed it appears that Wi-Fi will be an integral component of the next generation of ‘small cells’ being manufactured by vendors such as Ericsson, Alcatel Lucent, Cisco and Ruckus. Licence-exempt spectrum is likely to play a leading role in addressing the challenge of providing backhaul from these small cells[69]. This will push open access spectrum even deeper into the mobile network delivery chain.

Licence-exempt spectrum will also create opportunities for newer entrants. First, the existing providers of large-scale Wi-Fi networks[70] could adopt the use of the TV white spaces and automatic authentication to provide a more seamless mobile coverage. There are also

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[67] An initiative by the Wi-Fi Alliance

[68] Devised by the Wireless Broadband Alliance

[69] The leading solutions specify the use of light-licensed (70-95 GHz) and licence-exempt (60 GHz – BridgeWave; 5GHz – Ruckus, Belair networks , Cisco) spectrum

[70] Such as The Cloud in the UK, Towerstream in New York City or Tikona in India

opportunities for novel business models using the new authentication technologies to combine various partial networks and maybe even cellular access[71].

The cumulative impact of these smaller changes should also provide a material cost saving for mobile network operators by diverting traffic off their networks.

For fixed access, a number of firms are already using licence-exempt spectrum to deliver superfast broadband[72] and some are using this model to deliver conventional broadband speeds[73]. These low-cost wireless models may help in developed nations, where fibre based roll-outs are proving expensive and not hitting take-up targets[74], and in developing nations, where traditional fixed roll outs would prove too costly altogether

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[71] Intriguingly, these developments could signal the creation of liquid wholesale markets for data connectivity as 5Mbps of Wi-Fi connectivity in a specific place at a specific time is a commodity whose value can be assessed and then traded with the exchange facilitated by automatic authentication. Unlike 5MHz of a particular frequency of spectrum which without a network and equipment in place is of no use to anyone.

[72] This includes Webpass in San Francisco, USA which delivers service ranging in speed from 50 to 200 Mbps and numerous other nascent small-scale firms.

[73] Tikona across India

[74] Superfast broadband has been identified as an important goal in many in many countries however there are severe issues with low take-up and slow growth. For example, in Europe in 2011 take up of superfast broadband by the end of 2011 was only 18% (Ramsay 2012), in the US the take-up is around 25% (Rigsby 2012). This is troubling for operators, as most projects have a profitability threshold of 60-80% take-up (Bockemuhl 2011).

4 Connecting everything else

Throughout history our communications systems have primarily conveyed information between people, from the use of semaphore to convey orders across battlefields to the use of mobile telephone networks to place voice calls. However, for over a century machines have also played a role on these networks. Automated stock tickers were used to convey market information using the telegraph network and fax machines became a commonplace means of transmitting documents across telephone lines. Nonetheless, in each of these cases the machines involved can be understood as a mediated form of communication between people.

Both these paradigms of communication are also common on the internet. Email is most often a form of direct exchange between people, whereas bulletin boards in the past and social networks today represent more mediated interactions. However, the internet is also the arena for a third kind of interaction – one where some or all of the parties involved in communication are machines and not people. The totality of the machine actors is often termed ‘the internet of things’. Its existing extent may surprise many readers but the implication of the trends we are already seeing is nothing short of revolutionary.

The economic potential of any society is largely dependent on the technology that society has available. There are some developments, such as the widespread availability of electricity, that fundamentally transform the productive capacity, and even organisation, of a society. It is not an exaggeration to suggest that the applications enabled by the internet of things may prove to be similarly powerful.

Technologies using licence-exempt spectrum will play a vital role in enabling the internet of things. As described below, they will be responsible for providing connectivity to over 95% of over 100 billion intelligent devices in operation by 2020. The economic value directly underpinned by licence-exempt spectrum will be around a third of the total value generated by the internet of things..

4.1 What is the internet of things?

The internet is a system of interconnected networks, on which any of the network terminals is able to communicate with any of the others. Most of today’s terminals are devices used by people to interact with each other and online information. However, billions of the terminals on the internet are devices such as sensors and control systems embedded in a multitude of devices. These mechanisms are able to interact either with people or with other machines across the internet and their numbers are set to increase substantially.

As an increasing number of devices are being enabled with connectivity the number and variety of communications between machines, with minimal human intervention, is also increasing. For example:

- smartphones are able to assess when a user has changed her location and are able to automatically download context specific information, such as weather data,
- sensor networks placed in forested areas able to detect the first signs of forest fire, and
- health devices such as pacemakers using sensors and wireless technology to upload data to central computer systems capable of raising an alarm if necessary.

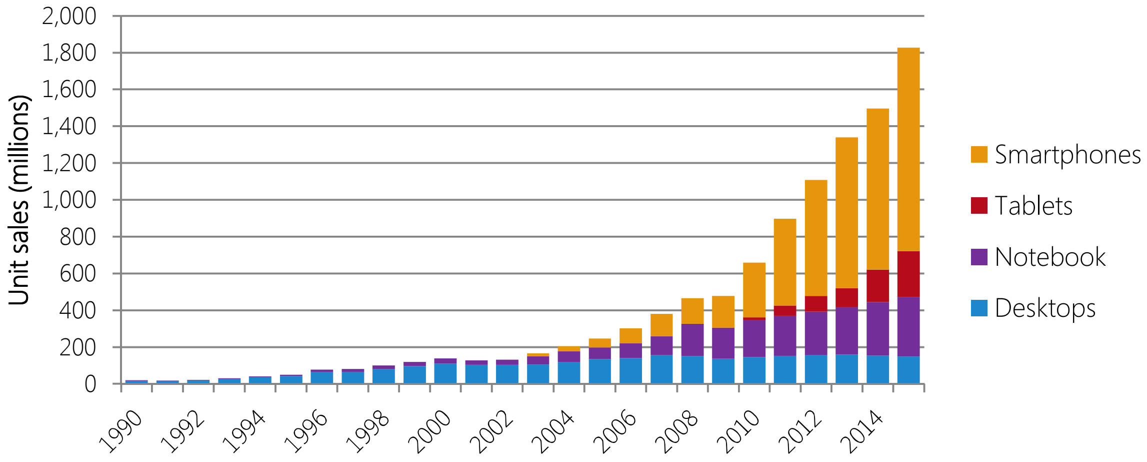
The collection of machine actors connected to the internet – from the very large such as cloud computing platforms to the very small such as pacemakers – can be collectively referred to as the 'internet of things'.

For a device to be considered to be part of the internet of things there are two prerequisites. First, the device must possess the ability to communicate across networks. Second, the device must be 'smart' in some sense. This means that it must have some degree of computing power. The following sub-sections map the current and possible future extent of the internet of things.

4.1.1 The human terminal

The principal machine actors on the internet have so far been traditional computers: servers, desktops and notebook PCs. In recent years they have been joined by new actors, including smartphones, tablet computers, smart TVs and other devices. Figure 20 below shows sales of these types of device for a twenty-five year period.

Figure 20 – Sales of internet capable devices since 1990



Until the mid-2000s the desktop PC dominated the sales of computing devices. However, the decade since 2002 has seen a number of dramatic changes. Sales of the notebook computer have risen to overtake those of the desktop, whose growth has stagnated. Sales of smartphones have exploded: in 2011 they exceeded the combined sales of both notebook and desktop computers. Overall sales of these devices have increased almost nine fold, from just over 100 million sold in 2001 to 900 million sold in 2011.

These trends have coincided with a significant change in the role of these machines. Previously, computers were often a stand-alone affair: users purchased software on physical media and used this software to perform particular tasks. The internet, where it was used, was largely in the form of dial-up narrowband. The mid-2000s saw a much wider availability of fixed broadband, Wi-Fi and then broadband mobile data services. These connection possibilities spurred on the take-up of more mobile computers and vice versa. Indeed, today's computers lose much of their usefulness if not connected to the internet and web services[75].

In any case, the combined sales of these devices are due to reach 1.8 billion units a year by 2015, equivalent to one device sold per one quarter of the world's population.

4.1.2 Future machine possibilities

PC, smartphones and tablets are the most visible devices connected to the internet. However, the possibilities for connected devices extend surprisingly further, in both scope and scale.

Although the term computer is often taken to mean traditional PCs, or increasingly tablet and smartphones, these devices do not encompass all or even a majority of computers. In fact, the majority of computers in the world are not the highly sophisticated microprocessors that power PCs or smartphones; they are rather the much simpler microprocessors found in microcontrollers. These are found in almost every electronic device, from digital watches to pacemakers to cruise missiles.

Unlike the powerful general-purpose chips and operating systems that sit at the heart of PCs and smartphones, microcontrollers have a well-specified role, such as working as a timepiece, monitoring a heart rhythm for abnormalities or measuring the temperature of a

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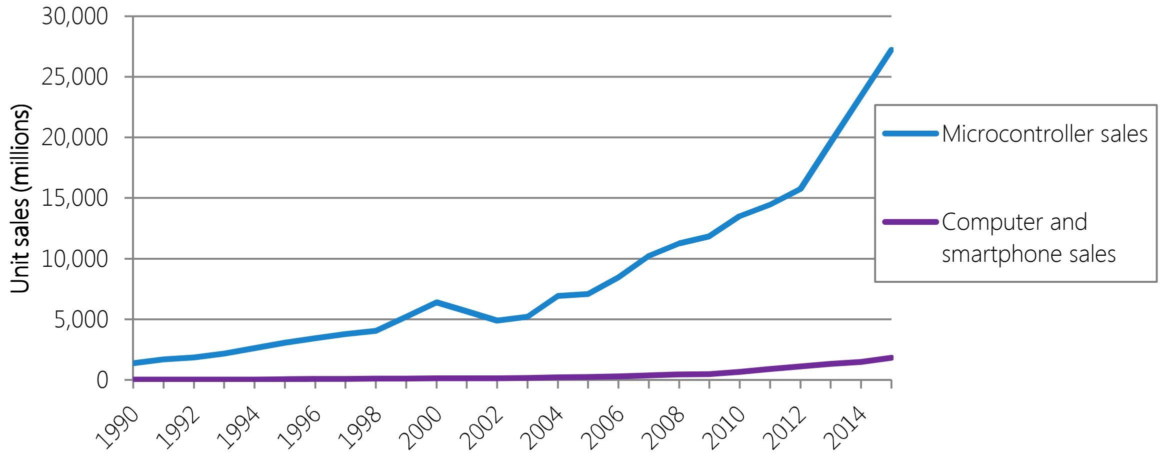
[75] These changes have affected even the stationary desktop; as demonstrated by the announcement by Apple that the latest iteration of its operating system will not be made available on physical media.

metal casing. In spite of their specialist roles these microcontrollers are fully fledged computers containing a CPU, memory and input/output abilities. The cheapest microcontrollers cost substantially less than $1 each.

Figure 21 - Sales of microcontrollers over time, below, compares the total sales data of the internet connected devices against the total sales of microcontrollers over the same period.

Figure 21 - Sales of microcontrollers over time



As can be seen, the impressive sales of internet-connected devices are dwarfed by the sales of microcontrollers. In 2011, almost 15 billion microcontrollers were shipped. In 2015 ARM Holdings predicts that almost 30 billion microcontrollers will be sold – the vast majority destined for devices other than PCs and smartphones.

4.1.3 Identifying the future members

Figure 22 below shows just some of the devices that contain one or more microcontrollers:

Figure 22- Devices containing microcontrollers

In comms networks
- Mobile phones
- Fixed line phones
- Fax machines
- Routers
- Switches

In PCs and smartphones
- Monitors
- Touchscreens
- Wi-Fi chipsets
- Hard drives
- Peripherals

In the home
- TVs, DVD players
- Games consoles
- Cameras
- Toys
- Appliances

In medicine
- Dialysis machines
- Defibrillators
- Ventillators
- Pacemakers

In vehicles
- Antilock brakes
- Air bags
- Keyless entry
- Fuel injection
- Climate control

In the military
- Aircraft
- Armoured vehicles
- Missiles
- Radios
- Artillery

In cities
- Street lighting control systems
- Parking meters
- Toll booths

In the environment
- Pollution/air quality monitors
- Weather stations
- Water level monitors

In industry
- Control circuitry
- Machine tools
- Monitors/sensors

To date only some of the devices into which these microcontrollers have been embedded have been equipped with the ability to communicate with external devices. However, the evidence suggests that this is changing at a rapid pace. Newer microcontrollers are more computationally capable, wireless connectivity is becoming cheaper and more battery efficient, and common language protocols such as IP are nearing universal adoption.

With many of the devices listed above, the benefits from the addition of intelligence and connectivity are quite obvious. For example a connected car could make faults easier to diagnose, connected toys could interact with each other for more play possibilities and the legendary smart fridge could detect unsafe food and warn accordingly.

The devices above already contain a degree of intelligence that could be enhanced through connectivity. In addition, the availability of low cost processors and easier networking also hold out the promise of extending intelligence and connectivity to entirely new objects. Some of the more surprising new terminals on the internet of things, such as grape vines[76], bridges[77] and human hearts are shown below in Figure 23.

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[76] Xiang, Xinjian. "Design of Fuzzy Drip Irrigation Control System Based on ZigBee Wireless Sensor Network." In *Computer and Computing Technologies in Agriculture IV*, edited by Daoliang Li, Yande Liu, and Yingyi Chen.

[77] Shamim N. Pakzad. Structural Health Monitoring of Bridges Using Wireless Sensor Networks,

Figure 23 - Machine terminals on the internet of things

Connected Grape Vine

- Sensors to check soil moisture, temperature and light intensity information
- Actuators to control drip irrigation system
- Trialled and described by Xiang 2011

Connected Bridge

- Wireless sensors monitors the pressure and vibrations in the structure
- Products already in use from Motorola, Innodev, Microstrain etc.
- Systems described by Xu 2004, Pakzad 2008, Harms 2010

Connected Heart

- Modern pacemakers and internal defibrillators constantly monitor heart activity
- Can upload information and be programmed wirelessly
- Developed by Elmqvist 1958, Mirowski 1978

This raises the prospect of a vast variety of new devices and objects being connected to the internet.

4.1.4 The size of the internet of things

Numerous estimates have been made for the possible extent of the internet of things.

Ericsson predicts that there will be 50 billion connected devices by 2020[78]. Although the exact methodology is not made available, the types of statistics that are considered include: 3 billion subscribers assumed to have 5-10 connected devices each, 1.5 billion vehicles globally (excluding trams and railways), 3 billion utility meters and a cumulative 100 billion processors shipped. Interestingly, this last figure only considers the advanced processors found in PCs and smartphones and not the simpler but more prevalent microcontroller. Cisco also claims a figure of 50 billion[79].

IBM using a wider definition that appears to include RFID tags, the diminutive circuits used in electronic smartcards, predicts that there will be 1 trillion connected devices by 2014[80].

Instrumentation & Measurement Magazine, 2010, Harms, T.

[78] Ericsson. *More than 50 billion connected devices*, 2011.

[79] MacManus, Richard. “Cisco: 50 Billion Things on the Internet by 2020.” *ReadWribeWen*, 2011.

[80] Williams, Alex. “IBM: A World with 1 Trillion Connected Devices.” *ReadWribeWeb*, 2010.

Using an alternative methodology, projecting the sales of microcontrollers forward and assuming that 50% of microcontrollers sold from 2015 onwards can be associated with an independent connected device with a lifespan of 5 years, I estimate that the number of intelligent connected devices could easily exceed 100 billion by 2020; the estimates by Cisco and Ericsson's could be substantially understated.

Such a large number may seem impossibly high. It does, after all, represent 10 intelligent connected devices for each person on the planet. However, considering the potential scale of just the few applications in Figure 23 above, this number quickly seems highly reasonable:

- The connected grape vine – there are approximately 30 billion grape vines under cultivation in the world[81]. In addition there are approximately 650 million olive trees[82], 500 million apple trees[83] and countless more peach, pear, coconut, cashew and others, each amenable to similar sensing, irrigation and pest control technology[84].
- The connected bridge – there are at approximately 9 million bridges in the world[85]. To provide a sensing capacity to all of them would require 900 to 1,800 million wireless sensors in total[86]. In addition sensing capability is equally applicable to other infrastructure, including dams, train tracks, roads, tunnels and airport runways.
- The connected heart – by 2020 approximately 2 million pacemakers and ICDs are likely to be fitted to patients each year[87] suggesting there could well be approximate 20 million such devices in operation. Sensing and control technology is also likely to

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[81] See http://superbwines.com/production_of_quality_wines.html

[82] Spain has 300 million olive trees (http://www.iberianature.com/material/olives.html) and is responsible for 46% of the world's production of olive oil (http://faostat.fao.org/site/636/DesktopDefault.aspx?PageID=636#ancorc)

[83] See http://en.wikipedia.org/wiki/Apple

[84] Ionela. "Wireless Sensor Networks in Agriculture – Olive Growing", 2009. http://dev.emcelettronica.com/wireless-sensor-networks-agriculture-olive-growing.

[85] The U.S. Bureau of Transportation Statistics, there are approximately 600,000 bridges in the United States, simply scaled up by share of world area (excluding Antarctica).

[86] Resensys. "Overview of Resensys Structural Health Monitoring System" (2012).

[87] ASDReports. "The Global Cardiovascular Devices Market is Forecast to Reach $43.4B by 2017", 2012. https://www.asdreports.com/news.asp?pr_id=289. – assuming a CAGR of 4% continuing past 2017 and a cost per device of $10,000

become common in implanted drug pumps[88], at the site of operations and in prosthetic procedures[89].

As for unintelligent connected devices, when one considers the number of smartcards issued, retail products sold, crates and containers transported and objects from library books to precious paintings archived then IBM's claim of trillions does not seem outlandish at all.

4.2 The applications and economic potential of the internet of things

The internet by itself is simply a set of connected devices, its value derives from the applications that have been developed to make use of it, such as email, the world wide web, voice-over-IP, video on demand, social networking and cloud services. The internet of things will create value by enabling new applications that make use of the world's connected devices and objects.

4.2.1 Understanding the scale of the economic possibilities

It is clear that a large number of possibilities arise when objects ranging from grape vines to pacemakers are connected to the internet. However, what is the potential economic benefit from this next expansion of the internet?

One way of attempting to address the question of value is to apply a simple numerical insight on the value of networks first expressed by Bob Metcalfe in 1980[90]. His observation was that as the number of users on a network doubles, the number of possible pairwise connections more than doubles, in fact it increases almost fourfold (by almost the square of the increase in users). If the value of the network to any user is proportional to this number of connections then the value of the network grows very quickly. Indeed many of the most valuable activities online can be seen as an exploitation of these connection possibilities, from the auction of an item on eBay to the discussions on scientific and technical mailing lists and forums.

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[88] Marketstrat. "Drug Infusion Pumps Market Expected to Grow Worldwide Despite Slowing Economy", 2009.

[89] Virtualmedicalcentre.com. "Implantable, wireless sensors share secrets of healing tissues", 2012.

[90] Metcalfe's Law, as it has come to be known, has been the subject of raging controversy as to the precise numerical relationship entailed. However, according to Reed Hundt – a former Chair of the US Federal Communications Commission – Metcalfe's Law and Moore's Law are the two key insights to understanding the vitality of the internet and the world wide web.

The possible number of connections in today's internet can be compared with those predicted in years to come of the internet of things. This is shown below in Figure 24.

Figure 24 – A comparison of projections for the size and scale of possibilities of the internet of things

	Today	Cisco and Ericsson predictions	This report's prediction	IBM's prediction
Number of connected devices	4 bn	50 bn	100 bn	1 tn[91]
Forecast Year	2012	2020	2020	2014
Number of connections	8×10^{18}	1.25×10^{21}	5×10^{21}	5×10^{23}
Ratio against today	1	156	625	62500

An internet composed of 100 billion terminals contains 625 times as many potential connections as the internet today, representing a very substantial increase in economic value generating possibilities. This increase in pairwise possibilities is of the same scale as that which happened on the human internet between 1997 (in the days of Windows 95, long before Google, Skype and Facebook) when there were 80 million users to today, when there are over 2 billion (having access to an infinitely greater range of services)[92].

It is, of course, difficult to make any firm predictions even of the magnitude of the economic benefits that might be achieved. However, using Metcalfe's analysis as a starting point it is possible to present highly indicative estimates. McKinsey estimates that the consumer surplus generated by today's internet is \$240 - \$370 billion dollars annually. Ignoring any producer surplus, this range can be taken conservatively as the full economic value generated by the 8×10^{18} connections present in the internet today. Therefore, even if each of the new machine interconnections on the internet were to generate only one one-hundredth[93] of the economic value of each of today's human dominated links, their combined economic contribution by 2020 could reach \$1.4 to \$2.2 trillion per year – around five times the value generated by the internet today.

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[91] IBM's figure also includes RFID based devices

[92] There is a case to be made that measuring the number of pairwise connections is helpful at measuring the value of a network that generates pairwise interaction

[93] Which given the more limited scope that, at least initially, will be possessed by these devices is not unlikely.

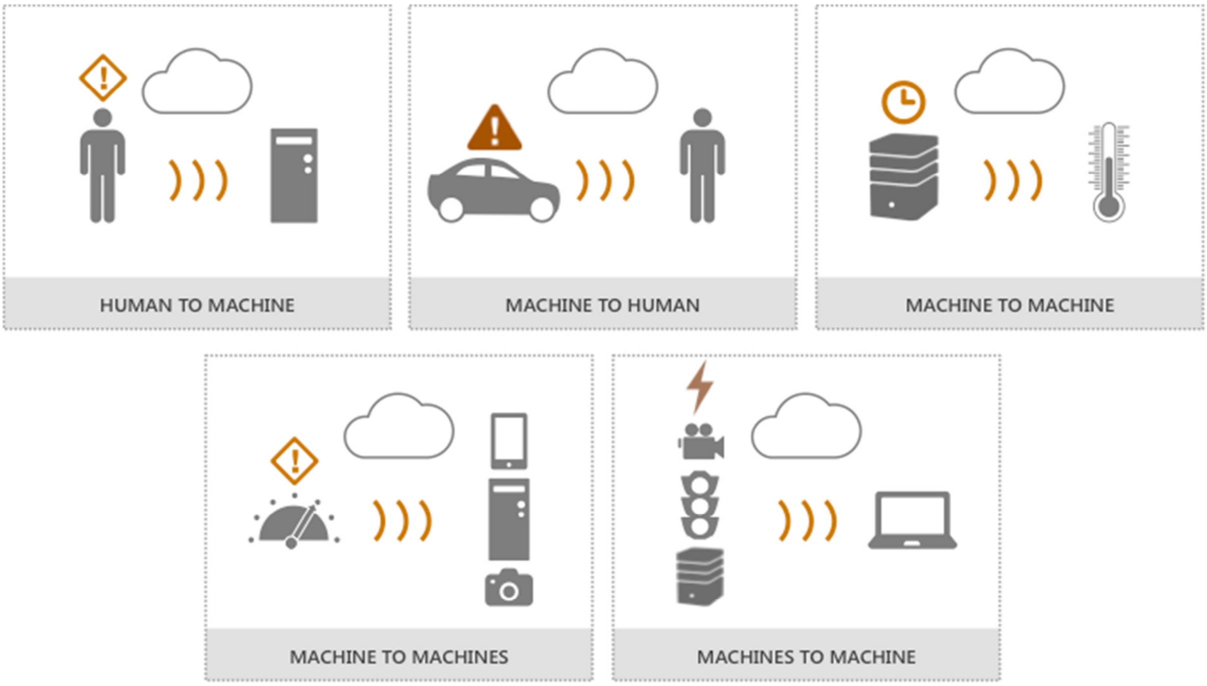
4.2.2 Illustrative applications

As is the case with people, not all of these potential connections are valuable. For example, there might be little reason for a citizen's home appliances to exchange information with a city's traffic lights. However, in many cases transmission between disparate machine and human users on the internet may be the source of important economic applications:

- **Human to machine** - Engineers using remote computers interacting with the safety systems of a compromised nuclear facility
- **Machine to human** - Early warning systems in cars along a motorway passing information to cars behind them giving drivers advance warning of a collision ahead
- **Machine to machine** – Industrial machinery control programs monitoring electricity spot prices overnight to determine the optimal time to run
- **Machine to machines** - Automatic warning beacons, set to activate under certain conditions (such as the detection of a forest fire), summoning help from all nearby listeners
- **Machines to machine** – City traffic control systems changing congestion toll levels in response to distributed sensing of congestion and pollution levels

An illustration of these uses is provided in Figure 25 below.

Figure 25 – An illustration of human and machine interactions over the internet



There is a vast range of useful connections. These possibilities are often categorised through the use of the adjective "smart" to describe more intelligent and more connected systems. Common examples include the smart city, the smart home and the smart grid.

In the smart city, transport, water and energy systems are made intelligent and able to respond flexibly to events such as traffic jams, high pollution levels and service outages. A number of cities around the world such as London, Yokohama, Nairobi, Newcastle, Rio de Janeiro and San Francisco[94] are actively pursuing these ideas. ABI Research reports that $8.1 billion was spent on smart city technologies in 2010, and that by 2016 spending is projected to rise to $39.5 billion[95].

The smart home is being actively pursued by companies ranging from Microsoft and Google to Lowe and Panasonic. The basic concept is to enable monitoring, control and interaction between numerous devices in the home. This would allow the automation of simple tasks, from lights switching on and off, to optimising the whole house usage of heating and electricity. Panasonic has even announced a smart indoor garden that uses sensors and cloud computing services to optimise the indoor growing of vegetables[96]. Smart home cloud services alone are expected to be a market valued at $6 billion in 2015[97].

The smart grid is discussed in greater detail later in this chapter.

4.3 The role being played by licence-exempt spectrum

> "Furthermore, the communication technology that bridges the air from a sensor to a regular node in the Internet has to bear up to the typical restrictions of a last mile in the IOT. It has to be wireless, robust, and, most of all, energy efficient. In some cases, the communication protocol must also enable security features, transport energy to run the sensor, or allow measurement of the distance (ranging) and localization."[98] – Professor Elgar Fleisch

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[94] See Osborne (2012), Hosaka (2010), Kamau (2011), Tweed (2010), Payton (2012), Falk (2012)

[95] ABI. "$39.5 Billion Will Be Spent on Smart City Technologies in 2016, Says ABI Research" (2011).

[96] Toto, Serkan. "Panasonic Shows Cloud-Based 'Smart Vegetable Garden' Device For Home Use." *TechCrunch*, 2012

[97] Cloud, On. "Smart home cloud services worth $6 billion in 2015" (2011).

[98] Fleisch, Elgar. "What is the Internet of Things ? - An Economic Perspective." (2010).

ABI Research, a research consultancy, projects that by 2016 there will be 365 million machine connections using cellular networks, and therefore licensed spectrum[99]. By extrapolating using the implied growth rate this could potentially rise to 800 million by 2020. Conversely, Machina Research, another research consultancy, expects there to be 2.3 billion machine connections to the internet using cellular technologies by 2020[100]. Even using Machina Research's larger estimates, in an internet of 50 to 100 billion intelligent connected devices less than 2% to 5% of all connections will use licensed cellular spectrum. In a wider internet of trillions of simpler connected devices the cellular representation becomes a very small fraction of 1%. The overwhelming majority of connections to the internet by things will use licence-exempt spectrum[101].

The reasons for this can be better understood in light of technical and commercial considerations.

4.3.1 Technical considerations

Perhaps the key reason why licence-exempt technologies are being used to provide the vast majority of machine connections is that homes, offices, factories, public buildings and outdoor spaces are increasingly blanketed by Wi-Fi networks. Most of the machines connected to the internet are likely to remain within a particular building or place that can be provided with connectivity – truly nomadic devices are likely to be a (potentially valuable) rarity[102].

There are a large number of widely used technologies utilising licence-exempt spectrum vying to extend internet connectivity to machine end points. Of this wide array, three important candidates are Wi-Fi, Bluetooth Low Energy and ZigBee[103]. Each has unique

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[99] Lucero, Sam. "Global Cellular M2M Connectivity Services Market to Rise to $35 Billion by 2016, Led by Automotive Telematics and Smart Energy"

[100] Research, Machina. "Machine-to-Machine connections to hit 12 billion in 2020 , generating EUR714 billion revenue" (2011)

[101] There may be a small contribution by other non-cellular licensed bands, but as shown below, the experience of the smart grid demonstrates that the greater research in and take-up of licence-exempt technologies tends to overwhelm proprietary licensed alternatives.

[102] For example, children's toys, household appliances, electronic card readers and security cameras are likely to stay put. Interestingly, even a number of nomadic devices worn by people such as internal defibrillators or tablet PCs can be considered fixed in relation to their users' smartphones. As such licence-exempt spectrum is likely to be prevalent in these connections also.

[103] In addition there are standards such as wireless HART, Z-Wave and many others.

properties that might suit some applications more than others. These are summarised in Figure 26 below:

Figure 26 – The varied attributes of licence-exempt technologies suitable for machine to machine connections

Wi-Fi	Bluetooth Low Energy	ZigBee
• Very high speeds (>5 Gbps) • 30-100 metre range • Moderate power consumption • Rich network architectures • Consumer electronics, industrial and scientific uses	• Medium speed (1 Mbps) • 10 metre range • Very low power consumption • Simple network architecture • Designed for mobile telephones and subsidiary sensor based devices,	• Low speed (250 Kbps) • 30-100 metre range • Low power consumption • Rich network architecture • Widely used in automation, mission-critical industrial, smart metering

Where high data rates are required Wi-Fi is an obvious choice. ZigBee has unique advantages when low power, fast connections and precise timing are required. Bluetooth Low Energy is increasingly being seen as a natural tool with which to connect smartphones with peripheral devices near the person, from pacemakers to sports equipment. This variety of technologies available allows solutions created using these licence-exempt technologies to be more closely tailored to the use cases that machine connections to the internet will require.

The roles played by machine terminals on the internet will vary tremendously, far more so than the various human users today. For example the connectivity requirements of a soil moisture sensor will be very different from those of critical safety monitors in a steel factory. The latter may have much stricter communications requirements, in terms of response time or uptime. Licence-exempt technologies can meet such bespoke requirements; indeed the ability of these technologies to respond quickly to market needs lies at the heart of the tremendous innovation they have seen over the last decade[104]. Licensed cellular based systems are often much more generalist in nature, making them less suited for more specialised tasks.

Some machine connections to the internet will be in devices that have access to mains electricity. However, many devices will be operating on batteries that may be difficult or inconvenient to replace frequently, for example, those found in bridge integrity monitoring or in pacemakers. In these cases licence-exempt networks can be designed to minimise the power draw of these devices, by using standards such as Bluetooth Low Energy or ZigBee

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[104] Thanki (2009)

and ensuring minimal transmission distances. Cellular-based systems communicating mobile operator's base stations are likely to use more energy.[105]

The final technical advantage that comes from the use of licence-exempt technologies is control over coverage area. Often we think of cellular networks as ubiquitous layers of connectivity, in fact there are a large number of not-spots, or areas without usable signals, that affect all mobile networks[106]. In these areas prospective users can do little to mitigate a poor connection. With licence-exempt technologies end-users are in control of the signal strength that they receive – in areas of poorer coverage they can deploy more equipment to boost the signal they receive.

4.3.2 Commercial considerations

In addition to technical factors there are a number of commercial considerations that favour the use of licence-exempt technologies in many types of machine connections.

The cost of licence-exempt solutions in many cases will be substantially lower than licensed solutions[107]. As is the case in the delivery of broadband, connectivity modules that use licence-exempt spectrum are likely to cost substantially less than modules that use the licensed spectrum of cellular networks[108]. In addition there are no on-going spectrum access costs with self-deployed licence-exempt networks as opposed to the data plans that are required to use cellular networks. This opens up the range of uses of licence-exempt technologies to a wider range of products as well as providing the convenience of a one-off purchase for buyers.

Another commercial attraction of licence-exempt technologies is the operational independence and surety that it grants its users. Once a network is built it can be run permanently with simply maintenance and upgrade costs as concerns. Faults and outages can be given a level of priority determined by the business whose operations have been affected. The operator of a multi-purpose cellular network will have to balance multiple

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[105] Balasubramanian, Niranjan. "Energy Consumption in Mobile Phones : A Measurement Study and Implications for Network Applications." *Energy* (2009).

[106] PA Consulting (2010)

[107] Some companies that have sought to acquire their own spectrum for their applications have failed to succeed in a number of markets. The example of the smart grid is given below. The reasons for failure include the diseconomoies of scale for bespoke equipment, the challenges of using narrow licensed bands and the costs of spectrum licences.

[108] Lawson (2012)

competing priorities. And finally, a real concern for users using a licensed band may be the very real possibility that the licence-holder repurposes the spectrum away from the technology they have used, rendering their equipment investment obsolete. For major networks such as smart metering deployments numbering in the many millions the scale of the costs imposed would be correspondingly large.

Licensed technologies will be technically highly suited to a relatively smaller number of specialist cases. For example the nationwide coverage of a cellular network works well for highly nomadic uses such as automobiles, supply chain vehicle tracking and mobile points of sale. In addition cellular data is likely to be one of the principal methods of backhaul from personal area networks comprised of Bluetooth enabled equipment.

4.3.3 The economic contribution of licence-exempt spectrum

It is clear that technologies using licence-exempt spectrum will play a pivotal role in enabling the internet of things, responsible for more than 95% of connections. To understand the value of the contribution of licence-exempt spectrum the counterfactual needs to be considered – how might the internet of things develop in its absence?

For some applications licensed cellular services might prove an effective substitute. Others might be possible to connect using a wired connection. In some countries an entity might even try to construct a 'private commons' collecting taxes or tithes from users it permits to transmit using this spectrum[109]. However, it is also plausible that a large number of the foreseen uses might not in fact be developed at all.

For example, a highly ambitious assumption might be that the methods above could reconnect 50% of the orphaned terminals of the internet of things were licence-exempt spectrum not available. This would result in a halving of the size of the internet of things.
It can also be optimistically assumed that the most valuable users are saved and only the least valuable – those whose additional connection possibilities were only one two-hundredth the average value of an existing human connection – have been lost. Under these assumptions, the resulting loss of economic value from the absence of licence-exempt spectrum would be $560 to $870 billion a year in 2020. This would imply that the economic contribution of licence-exempt spectrum to the internet of things could be over 30% of its

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[109] A theoretical construct in which an entity buys spectrum but allows certain permitted parties to use these bands to communicate. There are immense difficulties with global scale, the difficulty of collecting these taxes and perverse incentives for investment. Needless to say, such a scheme has not arisen in practice.

total value: by 2020 a yearly sum over twice the value of the entire consumer surplus of the internet today.

The preceding calculations are only an exercise in approximation, as stated they represent only a few lines of easily replicable and largely assumed transformations. However they demonstrate effectively the impact of network effects on extremely large networks: any effects that restrict the size of the network will severely limit its value. As has been shown comprehensively, licence-exempt spectrum will prove essential in allowing the internet of things to reach its maximum possible scale.

4.4 The role that could be played by new licence-exempt technologies

The existing globally licence-exempt bands at 2.4GHz, 5GHz and 60GHz will continue to see innovation and increasingly intensive use. A number of new technologies are being devised for these bands from new flavours of Wi-Fi such as 802.11ac in 5GHz and 802.11ad in 60GHz to new precise low power technologies in 2.4GHz. Each of these will extend and enhance the possibilities for machine communication. However, none of these technologies possesses the economic potential that is present in the TV white spaces.

The TV white spaces, being sub-1GHz spectrum, have particularly attractive propagation characteristics. Technologies using these bands will be able to communicate at long distances without line of sight, or at short distances using very little power[110]. This makes them perfectly suited for a number of situations needing seamless low power wide scale connectivity.

In larger homes or in buildings made of materials which block signals, the inclusion of a TV white spaces radio would ensure that appliances and devices would be able to connect with near certainty. White spaces could also find uses in battery powered devices, placed outdoors.

It is likely that Wi-Fi using the existing bands of 2.4, 5 and the upcoming 60GHz would meet most of an organisation's data heavy networking needs. However, the addition of a TV white spaces layer would provide a seamlessness that the other frequencies cannot, which could be important for ensuring connectivity to important devices:

- Constant monitoring – Patients' heart monitors in a hospital, Critical asset tracking

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[110] Cellular networks also use sub-1GHz spectrum, however power consumption is still high as devices with cellular connectivity will still need to communicate with potentially distant base stations.

- Constant connectivity – Beepers and call alarms of medical staff
- Complete coverage – Data coverage in large storage areas, underground

White space spectrum is perfect for outdoor usage, the excellent propagation means that outdoor long range coverage becomes much more cost effective. Its low power requirement could easily be harvested through the environment or kept topped up with a large battery. This could be used in a number of scenarios, such as:

- Environmental monitoring – monitoring pollution, water levels, forest fire alert systems and other such uses.
- Infrastructure monitoring – for bridges, aqueducts, dams, viaducts, pipelines, railroads and other remote infrastructure.
- Control systems – for agricultural machinery, toll booths, traffic lights, etc.
- Long hops in a mesh network – for example in city traffic management, local nodes could communicate using higher frequencies but could be linked to base with this spectrum
- Mobile elements within a city – coordinating mobile assets such as a taxi service, logistics or even public transport

With such a range of uses, it would not be surprising to see the TV white spaces eventually adopted in existing standards such as Wi-Fi and ZigBee[111] as well as the development of entirely new standards based in this band, such as the 'Weightless' standard proposed by the UK firm Neul[112].

4.5 The economic repercussions of spectrum unavailability – the example of Europe's smart grid

As detailed above, the emergence of applications using the internet of things has an immense economic potential. Furthermore, it has also been shown why the vast majority of the machine connections to the internet of things will use licence-exempt spectrum. The TV white spaces will also enable a large variety of new machine uses. However, at present, there is a global disparity in the progress being made to enable licence-exempt usage in this band.

This section attempts to illustrate and quantify the scale of economic benefits that might be created by allowing licence-exempt access to the TV white spaces. Specifically, it looks at the difficulties being experienced in Europe deploying smart electricity metering infrastructure

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[111] Zigbee has 10 channels for operation in the US in sub-1GHz spectrum but only 1 in Europe, severely limiting its usefulness. See Lee, Jin-shyan et al. (2007)

[112] See www.weightless.org

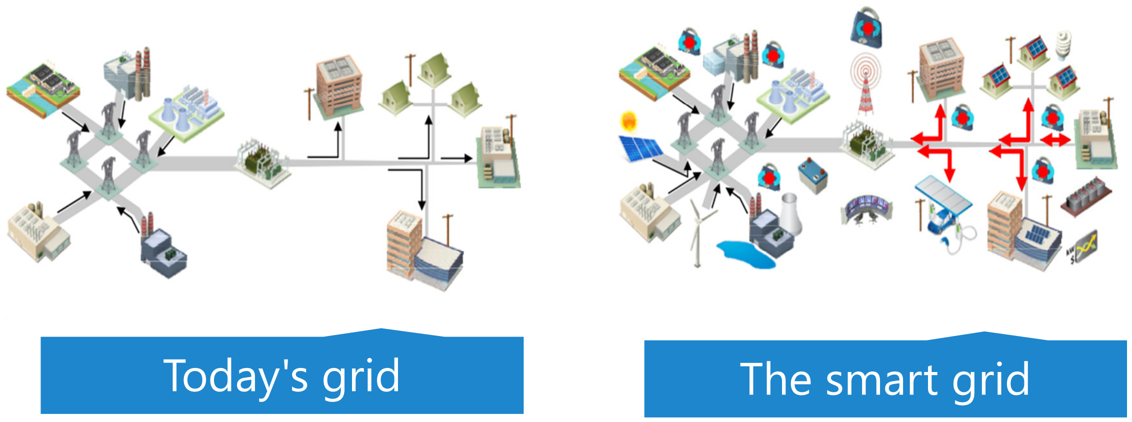
due to the lack of suitable sub-1GHz licence-exempt spectrum. Making available the TV white spaces on a licence-exempt basis can help ameliorate these costs.

4.5.1 The smart grid

Today's electricity grid is changed little from the system that was put into place in the 20th Century to facilitate the delivery of power from large centralised power stations to consumer premises. The limitations of this system are becoming rapidly apparent: it does not readily support micro-generation using renewable energy, it does not provide information to users about peak demand, and it is not ready to cope with the colossal challenges and opportunities created by widespread adoption of the plug-in electric vehicle.

Due to these shortcomings we are seeing the global upgrading of electricity networks. Many of these enhancements are being placed under the umbrella of the 'smart grid', whose essence is the creation of an electricity network enabling two-way information and power exchange between suppliers and consumers, thanks to the pervasive incorporation of intelligent communication monitoring and management systems. Figure 27 below shows the transition between today's infrastructure and tomorrow's smart grid.

Figure 27 – The transition to the smart grid[113]



The benefits that could be provided by such an upgrade have been well enumerated:

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[113] Illustrations taken from EPRI. "Estimating the Costs and Benefits of the Smart Grid" (2011). http://www.rmi.org/Content/Files/EstimatingCostsSmartGRid.pdf.

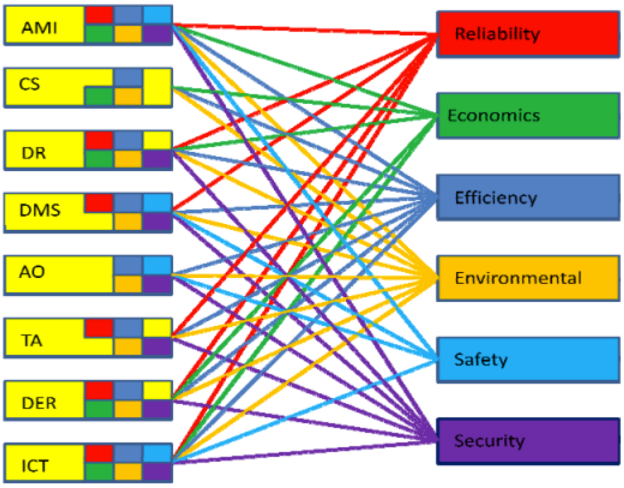
- Reliability – understanding consumer demand and better integrating diverse sources of supply will better allow demand to be met. A closely monitored grid will also be able to immediately respond to outages or potential problems.
- Economics – better markets in energy will be created as a smart grid will provide information on supply and demand conditions that parties can act on, to reduce their usage at peak times or supply more power to the grid.
- Efficiency – wastage and loss can be identified and eliminated, existing assets in the generation and distribution sectors can have their lives extended by careful management
- Environmental – better utilisation of wind and solar energy, lower overall demand for power, more scope for electric vehicles all work towards reducing CO2 outputs.
- Safety and security – a smarter grid will be more robust to deliberate and accidental mishap. In the event of a failure, customers who depend especially highly on electricity can be identified more easily.

However, achieving these benefits depends on the successful deployment of a number of technologies:

- Advanced Metering Infrastructure
- Customer Side Systems
- Demand Response
- Distribution Management System/Distribution Automation
- Transmission Enhancement Applications
- Asset/System Optimization
- Distributed Energy Resources
- Information and Communications Integration

The US National Energy Technology Laboratory characterises the relationship between these technologies and the potential benefits as shown in Figure 28, below.

Figure 28 – The links between the components and benefits of the Smart Grid[114]



Advanced metering has been called the 'backbone of the smart grid'. Indeed, once all end-points in the network are seen as both generators and consumers of power it becomes necessary to understand in detail the contribution and consumption of each.

Advanced metering infrastructure makes possible a number of applications. First it allows remote meter reading, permitting energy companies a near-real time picture of usage and the health of the grid. This same data can be used in customer side systems , access to real-time usage information has been associated with a usage reductions of 5-20%[115]. Finally, and perhaps most importantly, an advanced metering infrastructure enables distributed microgeneration and the storage of power in electric vehicles. Using both to supplement grid capacity effectively and smooth demand requires smart metering.

4.5.2 Advanced metering – different US and EU trajectories caused by spectrum availability

The difference between European and North American smart meter communications markets aptly demonstrates the role that the availability of suitable licence-exempt spectrum can play in a major technological transformation.

The chart below shows the sales of smart meters in Q1 2011 split by the type of communications technology used to communicate between the meters.

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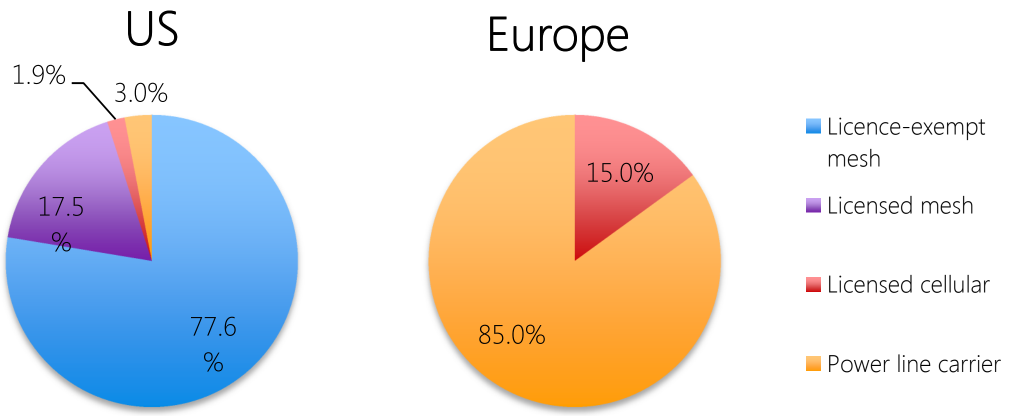
[114] Illustration reproduced from NETL. "Modern Grid Benefits" (2010).

[115] Darby, Sarah. "The Effectiveness of Feedback on Energy Consumption: A Review for DEFRA of the Literature on Metering, Billing and Direct Displays." (2006)

Figure 29 – The balance of technologies used in smart meter shipments in Q1 2011[116]



It is particularly striking that the large majority of the meters deployed in the US use licence-exempt spectrum to communicate but that meters in Europe only use power line carrier and cellular – technologies that are minority players in the US – and feature a complete absence of licence-exempt usage.

The cause of this imbalance can largely be attributed to the availability in the US of the 900MHz licence-exempt band, which provides 26MHz of spectrum possessing excellent sub-1GHz propagation characteristics. Although this allocation is not suitable for high-speed broadband LANs it is highly suitable for meshed smart meters.

Figure 30 below shows how a mesh network is organised.

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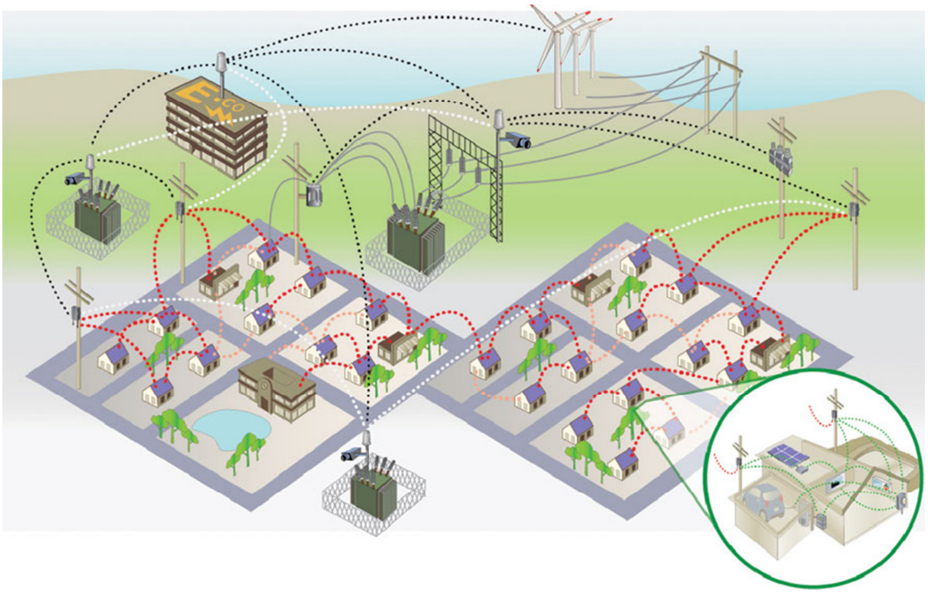
[116] Benkler (2011)

Figure 30 – The organisation of a mesh network for smart metering[117]



Such an architecture has a number of advantages that have led to its widespread adoption:

- **Cost effectiveness** – automatically forming meshes do not need concentrators or repeaters. Component costs for the widely used 900MHz band are also very low.
- **Security and control** – the resulting private network can be completely under the control of the utility in question, reducing the spans of responsibility and increasing security.
- **High bandwidth/low latency** – these networks can commonly achieve speeds to the meter of 100kbps and are upgradeable to 1Mbps. These speeds may not be necessary for basic meter reading but the future possibilities of the smart grid (such as variable time of day/geographic pricing, demand response and micro storage and generation, possibly using complex auctions) are likely to require high speed networks.[118]
- **Long term guaranteed access** – by its very nature, licence-exempt spectrum is used by multiple applications and so is unlikely to be reallocated.

However, in Europe (and the rest of the ITU regions 1 and 3) the available 900MHz licence-exempt band is heavily fragmented and restricted[119]. Therefore, European firms and governments have been forced to choose alternative technologies for the deployment of

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[117] Illustration reproduced from the website of Silver Spring Networks http://www.silverspringnet.com/

[118] As stated by Burlington Electric in Vermont, USA: "With regard to power line carrier, the transmission rates over power lines are very slow. These technologies tend to work well for bringing usage data back to the utility, but are not well suited for sending information to the meter or customer. Given the future functionality that BED anticipates the meters to need (and possibly required by Vermont state regulators) power line carrier technology was not a good fit."

[119] For example, the ZigBee standard can use 15 channels in the US, whereas in Europe it can use only one.

smart meters, primarily power line communications and cellular. Each of these has some benefits but also a number of disadvantages.

Figure 31 - Advantages and disadvantages of PLC and cellular systems in smart metering application

	Power line carrier (PLC)	Cellular systems
Advantages	• A controlled, secure network	• Uses proven reliable networks
Disadvantages	• Very low speed (<<100kbps) and high latency • Self-contained and difficult to expand (for example to mesh EV charging points in the future, etc)	• Power hungry • Expensive • Poor indoor coverage • Subject to network change and spectrum usage alterations (cell site changes and spectrum reallocation)

This European dilemma is creating problems for nations that have chosen both of these routes.

For example, Italy has been the world's leader at deploying smart meters and chose PLC technology. However, the majority of the meters deployed provide a bandwidth of only 2.5kbps[120]. This allows smart metering but severely hinders the next steps in the development of the smart grid. Furthermore, McKinsey reports that in Germany, where PLC is the chosen technology, one of the "big 4" electricity firms remains concerned about the bandwidth available[121]. In Scandinavia, McKinsey reports that there is pressure amongst operators to improve the outage detection capabilities of PLC solutions.

Unlike most of Europe, the UK is largely adopting cellular communications, specifically GPRS using 2G spectrum. However, this is creating problems in so-called mobile 'not-spots', which may include the locations of 10-15% of meters[122]. The UK programme has suffered a number of problems (technological, standards based, as well as political), and it looks increasingly unlikely that the Government's ambitious targets of deploying over 50 million meters 2019 can be met[123].

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[120] Cotti, Marco. "Smart Meters the technical potential and the commercial opportunities" (2010).

[121] Giglioli, Enrico, Cosma Panzacchi, and Leonardo Senni. "How Europe is approaching the smart grid." *McKinsey*, 2012.

[122] Morgan, Gareth. "Mobile not-spots impede smart meter rollout" (2011). http://www.computing.co.uk/ctg/news/2129040/mobile-spots-impede-smart-meter-rollout.

[123] Ravens, Stuart. "Cancelled British smart meter trials create risks for grid operators" (2012). http://ovum.com/2012/03/26/cancelled-british-smart-meter-trials-create-risks-for-grid-operators/.

Delays in installing sufficiently capable metering infrastructure threaten substantial economic costs. I have taken the comprehensive work done by EPRI on the benefits of the smart grid to the US and broadly adopted the numbers for the European context[124]. As the Figure 32 shows below, even slight delays to the stream of benefits that are expected from the smart grid project could impose substantial costs on the European economy.

Figure 32 - The economic costs from delaying the benefits of the smart grid

NPV of a delay in securing smart meter benefits ($bn)	Low benefits case	High benefits case
6 months	37	56
1 year	76	120
2 years	154	241

It is not unreasonable to believe that the lack of a key option in Europe to deploy the most fundamental pieces of the smart grid jigsaw could result in a 6 month delay to achieving its promised benefits. Even this minor delay would impose a one-off cost of $37 – 56 billion on the European economy. Should the delay extend to two years the costs would rise substantially: to $154 - $241 billion. These figures may understate the true costs if the replacement technologies used by Europe are not capable to delivering the full benefits of the smart grid[125]. In addition, Europe's lack of suitable spectrum has also likely created costs for regions where this spectrum is available, such as the Americas and Australia, by reducing the size of the global market in these bands and limiting competitiveness.

The scale of these costs may explain the decision of the Japanese regulator to open up the 920MHz band for licence-exempt use, and the rapid announcement by firms looking to exploit this band for smart metering mesh technologies[126]. Although Europe is restricted in its ability to follow suit, the TV white spaces offer an opportunity for not just Europe but all

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[124] I have adopted a very simple approach. First, the EPRI numbers are for the US and not Europe. I have scaled the benefits available by the ratio of electricity usage to population between the US and Europe. Then it has been assumed that the benefits from the smart grid accrue in proportion to the deployment of smart meters, with the full annual benefits being derived once the advanced metering infrastructure has reached a penetration of 100%. This is a substantial simplification but not unreasonable, given the importance of metering. The costs for Europe have simply been calculated by delaying the timing of the benefits stream.

[125] Which, when it comes to balancing bandwidth, cost and flexibility the evidence suggests that they might be – especially in future smart grid operations.

[126] OKI. "OKI Develops Japan's First 920MHz Frequency Band Wireless Multi-hop Communication System for Smart Communities" (2012).

nations to gain access to a global market in the next generation of machine applications. The economic consequences, which our analysis merely hints at, are likely to be enormous.

5 Creating robust and adaptable networks

Increasing connectivity between the people and the devices of the world is a trend that promises to deliver significant economic benefits. An increasing dependence on connectivity also carries risks. Traditionally, wired networks have been thought of as being more secure and resilient than wireless networks, and wireless networks built in licensed spectrum more reliable than those built in licence-exempt spectrum. However, evidence from applications in use and from new scientific understandings suggests that such distinctions are not as clear cut as they may seem. Indeed, local and wide area wireless networks relying, in part or in full, on licence-exempt spectrum are proving more robust and adaptable than networks built only to use licensed spectrum.

The introduction of technology using the TV white spaces will also extend the possibilities of licence-exempt operation. They will permit broadband links that span hundreds of metres and lower speed machine to machine links that span many kilometres. However, they can also be used at shorter distances to create highly reliable connections that can penetrate obstacles (intended or otherwise). White spaces will also provide a substantial boost to adaptability by enabling the creation of near ubiquitous networks very quickly in the case of disaster. It is not too surprising then that major white space technology trials are investigating disaster recovery capabilities.

5.1 The importance of robustness and flexibility in our global communications systems

Our global communications network is a multi-layered system composed of many different entities. On one level it is composed of the infrastructure over which communication takes place, from undersea fibre-optic cable to the Wi-Fi routers in homes and offices. However, the system also includes the commercial and non-commercial entities that own this infrastructure, as well as the organisations that provide services that run over the networks. In addition, these actors are affected by laws and standards set in place by the political process.

These systems have become central to our economic well-being. As described in Chapter 0, the internet is playing an increasingly important role in facilitating links between people, with substantial economic consequences. Furthermore, as shown in Chapter 3, the connection of an increasing number of previously unconnected objects promises a further potentially revolutionary change.

5.1.1 The importance of robustness

The importance of robustness for our communications systems can best be understood by contemplating the costs that would result from their failure. These are already high, and are likely to get higher – especially in the case of the internet. Different groups of users would be affected in different ways. However, the failure of internal systems or external connectivity are costly occurrences: in the United States alone CDW claims that one quarter of enterprise IT systems suffered unplanned outages of four hours or more in 2010 with an associated cost to businesses of $1.7 billion.

5.1.2 The importance of adaptability

Our networks will need the ability to change and adapt in response to a number of challenges.

1. Technological change will remain a constant force. It will affect the technologies that our networks are built using as well as the services that they will deliver. As existing technologies are refined and new technologies emerge our networks will have the task of integrating (or at the very least co-existing with) these changes.
2. A successful communications infrastructure will need to adapt to the needs of its users. For example, at present we are seeing a huge increase in consumer demand for broadband data download. In the future we may see a need for greater ubiquity, or wider uplink channels or for greater reliability of connections. In each case flexibility will be required.
3. From issuing licences for operation in certain spectrum frequencies to regulating the behaviour of last mile network operators –public policy is one of the key determinants of the structure and shape of our communications networks. However, although policy can change, or market events can render it obsolete, policy remains one of the key drivers of change in our communications networks.
4. As noted above, it is important that our communications systems are robust to shocks and disruption through technical malfunction or deliberate action. However, should our systems actually fail then it is important that temporary or permanent network services can be restored quickly to affected areas.

5.2 The robustness of individual licence-exempt links

There is a much repeated claim that technologies using shared access licence-exempt spectrum are necessarily less reliable than those that use exclusive use licensed spectrum, frequently serving as a prelude to calls for more exclusive-use licenced allocations.

However, a closer examination suggests that this assertion is based on a fundamental misconception of licence-exempt operation as well as too simplistic a notion of reliability. In reality, there are both challenges and benefits that come from licence-exempt operation, just as there are with operation in exclusive-use licensed spectrum.

5.2.1 The challenges of life in a noisy environment

The fundamental aim of wireless communication is to convey information between a sender and a receiver using radio energy. However, in addition to picking up the message carrying radio energy (the signal) a receiver will also pick up unwanted energy (noise) – this could come from other transmitters, other electrical processes or even from radioactive rocks and sources in space. For a message to be correctly received the wanted signal has to be discernible from the noise.

Operators using licensed spectrum are normally granted the ability to use higher power transmissions and the guarantee of a relatively noise free environment. These operators can therefore economise on costly network infrastructure roll-out. However licensed networks are still subject to noise from natural sources and perhaps more seriously noise from operations in neighbouring frequency bands[127].

Unlike their licensed counterparts, licence-exempt technologies operate in bands of spectrum where they are not guaranteed exclusivity of operation. This means that in addition to natural sources of interference they may also receive interference from other users of the band, translating to a noisier operating environment. In addition, they tend to be restricted to lower power levels.

Therefore, the essential challenge for operation in licence-exempt bands is to construct networks that can cope with lower power levels and higher and more uncertain noise conditions.

5.2.2 The benefits of life in a noisy environment

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[127] Due to the imperfections of radios, transmitters tend to radiate energy into bands outside their intended frequencies and receivers tend to be sensitive to energy in adjacent bands. In fact, this latter effect can be very serious. For example, in the USA for four years police and fire radio systems began experiencing interference from the operations of Nextel in the adjacent band before the FCC reorganised the frequencies see: http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-04-168A1.pdf

In spite of the challenges described above there are a number of reliability advantages that come from operating in the licence-exempt bands. The principal benefits are network control and a faster introduction and development of reliability enhancing innovations.

5.2.2.1 Control over network structure

For most firms and organisations the use of dedicated licensed spectrum for a particular purpose is largely out of the question. The acquisition of spectrum licences can often prove costly and difficult. Even if an operator or firm has licensed spectrum available the cost for bespoke wireless equipment is generally substantially higher than equipment designed for mass-market licensed or licence-exempt technologies. Moreover, spectrum licences for specific uses tend to cover only very narrow frequency ranges, affecting the capacity and reliability of the ensuing network[128]

Given these constraints, the options to companies are often limited to either using licence-exempt solutions or to use services that run over general purpose licensed cellular networks.

A key factor that often makes the licence-exempt option more robust and reliable than the licensed approach is that it affords the end-user greater control over the set-up of the network to be used. This has a number of advantages from the perspective of reliability.

Principally, the network can be engineered to provide the degree of reliability required. For a non-critical system a sparse network can be rolled out in which costs would be kept down but links would be more susceptible to being impaired by noise. For a critical system a dense deployment can be used in which signal strengths can be kept high between links to address issues caused by noise and other interference. This level of customisation by the customer is not normally possible when using cellular products, as the strength of a cellular operator's signal at a particular point cannot be altered. As shown in the previous chapter this has caused substantial problems with smart metering products based on cellular technology.

In addition a self-run network using licence-exempt spectrum also provides operators with greater independence from third parties. Their network will not be subject to the decisions by network operators to replan their frequencies or base stations; they will not be sharing bandwidth across the network with other users and responsibilities for repairing faults and for changing performance parameters will be retained. These factors can lead to greater reliability.

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[128] These factors together largely explain why licensed mesh solutions are lagging in smart grid applications – as was shown in the previous chapter.

5.2.2.2 A faster evolution of robust intelligent equipment

Licence-exempt communications were first approved for the international ISM spectrum bands. Due to the high-powered industrial processes that used these bands this spectrum was considered to be 'junk', unsuitable for any other use. However, as shown in this report, in twenty-five years the 2.4GHz band alone has been transformed through licence-exempt operation into one of the most economically important bands of spectrum in the world. Critical to this success has been a rapid pace of technological innovation in licence-exempt bands, many aimed at improving reliability in a noisy environment.

From their inception licence-exempt spectrum devices have been designed to combat expected channel noise. Licence-exempt communications adopted more resistant digital encoding more than five years before cellular technologies and Wi-Fi was the first major communications technology to utilise spread spectrum – originally used by the military for robust undetectable communication. Wi-Fi also pioneered the use of the more robust OFDM modulation method. More recently advanced antenna techniques that allow spatial multiplexing and beamforming have been introduced first into Wi-Fi, enabling greater throughput or more robust links at a given power output[129].

Figure 33 below shows that Wi-Fi has led cellular systems in the introduction of these techniques.

Figure 33 – The years of introduction of various radio technologies into Wi-Fi and cellular[130]

	Wi-Fi	Cellular
Digital signal encoding	1985	1991
Spread spectrum	1991	1995
OFDM	1999	2006
MIMO/Adaptive beamforming	2004	N/A

The effect of these technologies has been to expand the performance of Wi-Fi and to maintain and improve its reliability even in the presence of higher noise levels. This can be seen in a number of metrics: spectral efficiency, speed and range have all improved

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[129] In exactly this vein, a team of researchers at the TFA has recently demonstrated how it is possible to use orbital angular momentum (or twisting) of radio waves to dramatically increase the information that can be encoded into one spatial frequency channel. The researchers used modified Wi-Fi equipment to conduct their tests and it is highly likely that this innovation, if borne out, will appear first in licence-exempt spectrum.

[130] Reproduced from Thanki (2009)

substantially. However, the ability for Wi-Fi hotspots to co-exist perhaps underlines the scale of the improvement in performance. In 2000 the consultancy Aegis made a prediction that outdoor Wi-Fi use would be virtually impossible in the UK and that indoor use would permit a density of 40 points per square kilometre[131]. The reality has proved to be very different. A 2008 study found a Wi-Fi node density of just over 2,000 nodes per square kilometre in parts of London. The intervening four years have seen an explosion in Wi-Fi adoption[132]. The commune of Levallois-Perret in Paris is likely to now have a density of over 25,000 access points per square kilometre[133] (with Paris as a whole having a density of over 21,000).

Unlike devices operating in the licence-exempt bands, those in licensed spectrum have been protected from noise created by other users. In some licensed applications, this has reduced the incentives for spectrum owners and device manufacturers to strive to improve the performance of their equipment, or the configuration of their networks, contributing to spectral inefficiency[134]. In contrast, the dynamics of licence-exempt spectrum have encouraged efficient and innovative equipment that is better able to cope with a noisy environment.

5.2.3 Critical uses of licence-exempt links

Testament to the exceptional reliability that can be achieved with licence-exempt technologies is their use in a wide range of critical uses and applications. This ranges from control networks on oil rigs[135], medical instrument connections[136] to safety networks in mines[137] and use in corrosive and hazardous industrial processes.

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[131] Leeson, Helena, Paul Hansell, Ceng Miee, John Burns, and Ceng Miee. "Demand for use of the 2.4GHz ISM Band" (2000). http://www.aegis-systems.co.uk/download/ISM2.pdf.

[132] Strategy Analyics (2012)

[133] The population density of Levallois-Perret is 67,984 per square kilometer, average household size in Paris 1.75 (from http://www.paris.fr/english/presentation-of-the-city/demographics-a-cosmopolitan-city/rub_8125_stand_29896_port_18748) and the Wi-Fi penetration in France is 71.6% (Strategy Analytics, 2012).

[134] Some other licensed applications, such as cellular networks, have been more focused on efficiency since mobile data has become a popular product.

[135] For example, see "Deploying an Explosion Proof Wi-Fi Network for Oil Rigs." *cellular-news*, 2008. And "Wi-fi on offshore oil platforms - Invensys." *Finding Petroleum*, 2007.

[136] "Aruba Networks Reports Record Fiscal Third Quarter 2012 Financial Results." *MarketWatch*, 2012.

[137] Raghuram, P., and Veeramuthu Venkatesh. "Enhancing mine safety with wireless sensor networks using ZigBee technology" 37, no. 2 (2012).

5.3 The robustness and adaptability of networks built with licence exempt links

As detailed throughout this study, licence-exempt links are increasingly being used in a wide variety of applications and contexts. Numerous networks are being built exclusively using licence-exempt spectrum, from broadband delivery networks to machine to machine communications systems. Even traditionally licensed cellular networks are increasingly adopting licence-exempt technologies, both for providing connectivity to the end user as well as for future small cell backhaul.

These changes will profoundly affect the way in which our global communications networks are structured. A key question is to understand whether these increasingly licence-exempt networks will be robust and adaptable.

5.3.1 The importance of architecture and bottom-up construction to robustness and adaptability

It may seem initially that the goals of robustness and adaptability in a system so complex are mutually exclusive, but can a system be both robust and flexible?

From everyday experience, toughened systems designed to survive shocks and extreme conditions are not noted for their flexibility. There are numerous examples where this is the case, from fortified housing and clothing to emergency communications systems. In general, as systems are hardened to be able to complete a particular task their level of specialisation increases. As observed by the evolutionary scientists James Whitacre and Lawrence Bender, "evolvability and robustness are often in conflict within systems derived through human planning".

However, we know of a number of systems that are extraordinarily complex and yet also display high levels of both resilience and adaptability. These include many natural systems, such as genetic codes[138] and ecosystems[139], as well as a number of largely unplanned human systems, ranging from languages[140] to the dabbawala delivery system in Mumbai[141]. In

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[138] See Whitacre, James M. "Degeneracy: a link between evolvability, robustness and complexity in biological systems." *Theoretical Biology and Medical Modelling* 7, no. 6 (2010).

[139] Ecosystems can display an astonishing degree of flexibility and reorganisation. See Levin, Simon A. "Ecosystems and the Biosphere as Complex Adaptive Systems." *Annual Review of Ecology and Systematics* (1998): 431-436.

[140] For a good introduction to the notion of language as a complex adaptive system, I would recommend Beckener, C. "Language is a complex adaptive system." *Language Learning* 59, no. 1 (2009).

recent years these have been the focus of much study and investigation and our understanding has grown of the characteristics that might lead to these outstanding properties.

One of the key insights has suggested that a major source of these characteristics in natural systems is the presence of components and/or processes whose functions are not identical but overlap in different conditions[142].

Perhaps the best example is the action of the genetic system. Developmental processes are remarkably resistant to change, in many cases able to produce near identical organisms (similar phenotypes) even when DNA has been altered through natural mutation or scientific manipulation. However, these same genetic networks have a remarkable capacity to change very quickly. Sometimes they are able to produce varied organisms in response to environmental stress or to able to produce very new, potentially better suited organisms, from relatively small changes to the genetic code.

Other examples of robust and adaptable systems include:

- biological systems possessing two enzymes, possessing different roles but both able to speed up the same chemical reaction,
- ecosystems possessing two animals (such as foxes and falcons) whose range of prey overlaps in specific cases (such as for rabbits), and
- languages containing words whose meanings overlap in certain contexts but not in others.

A similar pattern of examples is being found in many fields of study, ranging from ecosystems science[143] to linguistics[144], from climatology to urbanism, and from computing to economics.

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[141] The hot lunch delivery system in Mumbai moves around 200,000 lunches every day with an astonishing accuracy. It is largely staffed by illiterate men and women in an organisation that has emerged with little central planning. See Harding, Luke. "A Bombay lunchbox." *The Guardian*, 2002.

[142] Edelman, Gerald M, and Joseph A Gally. "Degeneracy and complexity in biological systems." *Proceedings of the National Academy of Sciences* 98, no. 24 (2001): 13763-13768. This work is seen as one of the foundations of recent research in this area, inspiring a large body of research.

[143] Given the great diversity among organisms on earth, most ecosystems only changed very gradually, as some species would disappear while others would enter. However, certain changes, such as the emergence of a disruptive new species or environmental stress beyond a certain point can cause a rapid change in an ecosystem, from one evolving equilibrium to another.

[144] the majority of the words and grammatical structures in a language can be very resistant to change over time. However, in response to some conditions either whole languages or large parts of them can be subject to substantial change.

These overlapping processes and entities create the conditions for both robustness and adaptability: robustness because the system is buffered against the deletion of any particular entity, and adaptability because multipurpose components allow the system to reconfigure quickly. In contrast many human designed systems are designed in such a way that components have a very specific role and are organised in a hierarchy. For example, the wheel of a car is only able to be driven by a single axle and the components in a computer communicate through a central processor. When human systems are designed for resilience we tend to put into place backup systems and components which replicate precisely the role of the components whose failure we are guarding against, such as a spare battery for a car, a redundant data link in a network. This addition of redundancy has been found to make a system more robust but does not allow it to respond in an adaptive way if any particular component is exhausted[145].

It is also notable that each of the resilient and adaptable examples discussed here has resulted from a bottom-up evolutionary process. This is as evident in natural systems such as genetics as it is in resilient and dynamic human systems, such as musical form and armed insurgency. Indeed, the science of complexity is primarily concerned with systems whose unexpected properties emerge from the interplay of simpler units.

5.3.2 The architecture of our communications and its fragility

There is a disparity between the structure of our communication and that of the networks over which this communication happens.

The structure of our communication has a generally diverse form. People in social networks are normally connected to each other through multiple different routes; web sites have a similarly diverse link structure as do the internet servers that web content is delivered over. As well as reflecting the basic organisation of our society, these structures are changing our organisation by allowing new productive links to be formed, and distributing economic, political and social networks across spatial boundaries.

Although the core of our communications networks has also long employed a diverse structure, the edges of networks are often organised in a highly hierarchical tree structure. For example, in fixed networks the end user is connected via a single cable which links to a

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[145] Whitacre (2010) reports that Tononi et al found that alternative highly redundant (non-degenerate) systems were naturally robust but never hierarchically complex

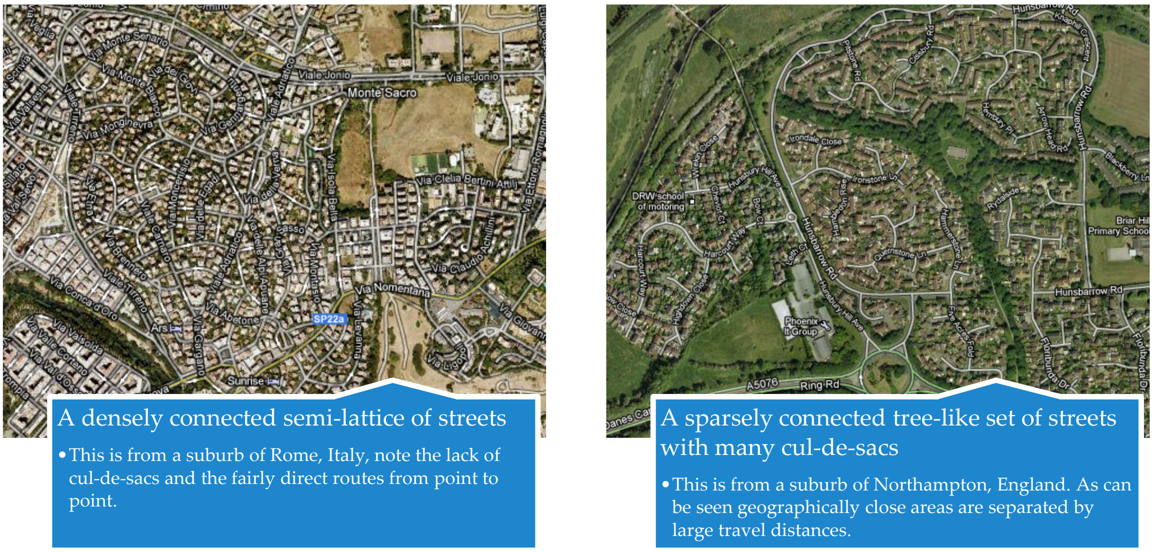
single exchange. Similarly, in mobile networks a single cell covers a particular geographic area.

The possible effects of a disparity between behaviour on a network and network structure found a very clear expression in a noted 1965 essay, "A City Is Not a Tree", by the mathematician and architect Christopher Alexander[146]. He contended that there exists a significant difference between the structure of 'natural' cities: those whose densely-connected structure has emerged in the absence of a grand design, and planned cities: those which have been designed as a neat tree-like hierarchy by master planners.

The network structure of the streets of the natural city can often be translated into a densely connected structure forming almost a tangled web or a dense grid. Whereas the connection structure of many examples of the planned city and suburbs are often tree-like, possessing a neat hierarchy characterised by a repeated branching process.

Figure 34 below shows examples of both type of structure.

Figure 34 – Comparison of a densely interconnected and a tree-like road system



A densely connected semi-lattice of streets

- This is from a suburb of Rome, Italy, note the lack of cul-de-sacs and the fairly direct routes from point to point.

A sparsely connected tree-like set of streets with many cul-de-sacs

- This is from a suburb of Northampton, England. As can be seen geographically close areas are separated by large travel distances.

Alexander's central argument was that the tangled web structure both reflected the social and economic organisation of human society, and also facilitated these processes. A number of problems and issues with planned cities and suburbs have been ascribed to their tree-like

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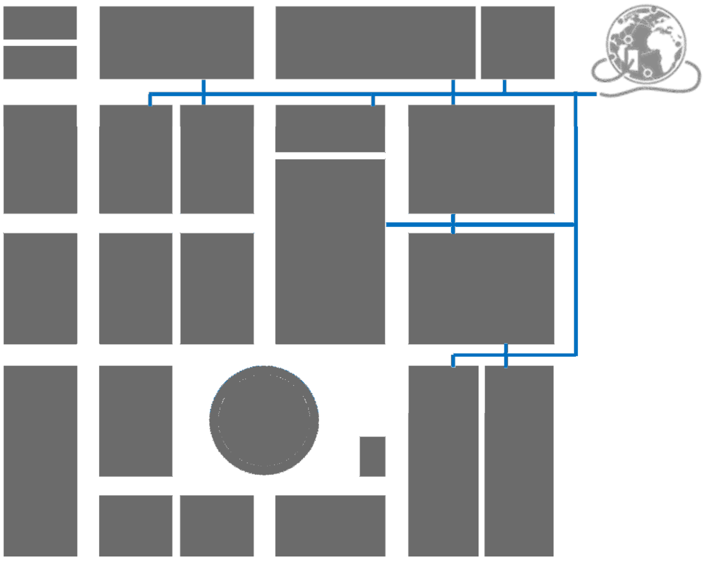
[146] Alexander, C. "A city is not a tree." *City* (1974). http://isites.harvard.edu/fs/docs/icb.topic1050153.files/A City is not a Tree.pdf.

architecture. Perhaps chief amongst these are those of route inefficiency[147], congestion[148] and fragility[149]. However, the attraction of this design is that it is cheap to build[150], with the savings accrued by the developer and the costs passed on as externalities.

An analogous set of considerations apply to our communications networks. Due to their tree like structure single points of failure can cut off local areas or even the whole network. However, these networks are organised in this way because it minimises the costs faced by a large organisation of covering a large number of people.

Figure 35 – A fixed communications network possessing a tree-like structure and therefore many points for failure



5.3.3 The robustness enhancing effects of licence-exempt operation

The growing use of licence-exempt technologies may create a greater robustness in our communications architecture.

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[147] In which moving small geographic distances requires large transport distances and also makes public services such as refuse collection costly to provide

[148] Caused by the profusion of dead ends and more frequent car journeys causing collector roads to become very busy very quickly

[149] As a single obstructed road can prevent access to many homes.

[150] As developers have to lay less tarmac and can fit more homes onto a piece of land. One analysis (Bradford 2009) finds that around 66% less roadway needs to be laid in a tree structure than in a more connected grid.

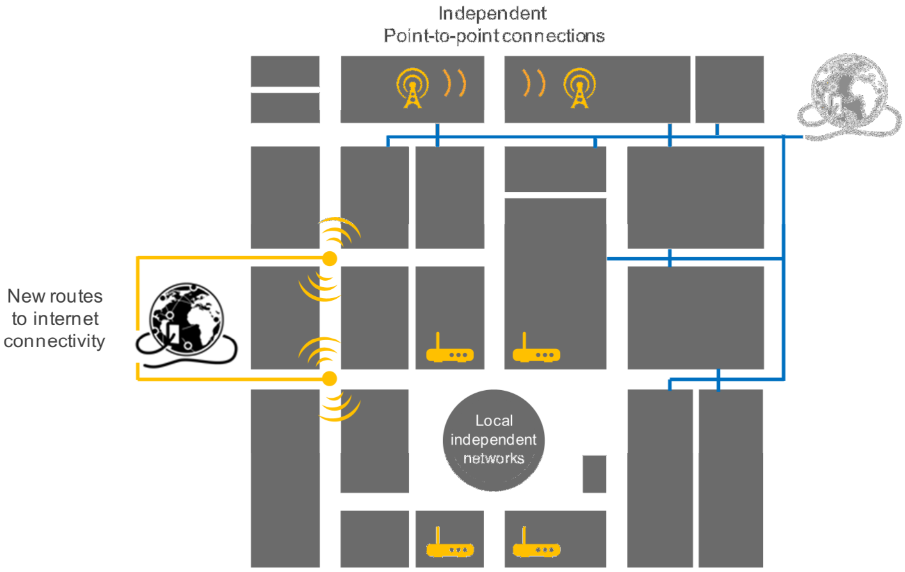
As shown in Chapter 0, licence-exempt spectrum has served to create a denser more diverse broadband delivery architecture. By decreasing the costs of creating network connections, licence-exempt spectrum is enabling new operators to roll out networks and existing operators to create denser deployments. This adds to resilience to broadband access in a number of ways:

- End-users have more routes to gaining connectivity – the failure of one system, or sub-system, is less likely to mean a total loss of connectivity.
- Greater capacity in the system – each deployed Wi-Fi access point, small cell or wireless base station adds to the total capacity of the whole system, making it more reliable to deal with spikes in demand.

The development of a multitude of independent networks that has been fostered by licence-exempt technologies has also created a substantial degree of robustness. For example, home users have created networks for entertainment or automation. Businesses use local networks for control and monitoring purposes, and wireless p2p links between their premises. Local governments have built city-wide networks as have private firms seeking to provide broadband. Each of these uses creates new networks and new functions that may only be loosely coupled to our traditional WANs and may be resilient to their failure. The use of independent networks also removes traffic from existing traditional wide-area networks, enhancing their reliability.

As shown in Figure 36 below, the addition of licence-exempt networks of all kinds are creating a much denser, more diverse and overlapping communications system.

Figure 36 – The diversity and robustness enhancing effects of licence-exempt spectrum



5.3.4 The adaptability-enhancing effects of licence-exempt operation

The widespread adoption of licence-exempt technologies has also had a positive impact on the adaptive capacity of our communications networks.

It has been described above how licence-exempt spectrum has encouraged technological innovation in devices. However, it has also spurred an innovation in business models. As detailed in the previous chapter with the example of broadband provision, a business model that uses licence-exempt spectrum can be much lower cost than one that depends on building fixed networks or networks in licensed spectrum. Access to the transmission medium is free and guaranteed and sunk costs are low due to the commoditised equipment. The costs of failure under a licence-exempt model are low – enabling new businesses to form quickly in response to innovative ideas and market demand and necessity – substantially enhancing adaptability.

Perhaps the clearest example of the adaptability that licence-exempt spectrum has encouraged is the ability of these technologies to responding to crises and change. Building networks using licence-exempt spectrum is quick and requires no authorisation. This makes it highly suitable for providing coverage across an area that has lost coverage or one that quickly needs greater capacity.

In emergency situations, such as the aftermath of a natural disaster or terrorist or military attack, telecommunications networks using fixed connections or licensed spectrum often fail. The repair of these networks requires specialised personnel or replacement equipment which may not be readily available or may not be forthcoming. The deployment of a licence-exempt network, however, may not require any specialised equipment. Off-the-shelf components or repurposed home and office Wi-Fi access points can be stitched together by any entity to create broadband networks. Such a response was seen in response to the Japanese Tsunami[151], Hurricane Katrina[152] and the Haiti earthquake[153].

Local spikes in demand, such as during a special event, can cause mobile networks to fail. It is increasingly common for organisers to deploy licence-exempt spectrum based solutions to address this extra traffic (for example, at the Sundance Film Festival or the forthcoming

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[151] FON networks worked to make its network of 500,000 Wi-Fi hotspots in Japan open access for the duration of the emergency.

[152] "Volunteers Use Mesh, WiMax, Wi-Fi in Katrina-Hit Regions." *WNN*, 2005.

[153] Lawson, Stephen. "Haiti Wi-Fi network links relief centers", 2010.

London Olympics). As SIM based authentication onto existing Wi-Fi networks (discussed in Chapter 0) becomes more common it may in fact become less necessary to deploy additional base stations and other infrastructure.

5.4 The role of upcoming licence-exempt technologies

A number of the upcoming innovations in licence-exempt spectrum which are already covered in this report are likely to have a role in enhancing the trends detailed above, and so impact upon reliability and adaptability.

New revisions of existing standards are being optimised along a number of dimensions, including lower power consumption, lower cost, higher throughput and more effective network formation. In addition the introduction of new high-frequency spectrum bands, such as 60GHz, will provide new possibilities. Each of these changes is likely to make feasible a number of new applications, increasing wireless density and diversity, which, as shown above, is closely related to the overall resilience and adaptability of a network.

However, perhaps the most significant impact in this area could be from the usage of the TV white spaces. This band provides excellent propagation characteristics, substantial bandwidth and a potentially global market. These characteristics could lead to uses that both enhance resilience and flexibility.

With respect to reliability, as described in Chapter 0 the TV white spaces will find a use in enabling a wider layer of broadband connectivity in both rural and urban areas. This will further diversify the mechanisms that we use for connecting people. In addition, as detailed in Chapter 1, the TV white space spectrum is likely to enable a range of machine-to-machine applications. In many parts of the world, without the TVWS there would be no spectrum suitable for many of these uses and they might have to resort to using general purpose networks – thus increasing their traffic loads as well as the negative consequences of their failure.

White spaces will also provide a substantial boost to adaptability. At present Wi-Fi and other technologies are used by citizens, rescue groups and authorities to create networks in the aftermath of a crisis that disables fixed and mobile networks. However, the propagation characteristics of the 2.4GHz band limit the range and thus the efficacy of these efforts. If TV white space devices were widely available they would enable people to create near ubiquitous networks very quickly in the case of a disaster. Such a use case is being trialled in Japan and Korea, two countries particularly susceptible to natural disasters and which unfortunately have experienced the disastrous consequences of networks lacking robustness and adaptability.

6 Policy implications and directions for further work

This paper has demonstrated the substantial economic benefits that are being delivered by technologies using licence-exempt spectrum. Licence-exempt technologies already carry the majority of the world's internet traffic, they will connect 95% of the devices in the internet of things, and they are enabling the bottom-up creation of a diverse and functionally complex data architecture that is both strikingly robust and near infinitely adaptable.

Policy makers and regulators have an important role to play in achieving and amplifying these benefits. I believe that the evidence available justifies three courses of action:

1) There is an overwhelming case for enabling licence-exempt access to the spectrum in the TV white spaces;
2) Requests that many hundreds of megahertz of spectrum be set aside for exclusive use licences should be treated with caution – the risks of regulatory and market failure are great; and
3) The standard economic model of spectrum, as a "finite natural resource", needs to be reassessed – it provides neither the insight nor nuance required to craft good policy.

6.1 The overwhelming case for licence-exempt access to TV white spaces

This report has considered the role of licence-exempt spectrum in three areas: delivering broadband connectivity to people, facilitating machine to machine connections and networks, and developing robust and adaptable networks. In each case the benefits currently being delivered by technologies in licence-exempt spectrum are hamstrung by a common factor: the lack of a harmonised globally available broadband-capable band of licence-exempt spectrum in sub-1GHz spectrum.

Neither existing fixed nor mobile networks will be able to deliver truly universal connectivity – that which is both available and affordable. The cost bases of both approaches are too high as are the barriers to competitive entry. Licence-exempt spectrum is being used to extend broadband to places that have no other means of connectivity. However, all of the bands capable of delivering broadband speeds exist at higher frequencies in which line of sight connections are required for longer links – effectively limiting the possibilities of licence-exempt technologies. However, sub-1GHz spectrum will allow more challenging links to be made in rural areas and allow more seamless layers of coverage in urban areas

For machine to machine applications in the internet of things sub-1GHz spectrum offers the ideal spectrum for a large number of use cases. For example, it has low power requirements enabling batteries to last much longer and it has excellent penetration allowing mesh networks to be formed more easily and sparse networks such as environmental monitoring systems to be deployed cost-effectively. In Europe the lack of usable licence-exempt spectrum in the 900MHz band has limited the capabilities and roll out of smart electricity meters in comparison to the US and Australia. The costs to the European economy will be in the tens of billions of dollars. Given the scope of the internet of things the total cost across all applications could be an order of magnitude greater.

Finally, the availability of sub-1GHz spectrum would allow a larger variety of licence-exempt architectures to be constructed in a bottom-up fashion enhancing both the robustness and adaptability of our communications networks.

The TV white spaces offer possibly the only realistic avenue by which a globally harmonised approach to licence-exempt sub-1GHz spectrum can be achieved. The economic possibilities are enormous. Given the additional reassurance that a geolocation database driven approach provides, regulators should move decisively to enable licence-exempt access to these bands.

6.2 Finding an efficient balance of new licensed and licence-exempt allocations to meet the world's growing demand for data

At present policy-makers around the world are being warned of an impending "spectrum crunch" due to the increasing demand for mobile data services. The solution to this problem, it is argued, is to create new exclusive-use spectrum rights: either by clearing and reassigning existing bands or by restricting the use of dynamic access radio technologies to particular licensed users (a scheme known as Authorised Shared Access[154]).

However, it should not be forgotten that the capacity of a network is directly proportional to two variables: the quantity of spectrum available and the number of sites deployed. It is therefore equally valid to say that mobile operators are suffering an "infrastructure crunch"; as they attempt to serve a growing volume of traffic attempting to maintain sparse network structures that were originally designed to provide outdoor voice services and not ubiquitous, largely indoor, data.

Before acting, policy-makers should consider a central question: what balance of additional licensed/exclusive-use and licence-exempt/open access usage rights is most likely to expand access to broadband and meet the growing demand for data?

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[154] More details can be found at http://ipsc.jrc.ec.europa.eu/fileadmin/repository/sta/corsa/docs/SDR_ASA.pdf

The analysis in this paper has shown that a strong case can be made for licence-exempt access as a major part of the solution. The majority of the traffic from PCs, laptops smartphones and tablets is carried over Wi-Fi. This is made possible because licence-exempt usage encourages the intensive reuse of spectrum by entity and geography. The aggregate spectral efficiency of the 2.4GHz is at least 30 times greater than the overall efficiency of any cellular band[155]. This represents a substantial amount of wireless capacity. Simple equilibrium economics suggests that this is driving down prices and encouraging use and take-up. In addition, the licence-exempt bands have encouraged innovation in radio technologies as well as business models.

In contrast the licensed bands are full of 'white spaces' where operators have not rolled out services and licence conditions prevent anyone else from doing so[156]. There is no evidence to suggest that a greater reliance on exclusive-use spectrum licences, whether through traditional licensing or by using ASA, has the potential to alleviate the spectrum inefficiency or oligopolistic markets that are the hallmark of a number of licensed spectrum applications.

Currently we are seeing a movement in the mobile industry towards small cell sites and an increasing reliance on Wi-Fi. Furthermore SIM-based authentication techniques for Wi-Fi networks have the potential to allow cellular operators to tap into vast reserves of capacity. At this juncture, for regulators to accede to requests that almost 1GHz of spectrum be made available in perpetuity on an exclusive-use basis carries an extremely high risk of regulatory failure leading to market failure.

6.3 Building economic theory around a better understanding of 'spectrum'

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[155] For example, analysis of the Mobidia data shows that Wi-Fi (overwhelmingly using the 85 MHz available at 2.4 GHz) is delivering over 4 times the traffic of the mobile licensed bands (which use at least 120 MHz in the 2.1 GHz band) in most countries surveyed. Furthermore the 2.1 GHz band is used only for mobile communications whereas the 2.4 GHz band is used for a multitude of other uses. Since fixed traffic is also predominantly carried over Wi-Fi in the 2.4 GHz and that fixed traffic is an order of magnitude higher than mobile, the true aggregate spectral efficiency of the 2.4GHz licence-exempt band may be easily two orders of magnitude greater than any licensed band.

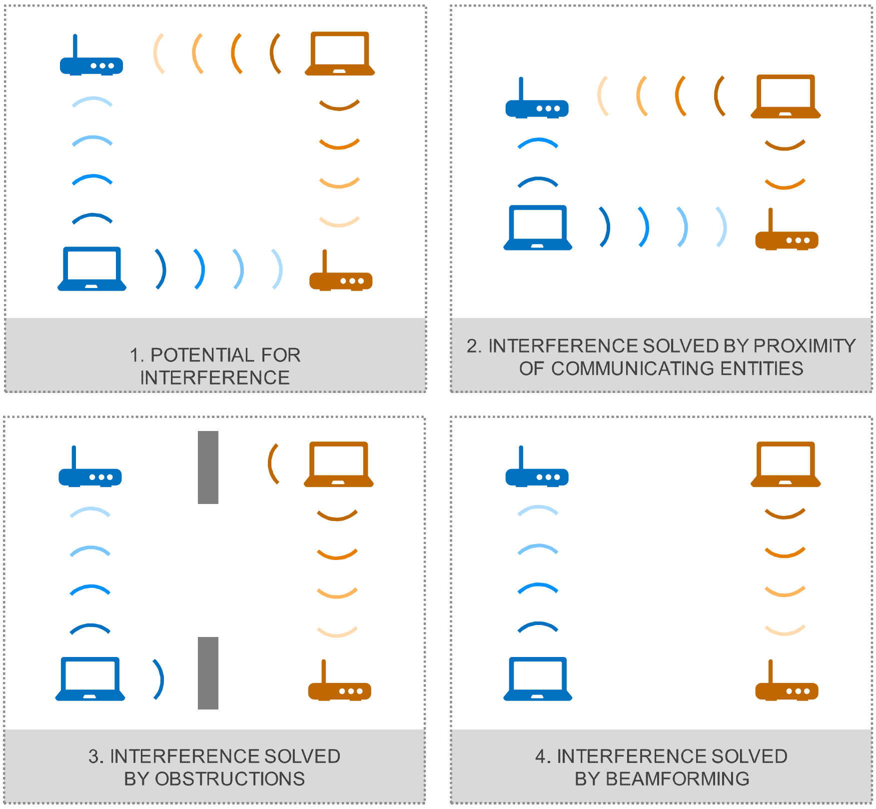
[156] This suggests that licence-exempt bands are less prone to regulatory failure than licensed bands. When regulators create licences for auction the packaging and technical conditions help pre-determine the type of use that the spectrum is put to. Should regulators have made mistakes the spectrum may often be used ineffectively, or maybe not even used at all. To correct for this would require licence revocation or an effective secondary market, which has not shown much effectiveness in transferring spectrum from one exclusive use to another. The possibility for licence-exempt usage may be permanently lost.

It is perhaps easy to see the logic that led Ronald Coase in 1959 to conceive of spectrum as a finite natural resource:

1) There are only a limited range of frequencies over which communication is possible in a given area
2) The division of frequencies between users is a zero-sum game

However, this line of reasoning has a critical problem: it assumes that the 'amount' of spectrum in a given area that can be used for communication is a fixed real quantity, like the volume of a room. This is simply incorrect, as is shown in Figure 37 below.

Figure 37 - The fallacy of spectrum as a finite resource



In this case there are two users, A and B, wishing to communicate with two different routers in the same area using a particular licence-exempt band of spectrum that is 100MHz wide. If spectrum truly were a scarce resource then usage of this 100MHz band would be a zero sum game. For every 1 MHz used by A, 1 less MHz would be available for use by B. This may be occurring in the panel 1 above where each target is receiving similar signal strength from each user[157]. However, this problem can be solved in a number of ways. Panel 2 and 3 show two classic solutions, moving the intended communicators closer to each other or use shielding to block out unwanted signals. In both cases both users are able to use the full

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[157] In cases such as this Wi-Fi is designed to share the capacity of the channel

capacity of the band in the same area. Perhaps most interesting though is panel 4. This shows the effect of a technique called 'beamforming' which allows a radio to direct energy at a particular target whilst blocking incoming energy from other directions. Such technologies are computationally intensive but due to Moore's Law they will become cheaper and more widespread over time. This allows both users in the room to use the capacity of the entire band without introducing any physical changes to the configuration from panel 1[158].

The logic underlying the notion of 'spectrum as a finite resource' is incorrect. As technology advances – driven largely by the challenges of operating in ever noisier environments – the utility of this notion will further decrease.

The analogy of spectrum as a finite resource has led economists and some regulators to embrace tradable exclusive-use spectrum licences, claiming that this would lead to a flexible and dynamic market for these licences that would allow innovation to flourish. This clearly has not come to pass.

Similarly many of the same economists have warned that creating licence-exempt spectrum bands, due to a lack of clear property rights, would result in a number of problems including a doomed "tragedy of the commons"[159], a wasteful "free for all"[160], or an ominous "Pandora's box"[161]. Looking at the major licence-exempt bands the first two of these prognostications have not come to pass, and due to the overall success of licence-exempt spectrum, the third has not been necessary to contemplate[162].

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[158] Therefore, it is quite clear that spectrum is a scarce resource only in the same way that the ability to converse at a large gathering of people is also a scarce resource; as long as conversation partners are closest to each other, or are shielded from others' conversations by walls or other obstacles, or are able to direct sound towards each other, no conversations will be prevented – even though each speaker may have to speak more loudly than they would in a completely quiet room.

[159] In which a shared resource is destroyed or degraded by the self-interested actions of those who have access. Hardin first proposed this theory in 1968. It is equivalent to a multiplayer version of the famous Prisoner's Dilemma.

[160] In which different manufacturers using different standards would rush into the newly opened spectrum resulting in a conflict in which valuable services could not be delivered.

[161] A fear that once a band of spectrum is made available for licence-exempt use it could never be reclaimed for any other use due to the profusion of devices using it.

[162] Though it should be noted that various countries have proposed a realignment of licence-exempt bands, such as Japan and Australia with sub-1GHz bands. No serious issues have been encountered in either case.

It is time that an analogy which has repeatedly led to such poor policy predictions is re-examined in the light of real world evidence[163].

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[163] For an excellent discussion of the notion of spectrum and the metaphors that might be applicable in describing it see Vries, JP De. "De-situating spectrum: Rethinking radio policy using non-spatial metaphors" New Frontiers in Dynamic Spectrum Access (2008)

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Annex 1 – Broadband affordability data by continent and country

The affordability of fixed and mobile broadband by continent

	Fixed broadband unaffordable (millions)	Total population (millions)	As a percentage (%)
Europe	57	751	8%
North America	102	528	19%
South America	221	389	57%
Africa	779	864	90%
Oceania	7	34	21%
Asia	2,778	3,886	71%
TOTAL	3,945	6,452	61%

	Mobile broadband unaffordable (millions)	Total population (millions)	As a percentage (%)
Europe	14 - 36	751	2 - 5%
North America	64 - 88	528	12 - 17%
South America	135 - 192	389	35 - 49%
Africa	704 - 753	864	82 - 87%
Oceania	7 - 7	34	20 - 20%
Asia	1682 - 2448	3,886	43 - 63%
TOTAL	2606 - 3524	6,452	40 - 55%

The affordability of fixed and mobile broadband by country

Country	Population[164]	GNI per capita[165]	Gini coefficient[166]	Cost of fixed broadband basket[167]	Cost of mobile broadband basket[168]	Lognormal approximation to Lorenz Curve[169]		Unable to afford fixed broadband	Unable to afford mobile broadband
	(million)	($)		($)	($)	μ	σ		
Albania	2.83	3,960	34.5	127	63	8.08	0.63	35%	7%
Algeria	37.10	4,450	35.3	178	89	8.19	0.65	49%	14%
Angola	20.61	3,940	59	1,682	841	7.60	1.17	99%	97%
Argentina	40.12	8,620	45.8	353	177	8.69	0.86	58%	27%
Armenia	3.27	3,200	30.9	400	200	7.91	0.56	97%	75%
Australia	22.87	43,590	30.5	436	218	10.53	0.55	0%	0%
Austria	8.42	47,060	26	329	165	10.65	0.47	0%	0%
Azerbaijan	9.11	5,330	33.7	165	83	8.39	0.62	32%	6%
Bahrain	1.23	18,730	36	243	122	9.62	0.66	4%	0%
Bangladesh	142.32	700	33.2	217	109	6.37	0.61	100%	98%
Belarus	9.47	5,950	27.2	232	116	8.57	0.49	40%	5%
Belgium	10.84	45,910	28	321	161	10.61	0.51	0%	0%
Belize	0.31	3,810	54	1,250	625	7.70	1.04	99%	95%
Benin	9.10	780	36.5	626	313	6.43	0.67	100%	100%
Bhutan	0.71	1,870	47	116	58	7.14	0.89	75%	46%
Bolivia	10.43	1,810	58.2	465	233	6.85	1.15	98%	92%
Bosnia and Herzegovina	3.84	4,770	36.2	176	88	8.25	0.67	45%	12%
Botswana	2.03	6,790	61	387	194	8.08	1.22	76%	56%
Brazil	192.38	9,390	53.9	235	117	8.60	1.04	44%	21%
Bulgaria	7.36	6,270	45.3	169	85	8.38	0.85	38%	13%
Burkina Faso	15.73	550	39.5	1,068	534	6.04	0.73	100%	100%
Cambodia	13.40	750	44.4	694	347	6.27	0.83	100%	100%
Cameroon	19.41	1,180	39	953	477	6.81	0.72	100%	100%
Canada	34.75	43,270	32.1	303	151	10.50	0.59	0%	0%

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[164] UN data

[165] World Bank data

[166] World Bank (2012)/CIA Fact Book (2012)

[167] ITU (2001)

[168] ITU (2011)

[169] Kemp-Benedict (2001)

Country	**Population**[164]	**GNI per capita** [165]	**Gini coefficient** [166]	**Cost of fixed broadband basket**[167]	**Cost of mobile broadband basket** [168]	**Lognormal approximation to Lorenz Curve**[169]		**Unable to afford fixed broadband**	**Unable to afford mobile broadband**
	(million)	**($)**		**($)**	**($)**	**μ**	**σ**		
Cape Verde	0.49	3,270	51	412	206	7.62	0.98	92%	77%
Chad	11.27	620	40	163	82	6.15	0.74	100%	95%
Chile	17.25	10,120	52.1	506	253	8.72	1.00	69%	42%
China	1347.35	4,270	41.5	252	126	8.06	0.77	73%	38%
Colombia	46.44	5,510	58.5	468	234	7.95	1.15	85%	67%
Comoros	0.75	750	64	4,009	2,004	5.78	1.29	100%	100%
Costa Rica	4.30	6,810	50.3	89	44	8.36	0.96	18%	5%
Côte d'Ivoire	21.40	1,160	41.5	522	261	6.76	0.77	100%	99%
Croatia	4.29	13,870	33.7	222	111	9.35	0.62	6%	0%
Cuba	11.24	5,520	30	20,921	10,460	8.47	0.54	100%	100%
Cyprus	0.84	29,430	29	265	132	10.15	0.53	0%	0%
Czech Republic	10.55	17,890	26	394	197	9.68	0.47	6%	0%
Denmark	5.58	59,050	29	531	266	10.85	0.53	0%	0%
Djibouti	0.91	1,270	40	664	332	6.87	0.74	100%	100%
Dominican Republic	9.38	5,030	48.4	252	126	8.10	0.92	68%	38%
Ecuador	14.48	3,850	46.9	235	117	7.86	0.89	75%	45%
Egypt	81.72	2,420	32	111	56	7.62	0.58	56%	15%
El Salvador	6.23	3,380	47	301	150	7.73	0.89	86%	62%
Estonia	1.32	14,460	31.4	260	130	9.42	0.57	7%	0%
Ethiopia	84.32	390	30	4,176	2,088	5.82	0.54	100%	100%
Finland	5.41	47,720	26.8	429	215	10.66	0.48	0%	0%
France	65.35	42,390	32.7	339	170	10.48	0.60	0%	0%
Georgia	4.47	2,690	40.8	503	252	7.61	0.76	98%	89%
Germany	81.83	43,110	27	474	237	10.55	0.49	0%	0%
Ghana	24.23	1,230	39.4	391	196	6.85	0.73	100%	97%
Greece	10.79	26,940	33	216	108	10.02	0.60	0%	0%
Guatemala	14.71	2,740	55.1	403	201	7.34	1.07	94%	81%
Guinea	10.22	400	39.4	10,378	5,189	5.73	0.73	100%	100%
Guyana	0.78	2,870	43.2	451	225	7.64	0.81	97%	83%
Honduras	8.22	1,870	57.7	275	137	6.89	1.13	94%	82%
Hong Kong	7.10	32,780	53.3	229	115	9.87	1.03	8%	2%
Hungary	9.99	12,850	24.7	244	122	9.36	0.45	3%	0%
Iceland	0.32	32,710	28	229	114	10.27	0.51	0%	0%
India	1210.19	1,330	37	74	37	6.96	0.68	69%	30%
Indonesia	237.64	2,500	36.8	315	158	7.59	0.68	96%	75%
Ireland	4.58	41,000	29.3	369	185	10.48	0.53	0%	0%
Israel	7.84	27,170	39.2	109	54	9.95	0.73	0%	0%

Country	**Population**[164]	**GNI per capita** [165]	**Gini coefficient** [166]	**Cost of fixed broadband basket**[167]	**Cost of mobile broadband basket** [168]	**Lognormal approximation to Lorenz Curve**[169]		**Unable to afford fixed broadband**	**Unable to afford mobile broadband**
	(million)	**($)**		**($)**	**($)**	**μ**	**σ**		
Italy	60.78	35,150	32	316	158	10.30	0.58	0%	0%
Jamaica	2.71	4,800	45.5	312	156	8.11	0.86	77%	47%
Japan	127.77	41,850	37.6	293	146	10.40	0.69	1%	0%
Jordan	6.28	4,340	39.7	247	124	8.11	0.74	71%	35%
Kazakhstan	16.70	7,590	26.7	175	87	8.82	0.48	9%	0%
Kenya	38.61	790	42.5	473	237	6.36	0.79	100%	100%
South Korea	48.58	19,890	31.4	298	149	9.73	0.57	3%	0%
Kyrgyzstan	5.48	840	33.4	633	316	6.55	0.61	100%	100%
Laos	6.35	1,050	36.7	2,000	1,000	6.73	0.68	100%	100%
Latvia	2.05	11,620	35.7	139	70	9.15	0.66	3%	0%
Lebanon	4.26	8,880	45	302	151	8.73	0.85	49%	20%
Lesotho	2.19	1,040	53	649	324	6.43	1.02	100%	99%
Lithuania	3.20	11,390	37.6	125	63	9.10	0.69	3%	0%
Luxembourg	0.51	77,160	26	463	231	11.14	0.47	0%	0%
Macedonia	2.06	4,570	44.2	160	80	8.08	0.83	49%	20%
Madagascar	20.70	430	47	1,114	557	5.67	0.89	100%	100%
Malawi	13.08	330	39	7,946	3,973	5.54	0.72	100%	100%
Malaysia	28.33	7,760	46.2	256	128	8.58	0.87	48%	20%
Maldives	0.32	5,750	37	161	81	8.42	0.68	30%	6%
Mali	14.52	600	39	530	265	6.14	0.72	100%	100%
Malta	0.42	19,270	26	251	125	9.76	0.47	0%	0%
Mauritania	3.34	1,030	39	303	151	6.68	0.72	100%	97%
Mauritius	1.28	7,750	39	209	105	8.70	0.72	31%	7%
Mexico	112.34	8,890	51.7	204	102	8.60	0.99	39%	16%
Moldova	3.56	1,810	38	91	45	7.26	0.70	64%	26%
Montenegro	0.62	6,750	30	223	111	8.67	0.54	31%	4%
Morocco	32.50	2,850	40.9	145	73	7.67	0.76	66%	31%
Mozambique	23.05	440	45.6	263	132	5.72	0.86	100%	99%
Namibia	2.32	4,500	70.7	1,202	601	7.31	1.49	97%	92%
Nepal	26.62	440	47.2	279	139	5.69	0.89	100%	99%
Netherlands	16.73	49,050	30.9	392	196	10.64	0.56	0%	0%
New Zealand	4.50	28,770	36.2	374	187	10.05	0.67	5%	0%
Nicaragua	5.82	1,110	52	460	230	6.51	1.00	100%	97%
Niger	16.27	370	34	779	389	5.72	0.62	100%	100%
Nigeria	162.47	1,180	43	631	316	6.75	0.80	100%	99%
Norway	5.00	84,290	25	590	295	11.24	0.45	0%	0%
Oman	2.77	18,260	32	383	192	9.64	0.58	12%	1%

Country	**Population**[164]	**GNI per capita** [165]	**Gini coefficient** [166]	**Cost of fixed broadband basket**[167]	**Cost of mobile broadband basket** [168]	**Lognormal approximation to Lorenz Curve**[169]		**Unable to afford fixed broadband**	**Unable to afford mobile broadband**
	(million)	**($)**		**($)**	**($)**	**μ**	**σ**		
Pakistan	179.07	1,050	30.6	180	90	6.80	0.56	99%	89%
Panama	3.41	6,970	51	209	105	8.37	0.98	49%	23%
Papua New Guinea	7.01	1,300	50.9	1,853	926	6.70	0.97	100%	100%
Paraguay	6.34	2,710	53.2	274	137	7.38	1.03	88%	70%
Peru	29.80	4,700	48	569	284	8.04	0.91	92%	75%
Philippines	94.01	2,060	45.8	264	132	7.26	0.86	94%	76%
Poland	37.24	12,440	34.2	224	112	9.23	0.63	9%	1%
Portugal	10.56	21,880	38.5	306	153	9.74	0.71	8%	1%
Romania	19.04	7,840	31.2	55	27	8.81	0.57	0%	0%
Russia	143.03	9,900	42.2	129	64	8.89	0.79	9%	1%
Rwanda	10.72	520	53	1,167	584	5.73	1.02	100%	100%
Sao Tome and Principe	0.17	1,200	51	3,605	1,802	6.61	0.98	100%	100%
Saudi Arabia	27.14	16,190	32	291	146	9.52	0.58	7%	0%
Senegal	12.86	1,090	39	453	227	6.73	0.72	100%	99%
Serbia	7.12	5,810	28.2	180	90	8.54	0.51	25%	2%
Seychelles	0.09	9,760	65.8	664	332	8.28	1.34	82%	65%
Singapore	5.18	40,070	47.8	361	180	10.19	0.91	7%	1%
Slovakia	5.45	16,830	26	320	160	9.62	0.47	3%	0%
Slovenia	2.06	23,860	28.4	406	203	9.95	0.51	3%	0%
South Africa	50.59	6,090	67	347	174	7.77	1.38	78%	61%
Spain	46.20	31,750	32	318	159	10.20	0.58	1%	0%
Sri Lanka	20.65	2,240	40.3	67	34	7.43	0.75	38%	11%
St. Lucia	0.17	6,560	43	446	223	8.47	0.80	78%	47%
Suriname	0.53	5,920	53	628	314	8.16	1.02	89%	71%
Swaziland	1.20	2,630	50.4	11,175	5,587	7.41	0.96	100%	100%
Sweden	9.49	50,110	23	401	200	10.74	0.41	0%	0%
Switzerland	7.87	71,530	33.7	429	215	10.99	0.62	0%	0%
Syria	21.50	2,750	36	297	149	7.70	0.66	93%	67%
Tajikistan	7.62	800	32.6	4,971	2,486	6.51	0.59	100%	100%
Tanzania	43.19	530	37.6	265	133	6.03	0.69	100%	100%
Thailand	65.93	4,150	53.6	249	125	7.79	1.04	76%	51%
Timor-Leste	1.07	2,220	31.9	1,072	536	7.54	0.58	100%	100%
Togo	5.75	490	34	2,212	1,106	6.00	0.62	100%	100%
Trinidad and Tobago	1.32	15,380	40	138	69	9.37	0.74	3%	0%
Tunisia	10.67	4,160	40	141	71	8.06	0.74	44%	14%
Turkey	74.72	9,890	39.7	257	129	8.93	0.74	30%	7%

Country	**Population**[164]	**GNI per capita**[165]	**Gini coefficient**[166]	**Cost of fixed broadband basket**[167]	**Cost of mobile broadband basket**[168]	**Lognormal approximation to Lorenz Curve**[169]		**Unable to afford fixed broadband**	**Unable to afford mobile broadband**
	(million)	**($)**		**($)**	**($)**	**μ**	**σ**		
Uganda	32.94	500	44.3	180	90	5.87	0.83	100%	97%
Ukraine	45.64	3,000	27.5	96	48	7.88	0.50	26%	2%
United Arab Emirates	8.26	41,930	31	335	168	10.48	0.56	0%	0%
United Kingdom	62.30	38,370	34	269	134	10.36	0.62	0%	0%
United States	313.23	47,390	45	237	118	10.41	0.85	1%	0%
Uruguay	3.20	10,590	42.4	275	138	8.95	0.79	33%	10%
Uzbekistan	28.00	1,280	36.8	2,793	1,396	6.93	0.68	100%	100%
Venezuela	27.15	11,590	41	220	110	9.07	0.76	19%	4%
Vietnam	87.84	1,160	37.6	157	78	6.82	0.69	96%	78%
Yemen	23.83	1,070	37.7	1,443	722	6.73	0.70	100%	100%
Zambia	13.05	1,070	50.8	784	392	6.50	0.97	100%	99%
Zimbabwe	12.75	460	50.1	6,225	3,112	5.67	0.96	100%	100%

Annex 2 – Value of Wi-Fi to fixed broadband by country

Country	Population[170]	GNI per capita[171]	Total fixed broadband connection[172]s	Total Wi-Fi connections[173]	Evenly scaled annual economic	GNI scaled annual economic value
	(million)	($)	(million)	(million)	($ million)	($ million)
Albania	2.8	3,960	0.10	0.08	18.2	1.5
Algeria	37.1	4,450	0.93	0.79	175.0	16.4
Angola	20.6	3,940	0.02	0.02	3.9	0.3
Antigua & Barbuda	0.1	13,170	0.02	0.01	2.9	0.8
Argentina	40.1	8,620	3.85	3.27	726.7	132.2
Armenia	3.3	3,200	0.09	0.08	16.7	1.1
Australia	22.9	43,590	5.30	4.51	1,001.0	920.8
Austria	8.4	47,060	2.01	1.71	379.7	377.1
Azerbaijan	9.1	5,330	0.49	0.42	92.8	10.4
Bahrain	1.2	18,730	0.15	0.13	28.4	11.2
Bangladesh	142.3	700	-	-	-	-
Barbados	0.3	12,660	0.06	0.05	10.7	2.9
Belarus	9.5	5,950	1.65	1.40	310.8	39.0
Belgium	10.8	45,910	3.41	2.90	644.3	624.2
Benin	9.1	780	0.03	0.02	5.2	0.1
Bhutan	0.7	1,870	0.01	0.01	1.6	0.1
Bolivia	10.4	1,810	0.10	0.09	19.7	0.8
Bosnia and Herzegovina	3.8	4,770	0.40	0.34	75.4	7.6
Botswana	2.0	6,790	0.01	0.01	2.3	0.3
Brazil	192.4	9,390	13.85	11.77	2,613.7	517.9
Brunei Darussalam	0.4	31,800	0.02	0.02	4.3	2.9
Bulgaria	7.4	6,270	1.08	0.92	204.3	27.0
Burkina Faso	15.7	550	0.02	0.01	3.0	0.0
Cambodia	13.4	750	0.04	0.03	7.6	0.1
Cameroon	19.4	1,180	-	-	-	-
Canada	34.7	43,270	10.35	8.80	1,953.9	1,784.0
Cape Verde	0.5	3,270	0.01	0.01	2.8	0.2
Chad	11.3	620	-	-	-	-
Chile	17.2	10,120	1.81	1.54	341.8	73.0

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[170] UN

[171] World Bank

[172] ITU

[173] Derived using Strategy Analytics 2012

Country	Population[170]	GNI per capita[171]	Total fixed broadband connection[172]s	Total Wi-Fi connections[173]	Evenly scaled annual economic	GNI scaled annual economic value
	(million)	($)	(million)	(million)	($ million)	($ million)
China, People's Republic of	1,347.4	4,270	126.65	107.65	23,899.0	2,153.4
Colombia	46.4	5,510	2.65	2.25	499.5	58.1
Comoros	0.8	750	-	-	-	-
Democratic Republic of the Congo	67.8	180	-	-	-	-
Costa Rica	4.3	6,810	0.27	0.23	50.3	7.2
Côte d'Ivoire	21.4	1,160	-	-	-	-
Croatia	4.3	13,870	0.79	0.67	148.2	43.4
Cuba	11.2	5,520	-	-	-	-
Cyprus	0.8	29,430	0.15	0.13	27.9	17.3
Czech Republic	10.5	17,890	1.55	1.32	292.6	110.5
Denmark	5.6	59,050	2.09	1.77	393.8	490.7
Djibouti	0.9	1,270	0.01	0.01	1.5	0.0
Dominican Republic	9.4	5,030	0.34	0.29	63.7	6.8
Ecuador	14.5	3,850	0.20	0.17	38.3	3.1
Egypt	81.7	2,420	1.47	1.25	277.6	14.2
El Salvador	6.2	3,380	0.17	0.15	32.9	2.3
Eritrea	5.4	340	-	-	-	-
Estonia	1.3	14,460	0.32	0.27	60.4	18.4
Ethiopia	84.3	390	-	-	-	-
Fiji	0.9	3,630	0.02	0.01	3.1	0.2
Finland	5.4	47,720	1.57	1.34	296.9	298.9
France	65.4	42,390	22.15	18.83	4,180.4	3,739.3
Gabon	1.5	7,740	0.00	0.00	0.6	0.1
The Gambia	1.8	450	-	-	-	-
Georgia	4.5	2,690	0.23	0.19	43.0	2.4
Germany	81.8	43,110	25.86	21.98	4,879.5	4,438.8
Ghana	24.2	1,230	0.05	0.04	9.1	0.2
Greece	10.8	26,940	2.14	1.82	403.1	229.1
Guatemala	14.7	2,740	0.26	0.23	50.0	2.9
Guinea	10.2	400	-	-	-	-
Guyana	0.8	2,870	0.01	0.01	2.4	0.1
Honduras	8.2	1,870	0.08	0.07	15.5	0.6
Hong Kong	7.1	32,780	2.15	1.82	404.8	280.0
Hungary	10.0	12,850	1.96	1.66	369.3	100.1
Iceland	0.3	32,710	0.11	0.09	20.9	14.4
India	1,210.2	1,330	10.89	9.26	2,055.3	57.7
Indonesia	237.6	2,500	1.90	1.62	358.7	18.9

Country	Population[170]	GNI per capita[171]	Total fixed broadband connection[172]s	Total Wi-Fi connections[173]	Evenly scaled annual economic	GNI scaled annual economic value
	(million)	**($)**	**(million)**	**(million)**	**($ million)**	**($ million)**
Iran	76.2	4,520	0.53	0.45	100.7	9.6
Ireland	4.6	41,000	1.04	0.89	197.1	170.5
Israel	7.8	27,170	1.97	1.67	371.2	212.8
Italy	60.8	35,150	13.43	11.42	2,534.5	1,879.9
Jamaica	2.7	4,800	0.12	0.10	22.0	2.2
Japan	127.8	41,850	34.37	29.21	6,485.6	5,727.5
Jordan	6.3	4,340	0.20	0.17	37.9	3.5
Kazakhstan	16.7	7,590	0.88	0.75	167.0	26.7
Kenya	38.6	790	-	-	-	-
South Korea	48.6	19,890	17.78	15.11	3,355.1	1,408.2
Kyrgyzstan	5.5	840	0.02	0.01	3.1	0.1
Laos	6.3	1,050	0.01	0.01	2.4	0.1
Latvia	2.0	11,620	0.40	0.34	74.6	18.3
Lebanon	4.3	8,880	0.20	0.17	37.8	7.1
Lithuania	3.2	11,390	0.66	0.56	124.2	29.9
Luxembourg	0.5	77,160	0.17	0.14	31.7	51.6
Macao, China	0.6	34,880	0.13	0.11	25.5	18.7
Macedonia	2.1	4,570	0.26	0.22	48.5	4.7
Madagascar	20.7	430	-	-	-	-
Malaysia	28.3	7,760	2.07	1.76	390.3	63.9
Maldives	0.3	5,750	0.02	0.01	2.9	0.4
Mali	14.5	600	-	-	-	-
Malta	0.4	19,270	0.11	0.10	21.7	8.8
Mauritania	3.3	1,030	0.01	0.01	1.3	0.0
Mauritius	1.3	7,750	0.08	0.07	15.2	2.5
Mexico	112.3	8,890	11.23	9.55	2,119.8	397.7
Moldova	3.6	1,810	0.27	0.23	50.4	1.9
Mongolia	2.7	1,870	0.06	0.05	11.9	0.5
Montenegro	0.6	6,750	0.05	0.04	9.7	1.4
Morocco	32.5	2,850	0.52	0.44	98.1	5.9
Mozambique	23.0	440	0.02	0.02	4.3	0.0
Namibia	2.3	4,500	0.01	0.01	1.8	0.2
Nepal	26.6	440	0.11	0.09	20.1	0.2
Netherlands	16.7	49,050	6.36	5.40	1,199.5	1,241.5
New Zealand	4.5	28,770	1.12	0.95	211.4	128.3
Nicaragua	5.8	1,110	0.05	0.04	8.8	0.2
Niger	16.3	370	-	-	-	-
Nigeria	162.5	1,180	0.16	0.14	30.7	0.8

Country	Population[170]	GNI per capita[171]	Total fixed broadband connection[172]s	Total Wi-Fi connections[173]	Evenly scaled annual economic	GNI scaled annual economic value
	(million)	($)	(million)	(million)	($ million)	($ million)
Norway	5.0	84,290	1.73	1.47	326.5	580.7
Oman	2.8	18,260	0.05	0.04	9.9	3.8
Pakistan	179.1	1,050	0.54	0.46	101.4	2.2
Panama	3.4	6,970	0.27	0.23	50.1	7.4
Papua New Guinea	7.0	1,300	0.01	0.01	1.3	0.0
Paraguay	6.3	2,710	0.04	0.03	7.2	0.4
Peru	29.8	4,700	0.92	0.79	174.3	17.3
Philippines	94.0	2,060	1.69	1.44	319.3	13.9
Poland	37.2	12,440	4.92	4.18	927.7	243.5
Portugal	10.6	21,880	2.05	1.74	386.6	178.5
Romania	19.0	7,840	2.67	2.27	503.1	83.2
Russia	143.0	9,900	15.73	13.37	2,968.9	620.2
Rwanda	10.7	520	-	-	-	-
Saudi Arabia	27.1	16,190	1.49	1.27	281.6	96.2
Senegal	12.9	1,090	0.08	0.07	14.6	0.3
Serbia	7.1	5,810	0.61	0.51	114.2	14.0
Seychelles	0.1	9,760	0.01	0.01	1.3	0.3
Singapore	5.2	40,070	1.28	1.09	241.6	204.3
Slovakia	5.4	16,830	0.88	0.75	165.4	58.8
Slovenia	2.1	23,860	0.50	0.43	94.7	47.7
South Africa	50.6	6,090	0.76	0.64	143.2	18.4
Spain	46.2	31,750	10.63	9.03	2,005.0	1,343.3
Sri Lanka	20.7	2,240	0.21	0.18	39.0	1.8
Suriname	0.5	5,920	0.02	0.01	3.0	0.4
Swaziland	1.2	2,630	0.00	0.00	0.2	0.0
Sweden	9.5	50,110	3.00	2.55	565.7	598.1
Switzerland	7.9	71,530	3.01	2.56	567.3	856.3
Syria	21.5	2,750	0.06	0.05	12.2	0.7
Tanzania	43.2	530	-	-	-	-
Thailand	65.9	4,150	2.57	2.19	485.2	42.5
Togo	5.8	490	0.01	0.00	1.1	0.0
Trinidad and Tobago	1.3	15,380	0.14	0.12	26.9	8.7
Tunisia	10.7	4,160	0.49	0.42	92.7	8.1
Turkey	74.7	9,890	7.32	6.22	1,381.8	288.4
Turkmenistan	5.1	3,790	-	-	-	-
Uganda	32.9	500	0.03	0.03	6.2	0.1
Ukraine	45.6	3,000	3.70	3.14	697.7	44.2
United Arab Emirates	8.3	41,930	0.87	0.74	163.7	144.9

Country	Population[170]	GNI per capita[171]	Total fixed broadband connection[172]s	Total Wi-Fi connections[173]	Evenly scaled annual economic	GNI scaled annual economic value
	(million)	**($)**	**(million)**	**(million)**	**($ million)**	**($ million)**
United Kingdom	62.3	38,370	19.56	16.63	3,691.4	2,988.8
United States	313.2	47,390	82.38	70.02	15,545.0	15,545.0
Uruguay	3.2	10,590	0.37	0.31	68.9	15.4
Uzbekistan	28.0	1,280	0.08	0.07	15.9	0.4
Venezuela	27.2	11,590	1.47	1.25	276.7	67.7
Vietnam	87.8	1,160	3.60	3.06	679.6	16.6
Yemen	23.8	1,070	0.07	0.06	13.5	0.3
Zambia	13.0	1,070	0.01	0.01	2.5	0.1
Zimbabwe	12.8	460	0.04	0.03	7.2	0.1

Annex 3 – Value of Wi-Fi to mobile operators

Country	**Population**[174]	**Urban population**[175]	**Area**[176]	**Urban area**[177]	**Total MBB connections**[178]	**Urban cell sites needed per operator for data coverage using 900MHz**[179]			**Urban cell sites needed per operator for data coverage using 2100MHz**		
	(million)	**(million)**	**(000 km2)**	**(000 km2)**	**(million)**	**10 MB / user /day**	**40 MB / user /day**	**80 MB / user /day**	**10 MB / user /day**	**40 MB / user /day**	**80 MB / user /day**
Angola	20.6	12.1	1,251.92	1.47	1.154	107	299	598	319	354	598
Argentina	40.1	37.1	2,736.39	55.15	5.135	3,726	3,844	4,001	11,703	11,851	11,979
Armenia	3.3	2.1	28.28	1.75	0.170	118	122	127	371	376	380
Australia	22.9	20.4	7,634.65	36.84	18.910	2,607	4,899	9,799	7,936	8,502	9,819
Austria	8.4	5.7	83.14	10.74	5.675	761	1,470	2,941	2,315	2,484	2,946
Azerbaijan	9.1	4.7	85.36	7.28	0.082	487	489	492	1,541	1,542	1,545
Bahrain	1.2	1.1	0.62	0.56	0.263	40	68	136	121	129	139
Bangladesh	142.3	39.9	136.30	11.15	0.285	747	754	763	2,360	2,366	2,375
Belarus	9.5	7.1	207.01	7.79	1.098	529	555	598	1,657	1,689	1,716
Belgium	10.8	10.6	30.55	12.42	2.504	850	907	1,298	2,646	2,721	2,781
Bhutan	0.7	0.2	38.04	0.20	0.002	13	13	13	42	42	42
Bolivia	10.4	6.9	1,069.35	6.20	0.146	415	419	423	1,311	1,315	1,319
Bosnia and Herzegovina	3.8	1.9	51.30	1.73	0.411	119	128	213	368	381	391
Botswana	2.0	1.2	559.50	2.09	0.128	140	143	147	442	446	449
Brazil	192.4	166.5	8,480.40	136.03	20.392	9,249	9,719	10,621	28,928	29,530	30,022
Brunei Darussalam	0.4	0.3	5.90	1.03	0.260	71	77	134	220	228	234
Bulgaria	7.4	5.3	111.31	6.70	1.804	462	507	935	1,430	1,484	1,527
Cambodia	13.4	2.7	179.49	1.13	1.192	85	309	618	249	318	618
Cameroon	19.4	11.3	465.77	3.69	0.175	248	252	257	781	786	791
Canada	34.7	28.0	9,458.89	126.35	5.142	8,486	8,604	8,762	26,764	26,900	27,040
Chile	17.2	15.4	721.23	12.05	1.225	815	843	881	2,558	2,593	2,624
China, People's Republic of	1347.4	632.6	9,198.10	380.59	26.947	25,647	26,267	27,094	80,703	81,464	82,149
Colombia	46.4	34.9	1,141.57	36.20	2.600	2,440	2,499	2,579	7,676	7,750	7,816
Costa Rica	4.3	2.8	51.02	4.08	0.237	274	280	287	864	871	877

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[174] UN data

[175] UN (2011)

[176] UN data

[177] GRUMPv3 (2012)

[178] ITU (2011)

[179] Derived using Ofcom (2009)

Country	Population[174]	Urban population[175]	Area[176]	Urban area[177]	Total MBB connections[178]	Urban cell sites needed per operator for data coverage using 900MHz[179]			Urban cell sites needed per operator for data coverage using 2100MHz		
	(million)	(million)	(000 km2)	(000 km2)	(million)	10 MB / user /day	40 MB / user /day	80 MB / user /day	10 MB / user /day	40 MB / user /day	80 MB / user /day
Croatia	4.3	2.5	56.41	5.31	1.686	368	437	874	1,137	1,187	1,228
Cyprus	0.8	0.6	9.27	2.32	0.514	159	171	266	495	511	523
Czech Republic	10.5	7.8	78.62	12.49	2.932	857	925	1,520	2,664	2,752	2,821
Denmark	5.6	4.8	42.48	9.27	3.053	643	791	1,582	1,984	2,075	2,148
Dominican Republic	9.4	6.5	48.09	5.10	0.206	342	347	354	1,080	1,086	1,091
Ecuador	14.5	9.7	246.70	10.89	1.260	737	766	805	2,312	2,349	2,380
Egypt	81.7	35.5	968.07	24.26	5.230	1,662	1,782	2,710	5,170	5,327	5,451
El Salvador	6.2	4.0	20.28	3.62	0.311	244	251	261	768	777	784
Estonia	1.3	0.9	43.18	2.62	0.107	176	178	181	554	557	560
Ethiopia	84.3	14.0	1,123.71	5.17	0.253	348	354	361	1,096	1,103	1,110
Fiji	0.9	0.5	18.25	1.73	0.012	116	116	117	367	367	367
Finland	5.4	4.6	317.00	19.45	4.222	1,332	1,429	2,188	4,145	4,272	4,372
France	65.4	55.7	547.12	86.63	23.395	5,970	6,563	12,123	18,501	19,201	19,757
Georgia	4.5	2.4	69.24	3.62	0.840	248	268	435	772	797	817
Germany	81.8	60.4	356.03	62.51	29.786	4,407	7,717	15,434	13,450	14,341	15,672
Ghana	24.2	12.5	231.73	6.28	0.145	421	424	428	1,328	1,332	1,336
Greece	10.8	6.6	131.89	18.51	6.289	1,286	1,629	3,259	3,964	4,152	4,301
Guatemala	14.7	7.3	108.52	4.14	0.544	281	294	311	880	896	909
Honduras	8.2	4.2	112.08	3.70	0.345	250	258	269	786	796	804
Hong Kong	7.1	7.1	1.05	0.91	5.292	343	1,371	2,742	343	1,517	2,742
Hungary	10.0	6.8	92.05	9.11	2.986	632	774	1,547	1,951	2,040	2,111
Iceland	0.3	0.3	91.12	1.02	0.143	70	73	78	218	222	225
India	1210.2	363.2	3,209.72	223.40	10.892	15,016	15,267	15,601	47,333	47,629	47,918
Indonesia	237.6	105.2	1,898.78	42.20	24.477	3,009	6,342	12,683	9,114	9,846	12,692
Ireland	4.6	2.8	69.47	5.68	2.167	397	561	1,123	1,219	1,284	1,335
Israel	7.8	7.2	21.88	6.40	4.874	465	1,263	2,526	1,392	1,538	2,526
Italy	60.8	41.5	299.29	73.77	36.101	5,208	9,353	18,707	15,879	16,959	18,892
Jamaica	2.7	1.4	11.06	3.03	0.214	204	209	216	643	649	654
Japan	127.8	85.4	371.71	108.93	112.182	8,147	29,065	58,129	23,899	29,899	58,129
Jordan	6.3	4.9	88.36	3.39	0.151	228	231	236	719	723	727
Kazakhstan	16.7	9.8	2,619.35	14.33	0.050	959	959	961	3,033	3,033	3,033
Kenya	38.6	8.6	579.62	4.17	2.162	295	560	1,120	899	964	1,123
Kyrgyzstan	5.5	1.9	184.76	4.62	0.225	310	315	322	978	984	990
Laos	6.3	2.1	230.23	1.02	0.025	68	69	70	216	216	217
Latvia	2.0	1.4	64.20	3.29	0.562	224	237	291	700	716	730
Lithuania	3.2	2.1	65.00	4.63	0.732	315	332	379	985	1,006	1,024

Country	Population[174]	Urban population[175]	Area[176]	Urban area[177]	Total MBB connections[178]	Urban cell sites needed per operator for data coverage using 900MHz[179]			Urban cell sites needed per operator for data coverage using 2100MHz		
	(million)	(million)	(000 km2)	(000 km2)	(million)	10 MB / user /day	40 MB / user /day	80 MB / user /day	10 MB / user /day	40 MB / user /day	80 MB / user /day
Luxembourg	0.5	0.4	2.59	0.81	0.369	57	96	191	174	185	196
Macao, China	0.6	0.6	0.02	0.02	0.314	20	81	163	20	98	163
Macedonia	2.1	1.2	24.70	2.67	0.428	182	192	222	569	581	592
Madagascar	20.7	6.2	592.97	2.30	0.166	155	159	164	487	491	496
Malaysia	28.3	20.4	329.94	16.00	7.707	1,128	1,997	3,993	3,442	3,673	4,046
Mali	14.5	5.2	1,248.14	2.91	0.160	196	200	205	617	622	626
Malta	0.4	0.4	0.32	0.29	0.129	20	34	67	62	66	69
Mauritania	3.3	1.4	1,036.91	0.78	0.104	53	55	59	166	169	171
Mauritius	1.3	0.5	1.99	1.29	0.283	88	95	147	274	283	289
Mexico	112.3	87.4	1,943.02	102.84	9.324	6,946	7,161	7,447	21,823	22,091	22,324
Moldova	3.6	1.7	34.01	2.62	0.545	179	192	282	557	574	587
Mongolia	2.7	1.7	1,546.29	1.32	0.323	91	98	167	282	292	299
Morocco	32.5	18.9	669.16	12.27	3.250	845	925	1,684	2,621	2,718	2,796
Mozambique	23.0	8.9	777.12	2.75	0.346	187	195	205	585	595	604
Namibia	2.3	0.9	819.96	2.47	0.174	166	170	176	523	528	533
Netherlands	16.7	13.9	41.36	12.84	6.306	907	1,634	3,268	2,765	2,953	3,298
New Zealand	4.5	3.9	265.33	8.11	2.978	565	772	1,543	1,739	1,828	1,899
Nicaragua	5.8	3.3	118.28	2.89	0.174	195	199	204	613	618	623
Nigeria	162.5	80.9	904.23	17.30	4.712	1,192	1,314	2,441	3,695	3,836	3,948
Norway	5.0	4.0	318.52	19.61	2.355	1,329	1,383	1,455	4,166	4,235	4,292
Oman	2.8	2.0	304.19	5.67	0.297	381	388	397	1,201	1,209	1,217
Pakistan	179.1	64.3	785.32	35.95	1.074	2,411	2,436	2,469	7,612	7,639	7,670
Panama	3.4	2.5	74.52	2.88	0.116	193	196	199	609	612	616
Paraguay	6.3	3.9	395.89	3.79	0.260	255	261	269	803	811	817
Peru	29.8	22.9	1,289.48	16.61	2.145	1,127	1,176	1,243	3,529	3,592	3,645
Philippines	94.0	46.0	295.41	10.86	15.606	1,011	4,043	8,087	2,417	4,151	8,087
Poland	37.2	22.7	311.20	30.56	11.546	2,131	2,991	5,983	6,551	6,897	7,171
Portugal	10.6	6.4	91.42	12.78	7.657	913	1,984	3,968	2,762	2,991	3,969
Qatar	1.7	1.6	10.97	1.52	0.483	105	125	250	325	340	351
Romania	19.0	10.9	237.06	15.70	6.246	1,097	1,618	3,237	3,368	3,555	3,704
Russia	143.0	104.7	16,680.00	186.70	24.887	12,671	13,244	14,096	39,679	40,410	41,015
Rwanda	10.7	2.0	24.35	0.52	0.139	36	40	72	112	116	119
Saudi Arabia	27.1	22.3	1,938.84	41.41	15.685	2,888	4,064	8,128	8,879	9,348	9,721
Senegal	12.9	5.4	196.15	1.83	0.334	125	133	173	390	400	408
Serbia	7.1	4.0	101.56	8.21	1.353	559	591	701	1,747	1,788	1,820
Seychelles	0.1	0.1	0.20	0.12	0.004	8	8	8	25	25	26

Country	Population[174]	Urban population[175]	Area[176]	Urban area[177]	Total MBB connections[178]	Urban cell sites needed per operator for data coverage using 900MHz[179]			Urban cell sites needed per operator for data coverage using 2100MHz		
	(million)	(million)	(000 km2)	(000 km2)	(million)	10 MB / user /day	40 MB / user /day	80 MB / user /day	10 MB / user /day	40 MB / user /day	80 MB / user /day
Singapore	5.2	5.2	0.60	0.57	3.613	234	936	1,872	234	1,048	1,872
Slovakia	5.4	3.0	48.87	6.33	1.470	434	468	762	1,349	1,393	1,428
Slovenia	2.1	1.0	20.22	2.51	0.675	173	190	350	537	557	573
South Africa	50.6	31.2	1,217.64	53.53	8.397	3,643	3,836	4,351	11,387	11,635	11,838
South Korea	48.6	40.3	98.98	21.96	44.208	2,863	11,454	22,907	4,985	11,759	22,907
Spain	46.2	35.8	505.27	69.90	25.731	4,870	6,667	13,333	14,982	15,751	16,363
Sri Lanka	20.7	3.0	65.83	4.04	1.983	285	514	1,027	870	929	1,037
Sweden	9.5	8.0	431.70	30.73	7.969	2,115	2,303	4,129	6,561	6,799	6,989
Switzerland	7.9	5.8	38.98	7.93	3.447	557	893	1,786	1,704	1,807	1,889
Syria	21.5	12.0	184.37	11.96	0.279	801	808	816	2,531	2,538	2,546
Tanzania	43.2	11.4	891.02	3.41	0.907	235	257	470	729	756	778
Thailand	65.9	22.4	513.62	36.68	2.505	2,471	2,529	2,606	7,777	7,847	7,911
The Gambia	1.8	1.0	10.84	0.47	0.009	31	32	32	100	100	100
Tunisia	10.7	7.2	147.88	10.07	0.117	674	677	680	2,132	2,134	2,137
Turkey	74.7	52.0	768.69	44.22	13.301	3,058	3,456	6,892	9,455	9,853	10,170
Uganda	32.9	4.4	206.97	1.23	0.198	84	88	102	261	267	272
Ukraine	45.6	31.4	588.42	32.20	1.963	2,168	2,213	2,273	6,826	6,881	6,931
United Arab Emirates	8.3	6.9	74.78	8.62	4.826	613	1,250	2,501	1,860	2,005	2,503
United Kingdom	62.3	49.6	247.19	60.05	34.888	4,282	9,039	18,078	12,969	14,013	18,090
United States	313.2	257.7	9,210.75	794.42	169.144	54,400	58,292	87,645	169,320	174,372	178,401
Uruguay	3.2	3.0	173.99	4.83	0.183	324	328	334	1,022	1,027	1,032
Uzbekistan	28.0	10.1	412.91	18.56	1.092	1,249	1,274	1,307	3,933	3,963	3,992
Venezuela	27.2	25.3	911.56	34.54	5.647	2,352	2,482	2,926	7,350	7,517	7,653
Vietnam	87.8	26.7	328.53	7.61	11.244	728	2,913	5,826	1,697	2,991	5,826
Zimbabwe	12.8	4.9	389.05	4.93	0.089	330	333	335	1,044	1,046	1,049