Capacity and Costs for 5G Networks in Dense Urban Areas

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Abstract

An initial analysis of 5G has shown that it is a radical departure from the generational trend: In particular headline rates and capacities which are X10 and X100 greater than the improvement attained with previous, more evolutionary, upgrades. In order to achieve these metrics will require extreme densification of the network given the spectrum that is available for 5G. A compelling case is made that this densification will cause costs to balloon.

To access this costs a techno-economic analysis of the 5G eMBB (enhanced Mobile BroadBand) scenario in dense urban areas has been accomplished by radio capacity modelling of probable 5G technologies within a 1km^2 grid representing central London. Different density networks were modelled at: 700MHz (macro network), 3.5GHz (micro network) and 24-27.5 GHz (hot spots) – together with 802.11ac access points. Using published data on network costs various deployment options have been evaluated for capacity, headline rate and CAPEX/OPEX.

It has been shown that reaching headline rates of 64-100Mbps everywhere is possible with a number of different technology options. Massive increases in capacity (in excess of $100\text{Gbps}/\text{km}^2$), however, can only be realistically achieved with millimetre wave (outdoor) and internal base stations. The cost of deploying such capacity, however, will be several times that of LTE – we estimate a 4 to 5 times increase in costs for a 100Mbps everywhere network that has x100 capacity increase over existing LTE networks.

One possible way of reducing the costs of 5G and increasing capacity is to place femto or distributed base-stations within buildings: we have demonstrated $3\text{Tbps}/\text{km}^2$ of capacity with 5,800 femto cells per km^2 for a neutral hosted solution. However, there is a substantial up-front cost to utilizing internal base-stations: fibre back-haul and internal fibre needs to be installed. This initial cost is identified as significant barrier.

Key words: Techno-Economic Modelling, 5G, WiFi, Mobile, Dense Urban, Cellular

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Statement of originality

This is to certify that to the best of my knowledge, the content of this thesis is my own work. This thesis has not been submitted for any degree or other purposes.

I certify that the intellectual content of this thesis is the product of my own work and that all the assistance received in preparing this thesis and sources have been acknowledged.

The views expressed here are mine and do not necessarily represent those of Surrey University, 5GIC, BT plc, the EU or anyone else associated with the project.

Dr. David Wisely

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Acronyms

3GPP	3 rd Generation Partnership Project
3GPP2	3 rd Generation Partnership Project 2
AAA	Authentication, Authorization and Accounting
AC	Access Controller
ACR	Access Control Router
ACK	Acknowledgement
AES	Advanced Encryption Standard
AH	Authentication Header
AN	Access Network
ANDSF	Access Network Discovery Function
ANG	Access Network Gateway
ANQP	Access Network Query Protocol
ANR	Access Network Router
AP	Access Point
API	Application Programming Interface
AR	Access Router
ARPU	Average Revenue Per User
ARQ	Automatic Repeat Request
ARPANET	Advanced Research Projects Agency Network
AS	Application Server
ASN	Access Service Network
ASP	Application Service Provider
ATM	Asynchronous Transfer Mode
B-ISDN	Broadband ISDN
BCH	Broadcast Channel
BCCH	Broadcast Control Channel (GSM)
BE	Best Effort
BER	Bite Error Rate
BGCF	Breakout Gateway Control Function
BGP	Border Gateway Protocol
BRAS	Broadband Remote Access Server
BS	Base Station
BSC	Base Station Controller
BSS	Base Station System (2G and 3G) and Basic Service Set (WLAN)
BT	British Telecommunications plc
BTS	Base Transceiver Station
CA	Carrier Aggregation
CAPWAP	Control And Provisioning of Wireless Access Points
CCN	Content Centric Network
CDMA	Code Division Multiple Access
CDN	Content Distribution Network
CDPD	Cellular Digital Packet Data
CH	Correspondent Host
CN	Correspondent Node
CoA	Care-of Address

CPRI	Common Public Radio Interface
CS	Circuit Switched
CSCF	Call Server Control Function
CSMA	Carrier Sense Multiple Access
CSMA/CD	Carrier Sense Multiple Access with Collision Detection
DES	Data Encryption Standard
DFS	Dynamic Frequency Selection
DHCP	Dynamic Host Configuration Protocol
DiffServ	Differentiated Services
DNS	Domain Name System
DOCSIS	Data Over Cable Service Interface Specification
EAP	Extensible Authentication Protocol
EDGE	Enhanced Data rates for GSM Evolution
E-DPDCH	Enhanced Dedicated Physical Data Channel
eICIC	Enhanced InterCell Interference Coordination
ETSI	European Telecommunications Standards Institute
EU	European Union
FA	Foreign Agent
FCC	US Federal Communications Commission
FCH	Frame Control Header
FDD	Frequency Division Duplex
FDM	Frequency Division Multiplexing
FDMA	Frequency Division Multiple Access
FEC	Forward Error Correction
FPLMTS	Future Public Land Mobile Telecommunication Systems
FM	Frequency Modulation
FTTC	Fibre To The Cabinet
FTP	File Transfer Protocol
GERAN	GSM EDGE Radio Access Network
GFA	Gateway Foreign Agent
GGSN	Gateway GPRS Support Node
GPRS	General Packet Radio Service
GRE	Generic Routing Encapsulation
GSM	Global System for Mobile Communications (ETSI)
GSMA	GSM Association
GTP	GPRS Tunnelling Protocol
HA	Home Agent
HACK	Handover Acknowledgement
HARQ	Hybrid Automatic Repeat Request
HLR	Home Location Register
HMIP	Hierarchical Mobile IP
HSPA	High Speed Packet Access
HSDPA	High Speed Download Packet Access
HS-SCCH	High Speed Shared Control Channel
HSUPA	High Speed Uplink Packet Access
HSS	Home Subscription Server
HTTP	Hyper Text Transfer Protocol
ICN	Information Centric Network
ID	Identity
IEEE	Institute of Electrical and Electronics Engineers,

IESG	Internet Engineering Steering Group
IETF	Internet Engineering Task Force
IFT	Inverse Fourier Transform
IM	Instant Messaging
IMS	Internet Multimedia Subsystem
IoT	Internet of Things
IP	Internet Protocol
IPR	Intellectual Property Rights
IPsec	IP Security
IS	Information Service
IPTV	IP Television
IRTF	Internet Research Task Force
ISDN	Integrated Services Digital Network
ISIM	IP Multimedia Services Identity Module
ISM	Industrial Scientific and Medical (band)
ISP	Internet Service Provider
ITU	International Telecommunication Union
LAA	(LTE) Licensed Assisted Access
LAN	Local Area Network
LTE	Long Term Evolution
M2M	Machine to Machine
MAC	Medium Access Control
MBNL	Mobile Broadband Network Limited
MG/MGW	Media Gateway
MGCF	Media Gateway Control Function
MH	Mobile Host
MIH	Media Independent Handover
MIMO	Multiple Input Multiple Output
MIP	Mobile IP
MME	Mobility Management Entity
MN	Mobile Node
MNO	Mobile Network Operator
MSISDN	Mobile Station International Subscriber Directory Number
NAP	Network Access Provider
NAT	Network Address Translation
NFC	Near Field Communication
NGMN	Next Generation Mobile Networks
NOMA	Non-Orthogonal Multiple Access
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OMA	Open Mobile Alliance
OS	Operating System
PDF	Policy Decision Function
PDN	Packet Data Network
PDCP	Packet Data Convergence Protocol
PDP	Packet Data Protocol
PDSN	Packet Data Service Node (cdma2000)
PDU	Protocol Data Unit
PEP	Policy Enforcement Point
PHY	Physical Layer

PIG	PSTN Internet Gateway
PIN	Personal Identification Number
PKM	Privacy Key Management
PSTN	Public Switched Telephone Network
OTT	Over The Top
QoE	Quality of Experience
QoS	Quality of Service
RACH	Random Access Channel
RADIUS	Remote Authentication Dial In User Service
RAN	Radio Access Network
RAS	Radio Access Station
RNC	Radio Network Controller
SG	Signaling Gateway
SGSN	Serving GPRS Support Node
SIM	Subscriber Identity Module
SIP	Session Initiation Protocol
SSID	Service Set Identifier
SWG	Signalling Gateway
TCP	Transmission Control Protocol
TCP/IP	Transmission Control Protocol/Internet Protocol
TDD	Time Division Duplex
TDM	Time Division Multiplex
TDMA	Time Division Multiple Access
TETRA	Terrestrial Trunked Radio
TTI	Transmission Time Interval
UDP	User Datagram Protocol
UHD	Ultra High Definition
UMA	Unlicensed Mobile Access
UMTS	Universal Mobile Telecommunications System
URL	Uniform Resource Locators
UTRAN	UMTS Terrestrial Radio Access Network
VLR	Visitor Location Register
VoIP	Voice over IP
VoLTE	Voice over LTE
VPN	Virtual Private Network
WAN	Wide Area Network
WCDMA	Wideband Code Division Multiple Access
WECA	Wireless Ethernet Compatibility Alliance
WEP	Wired Equivalent Privacy
WiFi	Wireless Fidelity
WiMAX	Worldwide interoperability for Microwave Access
WLAN	Wireless Local Area Network
WRC	World Radio communication Conference
WWW	World Wide Web

1 Introduction and problem statement

What is 5G? What services will it offer? The claims for what 5G will offer users, by politicians, industry commentators and suppliers are very wide ranging. If we are to believe what we are told, then 5G will enable [1-4]:

- Almost limitless download capacities – 10,000X that of today’s network
- Headline speed up to 20Gbps – 200X today’s top rate [3]
- Driverless cars
- Remote robotic surgery
- Drones that can deliver blood supplies in an emergency [1]
- Smart fridges and smart rubbish collection that will save the average UK household £450/yr [2]
- Augmented and virtual reality
- Coverage everywhere in the UK
- 99.99% reliability
- Latency of 1ms

All of these claims have continued to intensify since the inception of 5G and have become so entrenched in the minds of the general public that failure to deliver on these promises will seriously damage the industry. Chapter 2 provides an analysis of these claims and shows that some (such as rural coverage and reliability) are commercial, as opposed to technical issues. It then establishes a clear technical definition, on terms of capacity and coverage, of what a 5G network must supply to meet industry promises.

It is also important to determine the subset of these requirements that could be met by a “stretched” 4G – since that is a much cheaper option. Chapter 3 shows that in some circumstances the Quality of Experience of video users is not greatly enhanced by 5G from that which an evolved LTE network could offer. It does, however, point to the need for detailed techno-economic modelling of 5G to investigate the performance/cost trade off.

Surprisingly, there is little published research on the costs of rolling out 5G. This is a very important question – if the cost of 5G is many times that of LTE then new funding sources must be found. Chapter 4 describes the creation of a techno-economic model of 5G in dense urban areas.

In chapter 5 we show that the establishment of external networks at 3.5GHz and mmW (with umbrella coverage at 700MHz) can offer excellent coverage at 100Mbps with new radio systems that support ultra low latency services and greatly enhanced capacity. The cost of deploying these networks, however, will be several times that of LTE – we estimate a 4 to 5 times increase in costs for a 100Mbps everywhere network that has x100 capacity increase over existing LTE networks.

One way to reduce costs is to place 5G base stations within buildings. Chapter 6 extends the model to show that very high capacities – up to 3Tbps/km² – are possible with this approach. Costs are lower than for externally placed base-stations but only at high

capacities (typically 100-200Gbps/km²) when the large up front costs of fibre backhaul and internal wiring are less significant. There remain serious commercial questions around the leasing of property rights and cooperation between operators that may inhibit these solutions.

The key conclusions (Chapter 7) of this work are:

- 1) 5G can augment existing MBB (Mobile Broad Band) applications and provide extra capacity by adding 3.5GHz new radio to existing sites at low cost. High order MIMO (Multiple In Multiple Out) is essential to compensate for limited propagation
- 2) The eMBB (enhanced Mobile Broad Band) scenario should only be pursued if mmW becomes mainstream and suitable pico sites become available at reasonable costs. For internal users, femtocells represent the most scalable and least risky solution to adding high capacity. Even this should only be done if WiFi is not able to be integrated within 5G and does not offer sufficient capacity as it is potentially much cheaper
- 3) Ultra low latency applications that require coverage but not high capacity can be introduced much more cheaply than high capacity applications because relatively fewer (x10-X100 or so) base stations are needed for 90% coverage to 100Mbps than for capacities of 1Tbps/km² in urban areas.
- 4) 5G is unlikely to replace fixed Internet as it will not be cheaper or offer higher capacities. Commentators should not build this expectation amongst users.

Publication

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2 State of the Art and Analysis of 5G

“What is 5G?” turns out to be a more difficult question to answer than at first sight. We could take the promises of spokespersons, commentators and government officials mentioned in the introduction. We could define a set of 5G services and then the networks capable of delivering them would be, by definition, 5G. There are some in the industry who see 5G as an evolution of 4G – with changes in parameters such as headline rates and capacity as following the trend of previous upgrades. They are opposed by those with a more revolutionary view – that 5G will usher in completely new genres of applications and bear no resemblance to 4G.

In this chapter we analyse 5G use cases and plough through an extensive sweep of 30+ white papers and subsequent publications. This allows a clear set of 5G metrics to be defined whilst excluding largely technology neutral issues such as reliability and rural coverage. It is fair to say that the revolutionists have, for now, won the argument and that 5G is generally taken to include the likes of massive IoT device connections, autonomous cars and almost unlimited speeds and capacities.

There is, however, a lingering suspicion (and sound technical reasons) that not all of the proposed new 5G services will be a commercial success. There is also the “elephant in the 5G room” of costs and who is going to ultimately pay for the new spectrum, base stations, core and so forth. Given these uncertainties, it seems legitimate to ask the question as to what extent 4G could be upgraded to offer a subset of these new services. There are also architectural options for allowing a more gradual introduction of 5G – admittedly with less competition and more state intervention – that could reduce the risk of 5G failing to meet expectations. This is the modular 5G operator that is introduced at the end of the chapter.

2.1 Summary of 5G innovations

2.1.1 Spectrum

5G will, initially at least, employ spectrum not currently used for mobile services. Spectrum for 5G is conveniently divided into 3 categories:

- Sub 1GHz – this is the optimum spectrum for coverage and will be particularly valuable for IoT (Internet of Things) connections and rural coverage. Ofcom is currently (June 2019 - [121]) aiming to auction 80MHz of spectrum at 700MHz by spring 2020. This is a small amount of spectrum and, as later chapters show, will offer good coverage at low rates but only a modest capacity boost. In the future it is likely that other sub 1GHz spectrum will be made available (for example, from the TV broadcast spectrum or from re-use of 2G/3G spectrum).
- 1-6GHz – The main band in this range is the 3.4-3.8GHz band. Auctions and allocations have taken place in this band and early 5G services launches are mostly at these frequencies. In the UK EE have purchased 40MHz and are using this for their 5G service. A further auction of 120MHz in the 3.6-3.8GHz band is

slated in the UK for spring 2020. This spectrum is most useful in urban and sub-urban areas for both capacity and coverage.

- 6GHz+ - The first band in this range to be exploited for 5G looks like being the 24-27.5GHz band. This is a millimetre wave band – meaning that the range is much shorter than traditional mobile frequencies and that new techniques and electronics are needed, leading to a later introduction in 5G. In addition, the propagation through walls is very poor and it is unlikely these frequencies can be used inside buildings other than shopping centres or airports that are comparatively open. The great advantage of these bands is the amount of spectrum available – possibly 1GHz/operator. As will be shown later this can offer very considerable capacity uplifts compared to existing mobile networks. In the UK Ofcom has begun work on the auction of 3.25GHz of spectrum in this band [115] and is also working on the 66-71GHz band.

2.1.2 5G New Radio

5G utilizes a new radio system which is similar to that of LTE – with a waveform based on OFDM (Orthogonal Frequency Division Multiplexing) and a Cyclic Prefix. The new radio is highly scalable – meaning that it can be used in small and large spectrum blocks by modifying the sub-carrier spacing. It has also been designed with a very flexible slot structure (carrier and time duration) – this allows for very fast switching between uplink and downlink and significantly reducing the latency from that of LTE (20ms or so to 1ms). The slot structure efficiently supports a range of different traffic – including a high density of IoT devices. New channel coding is employed that is significantly more efficient than LTE turbo-codes at the high data rates expected in 5G, further increasing efficiency

2.1.3 MIMO improvements

The 5G New Radio has been optimised for massive MIMO (Multiple Input Multiple Output) – that is to say transmitters and receivers with 256 (eg 64x4) or more elements, as opposed to the typical 4x4 of LTE. With such large arrays it is possible to avoid interference from neighbouring cells and to concentrate radio energy where users are located and, in the extreme, forming beams that envelop only single or groups of users. A number of channel feedback features in the new radio enable this.

2.1.4 Network virtualisation and slicing

Initially 5G will launch in what is called a non-standalone mode (NSA) – with the new radio nodes attached to an LTE core. All control data will go over the LTE network and voice will be handled by VoLTE (Voice over LTE). In time a new 5G core will be deployed – this is different to the LTE core (although it provides many of the same functions such as mobility support and security). The new 5G core, however, has been specifically design for virtualisation on generalised hardware in data centres. This is claimed to increase flexibility and reduce overall costs.

Another feature of the 5G core is network slicing - the ability to allocate network resources and connectivity to a given use case. Each use case receives a unique set of optimized resources and network topology — this could be a so called vertical (such as IoT) or a very specific application (smart meters) or a specific user group (e.g. American Express or Netflix). In essence, network slicing allows the creation of multiple virtual networks atop a shared physical infrastructure.

The next section looks at how these features of 5G enable new use cases and better support existing ones. In many ways, however, it is the use cases that are the truly revolutionary aspect of 5G. As will be shown they go far beyond a generational trend improvement in speed and capacity. The technical innovations in 5G are necessary, but not sufficient, to support these use cases. The requirements of the use cases clearly need significant investment and the main aim of this work is to evaluate that cost.

2.2 Use cases

2.2.1 Use case 1 - Internet of Things

This is a very wide area – typically with applications covering fields such as transport, energy, health and home automation. Today machine-type communication over cellular is a small fraction of total traffic. Many devices are connected by GSM technology – because of superior coverage, low cost and low bit rates involved. Expanding beyond high-value applications that have access to mains power (i.e. do not require ultra low power radios), it is clear that current cellular technology will not meet the requirements envisaged for the IoT:

1. Power consumption. Many sensors will not have a power source and will rely on either energy harvesting or a long life battery. The power consumption involved in connecting, transmitting and disconnecting to current cellular networks is too high for these devices.
2. Cost. Many envisaged applications are inherently low cost: pallet-tracking, small sensors etc. The IPR cost of 3G or 4G radios alone is too much to support these applications. In addition, the cost of SIM-based security and a fair cost apportionment of signalling would also be excessive.
3. Bit rate. There is an enormous variation of potential bit rates. A vending machine might log on once a day to report that it is still working and does not need a service (a few bits/day) or a security camera may need to send HD video at 30Mbit/s.
4. Number of devices. Current cellular networks are not easily scalable to hundreds of thousands of devices per km². It is easy to imagine very dense sensor networks frequently trying to establish a radio connection to send small amounts of data. The RACH (Random Access CHannel) of cellular systems would not be able to cope with such a signalling storm.
5. Security. SIM cards are clearly unsuitable for many IoT applications. The cost and form factor alone would preclude a number of applications. In addition the security overhead for the aforementioned vending machine sending 1 bit (ie “everything is OK”) would be unsustainable. SoftSIM does not answer all these points as it still requires a substantial processor and memory.
6. Latency. The typical IoT application requiring very low latency is autonomous vehicles. Trains of cars are imagined interchanging information that activates braking and steering systems in response to, say, jaywalkers.

The future IoT thus generates a vast parameter space of requirements for 5G but mostly feeds in to the density of devices (high), latency (low for some services), power consumption and universal coverage requirements.

2.2.2 Use Case 2 - Video delivery

Over 50% of the traffic on today's mobile network is estimated to be video traffic of one sort or another and is growing rapidly (Fig.2.1).

Figure 2-1 Fixed and mobile total (left) and video (right) traffic growth: Source: Cisco[5]

In the future there are many reasons to believe that even more video traffic will need to be supported on 5G mobile:

1. End of wireless broadcasting: Following the switch from analogue to digital TV and the auctioning of the cleared 800MHz spectrum, together with increased delivery of TV from non-broadcast spectrum (satellite, IP multicast, IPlayer etc) discussions have started about removing terrestrial broadcasts and switching to IP-based delivery – including 5G.
2. Higher definition TV. Many users are switching to 4K TV there are plans for 8K to be introduced in the next few years.
3. End of real-time delivery. Users are increasingly wanting to watch TV on-demand rather than live TV- meaning many separate deliveries of the same content. On-demand delivery services (such a Netflix) will need to offer content at different data rates for users on a variety of terminals.

2.2.3 Use Case 3 - Better LTE

LTE provides an IP-pipe connection with speeds typically up to 100Mbit/s and latencies of 40-70ms. Some use cases proposed for 5G (see fig. 2.2) could be technically served by LTE (Rel.12). In addition, new spectrum (700MHz DTT spectrum) and spectrum re-farming could offer capacity increases. LTE (Rel.12) could be expanded and enhanced in a number of ways:

- Capacity – A combination of: new spectrum, microcells and femtocells could provide a very large capacity increase
- Average data rate – current LTE cell edge rates are still much lower than centre rates – this could be improved with technologies already being standardised such as CoMP (Coordinated Multi Point), CA (Carrier Aggregation) and higher order MIMO. Femtocells will could also improve edge rates
- Coverage – LTE coverage is limited to urban and suburban areas at present – by and large this is a commercial decision and regulation/subsidy could extent this
- Reliability – LTE is not 100% reliable (eg TETRA is more reliable) – investment in redundant links and national network roaming would massively improve reliability.

Figure 2-2 5G scenarios (Source METIS – [6])

Fig. 2.2 shows the EU project METIS [6] 5G use cases. Some of these applications are technologically suitable for LTE delivery but are held back by commercial or regulatory hurdles. For example, location services. Location services were introduced in 3G and third parties were able to pay MNOs to gain information on the user's location and use this to deliver a location-based service. Unfortunately, the high cost (approximately £0.05/lookup) acted as a stimulus to develop other mechanisms of determining user location (cell id, WiFi SSID etc) and the opportunity was lost. Similarly, there are numerous QoS classes defined in both 3G and 4G and operators can offer a range of QoS support for services. There is obviously a major commercial barrier to this as all data delivered over mobile networks in the UK only utilise "best-effort" QoS. Services relying on very high coverage levels or 100% reliability (smart meter reading and police communications, respectively, say) are further examples of services that LTE is technically able to deliver. Later sections in this chapter will look at how LTE might evolve further to cover more of the proposed 5G use cases. Indeed, EE have a contract to replace the emergency services TETRA network with an LTE-based equivalent that can also carry data and video (although this is late and over budget).

There are, however, other services that are not provided today by LTE because of more difficult technological barriers such as latency. Only a very radical overhaul of the LTE air interface would reduce the latency to ms levels. To support these use case a new air interface and a new network architecture is, essentially, required.

One aspect of better LTE is just faster mobile data. This has been named as the eMBB (enhanced Mobile BroadBand) scenario. This is often ill-defined and a conflation of better headline rates, average rates and user download volumes. It is obvious, however, that meeting the eMBB scenario will require massive increases in mobile capacity.

2.2.4 Use Case 4 - New Applications

This class of use cases require technologies/commercials/networks or spectrum that are not possible with evolved LTE. This is a whole genre of new applications that require both ultra-low latency (1ms), massive connectivity (every device connected to every other

device and the cloud) and very high data rates everywhere. Fig. 2.3 shows applications envisaged by 2 leading 5G promoters and are archetypal of what is being proposed.

Figure 2-3 Proposed 5G services: SK Telecom (Left – [7]) and NGMN (right) [8]

Most striking of these are the tactile Internet, real-time remote control and AR/VR (augmented reality and virtual reality). These are services requiring ultra-low latency – 1ms is a typical value given. Much emphasis is also given to “cloud” services – the idea that the high data rate and low latency everywhere means that services will be cloud-based and not require local storage or processing.

2.3 5G requirements

In the early days of 5G (2013-2016, when the requirements were being established) there were a plethora of white papers on what 5G would be. These often included use cases that were used to “derive” the requirements. To come to a consensus view over 30 sources ([6-36] – Including the EU project NORMA) were analyzed and from this it was possible to distill table 2.1 (which includes only some of the sources but is representative of the cohort). The final column show the improvement required over LTE Rel. 12.

	South Korea 5G Forum	ARIB 2020	IMT 2020	METIS	5GPPP	Nokia	NGMN	Improvement on LTE Rel 12
User-experienced data rate	1Gbps downlink; 0.5Gbps uplink		0.1–1Gbps	1–10Gbps	10–100 times more than 4G	100Mbps min	50Mbps everywhere	10-100X average 100X on edge
Peak data rate	More than 50Gbps downlink; over 25Gbps uplink	More than 10Gbps	10–100Gbps	No data	No data	10Gbps	1Gbps	10-100X average 100X on edge
Connection density	1000 times more connected devices	10 000 per cell	1 million connections per km ²	300 000 per access node	10–100 times more than 4G	10-100 x number of devices	150,000/km ²	x100
End-to-end latency	1ms user plane	1ms	About 1ms	About 1ms	1ms	1ms	1-10ms	X10
Traffic volume density			10–100Tbps per km ²	1000 times mobile data volumes	More than 1000 times higher cell throughput than 4G	10,000X more traffic	1-15 Tbps per km ²	X1000- X10,000
Mobility	More than 350km per hour	500km per hour	More than 500km per hour	500km per hour	1000 times higher wireless area capacity than in 2010		500km/hr	X1.5
Capacity	10bps per hertz downlink; 5bps per hertz uplink	More than 1000 times greater per km ²	5–15 times more efficient than 4G	36TB per month per user	More than 10 times greater than 4G	10,000X more traffic		X1000- X10,000
Energy efficiency	100 times more efficient than 4G		100 times more efficient than 4G	About 10% of current energy consumption	80% reduction in radio access network	Much lower J/bit	1/2000 that of LTE!	x100
Reliability				99.999% within time budget			99.999%	X10

Table 2.1. Summary of 5G requirements

In early 2017, ITU representatives partnered with academia and research institutions to complete a series of studies focused on the key 5G tech and performance requirements for IMT-2020. Their latest report [32] outlines key minimum specifications currently regarded as reasonably universal metric for 5G:

- Requirement for bandwidth at least 100 MHz
- Bandwidths up to 1 GHz are required for higher frequencies (above 6 GHz)
- Minimum requirement for connection density is 1 million devices per km²
- Downlink peak data rate of 20 Gb/s
- Uplink peak data rate of 10 Gb/s
- Target downlink “user experienced data rate” of 100 Mb/s
- Target uplink “user experienced data rate” of 50 Mb/s

One of the most surprising things about this table, and subsequent IMT work, is (despite differences in views amongst the various organizations involved) the commonality of requirements.

The first thing to do when analyzing these requirements is to tease out reliability and (rural) coverage. Reliability is related to properties such as redundancy, fall back, fail safe and stand-by services. GSM, 3G and LTE all could be made much more reliable – at a cost. There seems very little in 5G technically that makes it inherently more reliable than previous generations. Indeed, a virtual core with software running on generic servers looks, on the face of it and in early incarnations, much less reliable than the dedicated core of LTE. Rural coverage is another issue that 5G technology offers very little improvement over existing technologies. What is needed for rural coverage is low frequency (sub 1GHz) and only a very small amount of 5G spectrum is being released in this band. Urban areas are, typically, capacity limited and so each new or upgraded base station results in more traffic on the network. Rural areas are typically coverage limited. Investment cannot be justified on commercial grounds and the return plummets as the frequency of the spectrum rises. To provide coverage requires a subsidy – either from other users of the network (via regulation as in the Royal Mail), from company profits (as in Ofcom forcing Openreach to invest in fibre) or direct from the government (via various regional initiatives). The latest development (Spring 2019 [116]) is that operators EE (BT), Vodafone, O2 and Three UK have confirmed a new agreement that could help to boost the rural coverage of their 2G, 3G, 4G and future 5G networks. Under the deal a new infrastructure company will be established to help build masts in remote areas. This is awaiting Ofcom approval.

If a New Radio (the current physical/link/MAC layer) proposed for 5G is deployed with good coverage (see below) then it will offer low latency services if it is connected to a 5G core with low delay backhaul. It will also allow a very high density of IoT devices to be connected thanks to its flexible frame structure.

Headline rates feature very heavily in 5G promotion. By far and away the most mentioned figure, when talking about 5G, is 1-10Gbps. This has been “promised” to users by: researchers, MNO spokesmen, manufacturers and the UK government. Now it is important to note that the headline rate of a network is not actually that useful a metric of network performance. In a lightly loaded LTE network today it is possible to get 100Mbps when close to a base station in good radio conditions. It is much harder to get

100Mbps indoors and at cell edges – even at quiet times of the day. In a loaded network the maximum rate drops further and is limited by the total demand. A much better metric is the coverage of the cell that can be achieved at a lower rate when the network is loaded. Thus 95% coverage at 100Mbps or 200Mbps is far harder to achieve than 1Gbps+ in favorable conditions and, consequently, we will use this as a metric of “5Gness”. This is clearly related very closely to the “average” rate of table 2.1 and, indeed, nearly all users would sacrifice headline rates for higher average speeds.

The other key metric to emerge from table 2.1 is capacity (labelled in Table 2.1 as “traffic density” but referred to in the literature as capacity and measured in units of bps/km²). The “capacity” row of table 2.1 alludes to similar increases of X1000 or so but is not well defined in the sources and it is hard to differentiate the two when reading the material. With suitable assumptions on busy hour, it is possible to translate bps/km² directly into monthly download totals and this is done in a later chapter.

Current mobile capacity is running at around 1-5Gbps/km²/operator in central London (see later chapters). An increase to 1-10TBps/km² is a x1000 increase. As will be shown this is of the order of the fixed broadband capacity likely in central London in 2025.

It is, therefore, proposed that the metrics of 5G are:

- 1) 90%+ coverage at 100Mbps or 200Mbps in a heavily loaded network
- 2) Capacity of 1Tbps/km² in urban areas
- 3) A new radio deployed that covers 99% of the cell area – offering low latency services and very high device density (IoT)
- 4) Fibre backhaul with low latency (possible very short microwave hops)

Since all of the radio systems proposed for 5G are similar in nature to existing systems in their operation, the headline rate associated with these parameters will be 1Gbps+ (5-10X edge rate). To move beyond 99% coverage (at a given data rate) is more about radio planning, testing and greater expenditure than the concomitant services may not warrant commercially. Likewise, the network reliability can be traded off for extra cost.

In this chapter the consequences of these requirements are explored – leading to an understanding of what a 5G operator meeting these requirements would look like architecturally and defining the tightly integrated 5G MNO. Depending on services, revenues and commercial developments such an operator might struggle to compete with more lightweight operators. The tightly integrated 5G operator is then contrasted with a 5G operator who offers only a limited subset of services with relaxed network requirements. Such an operator is then better able to integrate with WiFi – potentially offering a large number of the most profitable 5G services at a much lower cost. To bridge the gap between these two extremes the concept of the “modular” 5G architecture is introduced. This starts with a core or minimum 5G architecture and proposes to add capabilities via upgrades and overlays. The key advantages of such an approach are that different operators can offer different service sets and some elements, such as very high coverage or emergency support, could be subsidised and limited to a single network. In some ways this might be considered an evolution of the original 3G layered approach (satellite, macro, micro, pico..).

Chapter 6 returns to the concept of network sharing and neutral hosting – picking up some aspects of the different architectures detailed here. The different architectures outlined in this chapter input directly into the analyses of the next two chapters that begin to tease out the costs of the various 5G options.

2.4 The tightly integrated 5G operator

In order to meet the requirements detailed above a 5G operator will need to be radically different to current 4G operators with a very different architecture. A totally new air interface will be needed, even in the sub 6GHz spectrum, to meet both the 1ms latency and support a high density of IoT devices. To meet the high headline data rates (10Gbps+) and capacities will require the use of cm and mm wave (mmW) frequencies (10-100+MHz). (In the recent auctions EE purchased 40MHz of 3.5GHz spectrum: to offer a headline rate of 1Gbps would require an efficiency of 25 and for 10Gbps 250). Whilst some lab demos may report such figures it is highly unlikely that the average efficiency (typically 2-4 for deployed LTE) will exceed 10-20 for 5G. This is further discussed in chapter 4 which describes a 5G radio model). These frequencies become increasingly LoS (Line of Sight) and so users will require beam tracking and beam forming technologies – fortunately the higher frequencies mean more antenna can be packed into a smaller space (up to 1000x1000 are proposed). mmW cells will have to be quite limited in range as these technologies will not be suitable for indoor operation (Other than open spaces – such as shopping malls or railway stations). For indoor capacity pico and femto cells in the sub 6GHz spectrum will also be required. To coordinate all these small cells control will always be vested with the macro network (C-plane, U plane split). The consequences of this are that it is very hard to envisage different ownership and control of the macro and small cell networks. Chapter 3 will explore WiFi/cellular integration and shows that it is possible for a tightly integrated 5G operator to include WiFi as U plane transport mechanism in different ways. Content delivery will need to be from within the 5G network to meet the 1ms requirement. In glass light travels at 2×10^8 m/s – 1ms is 200km one way or 100km each way. If 50% of the 1ms budget is required for the air interface and 25% for processing that means all content and interaction must be within 25km of the user (the GSMA [9]-suggests 20km). The RAN then is forced to cache large amounts of content: RAN caching is novel research concept at the present time but the MEC (Mobile Edge Computing) initiative may offer hosted 3rd party services close to users.

The RAN will require fibre backhaul (with a possible short microwave hop) to function in the way that is envisaged: high frequency operation will require the combination and joint processing of multiple beams from different small cells. Not least of all of the current trend is for smaller footprints at base stations with as much processing pushed back to aggregation points – adding content delivery capability means that copper technology will not meet the very high data rates and low latencies. For comparison the current latency on BT infinity (FTTC – Fibre-To-The-Cabinet) is 20-30ms.

5G mobile operators are also expected to operate a very different value chain to the existing one. By and large, current 3G and LTE operators offer voice, text and a data pipe. The data pipe offers only best-efforts and is priced by total data usage. OTT operators offer applications (including video and voice – eg Skype) from several app stores (eg Apple store). Different players offer payment services (eg PayPal) and still others offer content (eg Netflix). MNOs currently have no relationship with these

services. However, 5G vision papers (as epitomised by the NGMN – Next Generation Mobile Network alliance) envisage a much greater role for 5G operators in this value chain. These operators will be responsible for content delivery with guaranteed QoS, payments and many applications such virtual reality which will be served from within the 5G operator's network to meet the low latency requirements (see Fig. 2.4).

Figure 2-4 For low latency services any processing or content must be within the MNO's network but may be hosted on behalf of 3rd parties (eg using a MEC server) (Source SKT [7])

2.5 The evolved 4G operator

As a completely opposite approach it is legitimate to ask what cellular look would like if only evolved LTE was available. Could it, for instance, meet the ITU forecast[32] of mobile traffic growth assuming current mobile data trends continue (Fig.2.5) – a much lower estimate of mobile data growth than that shown in table 2.1 and expounded by 5G proponents.

Figure 2-5 ITU predictions for mobile traffic growth [32]

This is a much lower forecast of capacity (about X100 from 2011 to 2025) than the 1000-10,000X quoted by 5G white papers. LTE could support such an increase in data with improvements in 3 dimensions as explained below.

2.5.1 Spectrum

New spectrum in the sub 6GHz bands will be available in the 15 yr time frame [32] offers some insight into spectrum requirements. Ofcom (Fig. 2.3 [33]) show that available sub 5GHz spectrum will double from 300MHz in 2014 to over 650MHz in 2025. (Cambridge Consultants quote up to 963MHz available by 2025 in sub 6GHz spectrum – [34])

Figure 2-6 Spectrum that will become available for mobile comms in the UK (Source:Ofcom [33])

2.5.2 Efficiency

There are two ways that efficiency will be improved. Firstly, spectrum will be re-farmed from 2G and 3G for LTE. Since LTE is much more efficient than these technologies (table 2-2) then there is a big efficiency gain to be had from re-farming. Taking a 4X improvement for recycled 3G to LTE Rel.10) spectrum, together with a doubling of spectrum gets a total capacity gain of (about) x10.

Technology	Efficiency bit/s/Hz
GSM	0.04
3G	0.68
LTE (Rel. 8)	1.3
LTE (Rel. 10)	2.6
5G NR 32x1 MIMO Tx	6.27
5G NR 64x1 MIMO Tx	9.43

Table 2-2 generation efficiencies (Source: Cambridge Consultants – [34])

The second way in which efficiency increases is that further releases will incorporate improvements (eg carrier aggregation over 3 bands, better MIMO and so on) – that may well yield another 50% efficiency for a total gain of about X15.

2.5.3 Small cells and WiFi

Without expanding the macro network base sites, it would be possible to expand sectors to add another factor of 1.5 to 2 to the capacity – making something like X20-30 overall capacity gain. To cope with the gap to x100 requires either small cells (micro,

pico or femto) or an expansion in the use of WiFi. The main barrier to greater WiFi offload is the difficulties in discovering, selecting and authenticating to WiFi networks. New technologies – such as HoTSpot 2.0 – that allow handsets to exchange information with WiFi base stations before attempting to attach and authentication mechanisms using SIM and certificates are set to automate the process and, moreover, allow much simpler roaming between networks. Together with the trend towards home and business routers offering access to external users (BT FoN and a similar technology that has been announced by Virgin Media), it is not inconceivable that WiFi could offer a considerably enhanced offload capability. Add in developments towards higher WiFi speeds in the 5GHz spectrum and it is not impossible an evolved LTE+WiFi network could offer a factor of X100 capacity compared to current cellular networks.

2.5.4 Latency and headline rates

Latency will continue to reduce but is unlikely to fall below 10-20ms for LTE-based technologies and networks. Headline rates will improve and already are being demonstrated at 300Mbps.

2.5.5 Evolved LTE

Even if LTE is able to increase capacity by a factor of 100 and headline rates to 300Mbps it will not meet the criteria we have set out for 5G. It will clearly not support ultra-low latency services, it will not offer 100-200Mbps at cell edges and definitely not be capable of 1Tbps/km² capacity. If services that depend on these requirements prove a commercial success, then evolved LTE will be inadequate. If, however, services requiring 1ms latency are very niche and users rely on fixed networks for heavy data transfers (possible because of lower cost, say) then the evolved LTE operator might be commercially successful.

2.6 5G Evolution or Revolution

Having identified two extremes of 5G – the tightly integrated network offering 100--200Mbps everywhere and 1ms latency coupled with cm and mm wave technologies and the evolved LTE network operating in sub 6GHz spectrum, having very few small cells and relying on enhanced WiFi for offload. It is legitimate to ask where on this spectrum most organizations lie: in the wider literature there is a great variation of views:

- 1) “5G is an end-to-end ecosystem to enable a fully mobile and connected society. It empowers value creation towards customers and partners, through existing and emerging use cases, delivered with consistent experience, and enabled by sustainable business models.” NGMN 5G Vision [8]
- 2) “5G is on its way and rather than being another ‘next generation’ it will be a better integration of old and new technologies. This integration of different systems will enable more stringent requirements in some areas to be met, relaxed needs in others, with a focus on keeping overall costs and energy dissipation low. The combination of evolution and revolution, wide and local area, big and small cells and different carrier frequencies will enable a fully scalable service experience on demand, where people and machines will enjoy a virtual zero latency gigabit experience when and where it matters”. – Nokia [36]
- 3) “View 1 – The hyper-connected vision: In this view of 5G, mobile operators would create a blend of pre-existing technologies covering 2G, 3G, 4G, Wi-fi and others to allow higher coverage and availability ...” “View 2 – next-generation

radio access technology: This is more the traditional “generation-defining” view, with specific targets for data rates and latency being identified such that new radio interfaces can be assessed against such a criteria..” – GSMA [9]

By and large, however, most of these organizations tend to be closer to revolution than evolution (notable exceptions, in the evolution camp, are GSMA and Cambridge Consultants). The hard questions for the revolutionists is “how valuable are the services that can only be provided by revolution and not by evolution?” and “how much will they cost to provide”. One way to tackle this is to identify these is to look at the latency and headline rate requirements (Fig. 2.7 shows a GSMA version – [9]). Autonomous cars are clearly an area that needs 1ms latency (if real-time braking, pedestrian sensing and car-trains are to be introduced). These could, in theory, be provided on existing networks but would require a new air interface with much shorter time frames. Cars exchange information with each other in real-time and the environment to avoid crashing and allow coordinated braking etc. However, it has been pointed out that cars that can’t drive themselves without real-time network input are not truly autonomous and could be subject to network jamming by ne’er-do-wells and such like (as existing networks are easily jammed). The commercial potential of tactile Internet is seen by some commentators as “adult tactile” services [37]. These will be provided in static indoor locations and could just as well be served by a fixed Internet. Similarly, it is hard to find applications that need 1Gbps rates. Ultra high definition TV is one possibility (4K and 8K UHD) – but no one will be mobile with such a screen; unless there is a major breakthrough in portable screen technology (such as retinal scanning– although this has been under development for 20 years). Fig. 2.7 will be revisited after the modelling of later chapters, clearly showing that the low latency axis is potentially much cheaper to attain than the high speed (and inter-linked) high capacity axis. One of the main achievements of the project is to quantify the cost of providing these new services and providing a guide to the required revenues and investments to make them commercially viable.

Figure 2-7 Bandwidth and latency requirements of potential 5G use case: source GSMA intelligence – [9]

Following on from this argument there is the question of the relationship of 5G and fixed Internet provision. If 5G is providing data rates of 50Mbps everywhere and a top rate of 10Gbps plus 1ms latency, then this is likely to exceed the performance of UK fixed Internet. BT is currently wedded to FTTC (Fibre To The Cabinet) and DSL (Digital Subscriber Line) migrating to G.Fast for the copper drop – giving a performance of 100-300Mbit/s and 5-10ms latency. Cable networks, using DOCSIS technology, will offer slightly improved rates of 300-500Mbit/s and 5ms latency. Either technology is likely to be eclipsed by 5G performance (Headline rate and latency but not capacity – which will be similar for the two if 5G reaches 10Tbps/km² in urban areas) which leads to a very interesting question as to the relationship between 5G and fixed Internet. This is linked to the question of how 5G will interact with WiFi – since WiFi is the de-facto wireless tail for fixed connections. The following are possible scenarios:

- 1) The two delivery mechanisms diverge. Fixed Internet could continue to offer “bit-pipe”, best effort delivery of IP packets with OTT provision of most services. Latencies and headline rates would not match those of 5G but capacity would be higher. Wireless tails would be evolved-WiFi and there would have to be gateways to support IoT devices. 5G would offer integrated services delivery (especially video) with lower latency for some services (VR tactile Internet etc.) that could not be provided by the fixed Internet. Support for IoT would be much better from 5G.
- 2) 5G and fixed Internet converge. In this scenario fixed Internet develops to be more like 5G – with emphasis on integrated service delivery and QoS and a big technological push for lower latency and higher rates (eg more fibre deployment). 5G technologies would then displace WiFi as the final delivery tail. Users would likely be offered fixed/mobile combined tariffs and services.
- 3) 5G replaces and displaces fixed Internet access. If 5G is offering 50Mbps and 1ms latency everywhere (and headline rates up to 20Gbps) with enormous capacity, then the only reason for the continued existence of the fixed Internet is lower cost! Traditionally there has been a factor of 10 gap between fixed and mobile data traffic (and that is including WiFi offload as mobile) (Fig. 2.1 from Cisco shows a x7 factor in 2017). Also there has always been a considerable price premium between fixed and mobile (Ofcom - [38])
- 4) 5G is a premium service and LTE++ persists as a lower cost option. In this scenario 5G is more expensive than LTE (and hence much more expensive than fixed Internet) and becomes a premium service for special services that require high headline rates and ultra-low latencies. LTE continues to provide a data bit pipe for 10% of the data traffic and the fixed Internet provides a similar service for the rest.

2.7 5G-lite - towards a modular 5G architecture

The above scenarios point out the dangers that 5G will be a high-cost network and that applications with a small commercial base “infect” the 5G network with high basic costs. The consequences of that would be that the fixed Internet and short wireless tails (WiFi) would compete successfully for low value, best effort, packet traffic needing only a relaxed latency and headline rate. Moreover, LTE (Rel.12) and possible evolutions would also compete for this traffic.

There are many reasons to suspect that a tightly integrated 5G operator meeting NGMN (Next Generation Mobile Group) requirements would incur higher costs:

- Latency reduction: Squeezing the latency out of the network will inevitably increase costs. There can be no packet queuing or dropping or re-transmissions – all of which point to larger router handling and more robust coding that becomes a large overhead. All content will have to be provided from the RAN (increasing storage costs – since this will have to be duplicated in each RAN area). Worse still content for roaming customers will also have to be stored. Mobile Edge Computing (MEC) is being developed to fulfil this role in 5G.
- Reliability. If reliability is to be increased, as will certainly be needed for autonomous vehicle applications, then cost will be increased. Any network can be made more reliable – more redundant backhaul, hot standby of core elements and overlapping cells are just 3 examples – at a price!
- Headline rate. In striving for a headline rate of 10-20Gbps can only be supported by frequencies over 10GHz. These are more or less line-of-sight wavelengths and to provide continuous coverage would require a large number of small base stations – each with large scale beamforming capabilities. In a city this would be something like a base-station every few hundred feet. In an office or home a base station would be needed in each room.
- Reliance on fibre backhaul. It is very hard to see 5G meeting these headline rates and latencies without large-scale fibre deployment. G.Fast and XDSL are not capable of providing these capabilities and, without a cloud RAN, it is hard to imagine that interference cancellation, beamforming and distributed caching could be engineered.
- Closed value chain. NGMN envisage mobile operators playing a much larger role in the 5G value chain when compared to 3G and 4G. With both MNO voice and text services declining (and being substituted by Internet VoIP and messaging apps) and pricing increasingly just by data bundle, mobile operators are keen that 5G is about content delivery from their networks. Moreover, they are keen to offer location-based and payment service based on their networks. This is, judged by history if nothing else, likely to be a much higher cost solution than OTT service provision. The lack of competition and innovation if all services have to involve a 5G operator will keep charges high.

To avoid this pitfall it is proposed to offer a “modular” 5G architecture. The concept here is to build a base-line macro network in sub-6GHz spectrum. Spectrum usage and re-use is critical here:

- Existing LTE spectrum will continue to be used by operators for LTE and evolved LTE
- Existing 2G and 3G spectrum will be re-farmed to a new OFDM-based air interface that is backwards-compatible with LTE or simply LTE (Rel 12 + any 5G features that can be added)
- A small amount of 2G and 3G spectrum will be used for a national network that supports legacy devices of all operators. This network is controlled by a non-MNO body.
- New sub-6GHz is used to offer 3 overlay networks:
 - The lowest frequency (greatest coverage – probably 400 or 700MHz) available spectrum is used to create an IoT/M2M network. This would require approximately 2000 base sites [39] and would be a national network (ie only 1). It would run an M2M radio protocol (such as WEIGHTLESS [40]) and support low to mid data rate applications. This

- could be a regulated – open access – network – in much the same way that Openreach provides access to fixed copper network.
- Some new spectrum would be used for a new TDD based air interface with 1ms latency (possibly the 5G New Radio). This would be deployed in urban areas with an existing fibre network as a network for premium services. It would offer full mobility (for autonomous vehicles) and nomadic capability (for tactile internet and VR – which are not likely to be mobile). There is unlikely to be enough commercial pull for more than one such network in any given location.
 - Another large, contiguous block of spectrum, at the highest available frequency would be used for a 500Mbit/s service. Following on from the METIS analysis it might be possible to offer 300-500Mbps at 3.5GHz. This spectrum has a short range and multiple operators could be licensed in the same spectrum. It would mostly be deployed indoors or in urban areas where fibre backhaul is available.

Fig. 2.8 shows possible operators and the general architecture.

Figure 2-8 Modular 5G approach (author)

There are many advantages to this modular approach:

- Each operator does not need to build a high cost 5G network serving all requirements.
- The niche requirements of 5G (ultra-low latency, very high headline rate and IoT) are all provided by overlay networks whose economics and commercials can be assessed separately. Moreover, the cost of these networks does not infect the general IP bit-pipe delivery success of 4G.

- Services can be introduced gradually, in different locations, without the need to offer such a major upgrade for 4G in one step.
- Costs are more transparent
- There is no longer confusion and overlap with fixed Internet (+ WiFi)
- There is large scope for value-chain innovation – in particular for network subsidies for specific functions
- Decisions on who operates networks could be taken in a number of ways: the operator might have a management contract (i.e. just to operate it) or be offered a license for a number of years with a price cap/control mechanism.

2.8 Existing modelling

There is a long history of techno-economic modelling going back to 3G and continuing through LTE, femtocells and a very small number of 5G models. Markendahl [41] published a techno-economic model of macro cellular and femto deployments in an urban environment. Frias [42] provides an LTE model and costings and Nikolikj [43] provides cost estimates and models for LTE for 700MHz, 2.6GHz and WLAN in the 5GHz band. Yunis [44] provides a different model 4G and femtocells.

In terms of 5G modelling, EU projects NORMA [48] and METIS [45] include techno economic modelling. Smail [46] presents a simplistic radio capacity model for a number of 5G technologies. However, these models are either of 3G or 4G technology or do not offer the resolution and range of frequencies/technologies of the current work. As far as we are aware, this is the only work to create a detailed technical model of 5G at 700MHz, 3.5GHz and mmW and to compare the coverage and capacity with WLAN and LTE. Costings in this work are also based on a much wider base than those cited above – chapter 5 provides much more detail on this. Oughton [47] comes closest to the current work and provides costing for the rollout of 5G across the UK to provide 50Mbps coverage – now considered on the low side for 5G and below that offered by LTE in more urban locations. In addition, Oughton does not provide costs against capacity or consider mmW and internal base stations. Only a simplistic radio range estimate is used.

2.9 Conclusion

5G has been promised to: have a high headline rate, offer high average rates across cells, offer ultra low latency and add massive capacity to existing mobile networks. Clearly all of this is going to be expensive. Operators, regulators and vendors can offer different approaches – using shared and modular networks and adding support for unproven applications in a low risk fashion. In the next chapter the concept the different 5G architectures are represented by different operators in a first techno-economic analysis of these ideas.

There is a drive to 5G form the global ecosystem with operators obliged to deploy 5G networks because device vendors have convinced customers that they need 5G (see Webb [49] for more on this argument). The services proposed have not convinced all commentators and industry experts of their strong commercial potential and, moreover, there is a strong suspicion that 5G networks will be extremely expensive to deploy widely. It is very hard to decide these questions without techno-economic analysis. Chapter 3 starts by relating the actual user experience to the cost of providing that

experience – shedding some light on how quality of experience can be related to cost for different operators.

3 QoE, Costs and 5G – initial model

Having decided that only a techno-economic model can expose the various cost points in 5G it is necessary to make some basic assumptions to create one. In this chapter we use a simplistic rail station scenario – based in a UK city in 2025. On the radio side the model is basic – using only a very crude zonal propagation model. Because such an approach is very tractable (in terms of resources) it was possible to follow this through the whole rail station scenario and ascribe quantitative Quality of Experience (QoE) figures to the various users. In the next chapter a more detailed techno-economic model is described that models the radio propagation to every single pixel within a grid. This is far more accurate in determining throughput rates but computationally expensive.

3.1 Rail station scenario

The rail station scenario is illustrated in Fig.3.1. This is somewhere in the UK in 2025. There are three zones – outside the station, inside the concourse and on the platforms.

Figure 3-1 Rail station scenario for WiFi-5G integration (source: author)

A summary of the operators is given below (with more detail in table 3.6 later in the chapter):

- 1) A tightly coupled 5G operator of the “NGMN type” – with a 10Gbit/s headline rate, 1ms latency network that provides all possible services – with a strong service platform and limited emphasis on OTT services. This operator has both macro (sub 6GHz) and micro networks (10GHz+). MNO-A. This is a similar network to that used by Samsung for trials in Seoul 2017 [117]– the results of this trial are discussed in chapter 5.
- 2) An evolved LTE operator - with only a macro network (Sub 6GHz); 1 Gbit/s headline rate, 10ms latency and almost no service provision. MNO - B
- 3) WLAN – a single WLAN across the station – Operator C

The purpose of this example is then to compare how the cost and QoE vary between MNO-A and MNO-B with both loose and tight coupling to the WLAN network. This is done for a progressively more loaded network (since QoE will obviously depend on network loading). Users are treated in an aggregate way (ie no individual users are modelled) and video is the only service considered in detail. (Since this is the bulk of the predicted mobile traffic today and predicted to become even more dominant in the 5G era). Again the extension – with more resources – to a variety of services is relatively straightforward – at least conceptually. The steps used to relate cost to QoE are summarized below and the remainder of this chapter works through these steps – in a quantitative way with references to all sources – to arrive at illustrative cost/QoE charts.

3.2 Methodology explained

These are the inputs and pieces of the cost/QoE model.

Supply side:

- 1) Spectrum. Since spectrum is the key to capacity and, ultimately capacity is the major determinant of QoS, it is necessary to evaluate the likely spectrum that the 3 operators in this scenario might be able to utilize. There are quite a few sources to draw on for estimates of available spectrum within the 2015-2025 timeframe (such as Ofcom [33,114,115], Analysis Mason [51] and the ITU [32])
- 2) Spectral efficiency. In order to relate spectrum to capacity it is necessary to determine the spectral efficiency of each technology. For LTE and WLAN these figures have well-known ranges [35]. For 5G (and future WLAN) it is necessary to extrapolate – however, for sub-6GHz spectrum, the physics and likely developments (MIMO, interference cancelation etc.) are well understood.
- 3) Capacity. In the simplified rail-station scenario it is necessary to consider the network topology and how that is related to the capacity that each operator can offer. This will include the position of macro and micro base stations and the number of WLAN hotspots. The aggregate capacity of each operator is then determined.
- 4) Cost. There are different ways to calculate cost for mobile networks. In the bottom-up approach the cost of all the elements of a network (cell sites, backhaul, customer acquisition etc.) are estimated and used to determine the OPEX and CAPEX of each service. In the top-down approach the total cost of running the network (for example as taken from the annual shareholder’s report) is used to derive the aggregate cost of each GByte of data delivered. Estimates from both

approaches are available for LTE and WLAN operators but the extrapolation of cost to 5G is the most uncertain issue with the methodology. Obviously many costs will be common between LTE and 5G operators (site rental, backhaul, customer acquisition etc.). This will be valid for the evolved LTE operator and the WLAN but needs some more detailed extrapolation for the integrated 5G operator. The emphasis here is on RAN costs and items such as core network, advertising and customer acquisition are excluded.

- 5) 5G definition. To make the example tractable the tight 5G operator is taken to consist of:
 - a. A sub 6GHz macro network – with a new air interface that is capable of 0.25ms latency and supporting medium user headline rates. This shows some (trend) efficiency gain from LTE.
 - b. A 3.5GHz micro cell network
 - c. A 10GHz+ micro-network – essentially a Line of Sight (LoS) network that offers very high headline rates
 - d. A radically different network that requires fibre fronthaul (to allow full virtualization and a 1ms latency as well as network-embedded services).

In the next chapter a much more detailed model is developed from this framework.

Demand side:

- 6) Users and services. In this example the key users are consuming streamed video content. This is, by far and away, the largest contributor of traffic on the fixed and mobile Internet today (over 50% today with predicted growth of x4 (fixed) and x5(mobile) by 2025 – given by [5]. If 5G augments or replaces fixed Internet access (see the discussion in chapters 5 and 7) – then all of the Netflix, iPlayer etc. traffic will flow over it. That is not to say that there will not be significant amounts of traffic for applications such as AR./VR (Augmented and Virtual reality) or IoT (such as security video). In this example the key users are receiving video – all the other users just merge to create background traffic and reduce their QoS. Moreover, for video there are published trade-off between bitrate and quality (on, for example, a MOS (Mean Opinion Score) scale). This allows the final comparison of cost to quality of experience (QoE).
- 7) QoS. Given the capacity (Mpbs/km²) of each network it is possible to calculate how the video streaming of the users degrades as the network becomes more loaded. The different QoS schemes between the three different ways to provide the service (via MNO A(5G) MNO B (LTE+) with loosely coupled WLAN and MNO B with tightly coupled WLAN) then become apparent. The measure of QoS used is the video rate.
- 8) QoE. From the above information on changes on video rate fluctuations and freezing due to buffer emptying it is possible to use published studies on user perceived QoE under these different conditions to turn these into quantitative QoE scores [50]. One study uses the well established Mean Opinion Score (MOS) for video to turn video data rates into MOS scores.
- 9) Cost vs QoE. Since there are both CAPEX and OPEX elements to the cost of each network it is reasonable to assume that the different networks will incur different costs at different loadings. The model calculates the cost per Gbyte at each loading, translates this into the QoS (video rate) of the various users which is, in turn, translated into QoE values.

3.3 Spectrum.

The first key to understanding capacity is to calculate how much spectrum is available to the various operators. Clearly the amount and frequency of spectrum will have a very big impact on the cost of providing services.

It is convenient to divide the spectrum up into different categories as these have very different efficiencies and costs:

- 1) Sub 3GHz spectrum – suitable for macro sites. This will be used by MNO-A for new 5G services and by MNO-B for evolved LTE services (LTE+ or 5G-lite).
- 2) 3-4GHz licensed spectrum – suitable for macro (with high order MIMO), micro and femto cells. There is potentially 400MHz in this band in many EU countries and around the world.
- 3) Unlicensed WLAN spectrum. Currently 480MHz available at 5GHz in Bands A/B/C and 70MHz in the 2.4GHz band. There is also 802.11ad which will operate in the 60GHz ISM band.
- 4) 10GHz+ spectrum. This high frequency spectrum is effectively LoS and there are many bands that could be used – such as 24-28GHz, 32GHz, 60GHz and 80GHz. It is very likely that 5G microcells (or phantom cells as NTT call them – cells whose control plane is routed via a larger cell) will operate at these frequencies (with the control plane anchored on the macro network). The very high headline rates (10Gbit/s) and massive capacity of 5G is expected to come from these microcells

There are several sources as to the likely 5G spectrum availability (in this example for the UK in 2025 – to be specific).

Figure 3-2 Spectrum that will become available for mobile comms in the UK (Source:Ofcom [124])

Ofcom (Fig. 3.2) see a doubling of available spectrum below 6GHz (from 2x300MHz (currently GSM, 3G and LTE) to 2x600MHz. However – most of the new spectrum is over 3GHz.

Analysis Mason [51] give the following table:

Band	Bandwidth available	Merits	Band assignments	Spectrum potential
700MHz	Varies widely by country, but generally 2×30MHz to 2×45MHz	Ideal for wide area coverage as well as in-building penetration	Typically in lots of 2×5MHz or 2×10MHz	Expand wide area coverage, improve indoor coverage
3.4–3.8GHz	Up to 400MHz, paired or unpaired	Larger channels could be used (for example, 100MHz)	Multiples of 20MHz	Support for multiple operators with 100MHz channels
5GHz	Up to 300MHz will be considered at the ITU's World Radio communication Conference 2015 (WRC-15)	Likely to be licence-exempt	Multiples of 20MHz	Almost 800MHz available using established and new allocations
15GHz	Up to 500MHz	Supports high speeds (Ericsson has demonstrated 5Gbps). The limited signal range is ideal for dense access networks.	Multiples of 100MHz	Support for dense, very high-speed data services and multiple operators with 100MHz channels
28GHz	Up to 500MHz	Performance similar to 15GHz	Multiples of 100MHz	Similar to 15GHz
		15GHz	100MHz	
70/80GHz	Up to 5GHz	Performance similar to 15GHz	Multiples of 100MHz	Similar to 15GHz

Table 3.1 Analysis Mason's view of 5G spectrum ([51])

Cambridge Consultants [34] quote the following developments in UK spectrum up to 2025 (which largely mirror the Ofcom figures of Fig.3.2):

- 1) 5MHz of 3G spectrum reserved for voice services
- 2) 900MHz refarmed for LTE
- 3) 2.3GHz spectrum available from 2016
- 4) 3.5GHz spectrum available from 2017
- 5) 1.4GHz from 2019

6) 700MHz from 2022

Using this information, and the expectation of 4 MNOs in the UK to share the existing and new spectrum it is a reasonable assumption that the 3 operators of the simplified rail station scenario have the following spectrum:

Operator	New Sub 3GHz spectrum Suitable for macrocells	3-4GHz spectrum – suitable for microcells	5GHz unlicensed	10GHz+
MNO –A Integrated 5G operator	2x60MHz	40MHz at 3.4GHz		1x100MHz at 15GHz 1x100MHz at 28GHz
MNO-B – evolved 5G operator	2x80MHz	None		None
WLAN-C operator	70MHz at 2.4GHz		300MHz at 5GHz	

Table 3.2 Likely spectrum holdings of simplified rail-station operators in 2025.

3.4 Efficiency

Having estimated the spectrum that might be available to operators in 2025 it is necessary to convert this into capacity. At the very highest level this can be achieved by the use of a catch-all spectral efficiency. This is a crude measure – averaged across rural/urban and cell centre/edge – of the capacity each Hz of spectrum brings.

Cambridge consultants give the following table as a guide:

3G (HSPA 2x2) 0.7-2.1GHz	1.3 bits/Hz
4G (2x2 MIMO) 0.7-2.1GHz	1.5 bits/Hz
4G (4x4 MIMO) 0.7-2.1GHz	2.0 bits/Hz
4G 8x4 (Multi User MIMO) 2.3-2.6GHz	2.4 bits/Hz
Massive MIMO 3.5GHz	5.8 bits/Hz

Table 3.3 Spectral efficiencies. (From Cambridge Consultants – [34])

Figure 3-3 Spectral Efficiency [35]

Fig. 3.3 (From “A survey of 5G networks” – [35]) shows how the spectral efficiency of cellular technologies may evolve up to 2030. WLAN spectral efficiencies tend to be similar (see Ref. 67) to those of cellular – as WLANs use the same techniques (MIMO, OFDM etc) – although not CoMP or interference cancellation.

From these sources the following table (3.4) of likely spectral efficiencies has been constructed:

Technology	Spectrum	Operator	Spectral Efficiency Bit/s/Hz
LTE	Sub 3GHz	MNO-B	2.5
5G	Sub 3GHz (700MHz)	MNO-A	5
5G	3.5GHz	MNO-A	6
WLAN	2.4GHz and 5GHz	WLAN-C	2
5G	15GHz and 32GHz	MNO-B	6

Table 3.4 Likely spectral efficiencies for the spectrum being utilized in the simplified rail station scenario.

3.5 Capacity

The capacity that the various operators can offer is related to the topology of the network deployed and the layout and construction of the station area. To simplify the calculation, the station is divided into 3 areas:

- 1) Outside the station. This covers the station approach, the bus park, taxi rank and the immediate surrounds of the station. The street furniture here is owned by the council and the shops etc. are private enterprises. Macro, micro base stations and WLAN access points can be installed here.
- 2) The station buildings. This covers the terminal building, booking hall, toilets, cafes, restaurants etc. This is an indoor environment. As this space is under the control of Virgin Trains (who operate and control the station) only WiFi

access points can be installed here. (The macro cells of the cellular operators also provide coverage here but the 5G micro cells have very limited coverage (3.5GHz) and the mmW 5G is not able to reach here.

- 3) The platforms. These are only WiFi access points installed here but macro and micro cell coverage is better here – compared to inside the buildings. mmW is not available here, however.

Of course, the signal level (and throughput) will vary across the three areas for the different technologies. The signal level needs to be related to the spectral efficiency (which is an average over all signal levels) in order to differentiate the capacity between high/medium and low signal levels. Table 3.5 gives the extreme values of how the rate can vary across a cell and actual signal levels will vary between these. In the next chapter more accurate signal level modelling will be used to accurately, and in finer detail, look at the actual signal to noise rate for each user. The point here is that such techniques are well known and tractable – and will only alter the results given here as a first order correction. The purpose of this chapter is to demonstrate how cost can be linked to QoE for a variety of operators in the rail station scenario.

Macro network performance	Peak rate (Mbps)	Relative factor to typical rate	Typical user rate (Mbps)	Relative factor to typical rate	Cell-edge rate (Mbps)	Relative factor to typical rate
2015	40	8	5	1	0.4	0.08
2020	360	12	30	1	3.6	0.12
2025	520	14.4	36	1	4	0.11

Table 3.5 (From [51]) – Relationship of average user rate with peak rate and cell edge rate.

[52] gives equivalent results for WLANs – putting all this together results in the following throughput modifier with location (Table 3.6).

Table 3.6 shows the the signal level for each operator’s different technologies within the rail station.

Operator/technology	Throughput Outside the station	Throughput inside the station buildings	Throughput on the platforms
MNO-A Sub 3GHz Macro cell (5G)	2	0.5	1
MNO-A 3.5GHz Micro cell	1	0.1	0.2
MNO-A 15/40/60GHz	1	0	0
MNO- B Sub 3GHz Macro cell (LTE+)	2	0.5	1
WLAN – 2.4GHz	0.5	1	0.5
WLAN – 5GHz	0.2	1	0.3

Table 3.6 Throughput modifiers for different technologies in the rail station.

3.6 Capacity for each operator

The formula for the capacity of a radio network can be expressed as:

$$\text{Capacity (bps/km}^2\text{)} = \text{Spectrum(Hz)} * \text{Spectral efficiency (bps/Hz)} * \text{base station density (/km}^2\text{)} \quad (3.1)$$

This is actually more a definition of spectral efficiency in a particular context – in that spectral efficiency not a constant for a given technology but highly dependent on the network density, load and configuration. An isolated macro cell with 20MHz of spectrum say, might support a capacity of 50Mbps under typical conditions. If that cell is part of a dense network, then the interference from other cells re-using the same frequency could easily reduce the capacity to 10Mbps (in a loaded network). Thus the spectral efficiency falls from 2.5 to 0.5 just by adding neighbouring cells. It is justified to use the figures quoted from the literature, however, as they all refer to typical built-out networks at typical cell densities for each technology. For mmW and dense networks, however, the assumption of a single figure for 5G efficiency becomes less valid. In the next chapter a much more detailed model is described that calculates the Signal to Interference and Noise ratio (SINR) and this, effectively, calculates the efficiency for any given topology or load and avoids this assumption.

For a given signal level equation (3.1) is modified to:

$$\text{Capacity (bps/km}^2\text{)} = \text{Spectrum(Hz)} * \text{Spectral efficiency (bps/Hz)} * \text{base station density (/km}^2\text{)} * \text{Spectral efficiency modifier} \quad (3.2)$$

The only factor in this equation that has not been considered is the base station density. In 2019 typical figures for macro and micro base stations (per operator in dense urban areas) might be 20/km² and 10/km² respectively – (These are taken from the Ofcom database of mobile sites (<http://www.sitefinder.ofcom.org.uk/search>) in an area of 1km² around Liverpool Street). For WLANs the figure is 600-1000/km² [51].

Moving forward to 2025 the following figures for base station density seem reasonable:

- Macro base stations (<3GHz) – 15-20/km². There is very little prospect for new urban macro sites – these are increasingly expensive and will not provide the dramatic capacity gains that micro and pico cells will. In addition, the limited amount of sub 3GHz spectrum means that macro cells will not be able to offer the very high headline rates slated for 5G (10Gbps+). Rather the role of macro cells in 5G is seen as providing the control plane for microcells (eg the phantom cell concept) and to connect to IoT devices that do not require very high data rates.
- Micro base stations (3.5GHz) – 100/km². The very limited range and penetration of 3-4GHz signal means that a much higher density of micro base stations is needed. This will offer a considerable upgrade in capacity but not a very high headline rate.
- Pico base stations (24-27.5GHz) – 1000/km². At these frequencies the propagation is effectively LoS and a very high density of base station will be needed to provide anything like contiguous coverage.
- WLAN (2.4GHz) – 800/km². There are only 3 independent channels (20MHz) that are available in the 2.4 ISM band. In addition, the propagation at 2.4GHz is better than at 5GHz – all of which points to a lower maximum density.

- WLAN (5GHz) – 1200/km². With much larger amount of spectrum (300MHz) available at 5GHz, and the more limited range, it is easy to justify a higher density of base stations.

3.7 Capacity per operator

Putting all these pieces together it is then possible to calculate the capacity for each technology/operator combination (Table 3.7). Using the equation:

$$\text{Capacity (bps/km}^2\text{)} = \text{Spectrum(Hz)} * \text{Spectral efficiency (bps/Hz)} * \text{base station density (/km}^2\text{)} \quad (3.3)$$

Note that this is downlink capacity and assumes all TDD spectrum (WLAN, 3.5GHz, 15GHz and 28GHz) and half FDD (Sub 3GHz) is used for downlink (with the uplink on the sub 3GHz spectrum for MNOs A and B and negligible for the WLAN)

Operator	Spectrum range	Amount of spectrum/MHz	Spectral efficiency bps/HZ	Density of base stations/km ²	Capacity Gbps/km ²
MNO-A	Sub 3GHz	60	5	15	4.5
MNO-A	3.5GHz	40	6	100	24
MNO-A	27GHz	200	6	1000	1200
MNO-B	Sub 3GHz	80	2.5	20	4
WLAN-C	2.4GHz	70	2	800	112
WLAN-C	5GHz	300	2	1200	720

Table 3.7 Capacity of various spectrum/technology combinations

As a reality check it is important that these figures are compatible with other published estimates of future capacity. Cambridge Consultants [34] quote 365Mbit/s per macro base station in 2015 – making 5.4Gbps/km² at 15 base stations per km² – very much in line with the above estimates. The 5G capacity is dominated by mmW, high density, base stations. Comparing back to table 2-1 (a summary of 5G requirements) – typical figures are 1-15Tbps/km² and 1000X the capacity of LTE base station (in 2015) which is around around 1 to 1.5Gbps/km² – again implying a 5G figure of 1Tbps/km² or so. Thus it seems the above table is not an unreasonable starting point for the gross capacity that the various networks can offer in 2025.

3.8 Costs

Since the aim of this example is to relate costs to QoE, it is now necessary to determine the costs relating to the above networks. Typically, the cost of a given network is broken down into the capital expenditure (CAPEX) and the operational expenditure (OPEX). Capital expenditure covers items such as the purchase of radio equipment, installation and back-haul connection. OPEX relates to things such as site rental, maintenance and back haul transit charges. To achieve a single network cost figure, it is usual to consider a period (such as 10 years) over which the capital cost is depreciated and to use Net Present Value (NPV) [53] – a means of discounting future costs back to a

present day sum. [41] gives the following OPEX and CAPEX costs for a macro cell (Table 3.8) A different source [54] gives the following (Table 3.9).

CAPEX	£80k
OPEX components	
Site lease	£3.3-6.7k
Backhaul	£8K
O&M (operation and maintenance)	£3.3-6.7k
Power	£2.0-3.3k
Total OPEX	£16.7-24.6k

Table 3.8 (taken from [41]) – Macro base station cost estimates

	Macro – 3 sector LTE	Micro 3 sector LTE	WiFi
CAPEX	£k	£k	£k
Base station	18.3	4.7	1.2
Equipment – Wireless Backhaul	5.0	2.3	0.8
Equipment – Fixed Backhaul	1.3	0.9	0.3
Planning, Installation and Commissioning	26.7	4.7	2.4
Total CAPEX	Total Wireless- 50 Total Fixed-46.3	Total Wireless- 11.7 Total Fixed-10.3	Total Wireless- 4.4 Total Fixed-3.9
OPEX	£k	£k	£k
Site lease – base station	10.0	0.9	0.6
Backhaul – wireless	4.0	1.3	0.4
Backhaul – fixed	16.0	8.0	4.0
O&M (inc Power)	6.7	1.1	0.5
Total OPEX	Total Wireless- 20.7 Total Fixed-32.7	Total Wireless- 3.3 Total Fixed-10.0	Total Wireless- 1.5 Total Fixed-5.1

Table 3.9 – CAPEX and OPEX costs for macro, micro and WLAN base stations [54]

Cambridge Consultants provide the following costs for Urban macro (Table 3.10) and micro (Table 3.11) base sites.

CAPEX	£K
Sites and power	41.4
Base station tech	50.5
Backhaul	16.8
Spectrum	0.0
Total CAPEX	108.7
OPEX	
Sites and power	24.1
Base station tech	2.8
Backhaul	9.1
Spectrum	3.9
Total OPEX	39.7

Table 3.10 CAPEX and OPEX for urban macro cell [34]

Cost stack

	Capex	Depreciation	Annualised	Opex	
Site acquisition and planning	£1k	10 years	£0.1k		Assume block agreement with local authority
Site rental and rates				£0.5k	Assume block agreement with local authority
Power	£1k	10 years	£0.1k	£0.2k	Assume power exists already
Backhaul	£9k	7 years	£1.3k	£3.6k	Figures provided by AS for EAD-based 1000 Mbps, local access
2.1-2.6 GHz microcell	£5k	7 years	£0.7k	£0.4k	Single sector with 2.1-2.6 delivered via wide band radio
3.5 GHz upgrade	£2k	7 years	£0.3k	£0.2k	Estimate for second band
Massive MIMO upgrade	£3k	7 years	£0.4k	£0.2k	Estimate for additional DSP and RF chains
Total			£2.9k	£5.1k	

Table 3.11 CAPEX and OPEX for urban macro cell [34]

Further [34] suggests that mmW picocells will have an equipment CAPEX of £5.5K. If we assume the OPEX of these cells is similar to that of microcells then there is enough information in these sources to put together a cost estimate for all of the technology/spectra combinations in the simplified rail-station scenario. Using a 10 yr depreciation period the following table gives the annualised cost per base station of each type.

	Annualised cost/base station £k/yr
Macro base station (sub 3GHz)	33
Micro base station (3.5GHz)	7
mmW picocells	5.5
WLAN (Averaged over figures for 802.11g and 802.11ac)	2

Table 3.12 Final figures for annualised base station costs

It is useful (and has been used by a number of external commentators) to convert these costs into cost/Gbyte/month. This is useful here as it helps to connect the cost to the demand (covered in the next section). In order to make this connection there are two steps. Firstly, the total costs/km²/yr is needed. This is easily found by multiplying the base station density with the annual cost per base station – yielding table 3.13 In treating the macrocells it has been assumed that they are scratch built (to properly compare costs across technologies) – in practice 5G macrocells will initially be added to existing sites – much reducing costs (see chapter 4 for more details). The base stations are depreciated by assuming an upfront cost in year 1 (the Capex) and the running costs for 10 years (the

Opex) – suitably discounted because expenditure in future years is less costly now. The whole total is then divided by 10 to get an annual cost over 10 years. These are typical industry and accounting timescales.

Operator	Spectrum range	Amount of spectrum/ MHz	Spectral efficiency bps/HZ	Density of base stations/k m ²	Capacity Gbps/km ²	Annual cost/base station	Network cost £k/yr/km ²
MNO-A	Sub 3GHz	60	5	15	4.5	33	495
MNO-A	3.5GHz	40	6	100	24	7	700
MNO-A	15/28GHz	200	6	1000	1200	5	5000
MNO-B	Sub 3GHz	80	2.5	20	4	33	660
WLAN-C	2.4GHz	70	2	800	112	2	1600
WLAN-C	5GHz	300	2	1200	720	2	2400

Table 3.13 Network costs

The final stage in determining a cost per Gbyte/month is to convert the capacity of each network to a number of Gybytes per month. This is achieved with the following equation:

$$\text{Monthly traffic (GByte)/km}^2 = \text{Network capacity (Gbps/km}^2) \times \text{Load factor (\%)} \times 3600 \text{ (sec in hr)} \times 4 \text{ (weeks per month)} / \text{busy hour traffic (\%)} / \text{busy day traffic (\%)} / 8 \text{ (bits/byte)} \quad (3.4)$$

Using a load factor of 80% (a typical maximum network load), a busy hour fraction of 10% ([34] use 8.8% – due to video streaming concentration in the evenings but the station will be busier still at rush hours) and a busy day factor of 16% (because the station is busy only 6 days a week) it is easy to add the monthly capacity and monthly cost to Table 3.13 – producing the final cost table 3.14 that will be the basis of plotting QoE vs cost.

Operator	Spectrum range	Amount of spectrum/ MHz	Spectral efficiency bps/HZ	Density of base stations/k m ²	Capacity Gbps/km ²	Annual cost/base station	Network cost £k/yr/km ²	Gbyte/M onth/km ²	Cost £/Gbyte
MNO-A	Sub 3GHz	60	5	15	4.5	33	495	405000	0.102
MNO-A	3.5GHz	40	6	100	24	7	700	2160000	0.027
								10800000	
MNO-A	15/28GHz	200	6	1000	1200	5	5000	0	0.004
MNO-B	Sub 3GHz	80	2.5	20	4	33	660	360000	0.153
WLAN-C	2.4GHz	70	2	800	112	2	1600	10080000	0.013
WLAN-C	5GHz	300	2	1200	720	2	2400	64800000	0.003

Table 3.14 Network cost expressed in £/Gbyte

The figures for the high density networks seem very low. It is important to realize these will only apply if these very high capacity networks are fully utilized – in other words the capacity demand increase in 5G really does approach that shown in Table 2.1. If demand and, consequently, network usage falls short then the cost/Gbyte will rise proportionately.

As a sanity check [34] quotes a RAN cost of £0.1/Gbyte for urban macro cells in 2025 using similar assumptions and is also for scratch build macro sites in UK urban areas.

One further step is needed – the costs above are for the “average throughput” (as captured in the overall spectral efficiency figure for the whole station area). At each location within the station the costs will be modified by the signal strength and throughput actually achieved at that location (table 3.6). For example – delivering 1Gbyte of data deep in the toilets clearly requires more radio resources than 1Gbyte next to the base station. By using the signal strength (Table 3.6) and assuming an equal cost for all radio resource, then the cost of delivering 1Gbyte in each of the 3 zones can be calculated. Putting it all together gives table 3.15

Operator/technology	Throughput Outside the station £/Gbyte	Throughput inside the station buildings £/Gbyte	Throughput on the platforms £/Gbyte
MNO-A Sub 3GHz Macro cell (5G)	0.051	0.204	0.102
MNO-A 3.5GHz micro cell	0.027	0.27	0.14
MNO-A 15/40/60GHz	0.004	0	0
MNO- B Sub 3GHz Macro cell (LTE+)	0.076	0.306	0.153
WLAN – 2.4GHz	0.026	0.013	0.026
WLAN – 5GHz	0.0015	0.003	0.001

Table 3.15 Network cost expressed in £/Gbyte – as modified by the various actual throughput in different locations around the station

3.9 QoS – the demand side

Having looked at the supply side of capacity and costs it now necessary to consider the demand side – the users, their services and how this impacts of QoS and, ultimately, QoE

Quality of service is traditionally defined in terms of network throughput, packet loss and latency. In 3G and 4G a range of QoS-bearers were defined – based on just such parameters. The concept of QoS evolved from a telecom ancestry – for voice circuits it was a relationship between the numbers of exchange lines, the switch blocking probability for a given dimension and the likelihood of call failure can be worked out in a simple deterministic way. However, for Internet services things are far more complicated. Data rates vary all the time due to, amongst other: TCP; packet- dropping and queuing, buffering within apps and radio link re-transmissions. Operators who offer guaranteed rates over one hop (or domain) of the Internet are unable to offer true end-to-

end QoS for Internet apps. In part, this has been responsible for 3G and LTE only offering best effort data services (further reasons include the commercial failure of the IMS and the fact that fixed Internet applications are written to cope with variable rates – such as the use of buffering or rate adaptation – and this has been successfully ported to many mobile apps.

One of the facets of 5G appears to be a focus on the users' experience (more will be said about this in the next section under QoE). [56] promotes the idea of a QoE-layer – to sit about the traditional QoS layer (rate, latency etc.) – to feedback an estimated QoE for each user

3.9.1 Rail station QoS

In this scenario only MNO-A (the “NGMN-type” 5G operator) offers QoS-differentiation between users (Table 3.16). In this case it consists of (the traditional) gold, silver and bronze users. This is a very simple scheme but will serve to illustrate the relationship between costs and QoE. MNO-B and the WLAN operators offer only best-effort services.

	QoS-differentiation
Gold Users	Absolute priority for requested bandwidth – until 50% of total capacity is reached. Then pro-rata sharing.
Silver Users	Compete with Bronze users for bandwidth un-used by Gold Users but given double bandwidth of Bronze users if network is congested
Bronze Users	Compete with Silver users for bandwidth un-used by Gold Users but given half bandwidth of Silver users if network is congested

Table 3.16 – QoS differentiation of MNO-A

3.10 Provisioning

In fact, provisioning should, more logically, have been considered before QoS-differentiation. Provisioning, or network dimensioning, is about the relationship between the network capacity and the actual capacity used. Now, Table 3.7, showing the capacity of the various operators/km², is a bench mark. That is the capacity the technology will provide for the estimated number of base-stations. The key question in provisioning is “how many users and at what rate” will this capacity support? (Traditionally it is done the other way round, working from the demand to the number of base stations but this way makes the argument more logical). The answer depends on each operators different provisioning policy. More users, for a given infrastructure, bring in more income for the same expenditure but users may churn or complain if average rates are low. For mobile operators the last few years have been a balancing act between offering larger data bundles (Gbyte/month), improving WiFi off-load and increasing LTE/3G capacity as fast as possible to increase data rates. WLAN hotspots have embraced 5GHz and improved back-haul but the relentless rise in user numbers has meant that average data rates can be comparable or lower than LTE in many locations. (Care is needed here as if all the

WLAN users switched to LTE the LTE network would collapse under the load – the capacity of the two networks remains very different).

In the rail-station scenario the following provisioning is used (Table 3.17). This uses the concept of average rate per user in the busy hour on the busy day. To just clarify what this means imagine we have a single Wireless technology. If this can provide a capacity of C Gbps/km² then if there are N users/km² then each will get an average rate (A) of RC/N Gbps/user at the busy hour if R represents the maximum network load (typically 70% for 3G CDMA and taken as 80% in these calculations).

$$A = RC/N \text{ or } N = RC/A \quad (3.5)$$

The fixed network currently (June 2019) is provisioned at about 1Mbps/user. Mobile is 30-60Kbps (based on an average data download of 4-8Gbyte/month in the UK in 2018[113]). Remember this is not a headline rate but is the total traffic in the busy hour divided by the number of subscribers. In practice some will use a much higher rate intermittently and some will use nothing as they are out! In the simplified rail station scenario, the following average rates are assumed:

Operator	
MNO-A Gold	3000kbps
MNO-A Silver	1500kbps
MNO-A Bronze	750kbps
MNO-B	150kbps
WLAN	200kbps

Table 3.17 – average users rate (across all users/subscribers in the busy hour)

Taking the MNO-A Silver customer as the “typical” 5G customer this rate implies a 5G capacity increase (over 2016 12-15Kbps/user [34]) of 100X. This is, in fact, on the conservative side of 5G expectations (see Table 2.1)

To be clear, the rates shown in Table 3.17 are just examples of what 5G might provide and are chosen to be of the order of the fixed Internet in 2019 – which 5G reportedly will be rivalling. In the next chapters (and partly as a result of this analysis) this arbitrariness is removed by linking cost to overall capacity and not being so concerned in how it is apportioned between users. To make the link to QoE, however, this step is required.

MNO-B rates are set at a more sedate X10 improvement on 2016’s mobile average data rate – this is the expected improvement that can be made with LTE (extra sub 3GHz spectrum, more sectors and spectral efficiency gains from CoMP, CA and MIMO etc.) – as was described in chapter 2.

The WLAN rate has been set to 200kbps to reflect the fact that these networks are shared and it is likely that there will be a number of networks that are not under the control of the MNOs. This is especially true now that smartphones are able to act as hotspots. The nature of the WLAN protocol means that all nodes are effectively equal and data rates are much reduced by the presence of multiple networks.

There is no need to know how many users there are in an area as the assumption is that however many there are the network (base station density) is sufficient to deliver the rates shown in the table at the busy hour on average. Since we know the cost of delivering 1Gbyte of data (irrespective of network density) – all we need is to determine/decide how the actual rates experienced change with location/network load. That provides a cost and an average data rate (which translates into QoS and then QoE).

3.11 Data rates and cost modifiers

Accepting the above rates as reasonable the next step is to determine what rate the users of the above service actually get and how much that cost the operator to deliver. Taking an MNO-B customer as an example. What the above table (3.17) means is that the network is built so that, on average, in the busy hour, each customer gets 150Kbps – an ideal network is dimensioned to achieve as evenly as possible for all customers. (Of course, commercial considerations mean that this becomes prohibitively expensive in rural areas and important business areas tend to be over provided – but this can be ignored as a second order effect in this example). At any given time in the busy hour not everyone is using the service flat out. On the fixed network, the typical contention ratio was between 20:1 and 50:1 for consumer broadband – meaning that 50 users might share a 100Mbps connection. If they all used it at the same time they would only get 2Mbps but, since some not be using the service and some most applications would use it only intermittently speeds are much higher in practice. A speed test by any one customer might show a rate of 20Mbps – the limit of their copper line to the cabinet. In the rail station scenario, it is proposed to use a contention ratio of 8 – since users are far more likely to be using a mobile device in a railway station and the trend for contention ratios is towards 20:1 on the fixed network.

A contention ratio of 8:1 would mean, in the busy hour, a customer of MNO-B who is streaming a video continuously at a constant rate would get a bandwidth of 1.2Mbps for the duration of the video. Having watched the video, they may well then go and do something else and consume very little data for the next hour or so – so that on average they are consuming 150kbps over the whole month. The point is that a contention ratio of 8:1 sets the peak. It is acknowledged that (like the provisioning) the choice of 8:1 as the contention (or over-booking factor) is somewhat arbitrary. In the absence of detailed traffic models this is typically how the issue is approached. In subsequent chapters the shortcomings of this approach are removed by shifting the metrics to network capacity and coverage versus cost. These are metrics of the network and do not rely on decisions by the operators on QoS policies, number of users and usage patterns. In this chapter, which was essentially an early exploration of the methodology, assumptions are made to demonstrate that it is possible to link cost to QoE. In a real network all these assumptions could be eliminated by modelling actual traffic patterns and utilizing actual MNO QoS strategies.

Of course it is a serious question if the concept of a busy hour, a relic from the days of circuit voice networks, can still be used to dimension data networks in the modern Internet. It is certain that the variation of usage is far less than it ever was – with downloads, backups and user interaction taking place 24/7. Currently (2019) there is a data spike in UK Internet traffic on weekday evenings as workers return home and either game, catch up on TV or just browse more actively. [118] – provides some data on the total internet traffic by time of day in 2016.

Thus, under these assumptions, a user on MNO-B, the rate of the video streamers is 1.2Mbps and a one hour video would then consume:

$$1.2\text{Mbps} \times 3600(\text{s/hr}) \times 8(\text{bits/byte}) / 1000 (\text{Mbyte/Gbyte}) = 0.54\text{Gbyte of data.} \quad (3.6)$$

Using table 3.16 this costs the MNO $0.54\text{Gbyte} \times \pounds 0.31/\text{Gbyte} = \pounds 0.165$ or about 17p.

At first glance, it might be imagined that the MNO-A Gold customers will be more expensive per GByte – since they are provisioned at twice the level of Silver customers. However, in the examples used below they are consuming all the available data (ie twice as much data) – so effectively all the data capacity is used (at a constant per GByte costs) – just that Gold customers get to use more of it (and are charged accordingly – although pricing is not part of the example).

3.12 Rates as network load changes

Assuming no interaction between the WLAN (see below) then, as a first approximation, with users of each MNO/class sharing the bandwidth equally then sustained data rates available for each user is as shown below (Table 3.18) – using the average rates and a contention ratio of 8:1. What this table is saying is that, for example, MNO-A Gold customers are provisioned at 3Mbps and so get a peak rate of 24Mbps in the busy hour (at an average location and average total network load). Clearly, in different locations and at different times the load on the network will be lower or higher than average and the table shows how the peak rates for video users vary with the network load factor – consistent with the QoS policy shown in Table 3.16. Again this is assuming a certain QoS policy of the MNO and it would be equally possible that Gold customers could be guaranteed 4Mbps and the total rate would be capped at 10Mbps, say. However, this variation of bandwidth with load is the simplest option (for example a Gold user may be streaming multiple video views of a sports match and projecting/mixing them in a future 5G application – an application that might consume 100Mbps+ as this is the advertised/promised 5G rate).

Load Factor (Ratio to busy hour)	0.2	0.4	0.6	0.8	1.0	1.2	1.4
MNO-A Gold	120	60	40	30	24Mbps	20	17.2
MNO-A Silver	60	30	20	15	12Mbps	10	8.6
MNO-A Bronze	30	15	10	7.5	6Mbps	5	4.2
MNO-B	6	3	2	1.5	1.2Mbps	1	0.86
WLAN	8	4	2.67	2	1.6Mbps	1.33	0.875

Table 3.18 Data rates (Mbps) under different loads (fraction of busy hour load) – assuming no Cellular-WLAN coupling.

MNO-A does not couple to WiFi – it is a 5G operator with 50Mbit/s everywhere and 1ms latency. WiFi latency is too high and there are no QoS guarantees to offer its customers.

MNO-B, however, is a “no-frills” best effort MNO that offloads its traffic to WiFi. If it offloads all its traffic blindly to WiFi (loose coupling) then the data rate for users is increased but (as we shall see below) the rate variability is also increased. With tight coupling MNO-B uses a smarter strategy for offloading to WiFi and only offloads when the cellular network is at 80% maximum load or higher. This is added in table 3.19.

Load Factor (Ratio to busy hour)	0.2	0.4	0.6	0.8	1.0	1.2	1.4
MNO-A Gold	120	60	40	30	24Mbps	20	17.2
MNO-A Silver	60	30	20	15	12Mbps	10	8.6
MNO-A Bronze	30	15	10	7.5	6Mbps	5	4.2
MNO-B – no offload	6	3	2	1.5	1.2Mbps	1	0.86
WLAN	8	4	2.67	2	1.6Mbps	1.33	1.14
MNO-B Loose coupling	8 (V)	4(V)	2.67(V)	2(V)	1.6Mbps(V)	1.33(V)	0.875(V)
MNO-B Tight Coupling	6	3	2	1.5	50% - 1.6Mbps(V) 50% 1.2Mbps	50% 1.33(V) 50% 1Mbps	50%- 1.14(V) 50% 0.86Mbs

Table 3.19 WLAN coupling added to Table 4.18 – note (V- viable) denotes a WLAN connection and is a much more variable rate than that offered by the cellular connection. The data rates are plotted below in Fig. 3.4

Figure 3-4 Video rates (Mbps) vs load fraction of busy hour traffic – note the WLAN used is a combination of 802.11g and 802.11ac

3.13 QoS and Cost

From all of the above, the data rate on offer to each users is calculated (Table 3.19) and the cost of each Gbyte of data, for each technology and operator and location (terminal/platform/forecourt) is known – table 3.11. The next step is to calculate the cost of the video service that is assumed in this example. To simplify the calculations, it is assumed that the video streaming application uses the maximum possible bandwidth available and that the key users of a given technology and QoS class get the same data rate. It is assumed the video last exactly 1hr. From the above tables it is then simple to then calculate the amount of data downloaded in the hour (Table 3.20)

Load Factor (Ratio to busy hour)	0.2	0.4	0.6	0.8	1.0	1.2	1.4
MNO-A Gold	54.00	27.00	18.00	13.50	10.80	9.00	7.74
MNO-A Silver	27.00	13.50	9.00	6.75	5.40	4.50	3.87
MNO-A Bronze	13.50	6.75	4.50	3.38	2.70	2.25	1.89
MNO-B – no offload	2.70	1.35	0.90	0.68	0.54	0.45	0.39
WLAN	3.60	1.80	1.20	0.90	0.72	0.60	0.51
MNO-B Loose coupling	3.60	1.80	1.20	0.90	0.72	0.60	0.51
MNO-B Tight Coupling	2.70	1.35	0.90	0.68	50% -0.54 50% -0.72	50% -0.45 50% -0.60	50% -0.39 50% -0.51

Table 3.20 Amount of data (Gbyte) downloaded per user in 1hr

Now the cost of this 1hr of video can be calculated for each location is as follows (using tables 3.20 and 3.15) – giving tables 3.21-3.23)

Load factor	0.2	0.4	0.6	0.8	1	1.2	1.4
MNO- A Gold	21.60	10.80	7.20	5.40	4.32	3.60	3.10
Silver	10.80	5.40	3.60	2.70	2.16	1.80	1.55
Bronze	5.40	2.70	1.80	1.35	1.08	0.90	0.76
MNO B	20.52	10.26	6.84	5.13	4.10	3.42	2.94
WLAN	0.54	0.27	0.18	0.14	0.11	0.09	0.08
Loose	0.54	0.27	0.18	0.14	0.11	0.09	0.08
Tight	20.52	10.26	6.84	5.13	2.74	2.28	1.48

Table 3.21 Cost of one hour video at maximum rate – on the station forecourt – price is in Pence. Load factor is fraction of the busy hour

Load Factor	0.2	0.4	0.6	0.8	1	1.2	1.4
MNO-A							
Gold	1101.6	550.8	367.2	275.4	220.3	183.6	157.9
Silver	550.8	275.4	183.6	137.7	110.2	91.8	78.9
Bronze	275.4	137.7	91.8	68.9	55.1	45.9	38.6
MNO-B							
WLAN	1.08	0.54	0.36	0.27	0.22	0.18	0.15
MNO-B							
Loose							
coupling	1.08	0.54	0.36	0.27	0.22	0.18	0.15
MNO-B							
tight							
coupling	82.6	41.3	27.5	20.7	22.0	9.3	6.0

Table 3.22 – Cost of one hour video at maximum rate – in the station terminal – price is in Pence. Load factor is fraction of the busy hour

Load Factor	0.2	0.4	0.6	0.8	1	1.2	1.4
MNO-A							
Gold	550.8	275.4	183.6	137.8	110.1	91.8	78.9
Silver	275.4	137.7	91.8	68.9	55.1	45.9	39.5
Bronze	137.7	68.9	45.9	34.4	27.6	23.0	19.3
MNO-B							
WLAN	0.36	0.18	0.12	0.09	0.07	0.06	0.05
MNO-B Loose							
coupling	0.36	0.18	0.12	0.09	0.07	0.06	0.05
MNO-B tight							
coupling	41.3	20.7	13.8	10.3	5.5	4.6	3.0

Table 3.23 – Cost of one hour video at maximum rate – on the station platforms– price is in Pence. Load factor is fraction of the busy hour

3.14 QoS (Bitrate vs Cost)

It is now possible to plot the bitrate that the user experiences against the cost of delivering a 1hr video in the three station zones in the busy hour – using tables 4.19 and 4.21-23. These rates are shown in Fig.3.5

Figure 3-5 Average video data rate vs Cost (p) of delivering a 1 hr video – at the busy hour – in the three zones (forecourt, terminal buildings and platforms) of the station

The first interesting result is the wide spread of costs – the very highest costs represent the difficulty of covering the interior of the station terminal buildings with the 5G (MNO-A) macro and micro cells (the pico cells at 10GHz+ not reaching this zone). MNO-B's macro network also has high costs unless there is the option of WLAN coupling.

The offered bitrate is much higher for MNO-A customers – in line with 5G requirements for bitrates (Table 2-1) but this pushes up the total download size of the 1hr videos which, in turn, pushes up the total costs – even if the per Gbyte cost is lower. The station forecourt (upper of the 3 graphs) is the only location that MNO-A can supply video via the high frequency (27GHz) pico cells and, since these are much cheaper per Gbyte than the micro or macro cells, offer a high bit rate at much lower cost per Gbyte. They are more expensive than the tight and loose coupled options for MNO-B simply because they offer a higher bitrate and the cost of the 1hr video is the product of the per Gbyte cost and the total size of the download which is proportional to the bitrate. Of course all these results are in the busy hour – at lower loadings the QoS improves across the board. It is also important to realise these are internal MNO costs and would not be directly related to price. The MNO will sell data bundles or video services and aggregate the costs over the various technologies

3.15 QoE

The final piece then is to turn the data rates, over the various technologies, into a QoE value and then plot against the cost of delivering each rate for 1 hr. There are many things that affect the perceived quality of video in a streaming environment such as:

- Average bitrate
- Bit rate fluctuations – possibly leading to codec changes
- Time to start video (initial buffering)
- Freezing (buffer emptying)

It seems that MOS (Mean Opinion Score) is being used in quite a lot of QoE research and could form the basis of a defensible measure of QoE. There are other metrics, however, that could be used for QoE. Customer churn – discussed below – might also be argued to be a metric of experience. Some studies have also considered engagement-centric measures of QoE, such as video viewing time, fraction of video viewed, and number of page visits [50].

MOS is still subjective in that it is the opinion of a group of users under particular conditions. Users might alter their behaviour in different conditions. For example, if there is a small interruption at a key moment of a sports event (missed goal) – then the overall opinion of the video – even if the remaining 89 mins is of superb quality, is likely to be very low! Also the relationship between MOS scores and behaviour that is important to MNOs has not been actively researched. MNOs want users to return to sites (with paid content), they want users to rate their service highly in polls and in recommending it and they want users to watch videos to the end (if nothing else to collect important advertising revenues). It is not impossible that a fair measure of QoE – as defined by an MNO- might be the customer churn rate (rate of customers leaving) caused by network issues. After all, customer churn is costly – for each leaving customer a new customer must be recruited and signed up (with advertising, call centre and credit costs). Keeping existing customers is much cheaper. However, investing in network capacity to reduce churn is not cheap

and there is clearly a balance point where an extra pound spent on network capacity balances a pound gained through lower churn. Evidence from Ofcom, however, shows only a weak relationship between customer numbers and network capacity. O2 were consistently coming bottom of UK speed tests and had the smallest 3G (and latterly 4G) network of the UK operators [3]. However, strong advertising and attractive pricing and handsets allowed them to gain customers at the expense of the other MNOs!

The other approach to QoE would be to define it. By that is meant that if a packet trace is made of the connection over time then an algorithm exists that can take the variation in bandwidth, packet losses etc. and come up with a QoE value. This would be, say 0-100, with 100 scored for a perfect, constant connection. In fact, there is some consideration along these lines for the fixed Internet. Prompted by advertising claims for 30Mbps broadband that actually delivers a poor user experience (because, for example, it is heavily contented and over-subscribed at peak periods). Fixed Internet operators, some of whom have lower headline speeds but contend that their networks deliver a better user experience, have been researching this topic. EU project Leone (www.leone-project.eu) has begun to measure connections (fixed) using black boxes that download You-Tube videos and perform tests during idle times.

Research over the past 5 years has begun to link these QoS violations with QoE metrics (and MOS – in particular): [56] offers a good source of references to this work. Some work has looked at how traditional MOS scores change with a variation of these factors. Eggar [58], for example investigated how changing video quality (codec) for adaptive video streaming was reflected in MOS scores evaluated by several different audiences. The general conclusion was that the bit rate itself was well correlated with MOS but that the switching strategy (smooth or discontinuous) had only a small influence on MOS scores. Casas [57] also used an audience to record MOS scores against average bandwidth and bandwidth fluctuations. This was done for a wide range of applications from Google Maps to streaming video. The major correlation found was between average bitrate and MOS score with bandwidth fluctuations having a smaller effect. Sackl [59] also looks at the relationship between MOS score and outages and bitrate changes for several applications. Fiedler gives graphs of MOS score against packet drop rates for a number of video codecs as well as charts of page cancellation rate vs bitrate for general web browsing [60].

In a more detailed model it would be possible to go down to a level of detail of individual IP packets and then to apply a QoE algorithm to the IP stream. In this simplified example, however, it is necessary to have a measure of QoE that can be related to the average bitrate. The obvious choice, from the above discussion, is to use the work of Casas [57] [119] which presents a summary QoE vs bitrate results and which can then be used to translate the bitrates, at a given load factor and for a given technology into MOS scores (using the standard MOS interpretation and meaning). Fig. 3.6 reproduces a results of bitrate vs MOS from Casas [119].

Figure 3-6 Relationship between QoE (as expressed as a MOS score) and video data rate [119]

3.16 Final result

If we accept the provisos on QoE noted above, it is now possible to plot QoE vs cost by translating the data rates of Table 3.19 into MOS scores using the above (Fig.3.6) relation. 0.5 MOS score is further deducted for transmission over WLAN – since these are much more variable in bandwidth than cellular systems (using the data in [57] on how variable rates impinge and degrade MOS scores).

Fig.3.7 shows the result of QoE vs cost for a one hour video in the busy hour. It is interesting that on the station forecourt – using high frequency picocells – MNO-A can offer a better QoE at a cheaper price than MNO-B's macro network or MNO-B with tight WLAN coupling. Only with loose coupling and most of the traffic flowing over WLAN is the cost lower than for MNO-A. The QoE, however, is worse – due to the lower bitrate and also the variable bitrate of WLAN.

Figure 3-7 QoE (MOS Score) vs Cost (p) of delivering a 1 hr video – at the busy hour for the three station areas

Where MNO-A has to rely on macro and micro cells (the station terminal buildings and the platforms) the cost of providing excellent QoE appears much, much, higher. In fact, the rates offered are saturating the MOS score (according to the mapping used) and in practice either the rate could be reduced (concomitant with the cost) or the expectation and user ratings of MOS score for video will change as bigger screens become the norm (in other words what users are rating 5 on MOS score today might be rated only 2 in 2025 and 4x the current bandwidth could be needed to achieve a 5 score – in line with the growing expectations of 5G).

What the figure does show is that there is a spread of cost and QoE values – which was one of the major points of the qualitative analysis in chapter 3 and these graphs are the quantitative equivalents of tables 3.4-3.7 – which was the purpose of this chapter.

3.17 Conclusion

The point of this chapter was to demonstrate that it was possible to link network costs to the QoE of the user and that various different 5G architectures would offer a variety of trade-offs of cost vs QoE. It proved possible to attribute RAN costings on a macro level – i.e. without detailed radio modelling – albeit in a relatively crude manner.

Likewise, it was possible make general assumptions about provisioning and MNO QoS policy to create a framework of how user QoS might vary under different load conditions and for different technologies. This allowed a relationship between costs and video bit rate to be established and, finally, a published relationship between video rate and QoE was used to demonstrate that QoE could be related back to cost. Many assumptions about traffic and provisioning were required and it is clear that to remove these assumptions would require a very detailed traffic model (actual users moving around with packet-level application modelling). As resources were limited it was decided to use network coverage and network capacity instead as key metrics to determine against cost for the remainder of the work. These metrics have the advantages of being more objective, comparable with published figures and translatable into more common figures such as monthly data download figures.

Nevertheless, the work of this chapter has demonstrated that a link could be made from user QoE to network costs and that there is likely to be a large variation in costs for 5G technologies at different frequencies to deliver identical QoE. It has highlighted that areas not covered by mmW technologies – such as many internal spaces – will be more expensive to cover with external 5G base stations. It has been shown that WiFi can provide some boost for QoE but this is limited by the need for handovers and the best efforts nature of WiFi.

The next chapter describes a far more sophisticated radio model that builds on this example - replacing the rail station with a more traditional 1km² grid and using radio propagation models to determine actual throughputs and network capacity and coverage. It overcomes many of the drawbacks of the more simplistic model but does it at the expense of concentrating on the supply side and not continuing with the demand side analysis.

4 Radio model of the London Grid

The model of chapter 4 is very simplified and does not take into account the type of environment (urban, suburban, rural etc.). It also does not properly reflect the capabilities and different characteristics of the different technologies. Traditionally radio capacity and coverage modelling takes place at several layers and uses different modelling tools and techniques. Physical and link layer models are used to establish typical throughputs for different SINR values – assessing the performance of (for example) turbo codes, forward and backward error correction and MIMO. These models are too detailed and complex to be expanded to cover larger areas. Instead the results feed into system level models.

In this project we have created a system level model from scratch and summarized the results of 5G physical and link layer models and measurements as input to the model. This renders the computation tractable and also allows it to be extended to cover internal base stations at a higher level of detail as described in chapter 6.

The standard modelling methodology for calculating system capacity and coverage in a mobile network is relatively well established (see Fig. 4.1 for a summary of the steps involved [41]). In this chapter we shall describe how this process was adapted to model future 5G technologies, whilst especially adding detail on the design decisions made and the reasoning behind these. The format of the chapter will follow the steps outlined in figure 4.1. The only results presented here are representative and full results from the model appear in the next two chapters. Costings are discussed within those chapters as they differ from indoor to outdoor.

Figure 4-1 Steps of the system level model created to evaluate capacity and coverage of 5G. PF refers to proportional fair queuing and RR is Round robin

4.1 Topology

There are different design constraints and decisions on the topology. Firstly, the type of environment to be modelled (urban, dense urban, rural etc.). It was decided to, initially, concentrate on the dense urban environment. Past investigations and published research[47] has shown that the dense urban environment offers the best business case – meaning that the cost of providing a given coverage or capacity is lower per km². The reverse is true in that the scattered rural area offers the worst business case. The original intention was to extend the model to outer urban and suburban environments but resources have not yet been available. The model is, however, fully extensible and could easily be extended to these environments.

London was chosen as the target city for the dense urban environment. In work by other groups both Madrid [61] and Manhattan [62] have been used as the basis of dense urban modelling. In both these cases the researchers took a small area (typically 1km²) and created a stylised “grid”. These are not actual streets of buildings but representative heights, widths etc. in order to simplify the modelling. Fig.4.2 shows the Madrid grid from project Metis.

Figure 4-2 Madrid Grid as used by project Metis

It was decided to create a “London” grid based on a typical inner city location in London. Marylebone (Fig.4.3) was chosen as the basis of the creation of the London grid – it was seen as a typical mixed residential and business area with parks and a variety of building types, sizes and a mix of roads.

Figure 4-3 The 1km² of central London chosen as the basis of the London grid.

A typical grid specifies:

- The number and extent of buildings
- Heights of buildings
- Road widths and locations
- Open areas (eg parks)
- Building construction (eg stone, wood, cladding etc)
- Building use

To create the London grid a pedestrian survey was undertaken (to assess building heights, use and construction) and Google Earth was also employed. Fig. 4.4 shows one quarter section of the grid (it was necessary to simulate the 4 quarters of the grid sequentially as opposed to in parallel).

The survey looked at the extent and width of the roads, the size and extent of the open ground, building heights and sizes as well as the use of the buildings.

Figure 4-4 The London Grid (250 by 250m section). The grey areas are roads, the green areas are parks, the blue areas buildings (with the darker colour indicating height) and the yellow area part of the station.

The grid was modelled on the basis 10m by 10m pixels – this is a typical resolution for this area of capacity/coverage modelling (see e.g. [41]). In chapter 6 individual buildings are modelled on a 2m by 2m grid and the results are near identical to that of single buildings on the 10m by 10m grid. The propagation models used were compatible with this resolution.

The total ground area was 100pixels by 100 pixels in 1km². When building height is taken into account 3,336 pixels are outdoor and 23,200 indoor, with an average building height of 4 floors. Users are effectively evenly distributed across pixels – giving an indoor: outdoor ratio of approximately 7 to 1. The grid endlessly repeats – in that “shadow” base stations and buildings are included to avoid edge effects. Of the 1km²: 33% is either road or park with no buildings; 3% is covered by single-storey buildings; 13% by 2 storey; 10% by 3 storey, 32% by 4 storey; 7% by 5 storey and 2% by 6 storeys.

4.2 Technologies modelled

There have been a considerable number of frequencies proposed for 5G from 700MHz through to 100GHz+. In order to narrow down the eMBB scenario (the closest 5G scenario to that considered in chapter 3 – essentially just faster and more reliable download) it was decided to model 5G at: 700MHz, 3.5GHz and 24-27.5GHz frequencies. This represents traditional, “beachfront” spectrum at 700MHz (and would offer similar results for re-farmed 2G or 3G spectrum); higher frequency spectrum at 3.5GHz (where there is the prospect of substantial blocks of new spectrum but low enough for use by existing radio technologies) and, finally, a millimetre wave (mmW) technology with very different propagation characteristics. 700MHz has been proposed

for national 5G coverage and also suggested to act as the control plane anchor whilst 3.5GHz and mmW technologies have been tentatively assigned by the industry to urban eMBB and hot spot coverage, respectively. In addition to these 3 technologies it was decided to include both indoor and outdoor WLAN based on 802.11ac technology. In many future architectures WLAN is incorporated with cellular (possibly via a derivative of LWA – LTE/WLAN Aggregation) to increase capacity indoors or to reduce costs[63]. Table 4.1 shows the different technologies, bandwidths and multiplexing.

Table 4.1 Technologies modelled

Technology	Frequency /Bandwidth	Base-station density	MIMO Order
5G FDD OFDM – based air interface	700MHz (2x10MHz) (2x50MHz)	1-64 Macrocell/ km ²	2x4
5G TDD OFDM – based air interface	3.5GHz (100MHz)	1-256 Microcell/ km ²	4x4
5G TDD OFDM – based air interface	24.5-27GHz (1GHz)	1-128 Hot Spot/km ²	8x8
WLAN 802.11ac	5.8GHz 3x160MHz 1x480MHz	1-1664 Access point/km ²	4x4

The bandwidths represent the possible spectrum available to a typical UK MNO (Mobile Network Operator) by 2025. This assumes the current 4 MNOs – which looks likely following recent competition rulings. Note it was intended to model the specific holdings of a particular MNO and they were approached, through the 5GIC, but specifically declined and so a more generic approach was taken. At 700MHz there is an allocation of 80MHz to 5G [64] hence a reasonable allocation would be 2x10MHz per MNO. 2x50MHz was also included in the modelling to represent the possible re-farming of 2-4G spectrum in the sub 1GHz band. Within the 3.4-3.8GHz band there is a total of 274MHz currently available in the UK, following the recent auction. Ofcom is further looking at up to 400MHz being made available [65]. Given that the ITU has stated that the minimum continuous bandwidth for 5G in this band should be 100MHz [66] then it seems reasonable to allocate 100MHz to each operator. There is considerable spectrum available at mmW frequencies and the choice of 1GHz is based on that available from 24-27.5GHz [67]. More spectrum is available at higher frequencies and so 1GHz per operator would be possible. mmW could be used indoors at locations such as shopping malls and railways stations but would be prohibitively expensive to use in residential buildings and many offices: the lack of wall penetration necessitating an access point per room[68]. Here we do not consider the use of mmW indoors further.

Downlink traffic continues to dominate existing networks and most of the applications proposed for eMBB are highly asymmetric with a preponderance of downlink traffic. Thus we have chosen TDD, with a DL:UL ratio of 10:1, for all of the 5G technologies, with the exception of the 700MHz spectrum. In many proposed architectures this spectrum is used to provide “umbrella” or “cluster control” cells [69] and so there will be much heavier uplink traffic and FDD is proposed.

The densities and cell locations are chosen to reflect this located around the grid as follows:

- 700MHz Macro cells – 6 sector on building rooftops with down tilt antennae. 1-64macrocells/km²
- 3.5GHz Micro cells– Omni at lamppost height at road junctions or along roads. 1-256 microcells/km²
- WLAN indoor – initially 1 access point per floor increasing proportionately with base station density. 1 – 1664 Access Points/km²
- WLAN outdoor – access points at lamppost height at road junctions or along roads. 1-416 Access Points/km²
- 24.5-27GHz – 8x8 array at BS and 4x4 array at UE - access points at lamppost height at road junctions or along roads 1-128 hotspots/km²

Current macro cells densities are typically 10-20/km² in dense urban areas [71] Upgrading these for 5G would be the cheapest 5G installation option. Erecting new macrocells is expensive and it would be difficult to find sites for more than 64 macrocells/km², hence the actual number of 700MHz macrocells is unlikely to approach this number on cost grounds alone. In addition, the relatively small bandwidth available at 700MHz means that high base station densities would not greatly improve capacity, in comparison to other technologies and coverage would be excellent even for low densities. A higher density of 3.5GHz micro base stations would be possible at street level – using, for example, lamp posts. A maximum of 256 microcells/km² is used in the model and represents a spacing of only 75m between base stations. For 4 operators that would represent 1000cells/km². Because, as will be shown later, the poor indoor penetration of external 3.5GHz cells does not represent a very cost effective way of adding indoor capacity, it is unlikely that such cell densities will be exceeded for an out-of-doors network. At 24.5-27GHz external coverage can approach 100% with 50-100hotspots/km² – higher densities being economically unjustified by the very poor internal coverage and very high bandwidths potentially available to each base station. Larew et al. [70] have shown that in an urban environment it is possible to have up to 96hotspots/km² at mmW frequencies without serious interference. Hence the modelling of 1-128hotspots/km². In addition, the model was taking a considerable execution time

In this chapter it was decided only to deploy WLAN access points indoors and not cellular femto or pico cells. The issue is that building owners are very reluctant to install 3 or 4 different networks for each MNO. The failure (so far) to agree or regulate national roaming has led a situation where, in the UK at least, there is no mobile coverage in the London Underground tunnels. In chapter 6 we extend the model to cover the internal use of femtocells and the concept of neutral hosting (where a single infrastructure services a number of MNOs)

In the case of WLAN access points both a single frequency reuse of 1x480MHz and a 3 frequency reuse pattern (3x160MHz) were modelled with total (internal and external) WLAN densities reaching up to 2000 Access Points (AP) in 1km². Since there are typically 10,000 to 20,000 users in a km² of central London, then this represents 1 AP per 5 to 10 users. Not all WLAN spectrum will be available for 5G – some will be used for DSL and internal networks and some taken by personal hotspots. However, some mobile operators are proposing a converged 5G offering in which WiFi is integrated with mobile technologies. DSL provision would then probably fall within the service sold as “5G”. In a managed office block (or railway station/shopping mall) it is also quite likely that a single 5G solution will be installed involving both WiFi and internal cells.

Table 4.2 Radio Link and propagation models for the technologies modelled

Technology	Frequency	Propagation model	Tx Power	Rx sensitivity	External Wall Loss	Shadowing Standard Deviation	BS Height	Mobile Height
5G OFDM – based air interface	700MHz	Okumura–Hata Model	46dBm	-92dBm	10dB	8dBm	1.5m	30m
5G OFDM – based air interface	3.5GHz	3DUMi TR36.873	30dBm	-88dBm	10dB	8dB	1.5m	10m
5G OFDM – based air interface	24.5-27GHz	As detailed in [72]	30dBm	-77dBm	100dB	5.8dB (LOS) 8.7dB (NLOS)	1.5m	10m
WLAN 802.11ac Indoors	5GHz	As detailed in [73]	23dBm	-85dBm	10dB	7dB	3m	1.5m

4.3 Link budget and propagation model

Since there is no interaction between the technologies, such as re-use of frequencies, each can be modelled independently. For WLAN and LTE there are well established link budgets, propagation models and mapping between SINR and rates – as well as known overheads. In the case of new 5G technologies (700MHz, 3.5GHz and 28GHz) a different approach is required. The link budgets used are based on existing cellular and fixed-wireless access budgets for 700MHz and 3.5GHz. At 28GHz the power budget proposed in [72] is adopted. Propagation models for: WLAN at 5GHz; Cellular 700MHz, 2.6GHz and 3.5GHz are all well-established and extensively researched. Details of the link budget and propagation models used for all technologies are provided in Table 4.2. A suitable height adjustment (3.4dB/Floor – [74]) and modelling of internal walls (0.6dB/m internally – [75]) is used with the technologies at 700MHz, 2.6GHz and 3.5GHz as detailed in table 3. The external wall loss at used for each technology is also listed in the table.

For 28GHz the statistical approach to propagation of Akdeniz et al [72] is utilized. This was based on real measurements in New York City and provides a computationally tractive approach. Essentially there are three states that the path from a mobile to a base station can be in:

- Outage – no usable path between base station and terminal

- NLoS – Non Line-of-Sight connection between end points
- LoS – Line-of-Sight connection

The propagation model (and shadowing factor) differ for NLoS and LoS (as shown in table 5.2) with the probability of given pixel being in each state determined as:

$$P_{\text{out}}(d) = \max(0, 1 - e^{-a_{\text{out}}d + b_{\text{out}}}) \quad (4.1)$$

$$P_{\text{los}}(d) = (1 - P_{\text{out}}(d)) e^{-a_{\text{los}}d} \quad (4.2)$$

$$P_{\text{Nlos}}(d) = 1 - P_{\text{out}}(d) - P_{\text{los}}(d) \quad (4.3)$$

At 28GHz $1/a_{\text{out}}$ is 30m; and b_{out} is 5.2; $1/a_{\text{los}}$ is 67.1m and d is the distance in m

4.4 SINR to rate mapping

For all of the technologies, except for WLAN – which is explained below, the model calculates the SINR (Signal to Interference plus Noise) value at each pixel (including those on upper floors). Initially it calculates the strongest signal – assigning this as the serving base-station – and then summates all remaining signals as noise. The assumption made is that there is single frequency re-use in an OFDM-based air interface with no explicit modelling of interference reduction or cancellation. This is based on the emerging 5G New Radio.

In the case of LTE there is a standardised mapping from SINR to the modulation and coding scheme to be used [76] and, hence, the throughput at the IP layer once overheads are removed. With 5G technology there are currently no standards or link/physical layer models than can be used in the same way. However, the 5G air interface that emerges will still be bound by the Shannon formula. This has been modified by several researchers to simulate the real-life performance of different air interfaces via the Alpha-Shannon formula which translates SINR into throughput rates. For example, Bin-Salem et al [77] have modelled LTE with this approach:

$$C = \alpha * W * N_l * \log_2(1 + \omega * N_r / N_l * 10^{\text{SINR}_{\text{dB}}/10}) \quad (4.4)$$

Where $N_l = \min(N_t, N_r)$ and N_t, N_r is the transmitter and receiver antenna number, C is the throughput (Bit/s) at an SINR of SINR_{dB} (when measured in dB). W is the channel width (Hz) α and ω are parameters that can be calculated from the characteristics of the air interface α is calculated from the overheads and ω is related to the average spectral efficiency (Bits/Hz).

Following a review of measurements and modelling of the 5G air interface/link layer it was decided to use the the modified Shannon formula shown below– taken from [78] with the maximum spectral efficiency set to 12bits/Hz. This yielded an average spectral efficiency for 5G that varied from 2-8bps/Hz. Several commentators (such as [79] have quoted this as a realistic efficiency gain for 5. The loss factor (Δ) was set to 1.6dB [78] for the lower frequency bands but 3dB for the 24-2.5GHz band as suggested in [72].

$$C = W * \text{Min} \{ \log_2 (1 + 10^{(\text{SINR}_{\text{dB}} - \Delta)/10}), \rho_{\text{max}} \} \quad (4.5)$$

Where C is the throughput (Bit/s) at an SINR of SINR_{dB} (when measured in dB). W is the channel width (Hz), Δ is the loss factor and ρ_{max} is the maximum spectral efficiency (Bits/Hz).

In the case of WLAN the throughput needs to be calculated in a different way due to the CSMA protocol. [80] have shown the average (downlink) throughput of an access point is given by:

$$\text{Downlink Throughput} = N \times R \text{ with } 1/R = (\beta \times N + 1) \sum_{i=1, N} \text{Rate}_i + M \times \sum_{j=1, M} \text{Rate}_j \quad (4.6)$$

Where N is the number of stations the access point is transmitting to, there is a full buffer in the downlink and an uplink/downlink ratio of β . M is the number of access points and stations which are in carrier sense range but not within transmission range and hence contribute only interference.

MIMO (Multiple Input Multiple Output) and beam steering are included in the model in a technology-dependent way. For 24.5-27GHz the approach of [72] has been used with a 8x8 BS array and 4x4 UE array and beam steering used to maximise the SNR of the (effectively SISO – Single Input Single Output) channel. Current mmW technology can support antenna arrays with large numbers of elements [120] – in theory giving rise to substantial throughput gains. However, there are good reasons to believe gains will be, in practice and at reasonable cost, more limited in practical deployments for 5G. A full digital front end (with high resolution A/D (Analogue to Digital) conversion) for each element of the array will be expensive. Early systems have concentrated on using phase shifters in the RF regimes for combination before A/D conversion. This limits the number of spatial streams that can be processed. Another issue is that it is difficult to maintain the Channel State Information (CSI) at the transmitter – partly due to Doppler effects and partly due to requiring digital information for each antenna element. Akdeniz[72] have shown that the maximum instantaneous channel gain is bounded is given by:

$$\text{BFGain}_{\text{inst}} \leq 10 \log_{10} (n_{\text{rx}} n_{\text{tx}}) \quad (4.7)$$

Where n_{rx} is the number of receiver elements and n_{tx} is the number of transmitter elements. However, this gain is unlikely to be realized as it requires full CSI at both the transmitter and receiver. If beam forming is performed on only longer term channel fluctuations, then a reduced gain is realized but this does not require full CSI and will be much simpler to realize in practical systems – especially in the UE (User Equipment). In the study cited this reduced the gain from equation 4.7 by 2-3dB.

Akdeniz[72] found that there were typically 4 degrees of spatial freedom in the New York city study. In the above it is assumed that all the 4 degrees are aligned to offer the highest possible SINR. Of course it would be possible to send multiple streams over these spatial channels – enhancing the single user data rate very substantially. This was not considered in this work because the rates provided by mmW were already significantly above those of the other technologies. Also, by concentrating on maximizing SINR, the range of each base station is increased and the overall number, and the concomitant cost, is reduced. mmW networks in urban areas are coverage limited at low base station densities and so, with such a large capacity, this was considered a reasonable

simplification. Clearly it would be possible to explore the trade-offs of either spatial multiplexing or short term beam forming – using the results given by Akdeniz – in an expansion of the work.

4.5 Software design issues

The model itself is written in Visual Basic behind an Excel front-end with the cell-based sheets lending themselves to being interpreted as pixels and making output simple on a 2D basis. The possibility of using OPNET or NS3 was considered but the lack of licenses and/or training meant that progress could be made more quickly using VB. A library of built in functions (such as normal distributions and random variables) could be accessed and extensive break point and editing functions available. The use of OPNET would have permitted the use of inbuilt traffic models – this would have offered a better insight into the cost/QoS trade-off and would have allowed the user-experience of specific flows to be followed – and, for example, the MOS score of video streaming to be calculated over the entire flow duration. OPNET models of 5G new radio are also now (2019) available – although that was not the case at the start of the project – which also would offer a more detailed mapping of data rate against SINR. However, the current model is stand alone – meaning that it is easier to port, modify and adapt to new environments. It is also relatively simple and comprehensible – meaning that comparison with published results is simpler.

The disadvantages with Excel were that the entire model had to be written from scratch (although this did allow a full understanding of every step) and that execution times rose rapidly with the number of base stations). The advantages were that the cell based nature of Excel made it easy to assign one cell per pixel and to map the results very simply. In addition, the use of VB allowed any functions to be created and simulated and coding errors could be found relatively easily.

Typical run-times on a medium end laptop vary from 1 to 20 minutes for 1-256cellular base stations /km². A number of steps were needed to overcome the long run –times:

- Identification of time consuming sub routines and re-optimization
- The use of pre-populated look up tables (for loss or distance)
- The use of a zonal system – whereby rooms in the same same had the same external wall loss (pre calculated)
- Exploitation of symmetry in some buildings
- Use of 4 quadrants in the 1km²

Best software practices were adopted to manage the project:

- Version control with new releases incorporating extra features and bug fixes
- Extensive testing with published results of other researchers
- Structured programming
- Isolated units of code

One advantage of using Excel was that cell-based maps could easily be produced and Fig. 4.5 shows a typical ground level output with mmW base stations. The red/black pixels show the speed achievable at that location (there is no indoor penetration as the wall loss is set to a high value as explained in the next chapter – this leaves the ground floor of the buildings with no coverage and they are shown in blue/yellow). The darker

the pixel the greater the bit-rate. The grey pixels represent the outdoor locations with no coverage.

Figure 4-5 typical output of the model for 5G mmW

As some of the models involved probabilistic propagation models a number of runs were required to obtain statistically valid results. Typically, 10 runs were used – although in practice the variation was less than 4% between runs. This was explained by the fact there were many thousands of pixels and so the random variations in propagation tended to average out over a single run.

Another feature of the model was the use of shadow base stations – beyond the end of the grid in order to avoid edge effects.

4.6 Calculation of Coverage and Capacity

The model can be adjusted for any DL/UL(downlink/uplink) split and can utilise different QoS scheduling algorithms. In the results presented here the DL/UP split was set at 10:1 for all of the TDD technologies except WLAN – for which it was set at 100:1. The reason for this was that WLAN is likely to be incorporated into 5G only as part of control/user plane split architecture and using WLAN for uplink degrades performance significantly in high density deployments due to the operation of the CSMA sharing algorithm. In addition, it is assumed that much of the uplink traffic is carried on the “umbrella” 700MHz cell.

Proportional fair scheduling was used to evaluate bitrates and all traffic was treated on a best efforts basis to reflect the current cellular and WLAN networks and ongoing uncertainty in how, if at all, QoS classes will be utilized in 5G. Full buffers were assumed in the downlink – so that traffic was continuously received and no specific traffic arrival pattern was modelled. The raw capacity (in terms of Gbps/km²) could then be calculated. Only when looking at the number of users that could be supported are assumptions about the busy hour and overbooking factor required. These are further discussed in the next chapter.

For each technology a series of runs of the model were made as the density of base stations was increased. The downlink capacity was calculated from the average bitrate to each pixel across the whole grid. Coverage was then determined from the percentage of pixels that exceeded the set threshold minimum rate. Uplink capacity was not evaluated but was accounted for by reductions in slots for TDD technologies and, more explicitly, for WLAN by participation in the CSMA mechanism.

One particular improvement that was required was to include the option for 3 bands of 160MHz for 802.11ac. It was clear that this would offer better coverage at some throughputs and much improved capacity over a single 480MHz channel. Fig. 4.6 shows a typical output with a single frequency and Fig. 4.7 shows a three frequency run.

Figure 4-6 WLAN (802.11ac) with single frequency plan (outdoor)

Figure 4-7 WLAN (802.11ac) with 3 frequency plan (indoor)

Each set of logic steps was then coded and tested independently against manual calculations (eg for propagation loss). Finally, the results of test cases were compared with published results. Where agreement was not exact the reasons are understood.

4.7 Sensitivity analysis

When modelling it is always prudent to conduct a sensitivity analysis. All of the parameters listed above were varied to determine the differential slope of coverage and capacity. Different resolutions (2m and 10m pixels) were used. Different number of rings of shadowing interfering base stations were tried and extended number of runs undertaken to test that the results has statistically relevance. Chapter 5 gives a specific example of one such analysis. In general, the most sensitive factor was the wall loss – moving from 10dB to 20dB made a material difference to the results. Changing the resolution, number of rings of interference and extending the number of runs made less than 1% difference to the results. Modifying the UL: DL ratio had a large effect on WiFi (as expected and included in the equations used – and reported widely elsewhere).

One effect that was noticed was that sometimes the coverage appeared to fall as new base-stations were added. This was due to the system being loaded to 100% (to determine its ultimate capacity) - so that the extra stations created interference. At 50% load (more realistic for a real network) this effect disappeared. An example of this is seen in chapter 6.

4.8 Conclusion

The model performed adequately to calculate the coverage and capacity of 5G technologies. Visual outputs were simple to arrange and aided de-bugging but the prolonged execution times pointed to the necessity to move some of the extensive calculations to more optimized environments. Unfortunately, there was not time to improve the model to a state where it could be offered as shareware. It could be improved by the addition of a user-friendly interface and documentation and by the inclusion of a variety of well known propagation models. It was also intended to extend the model to suburban scenarios and create different grids. These ambitions are still possible as the code has been written in an extensible and modular way. Nevertheless, the model provided results and insights that went far beyond the simplistic approach of chapter 4 and delivered the results that were intended at the inception of the project. These results are presented in the next two chapters. Firstly, outdoor bases stations are considered (chapter 5), where coverage and capacity results are combined with economic factors. Secondly, in chapter 6, the modifications for modelling internal 5G base stations are explained and cost data used to compare a neutral host approach to an MNO-centric deployment.

5 Coverage, Capacity and Costs – External Base Stations

5.1 Introduction

When the 5G concept was first being proposed the improvement factor – in terms of: headline speed, capacity, traffic density and many other metrics – was much larger than the improvement achieved in previous generational changes. User-experienced data rates, to take but one example, were of the order of 0.1Mbps for 2G, 1Mbps for 3G and 10Mbps for 4G. However, the rate quoted for 5G often exceeds 1 or 10Gbps. It was thought by some in the industry that the requirements for 5G would moderate over time but this hasn't proven to be the case [49] – with 100Mbps everywhere as the generally accepted rate for 5G.

Is such a large increase in rate and capacity technically possible? From research into highly dense networks and work on millimetre wave (mmW) technology the answer is definitely yes [81]. However, what has not yet been addressed to any extent is how much such a network would cost to deploy? As the technology for 5G becomes better established so understanding the costs of delivering a 5G network is becoming more important.

There are a number of key scenarios being proposed for 5G, such as ultra-low latency services, eMBB (enhanced Mobile BroadBand) and the Internet of Things (IoT). Here we have concentrated on the eMBB aspect of 5G. For the eMBB scenario much of the data from existing cellular and WLAN networks can be re-used and realistic costs for meeting these targets derived. To be classed as a revolution 5G requires a step change in high speed coverage and capacity and these are challenging both technically and economically. If the eMBB scenario proves economically unviable then 5G could fall back towards the generational trend and be more evolutionary than revolutionary. This chapter provides a techno-economic insight into the comparative costs of the two approaches and is one of only a handful of studies into the possible costs of a 5G deployment – despite widespread interest from mobile operators.

Although it is difficult (even for operators) to exactly determine the costs related to RANs (Radio Access Networks) and interpolation is needed to cost 5G technologies, there are sound reasons for arguing that current reported OPEX and CAPEX figures for WLAN, micro and macro cells can provide a firm basis for assessing baseline 5G costs. Firstly, averaging costs from several sources reduces variability and, secondly, many costs associated with 5G RANs – such as site rental, backhaul, maintenance etc. – will not change materially from LTE. Using many published sources, we arrive at CAPEX and OPEX figures for all of the above technologies.

5.2 Coverage

The model can be adjusted for any DL/UL(downlink/uplink) split and can utilise different QoS scheduling algorithms. In the results presented here the DL/UP split was

set at 10:1 for all of the TDD technologies except WLAN – for which it was set at 100:1. The reason for this was that WLAN is likely to be incorporated into 5G only as part of control/user plane split architecture and using WLAN for uplink degrades performance significantly in high density deployments due to the operation of the CSMA sharing algorithm. In addition, it is assumed that much of the uplink traffic is carried on the “umbrella” 700MHz cell.

Proportional fair scheduling was used to evaluate bitrates and all traffic was treated on a best efforts basis to reflect the current cellular and WLAN networks and ongoing uncertainty in how, if at all, QoS classes will be utilized in 5G. Full buffers were assumed in the downlink – so that traffic was continuously received and no specific traffic arrival pattern was modelled. The raw capacity (in terms of Gbps/km²) could then be calculated. Only when looking at the number of users that could be supported are assumptions about the busy hour and overbooking factor required. These are further discussed below.

For each technology a series of runs of the model were made as the density of base stations was increased. The downlink capacity was calculated from the average bitrate to each pixel across the whole grid. Coverage was then determined from the percentage of pixels that exceeded the set threshold minimum rate. Uplink capacity was not evaluated but was accounted for by reductions in slots for TDD technologies and, more explicitly, for WLAN by participation in the CSMA mechanism.

One of the original requirements of 5G was 50Mbps “everywhere”, user experienced data rates of 100-1000Mbps and peak rates of 1-10Gbps [48]. Since it is never possible, at any reasonable cost, to provide coverage totally “everywhere”, the percentage coverage in the London Grid was evaluated for the different technology/frequency combinations with thresholds of 64Mbps (Fig.5.1) and 100Mbps (Fig.5.2) to gauge how these different technologies might deliver these requirements. 100Mbps was chosen as many consider this the minimum for 5G, but this results in only partial coverage and so we also show the 64Mbps results – this being one of the actual data rates of 802.11ac. Note that mmW (24.5-27GHz) technology is only modelled out-of-doors as it does not easily penetrate walls or metalized windows[68].

Indoors the 64Mbps coverage at 700MHz is of the order of 7% (at 20Mbps it approaches 100%). Coverage at 3.5GHz only approaches 50% - at a base station density of 256/km² – due to the significantly worse propagation at the higher frequency. It must be noted, however, that use of higher order MIMO could significantly increase indoor coverage at 3.5GHz – although this would not add any significant capacity. 802.11ac using both 1x480MHz and 3x160MHz approaches 95% coverage with 416 base stations/km²

Outdoors it is surprising how few base stations at 24.5-27GHz are required to achieve over 95% coverage at 64Mbps (32/km²) and 99% (64/km²)– given the highly directional nature of mmW. These results, however, are similar to those of Akdeniz et al [72] in New York City. WLANs approach 95% coverage at 64Mbps at 416 base-stations/km² and 3.5GHz coverage peaks at 66% before interference reduces coverage at 64Mbps (coverage is 100% at 32Mbps)

At 100Mbps only mmW and WLAN can offer significant coverage. Out of doors mmW at a density of 32base stations/km² offers 97% coverage. Indoors WLANs can offer 88% coverage with 1664 access points/km²

The key conclusions on coverage are that 64-100Mbps can be provided across a significant (90%+) part of a dense urban environment using mmW outdoors and WLAN technology indoors. 3.5GHz technology – with 100MHz of bandwidth – can provide outdoors coverage at 100Mbps but is not adequate for indoor coverage unless the micro bases stations are located within the buildings. This is discussed further below. 700MHz provides almost 100% coverage at lower data rates (typically 30Mbps) – making it an ideal for the umbrella (or phantom) cells and C-plane control.

(a)

(b)

Figure 5-1 Coverage at 64Mbps. (a) Outdoor (b) Indoor

Figure 5-2 Coverage at 100Mbps. (a) Outdoor (b) Indoor

5.3 Capacity

The downlink capacity of each technology is calculated from the average rate across all the pixels that are parented on a particular base station or access point. Fig.5.3 shows the downlink indoor and outdoor capacity that the different technologies provide respectively. Note the indoor capacity is calculated on the basis that all radio resources were dedicated only to indoor users who are assumed evenly scattered over the internal areas of the grid. Likewise, the outdoor capacity. Thus the actual capacity of 1km² is a weighted average of the indoor and outdoor figures – based on the relative distribution of users. In this model there are 7 indoor users for each outdoor user. The results are split this way because mmW is an outdoor technology and 802.11ac base station densities are very different internally and externally. In the case of WLAN the capacities are additive if all access points are deployed internally and externally. The capacity of the cellular technologies increases monotonically with base station density, whereas the single frequency WLAN (1x480MHz) saturates due to interference and then the capacity reduces. Using a 3 frequency re-use pattern moves the peak capacity to a higher density than that modelled. In this modelling only limited isolation of internal partitions (supplemented by much greater isolation between floors) is assumed – simulating a largely business district. In a residential district each access point might be isolated by an external wall offering 20dB loss. If this is assumed, then the total WLAN capacity can rise to 500Gbps/km² using the model.

Outdoors capacity is highest with 24.5-27GHz hotspots. Very good coverage can be achieved with a relatively low density of hot spots and increasing the density adds significantly to the capacity since the system is predominantly noise limited. The capacity is calculated as 129Gbps/km² for 32 hot spots/km² and 740Gbps/km² at 128 hotspots/km². There is no sign of capacity saturation at these base station densities and, as noted in the last chapter, higher throughput could be obtained with larger transmitter and receiver arrays and more complex beam forming. As expected, 700MHz does not provide anything like this capacity (due to the much lower bandwidth and being interference limited). At densities of 32/km² – which represents the likely economic maximum density of urban macro-cells (see below) the capacity is calculated to be 0.83 Gbps/km². This is lower than the existing LTE network capacity because only 2x10MHz of 5G spectrum has been assumed. 3.5GHz microcells can provide a total of 30Gbps/km² of external capacity with a micro base-station density of 256 per km². Outdoors 802.11ac WLAN can also approach 20Gbps/km² (using a 3x160MHz pattern at 400AP/km²). Table 5.1 summarises the capacity capabilities of the different technologies with realistic maximum cells densities. Also included is the result of modelling LTE Rel. 10 technology with the grid (2x30MHz at 800MHz at 16cells/km²).

(a)

(b)

Figure 5-3 Capacity increases. (a) Outdoor. (b) Indoor.

The table clearly demonstrates, firstly, that 700MHz macro cells will only offer umbrella coverage and not add significant capacity. 3.5GHz technologies offers capacity gains (out of doors) of x30 greater than the current LTE macrocell network. Whilst this is a very large increase it is much closer to generational trend (x10) than it is to the 5G requirements of x1000-x10,000 capacity increases. Only mmW technology offers almost a x1000+ increase in capacity.

Table 5.1 Outdoor Capacity Addition

Technology	Cell density	Capacity
Existing LTE (2x30MHz)	16/km ²	1 Gbps/km ²
700MHz 5G FDD Umbrella Macro (2x10MHz)	32 /km ²	0.83Gbps/km ²
3.5GHz Microcells	256/km ²	30.6 Gbps/km ²
802.11ac WLAN 3x160MHz AP	416/km ²	20.9 Gbps/km ²

Indoors the situation is different in that mmW technology does not penetrate through walls and would require one access point per room to be used indoors. 700MHz penetrates well into most buildings but the limited bandwidth available and the cost of building new macro base stations restricts the maximum capacity that can be added to 0.6 Gbps/km². 3.5 GHz technology penetrates poorly into buildings and can add only 25 Gbps/km² (compared to 30 Gbps/km² outdoors). Only 802.11ac can provide significant indoor capacity with 90 Gbps/km² added with 1664 AP/km² deployed in a 3x160MHz pattern. Table 5.2 summarises the situation.

Table 5.2 Indoor Capacity Addition

Technology	Cell density	Capacity
Existing LTE 2x30MHz	16/km ²	0.8 Gbps/km ²
700MHz 5G FDD Umbrella Macro (2x10MHz)	32/km ²	0.57 Gbps/km ²
3.5GHz Microcells	256/km ²	25.1 Gbps/km ²
802.11ac WLAN 3x160MHz	1664/km ²	86.9 Gbps/km ²

5.4 Sensitivity Analysis

In order to gauge the sensitivity of the results to the various radio parameters a base scenario was chosen – with 32base stations/km² in the 3.5GHz band (100MHz). The indoor coverage and capacity was then calculated with variations to the different radio parameters. This is shown in table 5.3.

Table 5.3 Sensitivity Analysis – below the base scenario is the changed parameter

Parameter change	Indoor coverage %	Indoor Capacity Gbps/km ²
Base scenario	60	3.7
Wall Loss 10dB		
Storey gain 3.4dB/Floor		
Internal loss 0.6dB/m		
Shadowing SD 8dB		
Wall Loss 5dB	75	5.8
Wall Loss 20dB	24	0.9
Storey gain 6dB/floor	67	7.1
Storey gain 1dB/floor	48	2.0
Internal loss 0.3dB/m	77	5.7
Internal loss 1dB/m	36	1.7
Shadowing SD 5dB	43	1.6
Shadowing SD 20dB	79	10.6

It is clear that the wall loss is an important factor and the results would vary with different building compositions and constructions. The reason for a very large (20dB) shadowing standard deviation causing improved performance is that many pixels then have a much higher than average SINR and strong throughput (an equally large number have poor SINR but, overall, the net result is a higher throughput). Such a large value of shadowing is never suggested in the literature at 3.5GHz.

5.5 Cost Modelling

There is a dearth of openly published data on RAN network OPEX and CAPEX costs. In part this is due to commercial considerations and in part due to the difficulty of accurately apportioning costs across a large, integrated, network. A survey of the literature has thrown up around a dozen references that form the basis of the costings used in this section. Markendahl [41] gives figures for macro cellular and femto deployments in an urban environment. Frias [42] summarises sources of costs for macro cellular base stations, transport and backhaul and Nikolikj [43] provides cost estimates for 700MHz, 2.6GHz and WLAN in the 5GHz band. Yunis [82] provides 4G and femtocell costing estimates that broadly equate with those of Markendahl, updated for LTE and adding energy consumption figures. EU projects NORMA [48] and METIS [45] provide costings for 5G rollout as does Smail [46] and Oughton and Frias [47] look specifically at rolling out 5G across the UK. Further costing information is given in: Johansson[83]; Walia [84]; Paolini [85] and the Ofcom review of the UK mobile network [86].

This work is unique in providing capacity and cost estimates for 4 different 5G bands/technology combinations using radio modelling to accurately predict capacities and using a wide range of sources for costings. Only Smail[46] considers all these technologies in 5G but does not add radio modelling – rather using simplistic range

estimates. Other works either refer to 3G or 4G or do not span all of these bands/technologies in 5G.

The costs of building and running a RAN can, largely, be broken down into 6 key areas:

- Initial building cost – including: site, works and equipment
- Site rental
- Backhaul
- Operations and maintenance
- Spectrum – initial costs and ongoing licence fees
- Power costs

Table 5.4 Cost data used to derive the 10yr TCO values shown in the text. All values in £K – using 10yr (2009-2019) average exchange rates for Euro and Dollar. See references for specific currency values.

Ref	[41]	[43]	[83]	[42]	[82]	[46]	[85]	[47]	[81]	[84]	[45]
Macro CAPEX	100	100.0	108.3	90.0	12.5	82.8	47.9	64.0	57.8		95.8
Macro OPEX	20.8 - 30.8	16.7	15.0	20.0	11.7	20.7	21.4	9.0	18.8		10.8
Micro CAPEX		29.8	29.2		12.5	25.2	8.6	15.8	15.8		9.2
Micro OPEX		8.7	15.0		11.7	7.2	2.9	6.0	2.0		0.9
WLAN CAPEX		2.1				0.7	4.6			0.8	
WLAN OPEX		1.3				0.1	1.5			0.5	
mmW CAPEX										6.6	9.2
mmW OPEX										1.9	0.9

A degree of extrapolation is needed to project some of these costs into the 5G time frame. However, whilst the cost of electronic goods and equipment in general is falling, all the other costs listed above are largely technology-independent and costs have not changed (or increased slightly) over the past 10 years.

Spectrum costs have been excluded from this section as the cost of spectrum has been very different between 3G and 4G and under different regulatory regimes. Table 5.4 shows the CAPEX and OPEX costings from the 11 sources used in this work and Table 5.5 shows a breakdown of cost categories in the case of macrocells (although the breakdown is not specifically required in this analysis).

Table 5.5– breakdown of costs by category for macrocells All values in £K – using 10yr (2009-2019) average exchange rates for Euro and Dollar. See references for specific currency values.

CAPEX									
Ref	[41]	[43]	[83]	[42]	[82]	[46]	[85]	[47]	[48]
Equipment costs			41.7	27.5	8.3		20.3	40.9	39.8
Site build out			58.3	62.5				5	18
Installation			25		4.2		27.6	18	
Total	100	100	108.3	90	12.5	82.8	47.9	64	57.8
OPEX									
Ref	[41]	[43]	[83]	[42]	[82]	[46]	[85]	[47]	[48]
Site Lease	4.2-8.3		8.3	11.7	4.2		10.3	5	4
Leased lines	10		4.2	8.3	1.7		4.1		7.8
O&M	4.2-8.3		2.5		5.8		6.9	4	7
Power	2.5-4.2								
Total	20.8-30.8	16.7	15	20	11.7	20.7	21.4	9	18.8

We evaluated the specifics of each figure – date; country; source interdependency etc. to derive a CAPEX and OPEX figure for each technology/band combination. The 10year Total Cost of Ownership (TCO) for each technology was then derived by assuming the CAPEX was spent in year 1 and the OPEX discounted each year by 5% (as a typical rate used the references) over the 10 year period that was the assumed life of the asset. The TCO was then converted to an annualized rate and is shown in table 5.6. It is important to note that spectrum costs as well as core network cost have been excluded. A 5:1 wireless backhaul to a fibre access is assumed for the microcell technologies (3.5GHz, 24.5-27GHz and outdoor WLAN).

Table 5.6 Annualised RAN Costs

Technology	Annualised RAN cost/base station £k/yr
Macro base station (sub 3GHz)	33
Micro base station (3.5GHz)	7
mmW picocell	5.5

From the graphs of capacity added against number of base-stations (Figs. 5.2 and 5.3) it is relatively straightforward to calculate the annual cost of a given base-station density – thus giving the cost (in £M/yr/km²) of adding new capacity (in Gbps/km²) and this is plotted in Fig. 5.4 for indoor and outdoor capacity. Note that 700MHz macrocells up to a density of 20 per km² incur lower cost than shown in Table 5.6 – as they are upgrades of existing base-stations.

Indoors 802.11ac can provide very high capacities at low cost but this is not for a fully fledged 5G service – with ultra-low latency, handover and QoS. Integrating WLAN within 5G to offer a fully seamless user experience is the subject of many current research topics. 3.5GHz, where the base-stations are located outside of the buildings, is less effective in adding indoor capacity than outdoors because of the poor penetration but is a cheaper way of adding new capacity than erecting new 700MHz macro cells. It would also be possible to trade capacity for coverage at 3.5GHz by using higher orders of MIMO – this could boost the range but would reduce the capacity for the same costs. As expected, new 700MHz macrocells are not cost effective to add capacity alone – being far more suitable as umbrella cells with excellent coverage but limited capacity.

For outdoor capacity 24.5-27GHz (and mmW in general) appears to offer much the cheapest route to add capacity. However, there are some important caveats with this. These results assume that 1GHz of spectrum is available and, more importantly, the costs of 5G base-stations is in line with existing cellular micro cells and that fibre links are widely available across the urban area. At the present time only prototype systems exist and low costs are dependent on future technical development. As expected, WLAN offers the next lowest cost but the same comments apply as above that this is not a 5G technology and may be hard to seamlessly integrate within the overall system. 3.5GHz micro cells, however, offer a cost-effective way to add 5G capacity without the uncertainty of mmW or the difficulties of integrating WLAN.

A typical UK MNO with 2x30MHz of 800MHz spectrum using LTE Rel. 10 with 16 macro base stations per km² (3 sector) has a capacity of around 1Gbps/km² – calculated on the London Grid and averaged (weighted) over indoors and outdoors. If such a network was build from scratch (as opposed to upgrading) then the annualised cost is calculated as £0.53M/yr/km². Current WLAN networks are carrying 5-10x this traffic. If an MNO deployed a very dense 5G 3.5GHz network –with a base-station density of 256/km² each – then the total capacity added could be 30Gbps/km² (weighted average across all users with a 7:1 indoor: outdoor ratio). The annualised cost of this would be £1.8M/yr/km² – a 30X capacity increase for a x3 increase in cost over LTE. With 802.11ac WLAN deployments a further 110Gbps/km² could be added internally and externally with 2080 access points/km². However, this would again have to be shared between 4 operators – meaning a maximum of 27Gbps/km² per operator – at an annualised cost of around £0.5M/yr/km² per operator for 2000 access points/km² in total and costs shared.

Figure 5-4 Costs of adding capacity. (a) Outdoor (b) Indoor

Both of these approaches would increase the available capacity by a factor of x30 to x50 over current cellular capacity (and much less over current cellular plus WLAN traffic). The only technology modelled that can offer X1000 or more capacity increases is mmW – with 1.5Tbps/km² requiring 256 base stations/km² with 1GHz of spectrum. However, this does assume major technical developments and does not address indoor users. Table 5.7 summarises the likely capacity gains and costs for a typical operator (of 4). Note that there is an apparent paradox in Fig. 5.4 in that the capacity of 802.11ac goes down as the cost goes up – past a certain point. This reflects the fact that, beyond a certain access point density, the capacity goes down with further base stations (Fig. 5.3). This is a feature of the 802.11ac CSMA (Carrier Sense Multiple Access) mechanism and is caused by the listen before access aspect of the protocol. Cellular systems have a different access system and generally transmit independently of neighboring cells – this means that capacity generally always rises with base station density at modest network loads but can fall due to interference (an example of this will be seen in the next chapter). 802.11ax is an improvement on 802.11ac and is due for deployment in 2019. 802.11ax is designed to operate between 1 and 7 GHz. Devices at CES 2018 showed a top speed of 11 Gbit/s. For dense deployments, throughput speeds are approximately 4× higher than IEEE 802.11ac and new methods to avoid interference have been included.

Marylebone is part of Westminster and has a resident population density of 11,500/km² which doubles to (approximately) 20,000/km² on a working day. This equates to 5000 users per operator. Other UK cities have similar user densities in the centre – for example Southampton has an average population density of 5000/km² and double that in the centre.

Taking just the 802.11ac and 3.5GHz networks (because mmW can only serve outdoor users and most are located indoors) then the cost of providing eMBB is £2.3M/yr/km² or £460/yr/user (assuming 5000 users per operator). This figure only covers RAN costs and the total cost would be higher due to other factors such as core network, handset subsidies, advertising and so forth. At a density of 5,000 users/km², a capacity of 56Gbps/km² (adding the 802.11ac and 3.5GHz capacity) translates (with appropriate assumptions about busy hour and overbooking) to 800Gbytes/month/user – or a continuous average rate of 2.5Mbps non-stop 24 hours a day to all users. It is difficult to conceive that users will be willing to pay significantly more than they do today for the eMBB service of 5G – meaning that there is likely to be a significant revenue gap that needs to be filled by new services (such as Virtual and Augmented Reality (VR/AR) and autonomous vehicle communication) to justify these levels of investment.

The results are clearly sensitive to variations in the annualized costs shown in Table 5.6 – but only in a linear relationship. Even if costs are reduced by 50% in 5G, over those assumed, then, on these figures, rolling out x100 capacity will still cost considerably more than rolling out the 4G network. Overall the conclusions would still be valid that the original targets for 5G, in terms of capacity and high data rate coverage, would be economically challenging without significant new revenue streams.

Table 5.7 Likely capacity additions and costs for a single operator (of 4) in a dense urban environment (Weighted indoor and outdoor average)

Technology	Cell density/km ²	Capacity Gbps/km ²	Cost £M/yr/km ²
LTE	16	1	0.53
700MHz	32	0.6	0.6
3.5GHz	256	30.6	1.8
WLAN	2000	20.9	1
(Shared)			
24.5-27GHz	128	740	0.64

5.6 Conclusion

We have looked at the case of dense urban deployment for the eMBB scenario of 5G and calculated how different 5G (and 802.11ac WLAN) technologies can add coverage and capacity both indoors and out of doors.

Results show that adding 100Mbps “everywhere” is much easier (lower cost) than adding very significant amounts of capacity above the generational trend of a x10 increase. 700MHz is an excellent frequency for providing blanket coverage and use for

5G umbrella (or C-plane) cells but will not provide 100Mbps coverage everywhere and will only add limited capacity. 5G technology deployed through a dense network of external 3.5GHz microcells (such as on lampposts) can provide a significant outdoor capacity and a reduced indoor capacity – although this is only of the order of x30 on existing LTE networks for realistic cell densities. Only with mmW 5G technology (here modelled as 1GHz of spectrum at 24.5-27GHz) can provide x100 to x1000 capacity out of doors increases but doubts remain over the timescales and costs of the technology. Internally mmW is not suitable and either 3.5GHz base stations will need to be deployed internally or 802.11ac technology will require integration within 5G to provide a x100+ capacity increase.

The cost of deploying the above networks will be several times that of the cost of deploying LTE – we estimate a 4 to 5 times increase in costs for a 100Mbps everywhere network that has x100 capacity increase. This cost is very unlikely to be born by existing mobile broadband users who, increasingly, expect higher speeds and larger bundles at a constant price. Either 5G costs must be reduced, for example by sharing internal networks or pooling spectrum, or new revenue streams, such as AR and VR, tapped to make make such an expansion economically viable.

6 Modelling results for internal base stations

6.1 Introduction

The results of the previous chapter show that attempting to serve the majority of users located predominantly indoors, utilizing external base-stations, incurs a radio loss penalty of 15-30dB. This directly translates into reduced capacity, reduced coverage and increased costs. The obviously solution is to locate the base stations closer to the user. Internal WiFi (as modelled in the previous chapter) showed the potential of this approach but it was not without its drawbacks. Firstly, it was not a 5G technology and so did not offer seamless handover or QoS support. Secondly the spectrum is unlicensed, meaning that it might be shared with multiple public and private systems, thereby degrading performance significantly. In addition, the network manager function, to offer seamless integration of WLAN and cellular, has been problematic with operators and device manufacturers vying for control and a general lack of standards. With 5G internal base-stations a much more integrated approach, without the commercial and technical complications of the handset and operating system vendors, is possible. In this chapter we consider a number of different architectures for placing 5G base-stations within the buildings of the London Grid.

The question of why indoor 2/3/4G coverage, as typified by that on the London Underground, is poor to non-existent is often asked. There are a number of technical issues around distributed antennas and backhaul but solutions exist for these and many such systems have been deployed around the world. The major impediment is actually commercial. A large hypermarket wants good mobile for all of its customers, whom, in the UK at least, are parented on 4 different networks. Negotiating contracts with all MNOs is complicated. Further attempting to install 4 base stations, 4 distributed antenna systems, 4 power supply systems and so forth is not really viable. The hypermarket's best solution is to sign a deal with 1 MNO, install one RAN and have customers of the other MNOs roam onto this network. However, national roaming has always been strongly resisted by MNOs keen to differentiate on network performance and control all aspects of the user experience. In India [87] national roaming is common due to the regional nature of operators. Another issue is the commercial incentive of site owners to maximise revenues over customer experience. This is well-illustrated by the situation at airports in the UK. Heathrow has partnered with Vodafone [88] with base stations located within airport. This is an exclusive deal and the other MNOs have base stations ringing the airport with sectors pointing in at the airport.

This chapter starts by classifying the different architectures according to the ownership, sharing arrangements and spectrum used. Some of these options seem commercially difficult but it is interesting to compare their performance as this may help to drive regulatory change towards lower overall costs for 5G users. Section 6.3 describes the internal model used to assess these different options. 6.4 then gives results for coverage and capacity and 6.5 discusses costs and gives costs of capacity/coverage options for the different architectures.

6.2 Internal sharing architectures

6.2.1 Spectrum

The most obvious delineation of internal architectures is through the ownership and size of the spectrum used. There are several possibilities:

- 1) The spectrum owned by an MNO is used exclusively by that MNO
- 2) The spectrum owned by an MNO is shared between multiple MNOs
- 3) The spectrum of several MNO is pooled for joint use
- 4) New 5G spectrum is licensed to multiple MNOs with interference avoidance/mitigation

6.2.2 Infrastructure and neutral hosting

It is possible to split the infrastructure into the antenna system (often distributed and capable of serving multiple MNOs/frequencies) and the base station(s) (which would be operated by a single MNO). The building owner might sign an exclusive deal or might be able to use a variant of the “neutral hosting” solution that has been proposed [89] In neutral hosting an MNO rents processing in RAN equipment which then runs the software/algorithms that the particular MNO specifies. The fact that 5G has been designed for network slicing and virtualisation makes such a design much simpler.

The RAN parts that can't be virtualized -the RF system and antenna -may or may not be shared depending on the variant of neutral hosting. Some systems [90] allow operators to rent more or less antennas.

The RAN equipment is then connected back to the operator core network and functions as a single 5G solution. Systems ([90-92]) are available today. Some standards effort has been presented in MOCN (Multi Operator Core Network) and MORAN (Multi Operator RAN) [93]– see Fig. 6.1.

Figure 6-1 Comparison of MORAN and MOCN from [93]

6.2.3 Scenarios

The aim of this part of the work was to investigate the possible cost savings if, firstly, an MNO is able to locate base stations within the buildings and, secondly, the advantages sharing RAN equipment and/or spectrum. Three scenarios have been used to examine these potential savings:

- 1) **Baseline.** The first scenario is simply that an MNO is able to place 5G femtocells within buildings. This provides a 15-30dB advantage over using external base stations and the cost saving, for a given capacity and coverage, can be estimated. This is a very simple solution and we make the assumption that the existing building wiring is able to connect the femtocells to a single gateway router. The key costs are then the femtocells, the router and backhaul and any lease payments to the building owner. Multiple MNOs could deploy in the same building and the network could start with only a limited density of femtocells and build up to a higher density progressively. For this scenario we have assumed 20MHz of spectrum at 3.5GHz.
- 2) **National roaming.** In this scenario one MNO invests in a building, installing an active distributed antenna system(DAS) and high capacity backhaul. More spectrum is allocated to the building and at least one other MNO roams its customers when in building. It is unlikely that existing building wiring (mostly Cat 5) could provide the high data rates needed for 5G base stations with a high level of MIMO – its is therefore assumed that the building needs re-wiring and that fibre connects a number of active units back to gNodeB somewhere in the building. The key costs are then the fibering of the building, the RAN and active

unit costs, backhaul and any lease involved. For this scenario we have assumed 40MHz at 3.5GHz.

- 3) Neutral hosting. In this scenario there is more spectrum available – possibly pooled from a number of MNOs. There is a single gNodeB that might be operated by an MNO or neutral party. There would also be fibre around the building connecting active remote units. Key costs are then the baseband and active units, backhaul, lease fees and the cost of putting fibre into the building. For this scenario we have assumed 100MHz at 3.5GHz. Fig. 6.2 shows neutral hosting in LTE with MOCN.

3.5GHz seems the most promising 5G frequency for internal base stations. mmW just does not propagate from room to room or floor to floor and 700MHz is far more likely to be allocated to umbrella cells. The limited penetration at 3.5GHz is actually an advantage indoors – providing better isolation between closely spaced base stations.

Figure 6-2 Neutral hosting in LTE with MOCN

6.3 Internal modelling

To build the internal model of the London Grid a new model was constructed – using the principles and elements of the external model. The first major design decision was to only serve internal users. In other words, base-stations located within buildings only serve users inside that building and not those outside or in neighbouring buildings. These represent the so-called “inside-out” scenario and has been proposed in the past for WiFi and 4G femtocell coverage [122]. In the context of dense urban 5G networks the concept of “inside out” is not so relevant and it is clear that there will be dense networks of external base stations. So we have limited the internal base stations to serving indoor users. This allows each building to be modelled separately – so that a single basic model of a building can be adapted to model buildings of different sizes (height as well as lateral extent). It also means that buildings can be modelled sequentially – greatly reducing the required computing power. Fig. 6.3 shows a typical floor in the building model. This is very typical of those found in the Marylebone area.

It was decided to use a 2m square pixel – (this did not yield significantly different results to 5m or 1m pixels) but was a good compromise between resolution and execution time.

The base stations operate at 3.5GHz – it seems highly likely that 700MHz will only be used for umbrella cells and that mmW would be extremely expensive (requiring close to one access point per room).

Figure 6-3 Ground floor pixel map of the general building model.

It is assumed that the base station power is 20dBm (100mW) and that omni-antennas are utilised with the base stations mounted on 2m high on internal walls (in the manner of WLAN interior installations). Antenna gain of 5dB and 2dB cable loss with a 9dB receiver noise figure were assumed as typical figures for indoor LTE cells. The same basic 5G physical and MAC layer models (and the use of the modified Shannon formula to convert SINR to data rates) was assumed, as utilised in the previous chapter on external modelling. After a literature search the WINNER model [94] of internal propagation was selected. This offers a well used, well-researched model that includes both LOS and non LOS models as well as shadowing (3dB was used). Both 32x2 and 64x1 MIMO was included (using the data of [95]) – in general using these 2 different orders, as well as

different MIMO modes, made only 5-10% difference to the results of coverage and capacity.

In order to gather results from a wide variety of base station densities (given that there are 66 buildings/km² in the London Grid) it was necessary to model: one base station per building (66/km²), one every other floor 132/km², one per floor (264/km²) and the up to 22/floor (almost 6000/km²). Given that the maximum number of users is 20,000/km², and that only around 14,000 of these are indoors at any one given time, this gives almost one base station shared between two users.

Figure 6-4 gNodeB decomposition and interfaces for 5G (Andy Sutton BT)

Fig.6.4 shows how a gNodeB can be split within 5G and the levels at which the splits take place. A passive DAS system effectively sits between the RU and the antennas. An active 5G DAS system (necessary for MIMO operation) would use the CPRI (or eCPRI) interface between a number of RUs and a centralised DU. The CU could be located either within the building or remotely (a C-RAN – Cloud RAN) with the F1 interface typically

transported on 1 wavelength of an optical DWDM (Dense Wave Division Multiplex). Either way the major upfront cost is the active DAS installation.

Using the WINNER model required the model to determine if there was a direct line of sight from the base stations to the pixels. This is typically a complicated resource intensive calculation. To avoid massive computational run-time resource a zonal system was used. This allocated each pixel to a unique zone – corresponding to a single room or partition. Before the many runs looking at different base station locations a different routine was used to pre-populate a table that determined the number of (internal) walls between all possible base stations positions (a maximum one per zone) and every pixel. This only required one (extremely long) run to populate the table. Each internal wall could be assigned a different loss (although this feature was set at 12dB in the modelling used in this chapter). Ceiling losses were set at 17dB (using the values suggested in [104] for similar building constructions). These were considered to be accepted values for the types of buildings encountered in Marylebone.

6.4 Coverage results

As far as the coverage modelling is concerned the only difference between the scenarios was the amount of spectrum allocated to the base stations – since it is assumed that sufficient base band and backhaul capacity is available to support the full capacity operation (this is priced in - see section 6.6). A single MNO might use 20MHz internally (so as not to share spectrum channels with its external network). This represents 50% of the spectrum won by several UK MNOs in the 2018 auction. Results were also obtained for 40MHz – ie 40% of the extended spectrum assumed for an MNO if the entire 3.4-2.6GHz band becomes available for 5G. These results are re-used in scenario 2, where a single MNO dedicates 40MHz to internal base stations but has a national roaming agreement with one other MNO. Finally, for the neutral hosting scenario, 100MHz of spectrum is assumed pooled spectrum from a number of MNOs.

As in the previous external results the base stations were all assumed to be at full capacity, as the point of the eMBB scenario is to discover the maximum capacity and the coverage at this – rather than the coverage at minimal load. This is akin to wandering around the city of London in the middle of the night and finding that 50Mbps is obtainable from LTE pretty much everywhere. During the busy hour the coverage at 50Mbps shrinks very dramatically. As we are more concerned with busy hour performance and coverage it is appropriate to evaluate coverage at full load. At each pixel the SINR – after suitable modelling of the MIMO order and scheme – is translated to a throughput rate via the modified Shannon formula used in the previous chapter.

Figure 6-5 Coverage at 50Mbps with 20,40 and 100MHz of bandwidth at 3.5GHz.

Fig. 6.5 shows the coverage results for a 50Mbps against the total number of base stations within a 1km² area of the London Grid for bandwidths of: 20,40 and 100MHz. There are 66 buildings within the grid – so the first data point corresponds to one base station per building. The second data point (132/km²) corresponds to one base station on every other floor and 260/km² to one per floor.

The graph shows that coverage is close to very good (75%+) at 50Mbps with one base station per building and excellent (90%+) with one base station per floor even with 20MHz. The reason for the decline in coverage after this peak at 20MHz is that this is the coverage at 100% usage – with all base-stations transmitting at maximum load. As the density increases so does the interference, to such an extent that it is difficult to find locations with a sufficiently high SINR to support a spectral efficiency of 5+. The coverage results were repeated at 50% and 25% load and it was found that the coverage was did not decline once it had reached 100% and remained at that figure however high the base station density.

Figure 6-6 Coverage at 100Mbps with 20,40 and 100MHz of bandwidth at 3.5GHz.

At 100Mbps (Fig. 6.6) the coverage requires 1 base station per floor (approximately $250/\text{km}^2$) to achieve 90% + coverage. It never quite reaches 100% for 20MHz but does so easily for 40 and 100MHz bandwidths. In the case of 40MHz (and, more pronouncedly, the 20MHz) of spectrum the dip that starts at 300 base stations/ km^2 is due to a combination of: interference; the fact that the coverage is given at full network load, that there is a cut off of 100Mbps and the topology of the buildings. To explain this, imagine an isolated base station. At every location there is a SINR (since there is no interference it is really a SNR – Signal to Noise Ratio). Only in locations where the SNR is over a threshold (that required to sustain a coding sufficient to allow 100Mbps in 40MHz) will that pixel count as having 100Mbps coverage. This may fall below 100% coverage if the signal is not sufficient to support a coding rate of 100Mbps – as is the case for the 20MHz of spectrum in the above graph. If the coverage at (say) 50Mbps is looked at it is 100%.

For base station densities up to $66/\text{km}^2$ there is one or less base station per building and, since the isolation between buildings consists of two external walls, there is effectively no interference and capacity rises with base station density linearly. Up to 300 base stations/ km^2 there is one or less base station per floor (The average number of storeys is 4.4 and there are $66/\text{km}^2$). Since the isolation between the floors is much more substantial than that of the internal walls of each floor this limits the interference. However, after this density, new base stations create substantial interference. This is much worse as the coverage is measured at full capacity – with each base station transmitting at 100% usage. If network usage is reduced to 50% then the interference is much reduced and the dip disappears. In practice there are interference mitigation systems (such as beam forming MIMO or eICIC (enhanced InterCell Interference Coordination)) – that can be used to avoid this dip.

As the base station density rises the fraction of pixels very close to a base station rises and these have a better SINR than those further away because the propagation falls off faster than a square law – this accounts for the rise with increasing density.

Figure 6-7 Coverage at 200Mbps with a total of 20, 40 and 100MHz of bandwidth at 3.5GHz.

At 200Mbps (Fig. 6.7) the coverage is poor to non-existent for 20MHz. Requiring a spectral efficiency of 10 or more (200Mbps/20MHz) this rate is not supported for any locations save those close to base station and within the same partition.

When the bandwidth is increased to 100MHz the coverage at 200Mbps hits 75% at one base station per floor and rise to 100% at 2 per floor. In this case interference is less significant in that a spectral efficiency of only 2 is required and so the graphs are similar in shape to those for lower loads.

The coverage from internal base stations is much superior to that from equal numbers of external 3.5GHz base stations and similar spectrum (100MHz) (Figs. 5.1 and 5.2) despite a much greater transmit power. This is a direct result of the difficulty of penetrating buildings at the (relatively) high frequency of 3.5GHz.

It appears that internal base stations can offer excellent coverage at 5G rates. Since cellular networks are typically either capacity or coverage limited it is important to assess the capacity of internal base stations. Excellent coverage can be obtained with quite low densities of base stations – the key question is does this density provide a sufficient capacity for 5G users?

6.5 Capacity results

We saw in the previous chapter that only mmW and WiFi were, at reasonably economic rates, the only external technologies capable of providing 100Gbps/km+ capacity increases. The original specifications for 5G, however, called for capacity

increases of up to 1-10Tbps/km² which will only realistically be reached with internal base stations.

There are difficulties in utilizing mmW technology internally – the transmission through internal walls, doors and partitions is too poor – necessitating almost one access point for each isolated area. For WLANs there is up to 480MHz of spectrum at 802.11ac and the technology for deployment of internal WLAN is well established. However, there are issues with WLAN that we noted earlier. In addition, the previous chapter showed that 802.11ac – even when used solely for 5G and with little uplink traffic could only provide a maximum capacity of 87Gbps/km² with a density of 1664AP/km². Thus internal 5G base stations – be they femtocells or remote units – offer a potentially much greater capacity.

To evaluate this capacity similar methods to those employed in the previous chapter were used. The users were effectively scattered over a given building evenly and allocated similar radio resource (so that the capacity would be increased by offering more resource to those with favourable radio conditions). The average downlink rate was then calculated and the procedure repeated to achieve statistical meaning. Each building on the grid was modelled separately – since the internal base stations were serving only internal users within the same building this was a valid approach. It also allowed a reasonable run time per building (1-20Mins) – allowing a resolution of 2m pixels. There was considered no need for shadow base stations – since any interference from internal base stations in neighbouring buildings were subject to the attenuation of two external walls and the distance between them. A small number of simulations were done to conform this. What it does imply, however, is that MNOs are not using the same frequency internally and externally – the so called “co-channel” use of femtocells. There was insufficient resource to investigate the diminution of coverage and capacity with this scenario.

Fig.6.8 shows the capacity results for bandwidths of 20,40 and 100MHz as the number of base stations is increased for the London Grid. There is a monotonic increase in capacity with BS density and a near linear response. The lack of linearity is due to interference factors from the (slightly) non-optimal and discrete nature of the base stations. A complex algorithm was employed to place the base stations in a sensible pattern on each floor – but in real life this would be run several times and an optimization function run to place the base stations for maximum coverage/capacity (and to minimise interference).

The capacity is close to being proportional to the bandwidth. Here competing factors are at work. Firstly, the efficiency rises as the bandwidth is increased but, secondly, the noise in the receiver also increases with the larger spectrum.

Figure 6-8 Capacity of the London Grid with 66 buildings/km² using internal base stations at 3.5GHz and the bandwidth indicated

What is clear is that the capacity can reach extremely high levels – nearly 3Tbps/km² is possible at 100MHz with 22 base stations per floor (average). This is within the original specifications of 5G and shows that this capacity is possible with internal deployments. The question then morphs into “what is the cost of these high density deployments?”. In the next section we look specifically at the cost in the 3 different scenarios outlined at the start of this chapter.

6.6 Costs

There are several elements needed to evaluate the costs of the three scenarios outlined in section 6.1:

- 1) Backhaul to the building – each building will require a fibre connection. In theory the cost of installation may range from zero – where there is spare capacity in an existing link or unlit fibres in a bundle – to the costs of a new connection. In both cases there will be an ongoing cost to transport the vastly increased data that 5G will generate
- 2) RAN equipment – this will either be centralized (and possibly shared) – with distribution through an active DAS/fibre system to remote radio heads- or distributed with 5G femtocells using existing wiring. Either way there is an equipment cost.
- 3) If femtocells are not used (or if the building internal wiring is not adequate) then fibre will need to be installed throughout the building for use by one or more MNOs. Current 4G DAS systems are active – meaning that the base band signals are digitised at the remote radio unit (RRU) and transmitted to the base band unit (BBU) using CIPRI (Common Public Radio Interface) over fibre. Moving to 5G

the high order MIMO and increased data rates have lead to a new standard – eCIPRI- that digitises at a higher point in the stack and reduces the front haul data rate requirements (see Fig. 6.4). There will be a significant cost for fibre installation and ongoing maintenance.

- 4) Lease costs from the building owners. At least some buildings will require payments to allow MNOs to install internal systems (e.g. airports and railway stations). Other buildings may offer free access – for example an office building that is rented out to multiple clients – with excellent 5G connectivity as a selling point.

To model the 3 scenarios outlined above, it was decided that:

- 1) For a single MNO using their own spectrum(20MHz), the cost would be evaluated using femtocells within the buildings. The costs elements would be: Backhaul, femtocells costs and site leasing costs
- 2) For a single MNO using national roaming and 40MHz spectrum with a DAS system then the cost elements would be: Backhaul, RAN equipment, site lease and DAS costs
- 3) For the neutral host scenario the costs would be: backhaul, DAS, RAN equipment (shared) and site leasing costs. 100MHz was considered needed for this scenario.

In the case of backhaul there is little difference between connecting to a building or to a macro/microcell. Thus the figures in the previous chapter can be used. A neutral host RAN would be very similar to a 5G gNode B in cost (per user)– and figures from the previous chapter can again be utilized. There are a number of sources for the cost of 3G/LTE femtocells that can be used to evaluate possible costs for 5G femtocells. The most problematic area is in obtaining costs on active DAS systems (or as a proxy for fibre installation)– but a number of references are available with respect to US installations. The sections below look at each of these costs in turn and come to a “consensus” figure that is used in the evaluation of the cost of each scenario in section 6.8.

6.6.1 Backhaul costs

There are several elements to the backhaul needed for each building. Each building will clearly need a fibre or dedicated 5G mmW backhaul connection. If the capacity reaches 3Tbps/km² then 66 buildings will need an average backhaul of 45Gbps (the larger buildings would need 150Gbps). This probably rules out many microwave solutions and so we concentrate here on fibre only solutions. Modern fibres are supplied as bundles and lit as required. The current record for a fibre is 255Tbps [97] and most can carry 100Gbps today with suitable transmitters and receivers. The backhaul cost is therefore either the cost of installing a fibre connection and the cost of data transmission or the cost of an upgrade to an existing fibre as well as the data transmission cost.

Given that many macrocells are located on the rooves of buildings and are connected by fibre in urban areas, it seems reasonable to re-use the costs attributed to these in the external model. Using table 5.5 a figure of £9k/annum Opex was considered a reasonably representative figure. In addition, BT Openreach have launched (2018) a “virtual dark fibre service”. Channels support 100Gbps and a max of 3Tbps can be added (using additional optical equipment on supplied ports). The service costs £7,845 per annum (ex VAT as of Jan 2019) with an installation cost of £15,550 [98] Backhaul equipment to increase the capacity would be needed for some buildings at high capacity and installation may also be necessary if a suitable connection does not exist. Set against these costs is the

general trend for lower backhaul costs – especially in urban areas with competing suppliers – and the discount that MNOs could expect for connecting a large number of base stations. Thus we feel justified in taking figures of £15.5k Capex and £7.8k/annum Opex as the representative costs.

6.6.2 Base Station Equipment costs

Again it can be argued that RAN costs (per user/per capacity) will not be so very different from the case of the outdoor model. Small buildings might have one or more micro base stations and large buildings the equivalent of a macro base station. Alternatively, the RAN equipment itself might be distributed with 5G femto cells deployed and only a router/gateway to connect to the backhaul link.

The RAN equipment needed rises proportionately with the capacity needed. This can be estimated using the cost of microcells – in section 5.5 we agreed a cost £7k/yr for a microcell. In chapter 5 we assumed that each microcell had an EIRP of 1W. Here we are taking 100mW for the base stations and so it is not unreasonable to add the cost of a microcell for each 10 internal base stations. This is justifiable because much of the cost of these base stations is the radio equipment (amplifiers, converters etc.) and that is proportional (or nearly so) to the total power output. So each time up to 10 base stations are added to a building the cost of an 5G micro base station is added.

6.6.2.1 Femto costs

There are a moderate number of sources for the costs of 3G/4G femtocells. Having analysed these they are summarized in Table 6.1

Source	Walia [99]	Liu [100]	Yunas [101]	Smail [102]	Nikolikj [103]	Markendahl [41]
OPEX	1000	1000	667	690	833	833
CAPEX	625/yr	133	417	345	417	417
Time scale	5yrs		10yrs	6yrs	10yrs	5yrs
Discount rate	10%		10%	10%	12%	5%

Table 6.1 Femtocell costs from a variety of sources. All figures are in £ sterling (using the 10yr average exchange rate for the Euro and Dollar – please see quoted references for the specific currency values).

It is difficult to come to consensus figures for Opex and Capex figures quoted in the table pertain to different dates and different technologies. Nevertheless, there is sufficient agreement around figures of £1000(Capex) and £400/Yr(Opex) for these to be taken as representative figures. This is, of course, a figure for 3G/4G but there are strong arguments that 5G costs will be similar. Many of the components/software is common (radio amplifiers of 1W power, IP packet interfaces, casing, power supply etc.). In addition, much of the cost of 3GPP radio systems is IPR payments. As there has been next to no research in 5G on cost reduction and no specific initiative to lower IPR costs then it is difficult to see that 5G femto cells could be cheaper than their 4G equivalents. (For the core the jury is still out as to whether virtualization can control costs).

6.6.3 DAS/Fibre costs

It is unfortunate that there is much less published material on DAS/fibre costs. Essentially the CAPEX costs dominate very heavily as the installation

[104] quotes £1.38-2.76 per sq ft. for a passive system.

[105] quotes £3.45-6.90 per sq ft for an active system

[106] quotes £1.38-6.90 per sq ft

Overall a figure of £3.45 per sq ft Capex and 5% of Capex/yr as Opex seems a reasonable figure to take as a mid-estimate and is supported by the more extensive work of [107]

6.6.4 Rental costs

To keep consistent with the previous calculations we exclude spectrum costs. On rental costs there are large unknowns. Building owners are likely (in this scenario) to sign a long term deal with an MNO. The building owner benefits from increased coverage but only from a single MNO and if the building offers public access (eg a theatre or train station) is likely to demand considerable premium (as happens at airports today – see discussion at the start of this chapter). Since these deals are very commercially sensitive, getting access to typical rates is quite problematic. One compromise is to use the rental rates for microcells and multiply by the number required (at 1 per 10 internal base stations as discussed above – since they are 10x less powerful). It is recognised that rental costs will vary and may be zero (or even negative) where there is a perceived value to the end customers of excellent 5G coverage to the building owner (eg a local authority).

6.7 Scenario costs

6.7.1 Scenario 1

In the case of femtocells the costs are:

- 1) Backhaul – installation cost and annual cost
- 2) Purchase and running costs of the femtocells
- 3) Rental costs

6.7.2 Scenario 2 – national roaming

40MHz is allocated to this scenario and, with higher order MIMO, it is assumed that fibre (with eCIPRI) will be required to offer the higher rates of 5G. Key costs are:

- 1) RAN equipment costs
- 2) Backhaul costs
- 3) Fibre/DAS costs
- 4) Leasing fees

6.7.3 Scenario 3 - Neutral hosting

In this scenario a single RAN node hosts as number of MNOs. 100MHz of spectrum is allocated to this scenario (pooled or leased from an MNO). A fibre system is required in the building and, again, rental fees and backhaul costs must be added.

6.8 Capacity vs costs for different scenarios

Figure 6-9 Capacity add with Scenario 1. Femtocells, internal WiFi and external 3.5GHz microcells compared

Fig 6.9 shows that deploying femtocells is cheap. On the face of it they are cheaper, access point for access point, than WiFi. However, this is not the whole story. Firstly, there are extra costs associated with the core – such as the security gateway that acts as a buffer between the MNO network and the femtocells carrying traffic over an open IP network. In addition there is the assumption that the internal IP wiring is able to carry the femtocells traffic without significant delays – if an upgrade is needed then that would incur a significant extra cost (of the order of the DAS installation costs - see below) Femtocells themselves are very cheap to add – with all the cost coming from the backhaul installation, site leases etc. – causing the high start up costs shown in the graph. Also there is a cost for licensed spectrum that has not been included. Up to 80-100Gbps/km² WiFi is cheaper even without these figures and it is only at the extreme densities – when WiFi interference becomes an issue – that femtocells have an advantage. As expected, external 3.5GHz microcells are the most expensive option.

Moving on to the national roaming scenario, Fig.6.10 shows the cost of installing an active DAS system, backhaul, site leases and shared RAN equipment. The major outlay is the DAS installation and this dominates the other costs – resulting in an almost horizontal cost graph: a big upfront cost and small marginal cost additions for extra capacity.

However, for capacities up to 150-200Gbps/km² WiFi is a cheaper solution –especially when additional costs such as core and spectrum are factored in. Even up to 25Gbps an external solution (connecting indoor users with external 3.5GHz microcells) is cheaper –

because it avoids the big upfront costs of DAS installation. Coming to the neutral hosting scenario, Fig. 6.11 shows the costs of this solution with 100MHz of spectrum.

Figure 6-10 Cost of adding capacity for scenario 2 – 2 MNOs sharing a 40MHz DAS solution

Figure 6-11 Costs of adding capacity with neutral hosting (100MHz)

Again the shape of the cost curve is very similar – with a very large start up costs (backhaul, DAS or fibre installation, site leases etc.) and a very low marginal cost (additional equipment). It is clear that only at very high capacities will the cost be comparable with WiFi and even at 40Gbps/km² an external solution is lower costs and lower risk.

It is apparent that internal solutions can offer a lower cost solution to the provision of high headline rates and very high capacities. Further, if mass data is the key service then WiFi is the lowest cost technology. It does not offer QoS, handover or the ultra low latency of true 5G. However, if these features are not required then it can be incrementally built out with low risk and low up front cost. The next lowest cost solution is to use femtocells. Again the low cost of these – probably similar to the cost of WiFi when all costs (spectrum, gateway etc.) are added in. These can be deployed incrementally and would offer many of the features of a true 5G network. However, they would require a commercial agreement with the building owners and it would be very difficult for a single MNO to sign deals with more than a small percentage of the real estate in dense urban areas. A neutral host solution is a major investment – with DAS installation and backhaul provision major cost items. Besides these the costs of RAN equipment and site leases are much lower. However, there is clearly a threshold, which appears to be 20-30Gbps/km² where it is cheaper to supply indoor users from external micro base stations. A much higher threshold towards 200Gbps/km² exists for WiFi. Again the issue of convincing a majority of building owners to sign a long term deal – to justify the considerable upfront expense and to right this off over a long timescale – is going to be a major challenge. Clearly this is an area in which government intervention – be that through subsidy (such as tax relief or direct grant) or by regulation (requiring a certain fraction of spectrum sold to be shared or pooled) – could make a substantial contribution.

6.9 Conclusions

Whilst there is scope for considerable further research into the costs of different internal solutions, it is clear from this study that excellent coverage at 100Mbps is easily obtainable with a small number of internal base stations and a modest amount of spectrum(20MHz). Increasing the spectrum to 40MHz allows excellent coverage at 200Mbps. There is no doubt, however, that there is a substantial initial cost for internal deployment. Firstly, the buildings will need high speed, fibre-based, backhaul. Secondly, if a DAS/fibre installation is required this is a very significant cost up front. Active DAS (ie fibre) will be required for 5G and this means that it will cost in only for higher capacities (typically over 50-100Gbps/km²). For higher capacities – up to 3Tbps/km² has been simulated with 22 base stations effectively per floor – which fall within the range of the original specifications for 5G – then neutral hosting and large spectrum usage (100MHz) appears to reduce costs substantially. However, there are still a number of difficulties that present quite significant barriers to the deployment of neutral hosting. Firstly, building owners will need to commit to long term deals, MNO will need to make a significant up front investment and also to sign commercial sharing agreements that, potentially, restrict competition. To overcome these barriers might well require intervention from government (local or national), regulators or even long-term investors.

7 Conclusion

The author gave a talk on 5G in April 2013[10], at a time when the key rationale and motivation for 5G was being discussed. This was around the time of the establishment of the 5GIC at Surrey university. The author asked the question “is 5G going to be just like 4G only a bit faster and cheaper or something totally new?”. If it is to be totally new then it is coalescing around three key areas: Device/machine communications (IoT, M2M etc), Vehicle based comms and VR/AR applications. What should be dismissed as hubris is talk of ultra reliability and very high coverage as a 5G problem. Reliability is an engineering discipline in its own right and is achieved by redundancy, fall back and rigorous testing. Any degree of reliability can be achieved in 2G/3G/4G and 5G with the requisite design and resources. However, every factor of 5 improvement in reliability is reckoned to double the cost [108]. In a likewise manner the issue of rural coverage has a very weak correlation with the technology used and a very strong inverse correlation to the frequency. This is a basic law of radio propagation that can only be mitigated by trading off costs (larger antenna arrays, denser base stations...). These are not issues that 5G can intrinsically change to any great extent at a technological level.

Coming to the new applications they are certainly visionary but the proponents of these often fail to clarify what the specific failings of existing networks are that prevent the deployment of these applications today. To give but one example: there are millions of sensors in different machines, cars, stock, pets.... All of which would be more useful if they were connected. However, they are not connected today largely because of cost. Hardly any of these sensors require high capacity or low latency. What they need is a lower cost connectivity solution or one with better coverage.

One major differentiator for 5G is ultra low latency – 1-5ms; something that is truly different from today’s networks. This is trumpeted as the key to unlocking virtual and augmented reality, autonomous vehicles and remote surgery. This could lead to significant new revenue streams for 5G that could be used to fund new networks. There is no doubt that driverless cars have the potential to save considerable sums: Reduced traffic congestion, reduced pollution, faster journey times, fewer vehicles required.... However, the network requirements are exacting: very high levels of coverage along roads, very low latency and very high reliability. As we discussed above, reliability and coverage are strongly correlated to cost and frequency used. A new network – and it would require many new base stations (all with fibre connectivity for low latency) because the existing ones are not situated for street coverage – would be expensive. Too expensive for an MNO to fund and deploy in the hope of attracting cars to connect. No, there would have to be contributions from government, local authorities, car manufacturers, regulators and standards for this to be a viable future. (In much the same way that rail loses money on the fare box but is a net social good).

With mobile voice and texting in steep decline [109] the only growing revenue positive application on today’s networks is mobile data. When 3G launched there was so much talk of the “killer app” – the application that would be controlled and billed by the MNO and make significant profits. Various, picture messaging, music, video calling

and mobile gaming were launched and all fell away with the advent of mobile Internet access. The rise of apps (Facebook, Instagram) and mobile tailored web sites has resulted in the value chain being fragmented with the value captured by: app owners, app stores, content providers and payment authorities. What the MNOs provide is just data. There are various ways to quantify this: the most obvious being the data cap per month (Gbyte/month) but users are also concerned with the headline speed, the network capacity (since this limits the average speed and retransmissions) and the coverage. The early hype of 5G promised really ground breaking increases in headline speeds and capacities. In general, speed and capacity has improved by a factor of 10x or so per generation (2G at 100Kbit/s 3G at 1Mbit/s and 4G at 10Mbit/s or so). Thus the expectation, if 5G was an evolution of 4G, that rates would be 100Mbit/s. Similarly, the average monthly capacity might increase from today's average of 4GByte/ month to (say) 40Gbyte/ month. For the revolutionary version of 5G the rates are more than X100 improvement on LTE with headline rates of 1-20Gbps and user data capacities of 800Gbyte/month. This is significant in that current fixed Internet use is less than this [105]. It was expected that these rates would moderate in time as the hype faded but this has not proven to be the case and the expectation planted in the minds of politicians and the public at large is that 5G will offer these rates and capacities.

Headline speed in networks is a very poor metric of their capability. Go to any central London base site at 3am and LTE today will deliver 100Mbps +. Return at 9.30am and stand in the same place, you will often struggle to get 1Mbps. A much better metric is that of capacity – Gbps/km². This is what sets minimum guaranteed rate in the busy hour (via the number of users, activity pattern and overbooking factor) and the monthly data volume that the network can supply. 5G requirements look to move today's 1-5Gbps/km² to 1-3Tbps/km²

Again this is in excess of current fixed networks and asks the question of the future relationship between fixed and mobile internet access.

Figure 7-1 Scope of 5G (Author 2013)

Coming to the purpose of this work, it is apparent that 5G, if it is to be anything other than a simple evolution of 4G, will require very significant expenditure – up to £50B for London alone across 4 mobile operators. Just an upgrade of existing sites with new radios on the expected spectrum will not fulfil any of the above requirements. The basic physics of radio tells us that capacity is the multiplication of: spectrum, base station density and spectral efficiency. 5G can expand capacity by X1000 by either a major increase in one or a lesser increase in all of these factors. Large amounts of spectrum are available at millimetre wavelengths. We have seen that 4 MNOs might have 1GHz each of mmW spectrum. However, the range of these wavelengths is so short that coverage requirements would force a significant increase in base station density. Efficiency will increase in 5G but not by orders of magnitude. LTE is often running close to the Shannon limit and only larger order MIMO will offer predicted gains of 10-20dB (8x8 MIMO) depending on the radio environment. Again with the next largest spectrum block at 3.5GHz (possibly 100MHz per MNO) this radio gain will just about offset the lower propagation when compared to (say) 1500MHz LTE. Thus nearly all of the capacity gain possible in 5G must result from network densification.

Coverage comparable to existing LTE is possible by deploying 3.5GHz 5G new radio on existing sites with enhanced MIMO. This offers MNOs an easy and low cost evolutionary route for 5G. Extra mobile data capacity is created at low cost and 5G is seen to be launched (this was why LTE was quickly and cheaply launched – it was mostly added to existing 3G sites and new base stations have been quite rare as a percentage). However, this will not offer capacity gains over an evolutionary x10. The trouble with new base-stations is that they cost money – and the price has not been falling between generations. The actual radio kit is undoubtedly cheaper but site leases are static or increasing, 5G base stations will require fibre backhaul (for capacity and low latency) and

the cost of fibre installation is also static. Operation and maintenance costs (eg labour) are likewise on the rise. There is, therefore, a very real argument that cost will play a significant part in the roll out of 5G and that cost reduction should be a major feature of 5G. The big problem is that it isn't. In a very comprehensive survey [4] of 5G there are 30 pages on the technologies, network slicing and new applications but not a single mention of cost reduction or economics. Not one of the 200+ references relate to cost. In general, there is a considerable dearth of research on the costs of 5G and almost no work on cost reduction per se.

This work has quantified the costs of 5G in dense urban areas – mainly because these are the most promising deployments with the minimum up front costs. The focus is on the eMBB scenario. This is because it is the only scenario that exists today and can be extrapolated and for which research numbers exist.

Figure 7-2 5G application split by bandwidth and latency – those in the white box can be served by LTE (Adapted from the GSMA) – Relative costs added

Fig. 7.2 Illustrates 5G applications by bandwidth and latency. There should be another dimension to this chart that would be cost – as it would show applications that sit within the bandwidth and latency of LTE but for which a SIM-based module is too expensive (eg my car keys!). From the results of this work the relative costs of the new services are indicated by the pound signs – a major achievement has been to quantify these costs in an urban scenario.

5G is clearly not addressing this dimension but those of bandwidth and latency. If we calculate the cost of building new networks with high headline rates (and capacity as this

is actually a better metric of average and minimum rates as described above) then this in fact covers the cost of low latency as well since 5G new radios deployed will have an intrinsically low latency and, if we factor in the cost of fibre back-haul (with the possibility of a small number of micro base stations having a microwave hop to a concentration point) then we have automatically included the cost of this. Like most modelling/simulation radio capacity and coverage modelling can be done at different levels of detail. In this work we have chosen to model at an intermediate level of detail. Some researchers have used very crude propagation equations to estimate coverage but these are extremely simplistic and not suitable for dense urban areas or mmW. Very detailed approaches using, for example, ray tracing are too detailed and computationally intensive and are never used over wide areas. With a chosen topology (in this case 1km² around Marylebone London) all the required propagation models are available from the literature (including mmW at 27 and 54GHz). With the emergence of 5G new radio it is possible to interpret SINR into likely throughputs and hence assess the coverage and capacity of 5G systems over the 1km² of the London Grid.

The model was written in visual basic behind an excel front end – using a 10m resolution. This is a typical pixel spacing using in such assessments (and did not give materially different results to 5m pixels). Over the 1km² this translated to 7,000 external and 23,000 internal pixels – meaning typical run times of 10-100mins on a high end lap top at cell densities up to 256 (or 4000 in the case of WiFi and internally) per km². It became abundantly clear that the very limited spectrum available at 700MHz would only provide a small capacity boost and would, rather, be used as the umbrella coverage for the control plane and possibly a reliable uplink channel (since recent work has shown that 5G NR has a much smaller uplink range when compared to the downlink – because of MIMO asymmetry). 100MHz of 3.5MHz spectrum is optimistic – assuming the whole band is available to 4 MNOs (EE purchased 40MHz in the 2018 auction). External coverage can be achieved with relatively few base stations – due to the effects of MIMO arrays. However, for massive capacity gains there needs to be dense network of base stations – the classic microcells on lamp posts – possibly with some microwave backhaul aggregation to reduce costs. Whilst external coverage is good, it is far more difficult to serve users within buildings from external base stations – with the 10-20dB wall loss and internal losses a major obstacle. Included in these results is WiFi – since there is 480MHz of spectrum and a proven technology (802.11ac) that currently offers high rates. At mmW we modelled 1GHz of spectrum per MNO – given the available bands this seems reasonable and has been suggested elsewhere. What the propagation models show is that at 27GHz there is much more than LoS coverage – rays bounce around the urban canyons and extend coverage. A surprisingly small number of base stations can give reasonable coverage

Fig.7.3 reproduces the key coverage results for the 5G technologies (alongside WiFi for comparison). This clearly shows that 3.5GHz can supply 100Mbps over 90% of the modelled area with headline rates at modest (30/km²) base station densities. As noted above only 32/km² mmW picocells are needed for 90% coverage externally. Internally mmW is much more difficult, requiring 1 picocell per office/room division. Although it may have uses in shopping malls or stations.

Figure 7-3 Key results of coverage over London grid with 5G technologies and WiFi at 100Mbps (a) – Outdoor (b) – Indoor

This we conclude that coverage at 100Mbps is possible at relatively low base station densities (and correspondingly moderate cost – quantified below). For rates of 1Gbps and above only mmW is able to provide 90%+ coverage (and then only externally). This is not altogether surprising as 100MHz of 3.5GHz spectrum would need a spectral efficiency of 10bits/Hz at the cell edge to achieve this. 5G NR, even with 8x8 MIMO is not performing at this level.

If coverage is not a major technical problem, then what about capacity? Fig. 7.4 shows the capacity that can be added using external base stations – located at street level and (archetypically) on lamp posts or other street furniture. It is absolutely clear that there are only two technologies that can add 100Gbps/km² – WiFi and mmW. Even with a very high density of 256/km² 3.5GHz can only add 30-50Gbps/km². This is a 10fold increase on existing LTE and with less spectrum (reflecting the density of base stations and extra efficiency of the new radio). mmW can easily reach a capacity of 1Tbps/km² for

outdoor users but is not viable for internal use (other than in malls and large indoor spaces).

Figure 7-4 Key Capacity additions with external base stations (a) – Outdoor (b) - Indoor

Calculating the cost of the 5G radio network has proved problematic. There are relatively few published references to the cost of mobile networks (of which we have referenced and reviewed around 30 for this work). Indeed, MNOs themselves are not always able to accurately apportion the total costs of running a network in a logical and meaningful way. For example, cost and RAN equipment may be provided at subsidised rates from vendors with licence and upgrade fees. Spectrum costs are for the whole of the UK – how to apportion this between rural individual sites (by site number, users, monthly data..) never arises for an MNO but needs to be tackled to truly calculate the cost of an urban base station.

Our approach has been to review all of the available material and to come to a consensus figure for CAPEX and OPEX and to combine these into a 10yr cost of ownership via the usual discount rate approach. Whilst it must be acknowledged that there are variations in costs (with different countries, time scale, categories..) we believe

that this is the most reliable approach that can be achieved using openly published material. Using these figures, the cost of adding additional capacity can be calculated and is shown in Fig. 7.5

Figure 7-5 Costs of adding capacity with external base stations (a) – Outdoor (b) – Indoor

Attempting to use 3.5GHz spectrum with street level base stations to add capacity is a very expensive approach and is unlikely to be a viable solution. Part of the difficulty is that the majority of the users are indoors and that external base stations have to overcome a radio penalty of 10-20dB that translates into reduced capacity and coverage. WiFi is a cheap solution for capacity but is not a 5G technology in that the latency will be higher and ultra low latency services will not be supported. Moreover, there will be no QoS and hence no network slicing, no support for IoT devices (eg low power mode) and no seamless handover).

Table 7.1 Likely capacity additions and costs for a single operator (of 4) in a dense urban environment (Weighted indoor and outdoor average)

Technology	Cell density/km ²	Capacity Gbps/km ²	Cost £M/yr/km ²
LTE	16	1	0.53
700MHz	32	0.6	0.6
3.5GHz	256	30.6	1.8
WLAN	2000	20.9	1
(Shared)			
24.5-	128	740	0.64

For outdoor users, large capacity can easily be added with mmW picocells. In fact, for a coverage of 95% at 200mbps, only 32cells /km² are needed and this provides a capacity of 129Gbps/km² per MNO.

Table 7.1 shows the possible options facing an MNO looking at add capacity

Our clear conclusions are:

- 1) Not to add new 700MHz macro base stations. There is just not enough spectrum currently allocated to 5G to offer a significant capacity increase. The coverage is so good at 700MHz that this is the ideal spectrum for 5G control channel.
- 2) Not to add massive capacity via 3.5GHz spectrum at street level via microcells. The costs are too high running at 3x the cost of LTE for a 10x capacity increase. A much cheaper approach would be use 3.5GHz on existing macro sites with high order MIMO antennas and accept that capacity gains will be limited.
- 3) mmW offers a very high level of coverage for external users with a relatively low base station density of 50/km². At a cost much lower than 3.5GHz this still adds very considerable capacity of up to 300Gbps/km² for external users. The difficulty with mmW being that handsets and base stations are 3-5 years behind sub 5GHz technology and costs are still uncertain.
- 4) Providing high capacity for internal users is the most significant challenge facing 5G. WiFi provides cheap capacity but lacks the integration and low latency of true 5G.
- 5) Internal base stations for 5G could potentially reduce costs and increase capacity significantly
- 6) The eMBB scenario alone is unlikely to drive significant 5G deployments
- 7) MNOs would be better advised to concentrate on high coverage of low latency networks that could attract new revenues.

Coming to the final points – on eMBB. It is clear that users are demanding more and more data capacity with each passing year but are unwilling to pay more with per Gbyte prices falling rapidly over the past decade. If we take just the 802.11ac and 3.5GHz networks from table 7.1, then the cost of providing eMBB is £2.3M/yr/km² or £460/yr/user and equates to 800Gbytes/month/user (compared to an average of 4Gbyte/month in 2018) – or a continuous average rate of 2.5Mbps non-stop 24 hours a day to all users – over twice the provisioning on the fixed network in 2019. It is difficult to conceive that users will be willing to pay significantly more than they do today for the eMBB service of 5G. For the whole of London this equates to an expenditure of almost £50B by the 4 MNOs over a 10year period. Again it is almost inconceivable that this amount would be expended simply to support the eMBB scenario.

Figure 7-6 Coverage at 100Mbps for different bandwidths (Internal Base Stations)

Following these conclusions, the second phase of modelling was focussed on internal base stations and on the one cost reducing strategy suggested by 5G R&D – neutral hosting. The model could not scale to simultaneously modelling the 66 buildings within the 1km² of the London grid. By assuming that no outdoor users or those in adjoining buildings were served, it was possible to model each building sequentially, rendering the problem tractable. It also enabled a better resolution of 2m to be achieved and the inclusion of internal divisions. For a single MNO the most promising strategy is to deploy 5G femtocells. The cost of backhaul to a building is only a modest upfront cost (£15.5K with the latest Openreach product). With only 20MHz of spectrum allocated to the femtocells (at 3.5GHz) the coverage for 100mbps (Fig. 7.6) is 90+ with only one femtocells per floor(240/km²). Adding femtocells increases the capacity all the way up to 3Tbit/km² with 22/floor. Of course there are still difficulties with this approach. The internal IP wiring of the building may not have sufficient bandwidth to connect the femtocells to the router/switch concentrator that connects to the core.

The most difficult area, however, is the commercial agreement between the building owners/tenants over payments for the installation. As the coverage and capacity boost is for a single MNO it would be of only limited use to buildings with users on all 4 networks (such as shops, mixed businesses) and more attractive to corporate buildings with a MNO-specific contract.

Assessing the neutral hosting option it is obvious that either fibre throughout the building or an active DAS system will be required. This will provide better coverage and lower costs if very high capacities are needed but represents a very high initial cost and a long term commitment would be required to justify it.

Fig 7.7 shows the costs of adding internal capacity with both femtocells and neutral hosting compared to WiFi and 3.5GHz external base stations.

Figure 7-7 Costs of adding capacity with internal base stations. Top is with femtocells (solid line) and bottom is with neutral hosting (solid line)

There are several key conclusions that can be drawn:

- 1) For modest capacity increases external micro base stations 10Gbps/km² and WiFi (50Gbps/km²) are the cheapest option even compared to femtocells. In the case of WiFi the threshold is actually much higher because of core and spectrum costs not included here.
- 2) In the case of neutral hosting the thresholds are much higher – 50Gbps/km² when compared to 3.5GHz micro base stations and at least 200Gbps/km² for WiFi (and again much higher if total costs are counted)
- 3) Neutral hosting only makes sense if there is major up front investment and there is clear requirement for significant capacity that can't be met from WiFi (which can be installed and upgraded much more gradually and does not represent such a long term commitment).

- 4) Very high capacities are possible (Fig. 7.8) – up to 3Tbps/km² (with 100MHz of spectrum and 22 base stations per floor). Meeting all the original requirements of 5G.

Figure 7-8 Ultimate capacities with internal base stations (up to 22/floor)

Taking up the last point – the combination of internal base stations at a high density (be they femtocells or DAS) and mmW externally shows that the original high capacities posited for 5G are technically attainable. This then raises the question of the future relationship between 5G and fixed Internet access. If we assume 5000 houses in a typical km² of residential London, then the revenue from fixed internet access would be $5000 \times 12 \times £40/\text{month} = £2.4\text{M}/\text{yr}$. Coming back to the earlier figures for a mixed mmW and 3.5GHz network – the annual cost was £2.3M/yr/km² for a network providing each user with 800Gbyte/month. With average household use at 190Gbyte/month in 2017 (approx. 400GByte mid 2019 at current trends) it is easy to see that prices are approximately comparable. There is less scope for reducing domestic costs with internal base stations - using DAS in domestic buildings is not cost effective and femtocells are only possible where a fixed internet connection already exists.

Thus we are forced to conclude that 5G will at best be comparable with fixed internet prices but in reality fixed Internet has considerable scope to increase speeds and capacity and lower costs (through technologies such as fibre to the premises (FTTP) and G.FAST as well as cable upgrades. It seems very unlikely that 5G will replace fixed broadband for domestic and most office use.

In conclusion then we believe this work has made a significant contribution to the debate about the future direction of 5G. We have shown that the establishment of networks at 3.5GHz and mmW (with umbrella coverage at 700MHz) can offer excellent coverage at 100Mbps with new radio systems that support ultra low latency services. We have quantified the cost of these networks for dense urban areas. Extension of the range of 5G services to those that require high average speeds and ultra low latency has been shown to be much costlier. mmW provides the cheapest outdoors network. For indoor users at low to modest capacities (average speeds) the lowest cost solution is to add

3.5GHz to existing macro and micro sites and use high order MIMO to overcome the propagation loss of indoor transmission.

Key recommendations:

For MNOS

- 1) 5G can augment existing MBB applications and provide extra capacity by adding 3.5GHz new radio to existing sites at low cost. High order MIMO is essential to compensate for limited propagation
- 2) As of June 2019, two UK networks have launched 5G services. Vodafone U are reported [123] to have spent £4.5B on launching a 5G service. Vodafone are launching with 2 smartphones and a home hub (as a replacement for fixed-wireless access). Prices are speed-tiered with unlimited data allowance. For SIM-only deals the prices are (June 2019): 2Mbps -£23/month; 10Mbps £26/month and “maximum speed - £30/month. It should be noted that the first two tariffs are slower than most 4G connections. These prices are identical to Vodafone’s 4G pricing of unlimited data. Given the potential for some 5G applications to use very significant quantities of data, Vodafone will need to continue making major investments in its network to support unlimited data use. EE launched 5G in May and are offering SIM-only 5G deals at 20Gbyte/month (£32/month), 40Gbyte (£37/month) and 60Gbyte (£47/month). This is roughly £12/month premium on 4G deals but does include BT Sports or unlimited video streaming.
- 3) These prices suggest that the eMBB scenario will offer only a modest to neutral revenue increase for MNOs. Even more so in that sales of 5G home hubs cannibalize revenue from other parts of these companies. The full eMBB scenario should only be pursued if mmW becomes mainstream and suitable pico sites become available at reasonable costs. For internal users, femtocells represent the most scalable and least risky solution to adding high capacity. Even this should only be done if WiFi is not able to be integrated within 5G and does not offer sufficient capacity as it is potentially much cheaper.
- 4) Ultra low latency applications that require coverage but not high capacity can be introduced much more cheaply than high capacity applications because relatively fewer (x10 or so) base stations are needed for 90% coverage to 100Mbps than for capacities of 1Tbps/km² in urban areas.

For Regulators and government agencies

- 1) Achieving rural coverage with 5G is going to be challenging and will require regulatory intervention. Low frequency spectrum and sharing arrangements will be needed to make rural 5G cost effective. mmW is a short range technology and 3.5GHz is not suitable for large diameter cells
- 2) Internal building coverage is very important for low cost high capacity 5G. This will require significant investment in building infrastructure and backhaul. Tax incentives and other measures to reduce the cost and risk of investments would promote the spread of 5G
- 3) Street furniture (such as lampposts) will play a significant part in the deployment of 5G – the current fractured model of varied local authority ownership approaches, costs and exclusivity is not sustainable if 5G is to be introduced into urban areas. Site and infrastructure sharing offers the opportunity to further lower costs

For Researchers

- 1) Cost reduction needs a higher profile within 5G. Standards related to site and equipment sharing could offer significant savings
- 2) There is clearly a market appetite for further R&D into 5G techno-economics

For Investors

- 1) There is a danger for MNOs that 5G will entail significant expenditure on new base stations and new technologies that are not covered by new revenues. We have shown that the eMBB scenario has the potential to erode profitability – with static income and higher costs
- 2) New applications based on ultra low latency are far cheaper to introduce than high capacity applications.
- 3) It is quite clear that 5G will require many new base-station sites. At 700MHz there is insufficient spectrum for a major capacity uplift. At 3.5GHz there is more spectrum and this is currently being rolled out on existing macro base stations. Whilst MIMO can make up for some of the inherently poorer propagation of 3.5GHz (When compared to current 2G/3G and 4G frequencies from 700-2600MHz) – this approach will neither provide very high capacities nor good high speed coverage within buildings. To achieve this will require micro base stations at street level (for example, on lampposts). In addition, mmW offers very large bandwidths and, consequently, extremely large capacities. It is, however, a comparatively short range technology and will also require a dense network of new micro base stations for good street coverage. These will require good fibre connectivity, although they may be connected in clusters by microwave links. Street furniture and city fibre backhaul look to be key to the future of 5G and ownership of these base station sites could present a good rate of return.

Fixed Wireless Access

1. 5G could offer a fixed Internet access service in urban areas. Technically there is sufficient capacity in a 5G network using mmW (at a density of 32-64 access points/km²) to offer a fixed internet via a fixed receiver on the outside of buildings.
2. 5G at 3.5GHz with limited bandwidth (eg 40MHz) operating from existing macro sites is unlikely to have sufficient capacity to offer more than a very limited (either by number of subscribers or usage) fixed wireless access service.
3. If more spectrum is released at 3.5GHz and a dense network of base stations is established (eg on lampposts at densities of 100/km²+) then a larger fraction (but by no means all) of existing fixed users may be served by 5G
4. This study calculates that the cost of providing fixed wireless access in urban areas by 5G is, at best, comparable with current fixed costs. Moreover, it should be noted that fixed traffic is doubling every 18months and that copper, fibre and cable access all have evolution paths to much higher speeds and potentially reduced costs.
5. There is a sub section of the urban population that might benefit from 5G fixed wireless access more than the general user. These are typically students or transitory tenants that are more mobile, less frequently at home and find it difficult or inconvenient to sign long contracts for fixed access. This population is an ideal

target for a combined fixed-mobile offering and could be served at home by a cheap 5G modem than can be placed near a window (this avoiding a high installation cost).

6. 5G fixed wireless access poses a challenge to the regulator. Currently fixed lines come with legal conditions on reliability, back up supply, lawful intercept and so forth. 5G data only access may not offer these safeguards – which may make them cheaper in time – but may require new regulation to ensure regulatory aims are not side stepped.

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