techUK future technologies network

5G innovation opportunities- A discussion paper

Future Technologies Network

On the shaping of 5G technologies and networks, scope for wider service and applications innovation and UK strengths and opportunities

August 2015

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techUK helps companies broaden their network, build connections and deepen relationships with potential customers, partners and suppliers.

About the Future Technologies Network

The Future Technology Network (FTN) is a Technology and Innovation network, partnering with other industry networks and techUK activities, leveraging the 'network of networks' principle to address grand socio-economic challenges for the benefit of society, whilst creating the platform for UK innovation and international engagement increasing UK capability and UK wealth.

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The opinions and views expressed within this document have been reviewed by the members of the Future Technologies Network – Radio working group. The views and opinions do not necessarily reflect those of the individual members of the working group or the organisations that the members represent. See appendix 11 for paper writing process.

1 Introduction

5G means different things to different people, but an agreed definition that is emerging is that it is a wireless connectivity solution that will deliver seamless services, sufficient bandwidth, and in any context. Consumers don't care how their communications services are delivered, simply that they are delivered when they want them and where they want them. This is not how things work today, and it will be technically challenging to deliver. Integrating two independent networks can be complex enough when all the required information is "known." We are now moving into a world of "known unknowns."

To deliver 5G therefore requires a "network of networks." It needs to deliver higher speeds, quickly and reliably, whether fixed or mobile, in an energy and spectrally efficient manner, with improved battery life and based on common standards - and all this at a sensible cost that makes it a viable proposition for businesses, consumers and citizens equally. This will happen, and the countries pioneering 5G developments will energise their economies and create growth and high value jobs. The UK is no longer starting from a technology leadership position – but we have pockets of real excellence, and via tech UK and other industry networks we can sit down and try to better "know the unknowns."

The purpose of this paper is to alert interested parties to the UK's excellent capabilities in 5G, to identify the key technical challenges that must be overcome, and to stimulate the change needed to make the UK a true 5G powerhouse - by helping UK technology companies to play a valuable role in contributing to the development of key facets of 5G technology and applications as well as in the roll out and exploitation of 5G networks. It can be done. Investment of time and money in this sector does not just have huge business benefits. Socioeconomically too, when we all have more to do and less to do it with, we can still look after our ageing population, help local Government leverage the changes that are coming to provide their services ever more intelligently, and even improve remote learning to foster the key skills where they are currently lacking.

It is in difficult times that much creativity is often unleashed. This was so during the industrial revolution. So it is proving to be for the "informisation" and "digital" revolution. We may be living in changing times, but the energy, dynamism, and in particular the technical acumen of our scientific and technical community remains robust and ready for the challenge it now faces. With a properly joined-up strategy, united and decisive leadership from the very top, a shared vision, and the determination to succeed, this is one challenge that the UK is well placed to meet, provided we give it adequate focus with immediate effect.

Prototype 5G networks in some form will emerge in Korea in 2018 and in Japan by 2020. Everyone faces the same technical challenges, and those able to rise and meet those challenges will prosper.

The UK is ready to help – and with our innovation track record this could just be our moment. Whether you want to invest, to join UK R&D in 5G, to explore specific opportunities – whatever it is, the UK is where it will be happening. Notable activities already in place, including but not limited to the 5GIC[1] and the Bristol is Open[2] test bed, can help towards a far greater proposition for the UK proposed in this paper.

This document focuses particularly on the technology innovation challenges necessary to enable the technological evolution to 5G and examines user requirements, architecture, enabling technologies, spectrum and the future direction of the telecommunications network topologies.

Industry initiatives, such as GSMA's December 2014 paper on 'Understanding 5G: Perspectives on future technological advancements in mobile'[3], progressed thinking on 5G. It identified a set of eight core requirements:

1. **1-10Gbps connections to end points in the field (i.e. not theoretical maximum)**
2. **1 millisecond end-to-end round trip delay (latency)**
3. **1000x bandwidth per unit area**
4. **10-100x number of connected devices**
5. **(Perception of) 99.999% availability**
6. **(Perception of) 100% coverage**
7. **90% reduction in network energy usage**
8. **Up to ten year battery life for low-power, machine-type devices**

The UK Spectrum Policy Forum ("UK SPF")[4] vision for 5G[5], developed by the UK SPF 5G working group, was submitted by Ofcom to the relevant preparatory group for The International Telecommunications Union ("ITU"). It is not identical, but along similar lines to these 8 core requirements .

NGMN published a paper in February 2015[6] further exploring the 5G requirements and providing analysis supporting the requirements and challenges to be addressed. The paper is aligned in terms of the scope of this paper. An extract states:

> *"In 5G, NGMN anticipates the need for new radio interface(s) driven by use of higher frequencies, specific use cases such as Internet of Things (IoT) or specific capabilities (e.g., lower latency), which goes beyond what 4G and its enhancements can support. However, 5G is not only about the development of a new radio interface. NGMN envisions 5G as an end-to-end system that includes all aspects of the network, with a design that achieves a high level of convergence and leverages today's*

[1] 5G INNOVATION CENTRE, http://www.surrey.ac.uk/5gic/about

[2] Bristol is Open, http://www.bristolisopen.com/

[3] https://gsmaintelligence.com/research/?file=141208-5g.pdf&download

[4] UK Spectrum Policy Forum (UK SPF) https://www.techuk.org/about/uk-spectrum-policy-forum

[5] UK Spectrum Policy Forum, 5G working group vision https://www.techuk.org/events/meeting/item/1673-uk-5g-vision

[6] NGMN 5G White paper, https://www.ngmn.org/uploads/media/NGMN_5G_White_Paper_V1_0.pdf

access mechanisms (and their evolution), including fixed, and also any new ones in the future[7]*."*

Achieving the eight requirements above, requires a significant change with respect to networks and services and how industry addresses the challenges they present. Previously, evolution saw access networks evolve in silos (e.g. 2G, 3G, 4G, Wi-Fi, Fixed, Fibre, Cable etc.). In the 5G world all of these have to be working in a converged manner, transparent to the user and leveraging best available assets to achieve the bandwidth, density, capacity, quality of service and latency required.

Additionally, existing services which require multi network hops rely on non-deterministic internet based connectivity and interworking (which 5G has the opportunity to address the requirements across multiple network boundaries), and optimise and dynamically negotiate the required network connectivity parameters such as QoS, speed and latency, based on the service requirement or context of the 'User' or 'Thing' being connected.

The vision of **'Infinite capacity'** and the **'Perception of'** it is debated as a key 5G differentiator. This will require new 5G technology to be developed and radical new approaches enabling significant cooperation across multiple networks (new and existing) to achieve the required **COVERAGE**, **SPEED** and **CAPACITY** to be delivered in any context / geographic area. Extrapolating existing network usage and solving today's UK coverage and capacity challenges alone presents a compelling case for 5G innovation, investment, leadership and accelerated / early implementation.

Based on these challenges the future of 5G will require two approaches, closely coupled through evolved architectures for network and future service evolution:

1) **Traditional mobile evolution from 4G to 5G based on increased speed, lower latency and usage of new frequency bands, whilst dramatically reducing energy consumption for IoT nodes, user equipment and infrastructure.**
2) **Increased interworking, interoperability and connectivity across multiple network and services boundaries.**

To deliver the new model we require catalyst(s) in the form of test beds and trials in key areas.

The table below provides high level recommendations. The call for Government intervention is initially focused on providing funding to stimulate R&D test beds and trials intervention through instruments such as Collaborative R&D. In the short term we believe this is a focused activity working closely with Industry, Academia and (in particular BIS[8] and DCMS[9]). Longer

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[7] NGMN 5G White Paper, February 2015 page 9. Source: https://www.ngmn.org/uploads/media/NGMN_5G_White_Paper_V1_0.pdf

[8] Department for Business Innovation & Skills (BIS) https://www.gov.uk/government/organisations/department-for-business-innovation-skills

[9] Department for Culture Media & Sport https://www.gov.uk/government/organisations/department-for-culture-media-sport

term, 5G could form a key foundation for the UK critical national infrastructure, as well as being the fundamental driver for the Digital Economy. Therefore it is believed that all Government departments should be engaged with particular focus on exploiting the full potential of 5G in tackling the major socio-economic challenges such as Future Smart Cities, Transport, Health & Social care and Energy / Utilities.

Table of recommendations calling for test beds and trials

<table>
<tr><th>Challenge</th><th>Notes</th><th>Recommendations</th><th>Who</th></tr>
<tr><td>Assessing UK capability and current projects</td><td>Bring together existing research and activities.</td><td>Harmonise and link activties, and identify gaps to be addressed</td><td>techUK,
UK Spectrum Policy Forum, InnovateUK and the Digital economy Catapult</td></tr>
<tr><td>Mapping of network infrastructure, topology and 5G digital fabric</td><td>Leveraging new and existing network infrastructure – enabling network of networks</td><td rowspan="7">Create 5G & IoT innovation network

Test beds and trials, enabling 5G Digital Fabric and technology validation

Create UK eco-system to develop leading position for international 5G standards activity.</td><td rowspan="7">FTN industry and academic member contribution

Strategic government funded 5G & IoT innovation network providing steering, dissemination and co-ordination

Government – significant investment through R&D intervention instruments.</td></tr>
<tr><td>Radio technology evolution</td><td>Air-Interfaces and antennas</td></tr>
<tr><td rowspan="2">Spectrum engineering</td><td>Co-existence and interference, global economies of scale</td></tr>
<tr><td>Enhanced radio planning. 3D, mapping/terrain tools</td></tr>
<tr><td>Data processing, data handling</td><td>Data, Control and User plane - Big Data enabled networks, addressing the 3 V's = Volume, Velocity and Variety</td></tr>
<tr><td>Socio Economic challenges</td><td>Technical use case validation. Health & Social care, energy and transportation</td></tr>
</table>

The authors of this paper would like to thank the members of the Future Technologies Network for attending the paper review meetings, developing and providing vital feedback / guidance in developing this report. From September '14 to the publication date of the paper, seven Future Technologies Network working group meetings (with approx. 250 attendees) took place to review and develop the content used within this report. Several ad-hoc, 'Chatham House Rule', meetings took place in between the main working group meetings.

2 Executive summary, conclusions and recommendations

A Network of networks capable of delivering the eight core 5G objectives identified in the Introduction requires a "joined-up" approach to the research and development efforts needed. It was not as important in the pre-Internet age to worry about the way in which things inter-worked. Often people were just happy that they did at all! The transmission of the first electronic fax[10] is a good example - previously the capability had not even existed. In the 5G and Internet of Things ("IoT") age, where everything is connected to everything else, such an approach will no longer work.

Today's infrastructure comprises a range of fixed and mobile architectures that have evolved significantly. The fixed network was originally only designed for voice, as was the mobile network. Now it is data that comprises the bulk of the bits that they move about – globally. In a converging world, 5G does not "see" any of these traditional silo based approaches. It starts from the customer centric viewpoint that they don't care anyway. We therefore have to evolve what we have already and identify areas that we need to develop.

2.1 Key innovation opportunities

So, how can we join up our thinking and decide where to focus our R&D activities to best effect? The table below maps the 8 core requirements describing 5G, identified by GSMA, to the main opportunities we see for innovation and rapid development. The table is spilt into key areas:

1. NETWORK INNOVATION (Network of Networks and interworking), highlighted in light blue
2. RADIO INNOVATION (including licensed and licence-exempt), highlighted in yellow

Because a network of networks approach is required, one must include all networks, as well as consider what they are capable of delivering as well as how they deliver it. We also have to consider both current and future radio technology factors, as a part of the matrix. What becomes clear is that R&D activity falls into two key areas. There are certain specific challenges that relate only to one part of the overall network of networks, and others that absolutely need to be developed and tested in a cross network environment.

It should be noted that this is a high level table and brings together a range of applicable contexts. For example, the requirement for a 10 year battery life is only needed for battery operated Internet of Things ("IoT") and Machine to Machine ("M2M") communications in a particular context where no power is available and therefore the device needs to operate from a battery without charging. For further information on the different requirements related to context please see Appendix 8's Spider Diagrams developed by the UK SPF 5G working group. In the future 5G world, all of these different context settings have to be taken into account.

[10] It was in 1980 that the ITU G3 Fascimile Standard was developed, primarily by Japan's domestic telephone company NTT and overseas telephone company KDDI. Source: http://faxauthority.com/fax-history/#TelephoneTransmission

		Technology and Innovation opportunities						
		NETWORK INNOVATION (Network of Networks and interworking)				RADIO INNOVATION (including licensed and licence-exempt)		
	Core 5G requirements	Mobile (Cellular)	Fixed (Satellite, Broadcast, xDSL, Fibre, Wireless)	Content delivery (CDN – edge / user)	Core Networks / Management (SDN/NFV)	<1GHz	1-6GHz	>6GHz
1	1-10Gbps connections to end points in the field (i.e. not theoretical maximum)	5G Radio Access Technology	Access technologies	Content / stored data nodes near to the EDGE and USERS	Backhaul and core network connectivity	Leveraging best available existing air interfaces and evolution to 5G RAT.		Developing new technologies and 5G RAT
2	1 millisecond end-to-end round trip delay (latency)	CROSS NETWORK = 5G DIGITAL FABRIC Interworking Innovation enabled through Trials and Test Beds. Including cross boundary Security, Policy, Control, Identity and Monetisation.				MULTIPLE RADIOS = 5G DIGITAL FABRIC Spectrum usage and management innovation enabled through trials and test beds. Multiple networks, bands and/or air interfaces and control and/or user plane.		
3	1000x bandwidth per unit area							
4	10-100x number of connected devices							
5	(Perception of) 99.999% availability					Low capacity, good for control / coverage	Medium Capacity, good for control and user plane	High capacity, good for user plane
6	(Perception of) 100% coverage							
7	90% reduction in network energy usage	✓	✓	✓	✓	✓	✓	✓
8	Up to ten year battery life for low power, machine-type devices	✓	✓	✓	N/A	✓	✓	✓

Key: ✓ MAJOR CHALLENGE - Radical low energy technology evolution at multiple levels for each area: materials, device, systems and cross network

Figure 1 - Capability requirements and challenges = innovation opportunities

2.2 Funding test beds and trials

The above table demonstrates a significant opportunity and available first mover advantage for the UK to lead the 5G evolution to address socio-economic challenges whilst enabling new jobs and creating wealth through global exploitation.

No industry that we know of anywhere in the world is currently addressing the 5G challenges for cross industry collaboration in this way. There is in particular a key role for Government to act as technology enabler, to facilitate a properly joined-up 5G strategy, and to promote the UK globally as the best place to do 5G technology and service innovation.

It is strongly recommended that the UK Government enables this strategy through collaborative R&D seed funding for the UK innovation communities to work "across the silos" to develop the technology and solutions required. This could be achieved by leveraging traditional instruments providing the catalyst for significant industry funding multiplying the capability and providing economies of scale to attract further inward investment and growth.

The trials and test beds will initially be focused on technology building blocks addressing the key 5G and IoT future capability requirements, evolving to 5G and IoT systems, Digital Fabric and network of networks cross sector approaches. Longer term infrastructure developed and deployed will then start to address new services and applications trials focused on major socio-economic challenges such as Future Smart Cities, Transport, Health & Social care and Energy / Utilities. See figure below.

Figure 2 - Trials and test beds chronological evolution

3 5G use cases and commercial considerations

5G is about better end to end performance, better support for non-traditional applications, and longer battery life. It is not necessarily about higher speeds, new air interfaces, or enabling M2M, although any/all of these may be ingredients.

Different applications and their users make different requests on the network in relation to quality of service ("QoS"). The QoS parameters include bit-rate, time of session, latency, response time, tolerance to information loss, and security (in some cases only a sub-set of these parameters are required and characteristics vary by service). One example application might be autonomous driving, which requires extremely reliable real-time communications, location awareness with low latency and mapping. Other applications needing reliable and low latency communications include the tactile internet and remote computing. None of these applications necessarily require very high speed data-rates. However, a broadband connection at home, where a user for example undertaking on-line banking requiring a reliable connection with high security, then decides to download a movie to watch over the next couple of hours signifies a different type of application. The user's average bit-rate during the evening is less than 10Mbit/s but if (s)he then demands the movie in 10 seconds, and is prepared to pay a premium to get it that quickly, a burst of 1Gbit/s will need to be delivered.

The use-cases defined prior to launching a new ecosystem of services have traditionally considered the likelihood of a positive business case for network and service providers offering those new services. Here we list the influencers in the definition of the use-cases of such communication services as stakeholders in their communication eco-system.

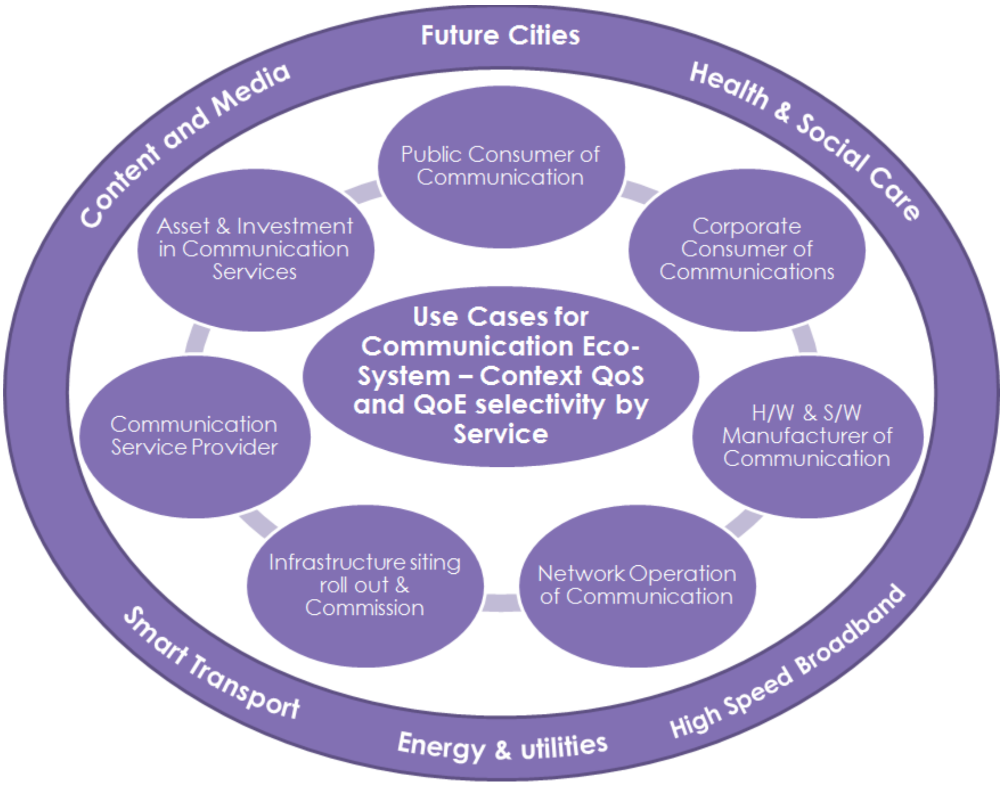

Figure 3 - Stakeholders in Fixed / Mobile / IoT eco-system

The table below provides an example of 5G use cases working seamlessly together. Individually, each use case will require new developments and technologies. Mapped against the eight key requirements, with the addition of a ninth requirement for inter-networking, the table areas marked 'High'(in functionality) indicate applications which are not achievable with infrastructure, technologies and services available today. See key at the bottom of table for more detail on the high, medium and low categorisation. In the scenario described, you can see that no area has been categorised as Low, i.e. capable of being delivered today using current technology, services and infrastructure.

5G example use cases - combined to deal with an emergency incident generated through traffic accident in a congested city	*Smart Transport / Cities* IoT enabled eco-system, covering connected car, traffic control and route planning. From collision detection and avoidance to prevent incident through to linking and interacting with city infrastructure	*Health & Social Care* Emergency response, patient data on site, low latency remote diagnostics, remote clinician / medical / robotic operation	*Content & Media* Higher resolution / increased video usage on site - users, emergency services and local businesses
1. 1-10Gbps connections to end points in the field (i.e. not theoretical maximum)	●●	●●●	●●●
2. 1 millisecond end-to-end round trip delay (latency)	●●●	●●●	●●●
3. 1000x bandwidth per unit area	●●●	●●●	●●●
4. 10-100x number of connected devices	●●●	●●●	●●
5. (Perception of) 99.999% availability	●●●	●●●	●●●
6. (Perception of) 100% coverage	●●●	●●●	●●●
7. 90% reduction in network energy usage	●●●	●●●	●●●
8. Up to ten year battery life for low-power, machine-type devices	●●●	●●●	N/A
9. Network of Networks - to achieve requirements of 1 to 8 listed above, operating seamlessly together.	●●●		

Key to table:		
	●●●	High level functionality of 5G required. Not achievable using current technology, requires 5G RAT and 5G Digital Fabric
	●●	Achievable using current technology, but requires significant network of networks cooperation not achievable today
	●	Can be achieved using current technology and networks

Traditionally, services are created by considering the social behaviour of the members of public or corporations forming the use-cases. The use-cases are normally processed into scenarios and then into business cases. As we are going forward in time from our 1G network toward the upcoming 5G networks, the capture of use-cases are becoming more complex as the types of stakeholders are expanding in this ecosystem. For example in Figure 3 above the public and corporate consumers of communications are expanding to include government bodies, emergency services, military, and manufacturing plant machinery control services.

Also, there is a trend towards the blurring of traditional demarcations in the value chain. For example equipment vendors increasingly tend to provide not only installation and commissioning services but often also incorporate divisions that provide network operation. From another angle, asset management and infrastructure sharing has become a must for network and service operators in allowing them to meet their target coverage and capacity set by regulators and the market demands. In recent years we are have seen the emergence of the Over The Top ("OTT") Service providers who provide services over a universal IP network via fixed or wireless connections made available by network operators.

All in all this leads us to consider the use case of the future 5G networks in the context of the likely shape of such a communication eco-system along with their stakeholders.

The focus now, within the constraints of their commercial policies, is for service providers to give customers the appropriate user experience, based on context, for the price they are willing to pay, rather than specific headline speeds.

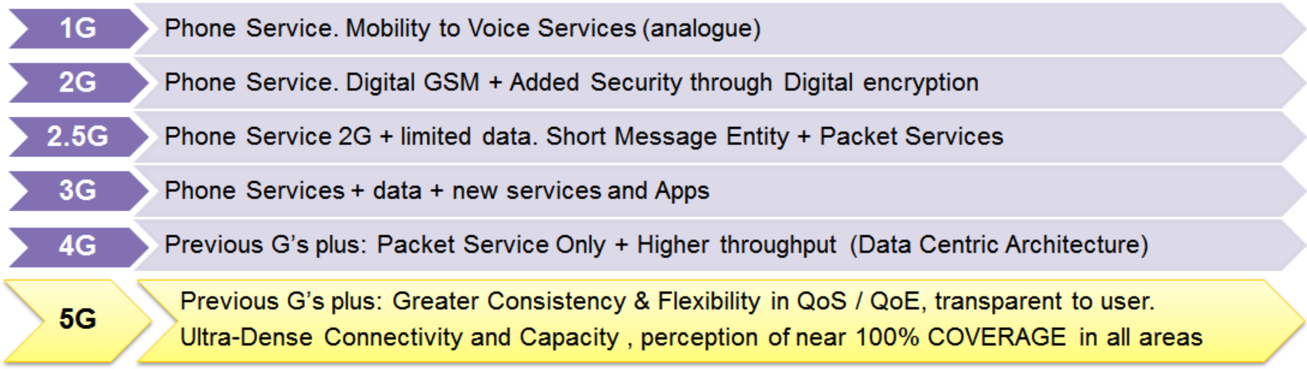

Figure 4 - Key Service features provided by each generation of Mobile Networks

A quick look at trends of successive mobile network generations and their service offerings and capabilities suggests that 5G networks should provide us with a solution for ultra-dense connectivity to enable a path towards services such as tactile internet, as described later in this document, see section 4, 5G Technology and Innovation. For such services and use-cases to be made available we require high throughput from a single cell plus an improved resource scheduler in the network, providing sufficient bandwidth and latency for the service in demand.

The 'appropriate user experience' depends on several parameters: support for the particular application, time to deliver, latency, consistency, reliability and security.

The NGMN has defined 25 use-cases in eight families with recommendations on these parameters[11], and the purpose of this paper is not to repeat this work, but to highlight opportunities for research and innovation.

These eight families are

- Broadband access in dense area
- Broadband access everywhere
- High user mobility
- Massive Internet of Things
- Extreme real-time communications
- Lifeline communications
- Ultra-reliable communications
- Broadcast-like services

[11] NGMN 5G White Paper, version 1.0 dated 17 February 2015, section 3
https://www.ngmn.org/uploads/media/NGMN_5G_White_Paper_V1_0.pdf

Current systems such as Wi-Fi, LTE, Broadcast, Internet etc. are already addressing the eight families listed above. 5G systems will build on the capability of these existing systems, in some cases building on legacy and leveraging previous generation assets. The extended capabilities outlined in sections 1 and 2 will require a new approach and will move towards a library of fixed and wireless connectivity options and select the best option or combination of options according to the user requests, the options that are available at the user location, and the operator(s) policy. In some cases the 5G core network will leverage previous communication generation assets to deliver the service in the context required, therefore leveraging and building on existing CAPEX. This approach presents exciting new CORE network opportunities in advance of 5G RAT being available: Evolving existing CORE networks to be 5G ready leveraging all available transport communication pipes.

Some 5G system parameters will have choices associated with them, so that the user can, for example, have the option of paying a premium for a permanent or temporary grade of service that is above his or her normal service bundle. This could include higher bit-rate, additional security or reduced latency. Therefore the requirement on the 5G system is to adapt to users' needs in a way that includes decisions to temporarily upgrade, and hence dynamically shift user plane capacity among users. User traffic is bursty in nature, and will probably become more bursty in future, and this suggests that separation of control and user plane would be of benefit, with the control plane being served perhaps from a number of macrocell sites, while the user plane can be served by more local and smaller cells as appropriate. Separation allows for lower latency and higher reliability on the control plane, and these attributes may be more important than on the user plane for some applications.

The choice of connectivity options available to the user will depend on the location, which could be from sparse rural to dense urban, and indoors or outdoors. Information relating to user type, user location and network topology is usually held centrally in the operational support system (OSS). The choice of connectivity can also depend on the location of the content that the user wishes to access. So decisions about which connectivity option to offer the user will depend on information about the user, the network (including backhaul) and the content. So in the design of 5G system there are several areas where opportunities for innovation exist. These include:

- Where information should be located and how it is to be used in deciding on connectivity options, to enable the system to dynamically allocate network resources in response to user requests,
- Greater interaction with the user to offer premium QoS and inform about trade-offs such as large file delivery time, reliability risks, cost and battery life, building on today's connection managers,
- Where content is best located, depending on content type, network topology and user behaviour,
- Dynamic radio resource management including transmit energy, spectrum choice, waveform choice that allows sufficient QoS with minimal wastage.

As use cases are ultimately means of capturing the requirements for the next generation of networks; further use cases for the 5G network should consider necessary architectural capability to provide communication services using, integration of fixed networks; licensed and unlicensed terrestrial wireless networks for peer to peer or broadcasting as well as use of satellite communication where possible.

This also means the future networks require to operate and integrate the new generation with their legacy networks in providing a holistic approach to serving the communication demands of the future.

3.1 Commercial considerations, Cost per bit – EBITDA

Most operators in most markets are presently experiencing reduced EBITDA[12] even in relatively high ARPU markets such as the US.

This suggests a reverse coupling between increased data rates and profitability - as data rates go up, EBITDA and associated operator margins go down. Partly this is due to the increased maintenance and management costs that are a consequence of increasing network density.

Higher density networks also increase capital spending and reduce ROI. In the short term the Mobile industry is addressing EBITDA through rationalisation of their cost base[13], but in the longer term there is a requirement to achieve step function reductions in cost per delivered user bit.

Many different views of 5G are currently being formed including the need for networks to be designed as 'ultra-dense high capacity networks' -a view that is true, but maybe misleading. Wide area large cell high capacity high data rate physical layer options are also required and must be considered as part of 5G. In some cases the use of different frequencies for control and user plane will provide the capability to adapt and provide flexibility in a dynamic way - see Figure 1 - Capability requirements and challenges = innovation opportunities.

With respect to high speed / density, the millimetre bands (30 to 300 GHz) are usually discussed in the context of dense urban topologies but these environments are typified by high levels of specular reflection and by surface and resonant absorptions at 24 and 60 GHz[14].

The counter argument is that millimetre wavelengths are better suited to line-of-sight access which implies coverage from high towers or sub-space or satellite platforms which in turn can support large high capacity cell topologies. At this point both approaches from innovation and technology development perspectives are valid i.e. these frequencies could be applied to provide, user connectivity for, both, short range small cells (indoor and outdoor), and, by leveraging smart antenna techniques for larger cells / longer distances, as well as fixed point

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[12] EBITDA Earnings Before Interest, Taxes, Depreciation and Amortization

[13] The Mobile Economy 2014 GSM Association Europe report http://gsmamobileeconomyeurope.com/GSMA_ME_Europe_2014_read.pdf

Extract from report: A combination of declining revenues, competitive and regulatory pressures and the economic backdrop have also led to falling profitability for the European mobile industry. EBITDA margins have declined by almost seven percentage points over the last five years, with negative economies of scale a key factor. Operators are taking a range of measures to maintain profitability, including a move away from handset subsidies (in order to reduce subscriber acquisition costs) as well as ongoing rationalisation of their cost base.

[14] www.fcc.gov/Bureaus/Engineering_Technology/.../oet70/oet70a.pdf

to point backhaul connections, which may be the only solution in specific scenarios (eg. in highly built up areas. It also suggests a need to amortize development, build and coverage costs across industries beyond consumer mobile broadband.

Section 5, Frequency related radio innovation opportunities, explores potential for 5 G deployments in different frequency bands.

4 5G Technology and Innovation

The following section provides some further technical information with respect to the different technologies, capabilities, candidates, innovation opportunities and research activities currently taking place. It is likely that 5G systems will evolve leveraging multiple assets from previous generation networks plus adding new technologies to the eco-system. Therefore, these sections need to be read in the context that these are options in a future infrastructure that are currently in the research phase and therefore subject to change.

The evolutionary approach is an important factor in preparing for a future 5G world, where many technologies may be introduced in a progressive manner. One of the key recommendations of this paper is for further trials and test beds which could be used as a vehicle to stimulate industry and the supply chain to develop solutions that are 5G ready in advance of a full 5G roll out. To assist navigating this section, please see table below for explanation:

Section	Page	Section Title	Description / explanation
4.1	18	Radio Access Technology (RAT) – Air Interface	Several candidates and combinations of the candidates are currently being considered for the future 5G RAT. This section only describes some, but not all of the techniques and technologies being researched and considered.
4.2	20	Radio technology options and building blocks	All of the sub sections are focused on >6GHz frequencies; the use of spectrum above 6GHz is attractive to deliver high data rates due to large amounts of bandwidth available.
0	27	Radio technology options and building blocks – non Frequency Specific	All of the sub sections are NOT frequency specific and can be applied in any Frequency. Techniques and technologies such as Power Amplifiers, Massive MIMO, duplexer, diplexers and CMOS filters are explored in this section.
4.4	37	Core networks, Virtualisation and Software Defined Networks (SDN)	This section is focused on the CORE network and the building blocks required to address the **5G Digital Fabric concept** for a capable 5G core(s) that can also interoperate across network boundaries enabling the Network of Networks principle required to support the concept of sufficient bandwidth, in any context providing seamless user services.

4.5	54	Energy and Throughput Efficiency Metrics for 5G Wireless Networks	The imminent development of the 5G wireless standards emphasises throughput efficiency in order to meet an expected 1000 fold increase in the amount of data traffic. One of the biggest challenges to achieve increased throughput will be energy usage in all areas of the network. This section explores the challenge and the need for further granularity, framework and measurement.
4.6	57	Security of 5G	5G aims to yield a more virtualised, distributed and fluid environment comprising different communication technologies and compute objects. It is imperative that security is 'designed-in' at all levels to ensure resilience, robustness and address the future hyper-connected connected that will be enabled by 5G and IoT systems
4.7	60	The Internet of Things (IoT) and Tactile Internet in 5G Networks	The Internet of Things and Tactile present many challenges around coverage, capacity, quality of service, deterministic / low latency connections for real time activities which present 5G a plethora of innovation opportunities which can part of future critical national infrastructure based on a 5G architecture. The section explores these challenges with a view to address these in a 5G evolving architecture.

4.1 Radio Access Technology (RAT) – Air Interface

Several candidates and combinations of the candidates are currently being considered for the future 5G RAT. This section describes some, but not all of the techniques and technologies being researched and considered.

Multiple access techniques allow multiple mobile users for sharing the limited bandwidth resources and being admitted by service providers in modern mobile networks. During the last four decades, the paradigm shifts of multiple access techniques have been the key milestones of the evolution of cellular networks. In particular, time division multiple access (TDMA) and frequency division multiple access (FDMA) have been used in the first and second generations of mobile networks. The third generation of cellular networks are based on code division multiple access (CDMA), and the currently being deployed fourth generation (4G) is based on orthogonal frequency-division multiple access (OFDMA).

5G mobile networks are expected to support 1000 times higher wireless area capacity and more diversified broadband service than 4G networks. One promising solution to keep the pace with such exponential growth of 5G traffic and combat the phenomenon of spectrum crunch is to develop more spectrum and energy efficient multiple access techniques for future generations of mobile networks. Most existing multiple access techniques were designed to ensure the orthogonality between the channels allocated to different users, in order to avoid co-channel interference. However, such orthogonal multiple access can potentially reduce spectral efficiency. For example, one frequency channel allocated to one user based on FDMA cannot be accessed by other users, even if this channel is not fully utilized by the admitted user. Motivated by this, a few non-orthogonal multiple access techniques have been recently proposed.

NOMA, power domain non-orthogonal multiple access[15], can efficiently improve spectrum efficiency by opportunistically exploiting a users' channel condition. The idea of NOMA can be simply described using the following example. Consider a cell with one base station (BS) and two users, A and B. Without loss of generality, User A has a better connection to the BS than B. The key idea of NOMA is to serve both users at the same time/code/frequency channel, and the signal transmitted by the BS is a superposition of the two users' signals, where the user B's signal is put on a higher power level. User B will simply treat User A's signal as noise and decode its own signal. Successive interference cancellation (SIC) will be carried out at User A which will decode User B's signal first and then decode its own information after subtracting User B's signal from the observation. If conventional orthogonal multiple access techniques are used, no one else can be admitted to the channel allocated to User B, even though User B cannot fully use this channel due to its poor connection the BS. The benefit of using NOMA is that the bandwidth resource allocated to the users whose channel conditions are poor is released to other users.

The benefit for using NOMA can be alternatively explained by viewing NOMA as a special case of cognitive radio (CR) networks. Particularly User B can be viewed as a primary user in CR networks. Because of the use of NOMA, User A is admitted to the same channel as User B. With careful power allocation, it can be ensured that admitting User A will not cause too much performance degradation for User B, but the superior channel condition between User A and the BS ensures that the spectral efficiency can be improved significantly. NOMA can also be combined with conventional orthogonal multiple access schemes. For example, users in one cell can be divided into multiple clusters, where NOMA is implemented within each cluster and conventional multiple access can be used among the multiple cluster.

SCMA, sparse code multiple access, provides an alternative to implementing non-orthogonal multiple access. Particularly a SCMA encoder maps each user's information to a K-dimension codebook, and each codeword has a small number of non-zero entries. Similar to NOMA, SCMA is naturally complimentary to OFDMA, where SCMA codewords are multiplexed over K orthogonal subcarriers. When the number of non-zero entries in each codeword is much smaller than K, i.e., the codebook is sparse, SCMA can serve more than K users simultaneously over K orthogonal subcarriers. SCMA naturally combines forward error correction coding, modulation, with multiplexing,

[15] Newly proposed coding strategy, Source: Zhiguo Ding; Zheng Yang; Pingzhi Fan; Poor, H.V., "On the Performance of Non-Orthogonal Multiple Access in 5G Systems with Randomly Deployed Users," Signal Processing Letters, IEEE , vol.21, no.12, pp.1501,1505, Dec. 2014 doi: 10.1109/LSP.2014.2343971 Globalnet News April 30 2015
http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6868214&isnumber=6866947 and
http://www.rfglobalnet.com/doc/moving-to-the-next-generation-in-wireless-technology-0001

where advanced encoding/decoding algorithms based on LDPC and lattice have been proposed. In addition to its superior spectral efficiency, SCMA also yields low signalling overhead, low delay, and support of massive connectivity.

	Domains used for MA	Open Loop	Compatibility with existing MA	Rate gain over OFDMA	Support to high order modulation	Resilient to high mobility
NOMA	Power	Partial	Yes	Positive	Yes	Yes
SCMA	Frequency -time-code	yes	Partial	Positive	Yes	Yes

In addition to those newly developed multiple access techniques, like NOMA and SCMA, **OFDMA** has also been identified as a potential multiple access candidate in 5G networks because of its superior resilience to inter-symbol interference, a challenging issue in broadband mobile networks. However the use of conventional Fourier transform might not be sufficient to support the high system throughput expected for 5G, and there have been a huge amount of efforts to find new waveforms. For example, generalized frequency division multiplexing (GFDM) has been proposed to efficiently supress the peak-to-average power ratio, an issue which has limited the application of conventional OFDM in 5G systems. In addition, GFDM is also particularly useful for the scenario with spectrum fragmentation, a feature which further improves the spectral efficiency of 5G networks.

Filter Bank Multicarrier (FBMC) is another waveform which is being considered due to the fact that conventional OFDM requires the use of cyclic prefixing (CP). While the use of a CP removes inter-symbol interference (ISI) between OFDM symbols, it also reduces spectral efficiency. The key feature of FBMC is to keep the advantages of conventional OFDM without using CP, by applying advanced filter bank techniques. It must be noted that FBMC offers advantages in other areas, including good sidelobe performance. However, further research is recommended with respect to MIMO implementations, as it has long filters that make it inefficient with short messages. Because of this, Universal-Filtered OFDM (UF-OFDM), also known as Universal Filtered Multi-Carrier (UFMC) is being considered to address the limitations of FBMC such as long filter challenges, use of MIMO and Coordinated Multipoint (CoMP).

4.2 Radio technology options and building blocks > 6GHz

A key requirement for 5G mobile is the addition of a new gigabit rate capable air interface. The use of millimetre wave spectrum to deliver these data rates is seen as being very attractive due to large amounts of bandwidth available and the ability to re-use the spectrum through natural (free space, rain and oxygen) propagation losses and the use of directional antennas (combined with electronic beamforming). The use of millimetre wave for communications is not, however, new and many established systems are currently operating in these bands – typically deployed as point to point communications links using high gain (>30 dBi) fixed antennas. The technology used in these solutions would not be fit for purpose for direct transfer into mobile applications, due to the increased complexity for mobile use, smaller form factor and associated integration to achieve the cost, size, performance and power consumption required. However, wireless technologies are already emerging which are reaching the necessary power, cost and performance requirements for mobile devices, therefore providing the economies of scale. The Wi-Fi Alliance is currently working on launching 'WiGig certified' products, based on the IEEE 802.11ad standard. This operates over 4 x 1.76 GHz channels in the 57 – 64 GHz band and is specified to deliver data rates of between 1 and 7 Gbps over ranges of 10 – 20 m (depending on the radio configuration). Moreover, the use of beamforming is enshrined within the standard thus allowing implementers great flexibility to provide innovative solutions around antenna, transceiver and baseband technologies. Pre-certified products are available today (e.g. from Qualcomm – Wilocity) and the Wi-Fi Alliance currently projects that the 'WiGig Certified' interoperability programme will be complete by H2 2016. This wireless technology will drive the economies of scale and set the scene for adaptions and extensions to meet the needs of 5G mobile.

Mention should also be made about the two main classes of applications for millimetre wave wireless in the context of 5G as follows:

1) Mobile applications

Integration of millimetre wave wireless within user devices to provide complementary gigabit rate access to current and emerging LTE and Wi-Fi (e.g. 802.11ac) technologies. Typical data rates in the region of 1-4 Gbps with power consumption requirements of 100 – 200 pJ/bit and volume chipset costs measured in the $10's maximum. This is the market targeted by the Wi-Fi Alliance with their 'WiGig certified' program and where projections of additional volumes of up to 1B units are over current Wi-Fi chipset volumes of 2B units in the timeframe 2017-18.

2) Infrastructure applications

A key Infrastructure consideration is the need for wireless backhaul of data rates from 100 to 1000MBps over ranges of 100 to 300m from LTE base stations to the core network – for example for use within small cells. Network densification, particularly in fast growing urban areas in emerging economies such as India and China, is driving the need for cost effective gigabit rate backhaul solutions. Current back haul solutions operating in V band (60 GHz) and E band (70/80 GHz) are considered as good innovation opportunities to reduce size and cost to make them more attractive for larger scale deployments (Mu's). Hence there is an opportunity to adapt the WiGig derived technologies for mobile applications for extended range operation for this application in the above mentioned markets.

The following areas summarise the key challenges for technology and standards applicable to the use of millimetre wave wireless for 5G mobile applications.

4.2.1 Choice of Frequency bands – leveraging existing technology

Spectrum is discussed in more detail elsewhere in this document but an example of 'leveraging' opportunities relating to the high bandwidth millimetre wave frequencies is in the range 66-71 GHz (just above the band specified for 802.11ad). This offers the potential for simple adaption of radio technologies designed for WiGig mobile applications (57 – 64 GHz) which would leverage ongoing investment in the development of RF semiconductors for this market. Other options at E band and W band are also of interest for 'lightly licensed' applications aimed at infrastructure. The 66 -71 GHz band was one of three bands mentioned as being worthy of further consideration for 5G in the recent consultation from OFCOM[16] and was one of the options proposed by the FCC in their ROI (FCC 14-154) dated October 2014. Other bands under consideration are outlined in more detail elsewhere in this document.

4.2.2 Propagation modelling and measurement

Typical outdoor operation at millimetre wave frequencies use near Line of Sight (LoS) conditions rather than traditional mobile operation at ~2 GHz where non-LoS operation dominates. Rician channel models, where LoS propagation combines with non-LoS multipath, is typical and the parameters (k factor and delay spread) are key parameters in designing optimised PHY interfaces. In addition, frequency re-use of channels for increased capacity and interference avoidance require accurate propagation prediction tools which can account for complex propagation conditions in urban environments. As networks move to self-optimisation these techniques and associated research will be essential in helping to inform and develop the algorithms required to operate in this the real time dynamic mode required. Such tools need to be based on ray tracing methods and also need accurate models for reflection and absorption from a wide range of materials such as glass, concrete, wood and of course vegetation. Models also need to account for frequency dispersion caused by mobility. Finally, these tools also need to allow for a wide range of (phased array and fixed gain) antenna specifications as this has a major impact on channel conditions. Tools are beginning to emerge but more work is needed on propagation measurements and optimised (cloud based) computing to increase the integration with geo-mapping databases (e.g. Google Maps), accuracy of channel estimation and computing efficiency of tools.

4.2.3 User Equipment Antenna Design for mm-Wave Bands

This is a key consideration as the antenna design will dominate radio link budget and physical size of the user equipment. It is accepted that active phased array antennas[17] may offer benefits of conformal design and small size compared to traditional fixed antenna structures. Typical design rules for a phased array includes spacing an array of antenna

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[16] Laying the foundations for next generation mobile services: Update on bands above 6 GHz http://stakeholders.ofcom.org.uk/consultations/above-6ghz/update-apr15/

[17] (A phased array is composed of a set of antenna elements, signals to which are fed directly and phased in order to collectively form an overall and potentially variable antenna pattern

elements by half wavelength spacing (wavelength of 10mm at 30 GHz or 5mm at 60 GHz) in 1 or 2 dimensional arrays. Assuming array sizes ranging from 4 elements through to 16 or even 32 elements for mobile devices up to laptop sizes will be required, an array may vary in size from 10 x10mm for a 2x2 array at 30 GHz or 5x5mm at 60 GHz through to 10x10mm for a 4x4 16 element array at 60 GHz. The later array configuration delivers antenna gain in the region of 12-14 dBi and half-power beam width (HPBW) of 30 degrees in elevation and azimuth. For infrastructure applications increased gain of >+20 dBi require larger arrays or optimised antenna element design to deliver the system link budget needed for extended range operation over 100m.

4.2.4 Radio Transceiver

The rapid development of deep sub-micron CMOS and SiGe BiCMOS semiconductor technologies has seen the introduction of complex single chip phased array transceivers which combine up to 16 Tx and Rx chains, RF beamformers, low phase noise synthesis and baseband analog processing compatible with delivering ~2 GHz wide channels with Tx output levels of typically +10 dBm per PA and Rx noise figures of +6 dB per Rx LNA. Several manufacturers (notably Si Beam, IBM, Intel, Qualcomm, Samsung) have such devices in production today operating in the 60 GHz band.

While Si based transceiver chips operating in the E Band and even W band are emerging there remains a substantial performance gap compared to traditional transceivers based on GaAs technologies. In short range E band applications Si/SiGe transceiver chips may offer cost effective performance with phase noise compatible with 64QAM operation but for carrier grade backhaul links of greater than 1km they must be used in conjunction with external GaAs Power Amplifiers, LNAs and VCOs.

This is an area of innovation requiring $100M's of investment and one that is dominated by Tier 1 Semiconductor and well-funded fabless semiconductor companies. Therefore, large investment instruments through venture capital and/or Government funding would be required for UK companies to be able to make a major impact.

However, an area where UK companies can make an impact is in 5G backhaul which will see a huge increase in capacity which can be addressed by moving to even higher frequencies. This will present UK companies opportunities to develop MMICs[18] and transceivers for these bands, opening up new innovation opportunities for 5G 92GHz to TeraHz Backhaul[19].

Higher frequency mm Wave bands under consideration for back haul include 92GHz to 134GHz, 141 to 175GHz and 192 to 275GHz to support data rates up to 40Gbps.

4.2.5 Baseband processing

Baseband PHY and MAC design for the delivery of 1-10 Gbps of wireless data rate requires Teraops of real time signal processing and packet processing. Current implementations lean

[18] MMIC - Monolithic Microwave Integrated Circuit

[19] TeraHz Backhaul – Innovation opportunities working up to 1THz

heavily on either FPGA implementation (high cost and power) for infrastructure applications or dedicated custom hardware SoC for cost & power optimised mobile applications (e.g. for WiGig handset applications). 5G applications for millimetre wave are expected to demand more flexibility than the latter and lower cost and power than the former in order to deliver adaptable platforms capable of both infrastructure and mobile applications. This suggests a combination of parallel processing, vector signal processing and hardware acceleration - targeted at deep sub-micron (40, 28 nm or below) nodes with the ability for software re-configuration for application optimisation. The addition of MIMO based methods and channel bonding as being considered for extended data rate operation above 10 Gbps (see below) further compound the challenge. This is an area where the UK's skill base in wireless system design, digital signal processing and parallel processor design can create significant value – particularly when leveraged with advanced high level integrated circuit CAD design tools (C to Silicon) and partnerships with international semiconductor suppliers. This is the value added proposition from Blu Wireless Technology where its HYDRA PHY/MAC technology allows application scalability from mobile through to complex infrastructure applications.

4.2.6 Technology example – 60GHz Blu Wireless Modem

An example of a millimetre wave platform, designed for street level outdoor operation, is the 'Lightning' 60 GHz wireless modem from Blu Wireless Technology. This is a demonstrator grade evaluation platform based on Blu Wireless's HYDRA PHY/MAC technology integrated within the PHY1 SoC which is based on the IEEE 802.11ad TDD wireless standard together with several extensions for optimised operation in outdoor conditions. A 60 GHz active phased array antenna is used to deliver electronic beam steering with 2x12 element antenna arrays for transmit and receive operation. Several channel bandwidths are provided up to the full 802.11ad channel width of 1760 MHz are supported with typical ranges of >200m at 1 Gbps. The platform also includes a programmable FPGA engine for MAC and a LINUX based embedded controller and is designed to software upgradable in the field. GPS for location detection and Bluetooth for remote control and software upload is also provided. A network of 'Lightning' modules is currently being deployed as part of the 'Bristol is Open' project and is expected to report first results by the end of 2015. Notably, a key objective of this project is to explore open source SDN methods based on 'Openflow' and therefore the 'Lightning' module will support an Openflow client for SDN control. The 'Lightning' module is mounted in a weather proof enclosure of size 400x140x50mm. Further development is under way to increase integration levels with a production ready version planned for release in 2016 with approximately 20% of this size. Looking ahead to 5G this software defined platform will be used to explore various scenarios for 5G millimetre wave operation.

Figure 5 –
60GHz Blu Wireless Modem

4.2.7 Technology example – 60GHz Wi-Fi capable of 4.6Gbps

Samsung has already tested 5G systems at circa 61 GHz. Samsung developed 60 GHz Wi-Fi capable of 4.6Gbps entering the 60GHz 802.11ad Wi-Fi development. Samsung says it has a commercialized version of 60GHz Wi-Fi (aka WiGig) that's capable of 4.6Gbps, or 575 megabytes per second — about five times faster than current dual-stream 802.11ac devices, or fast enough to download a movie in a couple of seconds. Samsung says the first devices supporting its 60GHz Wi-Fi tech will be available in 2015[20].

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[20] http://www.extremetech.com/computing/191872-samsung-develops-60ghz-Wi-Fi-capable-of-4-6gbps-will-be-in-devices-next-year

4.2.8 Technology example – 71-76/81-86GHz Filtronic Transceiver Module

Examples of E-band transceiver modules designed for deployment within high capacity backhaul links are the Theseus and Orpheus modules from Filtronic Broadband. These are carrier grade transmit / receiver modules incorporating integrated no tune diplexers together with differential IQ interface, direct conversion chipsets and an on board microcontroller - simplifying integration between the modem and antenna. The low phase noise, wide-band architecture means that these modules could support >10Gbps in 2GHz channels at 128/256QAM modulation, once modems have been developed sufficiently to support wider bandwidths. Theseus is Filtronic's second generation module released last year, with significant quantities now deployed in the field for multi-gigabit applications. Filtronic have a reference link employing Theseus already demonstrating 3.2Gbps in 500MHz channels. Orpheus is the third generation product due for release later this year, incorporating a simplified receive architecture and smaller, lower cost mechanical construction. Roadmap development of the platform, including MMIC redesign by Filtronic's MMIC team, is planned in order to keep pace with both the commercial and technological pressures dictated by this demanding market.

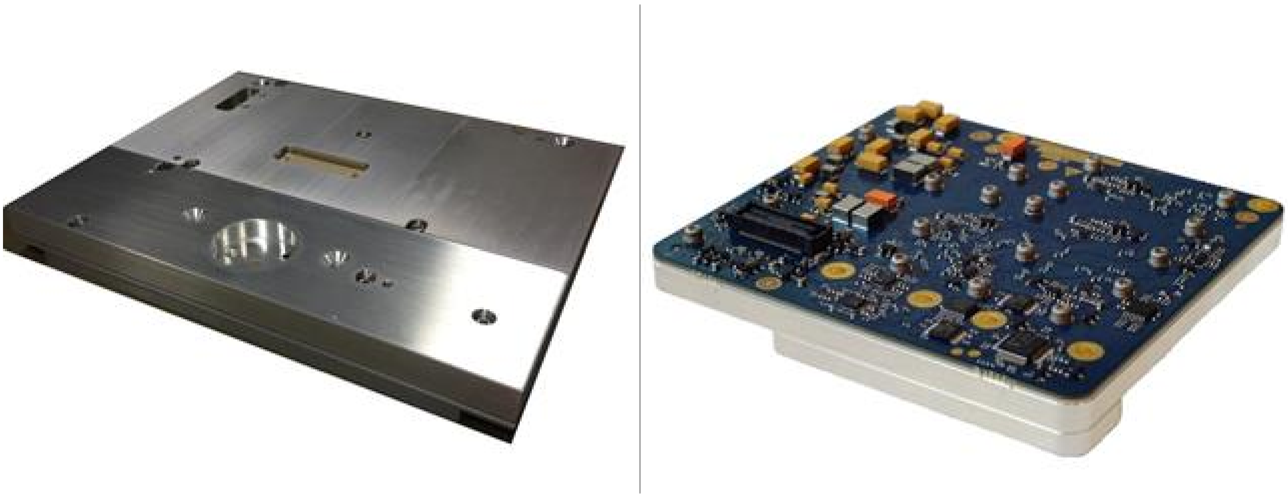


Figure 6 - Filtronic E-band modules (Theseus on left, Orpheus on right)

4.3 Radio technology options and building blocks – non Frequency Specific

4.3.1 Power Amplifier (PA) Architectures[21]

Wideband PA architectures are good candidates for sub-6GHz band for 5G due to the complex frequency-space slicing that has evolved over several decades of wireless communication standards evolution. Despite this, fixed channel multi-band architectures currently offer higher performances in term of efficiency, since these customised architectures align well with specific frequencies on a per country/continent basis. However, wideband PA designs are likely to offer the most efficient solution for dynamic inter-band carrier aggregation.

A wideband PA consist of the PA and associated baseband and up-conversion blocks. The chosen topology will depend on the amount of signal processing involved to compensate for the nonlinear behaviour of the PA. One architecture, presented below, shows a wideband transmitter composed of a single baseband and up-conversion block.

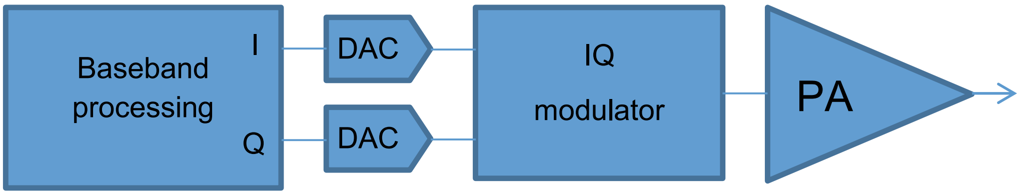


Figure 7 - Wideband transmitter architecture

Multiple design challenges exist within each of the blocks within the figure above. Firstly, new nonlinearity compensation algorithms are required to cancel out the PA nonlinear behaviour in the presence of wideband signals (more than a GHz bandwidth). This requires substantial new research in the field of microwave instrumentation to characterise PA nonlinear behaviour in the presence of wideband signals. Compensating for the nonlinear behaviour of PAs in the presence of wideband signals from the baseband is also challenging. Some analogue linearisation schemes will have to be considered and future linearisation methods are likely to be of hybrid type, i.e. digital baseband and analogue RF based.

[21] PA Architecture Research, Dr Souheil Ben Smida, University of Bristol

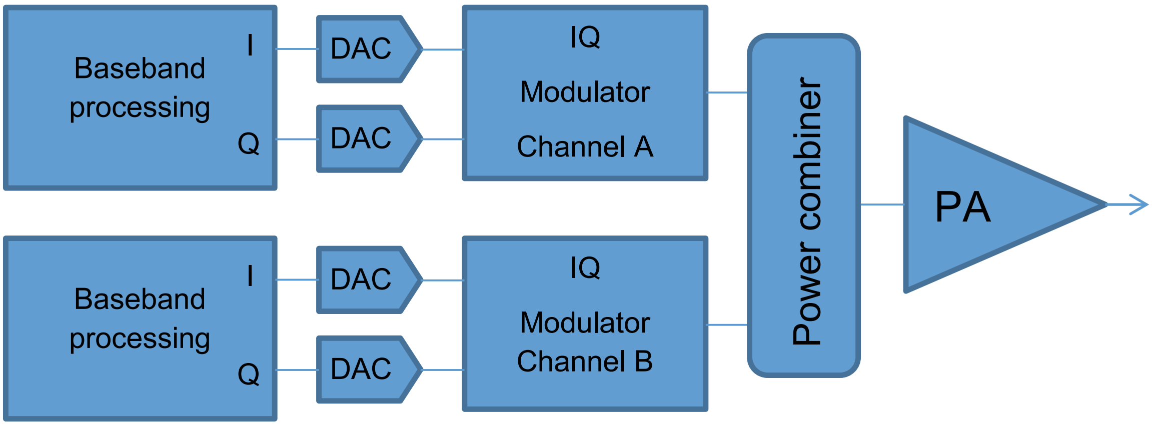


Figure 8 - Multi-band baseband topology with wideband PA architecture

In an inter-band carrier aggregation scenario, the architecture shown above is a possible candidate when a single wideband PA is used.

New linearization algorithms are currently being developed to cancel out the PA nonlinear behaviour when 2 or 3 waveforms (carriers) at different frequency bands are concurrently driving the PA. Future work in this area requires the development of highly efficient, and hence realistically implementable, algorithms in the baseband domain. In this context, the diplexer/triplexer block (not shown here) will present challenges and might become the new 'bottleneck' for wide-band and multi-band transceivers architectures.

PA architectures that are currently being considered can be divided into two categories. The first consists of classic architectures such as Linear amplification using nonlinear components (LINC), Doherty and envelope tracking (ET). The second, consists of digital architectures such as Sigma-Delta architectures. Both approaches present advantages but not able to provide the specifications required by 5G in terms of bandwidth, efficiency and linearity. Therefore, ambitious research needs to be done to come up with innovative solutions. One direction, could be a hybrid solution that combines analogue and digital principles to perform the amplification. In addition, further work and research with respect to RF Power DAC[22] technology could offer future alternatives and hence recommended as an area for further work.

More than ever, PA designers will have to explore the surrounding building blocks of the PA transmitter architectures and get used to a holistic design approach to come up with appropriate solutions. In addition, due to the increased complexity the nature of these amplifiers will require innovative thinking to develop new verification and testing methods.

[22] RF Power DAC, Radio Frequency Power Digital to Analog conversion

4.3.2 *Massive MIMO*[23]

Massive MIMO, with base-station or access point deployments with >50 antennas and user equipment with a few antennas, represents a fundamental shift in the architecture (hardware and algorithms) of wireless MIMO operation as we strive for the x1000 capacity goals of 5G. In a massive MIMO system, the large antenna array exploits the spatial diversity of the radio channel to allow many terminals to use the same time-frequency resource, simultaneously increasing energy efficiency and reducing the requirements on the RF chains as illustrated in figure below.

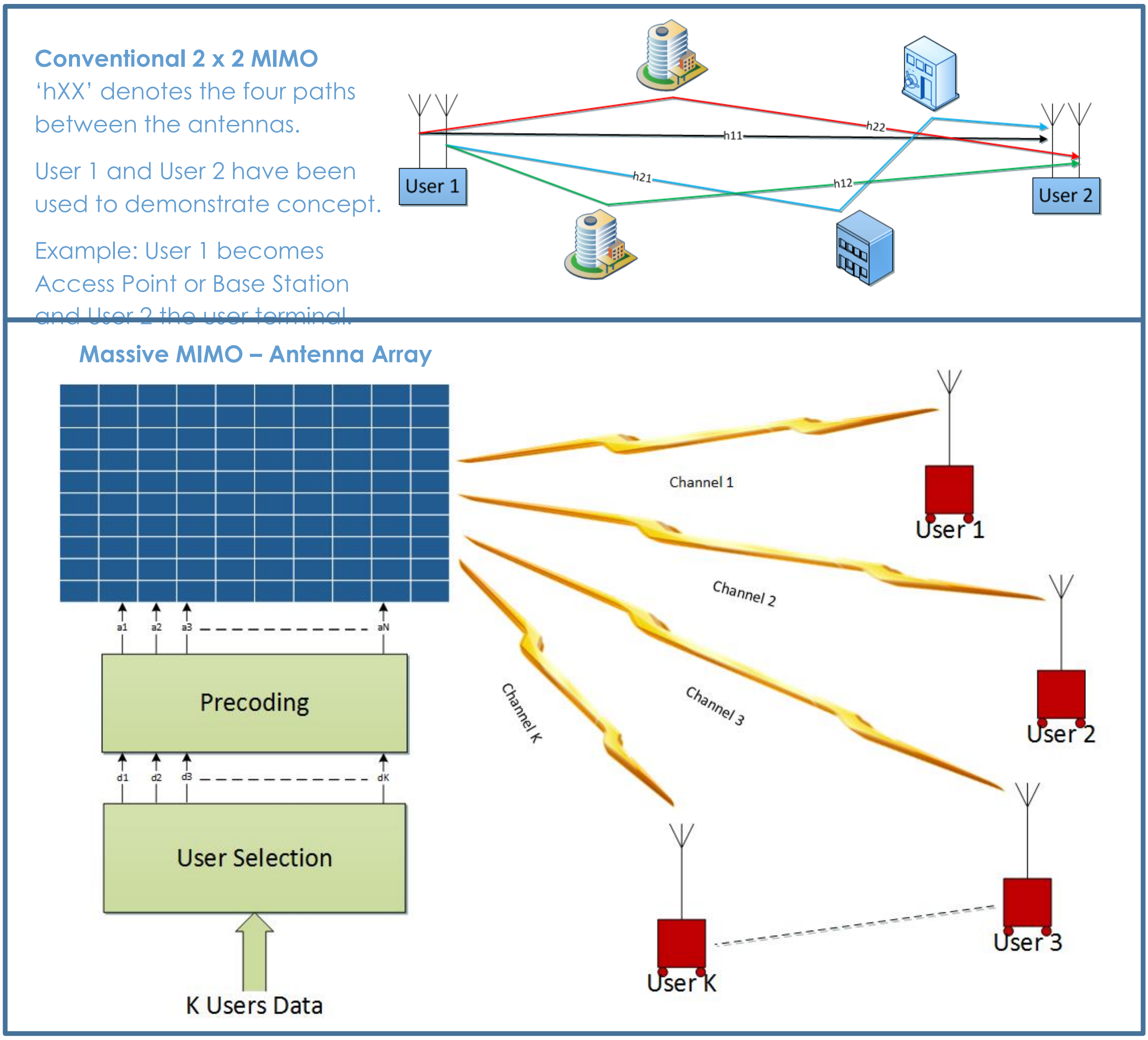
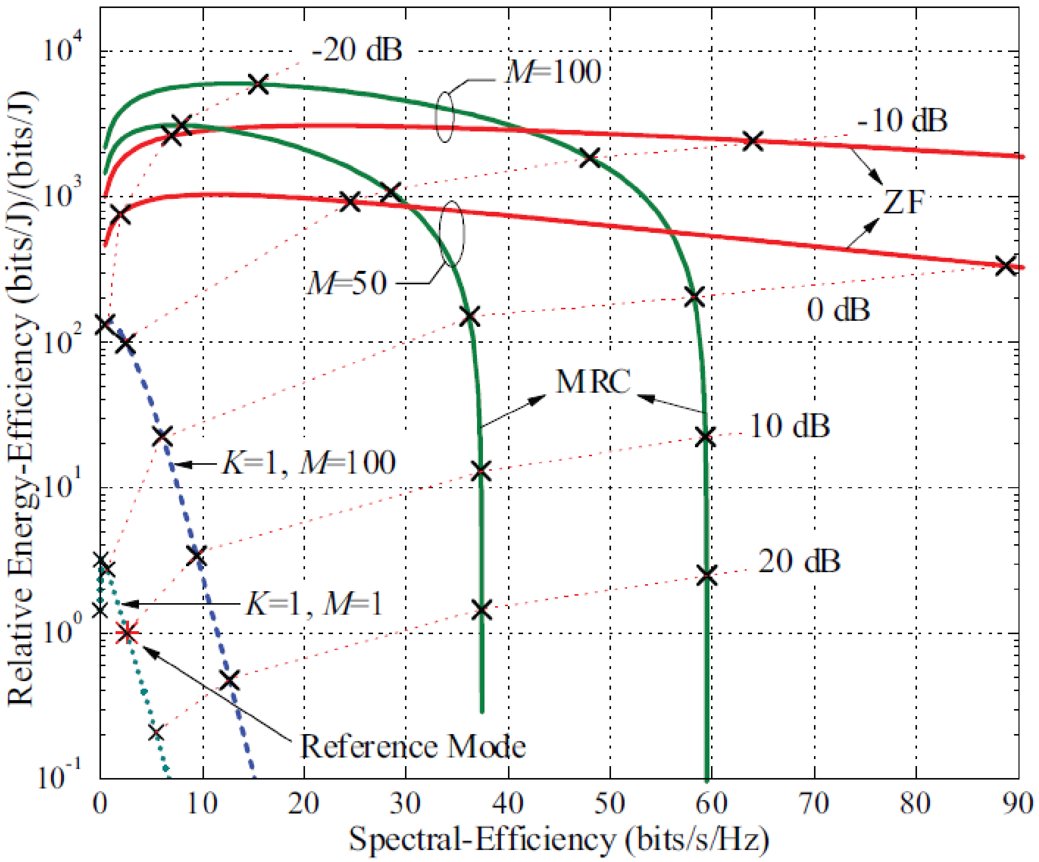


Figure 9 - Top conventional MIMO, below massive MIMO system

A significant body of theoretical analysis has been undertaken to ascertain the potential benefits of massive MIMO, as illustrated in the figures below, illustrating the relative energy-

[23] Massive MIMO research, Paul Harris, University of Bristol

efficiency gains of the approach for two different precoding schemes (red and green curves) compared to a SISO reference (light blue, bottom left). The results indicate a 6-fold increase in spectrum efficiency for the single user case when identical radiated powers are considered, when extended to the multi-user case sum-rate capacities of up to 85 bps/Hz have been reported[24].



ZF = Zero-Forcing and MRC = Maximal Ratio Combining

Figure 10 - Relative Energy Efficiency of conventional and massive MIMO[25]

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[24] C. Shepard, H. Yu, N. Anand, E. Li, T. Marzetta, R. Yang, and L. Zhong, "Argos: practical many-antenna base stations," in Proceedings of the 18th annual international conference on Mobile computing and networking - Mobicom '12, 2012, no. i, p. 53.

[25] E. G. Larsson and T. L. Marzetta, "Energy and Spectral Efficiency of Very Large Multiuser MIMO Systems," *IEEE Trans. Commun.*, vol. 61, no. 4, pp. 1436–1449, Apr. 2013.

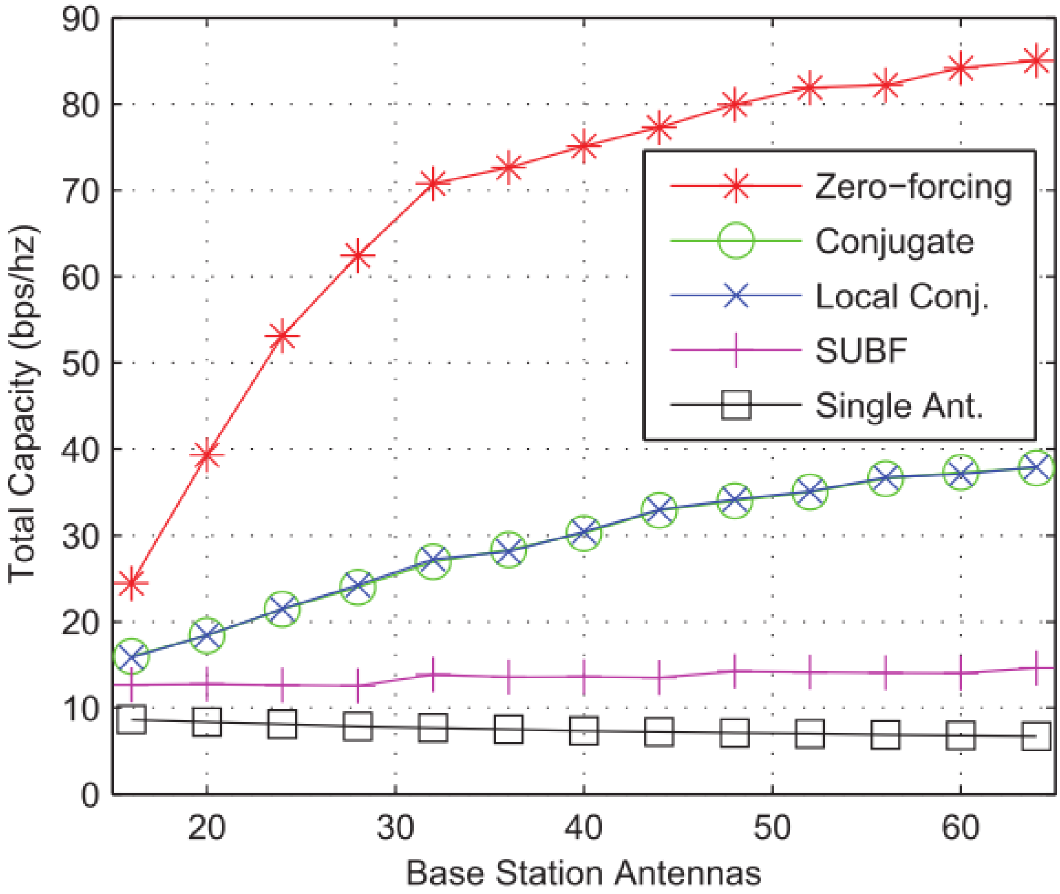

Figure 11 - Sum-rate capacity for BS antenna numbers with different precoding[26], single antenna case shown for reference.

There is now a significant body of activity to take the massive MIMO concept and demonstrate the practical viability as well as addressing the known research challenges. The table below provides a summary of the currently known test beds.

[26] C. Shepard, H. Yu, N. Anand, E. Li, T. Marzetta, R. Yang, and L. Zhong, "Argos: practical many-antenna base stations," in *Proceedings of the 18th annual international conference on Mobile computing and networking - Mobicom '12*, 2012, no. i, p. 53.

Organisation	Configuration	Hardware	Notes
University of Bristol, National Instruments	128 antennas dual-polar patch antennas in 4x 32 element subsystems. Centralised and distributed FPGA processing. Up to 20 UEs. 3.5 GHz. TDD.	National Instruments PXIe, FGPA and USRP RIOs. Octoclock synchronisation.	This system builds upon the work done by Lund University and is designed to be inherently distributable.
Lund University, National Instruments	100 dual-polar patch antennas with both centralised and distributed FPGA processing. Up to 10 s. 3.7 GHz. TDD.	National Instruments PXIe, FGPA and USRP RIOs. Octoclock synchronisation.	Built with COTS NI hardware. Uses a LabVIEW software framework[27].
Nutaq's Titan MIMO	100x100 SISO links.	Perseus 6111 AMC FPGA cards, Xilinx Aurora-4x high speed serial interface.	A focus on OTA (over the air) RF to baseband processing rates and throughput. Total system throughput of 256 Gbps[28].
Rice University's Argos System	64 antennas, 15 clients. 2.4 GHz TDD.	WARP boards, Maxim 2829 transceiver, MATLAB Framework	85 bps/Hz sum-rates reported. Modular and scalable.
Commonwealth Scientific and Industrial Research Organisation (CSIRO) - Ngara	32 vertically polarised dipole antennas, 14-18 users. FDD – 638 MHz & 806 MHz.	Xilinx Virtex 6 FPGAs, VLX240T RF front ends.	Symmetric 50 Mb/s uplink and downlink for at least 12 simultaneous users[29].

Table: Known massive MIMO testbeds

The University of Bristol massive MIMO testbed shown in the figure below is the only known prototype of the technology within the UK and one of a select few worldwide. Using the same COTS hardware as the Lund University system through a collaboration with National Instruments, it can operate with up to 128 antenna elements and has the ability to perform

[27] E. Luther, S. Product, and M. Manager, "5G Massive MIMO Testbed : From Theory to Reality," 2014.

[28] M. Brown and M. Turgeon, "TitanMIMO," 2014.

[29] H. Suzuki, R. Kendall, K. Anderson, A. Grancea, D. Humphrey, J. Pathikulangara, K. Bengston, J. Matthews, and C. Russell, "Highly spectrally efficient Ngara Rural Wireless Broadband Access Demonstrator," in *2012 International Symposium on Communications and Information Technologies, ISCIT 2012*, 2012, pp. 914–919.

both distributed and centralised hardware processing using FPGAs. The hardware is all programmed using National Instruments' LabVIEW graphical programming language which should provide a solid framework for other researchers to build upon. As part of the Bristol is Open (BIO) programmable city testbed, it will ultimately be linked to the existing fibre optic network in Bristol, which is seen to be an enabler for distribution of the base station into four constituent nodes. Distributed massive MIMO has yet to be explored in great depth and could offer a more feasible deployment strategy for the technology, so enabling practical research to be conducted is an important role for this system.

The University of Bristol massive MIMO testbed is the only known prototype of the technology within the UK and one of a select few worldwide.

Figure 12 - University of Bristol Massive MIMO Testbed

4.3.2.1 Massive MIMO frequency considerations

Massive MIMO includes 2D Beamforming (or classic Beamforming, i.e. creating a beam in a particular angular direction) and 3D Beamforming (or Full Dimension Beamforning, i.e. creating a particular location of coherence or incoherence in 3D space by exploitation of the multipath radio channel). For mm-Wave bands, where increased spectrum bandwidth is available to serve capacity needs, but where LOS dominates / is required, 2D beamforming for example allows the required gain to be developed for the link budget. At sub 6GHz however where non-LOS, rich scattering propagation dominates then 3D Beamforming promises huge gains in spectral efficiency.

4.3.3 Filter technologies[30]

RF Filters remain a significant constraint on radio system design in cellular base stations, though there have been innovations such as multi-channel power amplifiers which have removed the need for large resonant combiners. However, the complexity of the RF system has increased with the requirement for aspects such as MIMO transmit and receive, support for multiple RATs and operators, adaptive down-tilt and so on, and this in turn has increased the filtering requirements. At the same time the radio unit has become smaller and moved to the masthead, and so the filters have to move too. Filter size does not scale in the same way as the other electronics and thus the size and weight of the filters is a larger proportion of the overall masthead system. There are no apparent breakthroughs that will change this and a significant increase in research and development is required to address this challenge.

In handsets, over the past 5 years the need to build multiple bands into LTE user equipment has led to higher levels of integration as vendors that can supply PAs, switches and filters integrate all of these components on to a single substrate. This also allows optimum matching of the components, without needing conversions from and to 50 ohms, which reduces loss/increases efficiency. At the same time in an example the PCB area needed decreased by more than 5:1 for a 6-band front end. In addition to "brute force integration" new approaches are being investigated such as tuneable SAW filters diplexed with new types of surface mount technology (SMT) circulators; and novel duplexing methods using for example hybrid junctions with adaptive impedance tuning and active cancellation. Challenges remain such as the need for multiplexing networks for uplink MIMO and carrier aggregation, and the passive intermodulation products that result. Looking at 5G specifically presents a whole new set of filter problems, not yet thought about, for example:

- Massive MIMO (128 active antennas) is a big challenge (e.g. integration)
- 5G and Massive MIMO at higher (mmWave) bands likely to be TDD; therefore the duplexing filter challenge goes away and therefore do we need any filtering at mmWave?
- 5G FDD, if active signal cancellation is achievable then the FDD duplexer problem reduces

[30] Information generated at 8th June 2015 FTN Radio Group workshop. For further information please contact stuart.revell@rtacs.com or

4.3.4 Full Duplex[31]

A long held assumption in wireless communications is that it is not possible to transmit and receive on the same frequency at the same time, due to the Interference resulting from one's own transmission. This *self-interference* is typically many orders of magnitude large than the receive signal. For example, for a 4G cellular handset, with a transmit power of 23dBm and sensitivity of -95dBm, we would require 23dBm – (-95dBm) = 118dB of self-interference suppression to reduce the self-interference to the same level as the noise floor. This requirement for extremely high transmit-to-receive isolation poses significant technical challenges.

Current radio systems simply avoid the problem of self-interference. In Time Division Duplexing (TDD), the uplink and downlink channels share the resources separated in time, thus avoiding self-interference altogether. In Frequency Division Duplexing (FDD) systems, self-interference is present, however the duplex frequency separation allows the interference to be supressed through filtering. In a full duplex system, the *same spectral resources* can be utilized for *uplink and downlink,* theoretically doubling spectral efficiency. With full duplex transceivers spectrum access is *virtualised,* TDD is rendered obsolete, and FDD may also be supported without or significantly reduced requirements for filtering.

UK researchers were the first to develop full duplex radio transceiver technology. In the 1980s, Plessey developed "Groundsat": an on-frequency full-duplex man-pack repeater for combat-net radio, and during the 1990s, researchers at Bristol University demonstrated a prototype full-duplex radio handset. In recent years full-duplex has become a hot topic in wireless research, as the processing power available in modern systems makes digital and RF self-interference cancellation feasible in consumer devices.

Full duplex transceivers invariably combine multiple methods to achieve such high levels of isolation. Typically, a full duplex architecture will employ three "layers" of isolation: antenna based isolation, RF domain cancellation, and digital baseband cancellation. Generally speaking, digital self-interference cancellation is well understood, however antenna based techniques and RF domain cancellation remains a challenge. Using separate antennas for transmission and reception (see figure below section - a) is a simple and effective method for obtaining some antenna based isolation, however the isolation is fundamentally limited by the physical separation of the antennas. In infrastructure applications, where relatively large antenna separations are possible, antenna isolation over >70dB has been achieved. However, in mobile device form factors, where antenna separation distance is extremely limited, the performance is much lower, at around 30dB. Single antenna full duplex architectures can exploit circulators to obtain some antenna based isolation (see figure below section - b), although performance is limited by antenna mismatch. A recent development in this field is the *Electrical Balance Duplexer* (see figure below section - c), which has adapted an existing duplexing technology used in wired telegraphy and pre-electronic telephone systems from the early 20th century, and obtains isolation by exploiting balanced signals in hybrid transformers.

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[31] Full Duplex research, Leo Laughlin, University of Bristol

RF domain cancellation methods can be divided in to passive and active methods. Passive cancellation techniques (see figure below section - b) use a tapped portion of the RF transmit signal after the PA, which is processed in the analogue domain to generate a replica of the interference and then subtracted prior to the receiver input. This method has the advantage of cancelling transmitter imperfections, however analogue signal processing is costly, thus limiting the order of filtering which can be applied and hence the accuracy of the cancelling signal. Active cancellation (see figure below section – a &c) uses an additional transmit chain to upconvert a digital baseband cancellation signal to cancel self-interference. Since the cancellation signal is being generated in digital baseband, high order filtering can be readily applied to create an extremely accurate model of the self-interference. However transmitter imperfections are not cancelled by this technique, and cancellation levels are therefore limited by the Error Vector Magnitude (EVM) of the transmit chains.

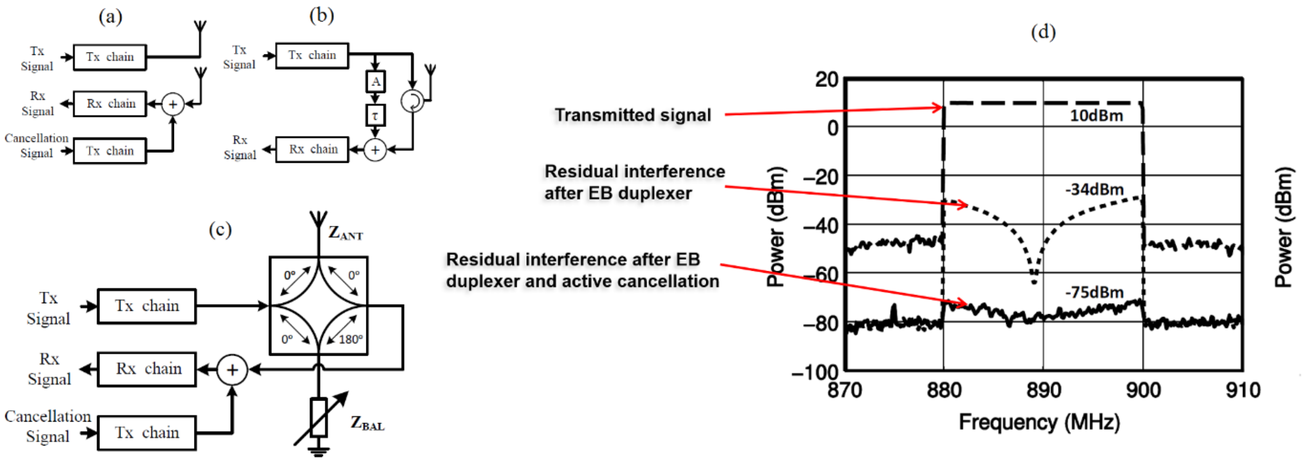

Figure 13 - Full duplex architectures: (a) Antenna separation and active analogue cancellation[32]. (b) circulator and passive analogue cancellation[33]. (c) Electrical balance and active analogue cancellation[34]. (d) Measured isolation of EBAC full duplex architecture[35].

Researchers at the University of Bristol have developed a prototype full-duplex transceiver combining Electrical Balance and Active Cancellation (EBAC), as depicted in figure above section c. The isolation provided by the electrical balance duplexer is determined by how

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[32] Chen, S.; Beach, M.A.; McGeehan, J.P., "Division-free duplex for wireless applications," *Electronics Letters* , vol.34, no.2, pp.147,148, 22 Jan 1998. doi: 10.1049/el:19980022

[33] D. Bharadia, E. McMilin, and S. Katti, "Full Duplex Radios," in Proc. 2013 ACM SIGCOMM, Hong Kong, 2013

[34] Laughlin, L.; Beach, M.A.; Morris, K.A.; Haine, J.L., "Electrical balance duplexing for small form factor realization of in-band full duplex," Communications Magazine, IEEE , vol.53, no.5, pp.102,110, May 2015 .doi: 10.1109/MCOM.2015.7105648

[35] Leo Laughlin, Chunqing Zhang, Mark A. Beach, Kevin A. Morris and John Haine, "A Widely Tunable Full Duplex Transceiver Combining Electrical Balance Isolation and Active Analog Cancellation", IEEE VTC 2015, Glasgow, May 2015

closely a '*balancing impedance*' can mimic the antenna impedance. Since the antenna impedance can vary significantly with frequency, isolation reduces with bandwidth, and this type of duplexer typically provides higher isolation at the centre of the band than at the band edges. However, the electrical balance component is well suited to combination with active cancellation techniques. The Bristol full duplex architecture uses an electrical balance stage to provide approximately 45dB of isolation over a 20MHz bandwidth. The system then measures the residual self-interference at the receiver and generates a cancellation signal using the auxiliary transmitter, providing a total transmit-to-receive isolation of >80dB, as shown in figure above section - d. This architecture requires just one antenna, and can be implemented on-chip, making it a suitable choice for low-cost small form factor mobile devices.

Many technological challenges remain to bring full duplex radio transceiver technology from lab to full commercialised product, covering multiple applications. The cost, complexity and power consumption of current architectures must be reduced before the technology is ready for deployment in handsets, however deployment of full duplex technology in infrastructure applications is feasible with the current technology and some examples are beginning to appear. In this application, basestations could, for example, provide simultaneous access and backhaul in the same frequency band. Many challenges remain in understanding the impact of full-duplex operation at higher layers, and novel protocols are required to efficiently exploit this technology in order to maximise network capacity.

4.4 Core networks, Virtualisation and Software Defined Networks (SDN)

Optimised delivery of gigabit rate data streams over a heterogeneous network comprising a mixture of wired and wireless access mechanisms requires end to end network optimisation at L2 and above. SDN methods are beginning to be deployed in today's mobile systems and have also been extensively deployed in optical based networks. A paradigm shift is required from the use of legacy network systems (based on fixed implementations of IETF RFCs) to a more dynamic and open model as exemplified by the 'Openflow' network architectures. Such an approach offers benefits of increased network control transparency, tighter integration of wireless and wired communication domains and easier upgrade to enable new applications to be dynamically added to 5G networks. This is a particularly exciting area for innovation explored in the sections below.

4.4.1 Topologies

A significant trend emerging in networking that is impacting the mobile networking domain is the re-use of techniques that have been tried and tested in IT/data centre networks. The advantages are separation of the hardware and software domains (by use of virtualisation - NFV) and the more flexible configuration of the network platform by utilisation of software defining (Software Defined Networks – SDN). The trends underpin the new architectural approaches that are emerging in standards now, with the introduction of 5G perhaps impacting the detail of the implementation but not reversing these trends.

Bringing the core to the network edge is a significant trend. Especially as MNOs seek approaches to maximise utilisation of their infrastructure that is deployed to deliver traditional voice and messaging services, with the advent of greater data oriented services the opportunity to bring assets that were traditionally hidden in data centres out over the core to the network edge is compelling.

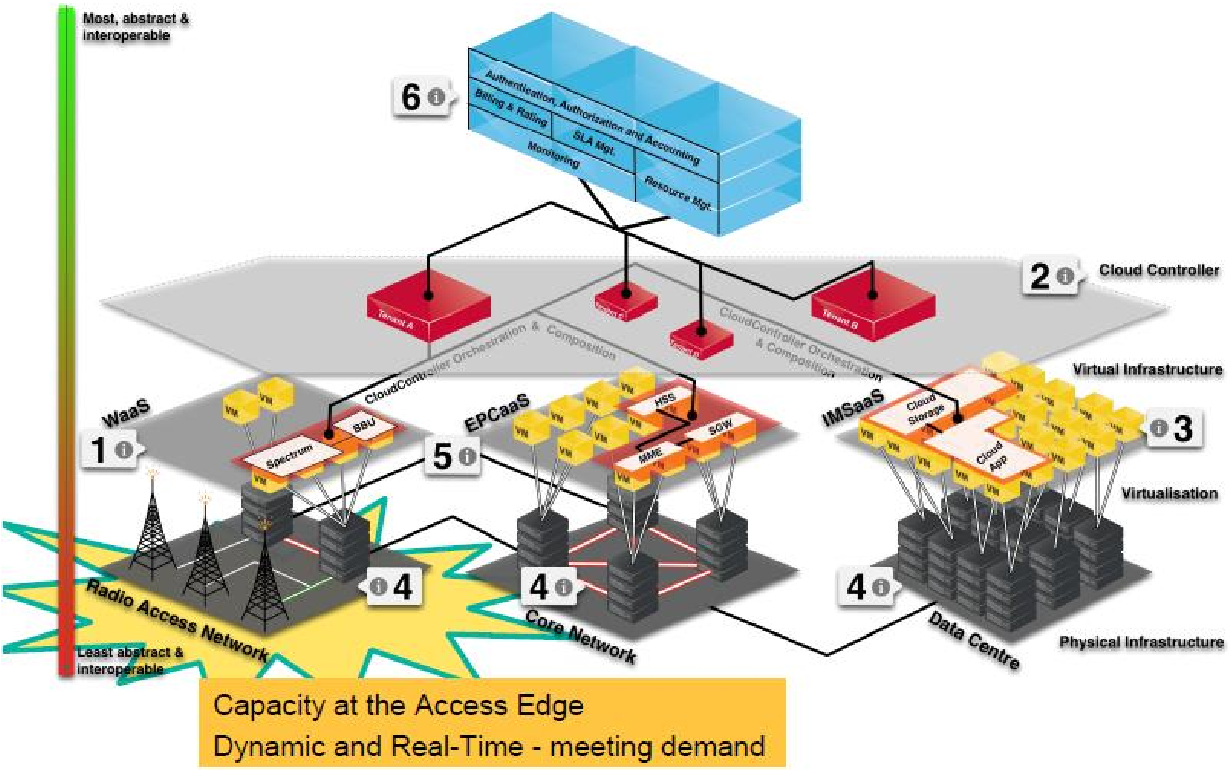

Figure 14 Virtualizing Mobile Networks - Mobile Cloud architectural overview (Source NEC)

4.4.1.1 Edge Computing

The increased interest in particular from the M2M applications domain to be able to reduce the round trip time (“RTT”) of application layer response to end users is resulting in the development of approaches that enable efficient placing of resource close to the network edge. The Over-The-Top architecture with Internet services residing in large data centres breaks down. The resource may be accessed in a dynamic (cloud) and real-time (reduced RTT) way. NFV introduces mechanisms that can be used to dynamically request primitive resources (such as compute and storage) and retain their utility for the delivery of services. These approaches build upon and go beyond classic video Content Distribution Networks (CDN), allowing the insertion of servers into the radio access network architecture enabling network services such as caching and application acceleration.

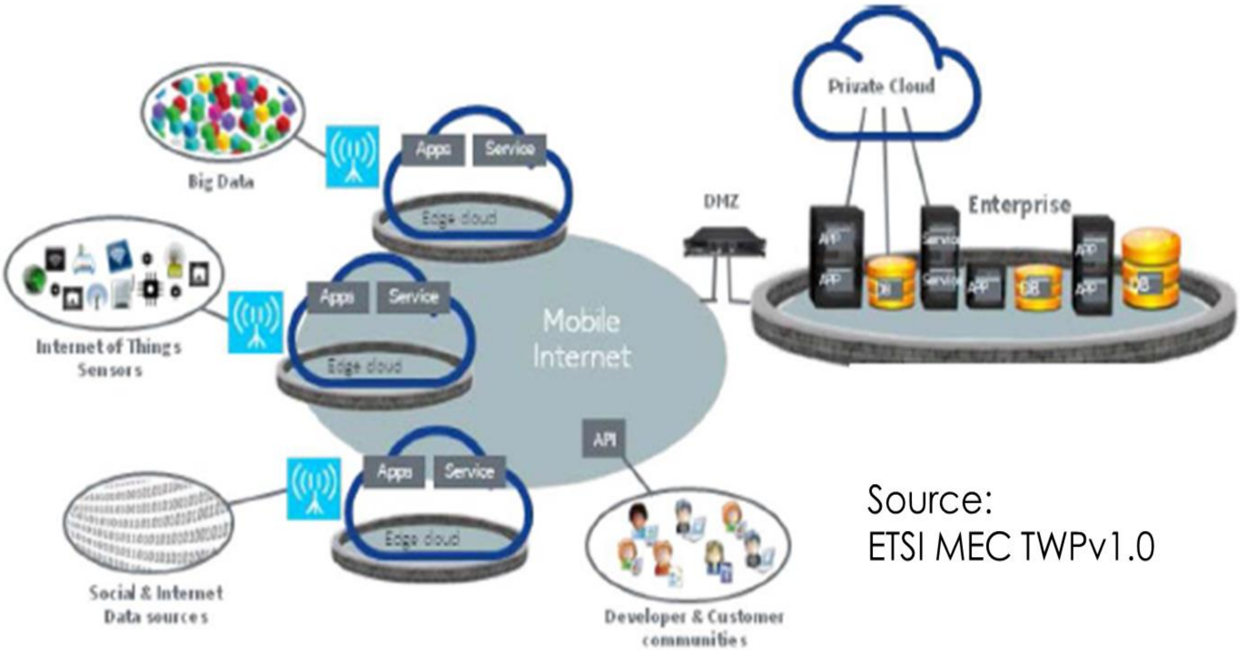

Figure 15 - Edge Compute Availability, starting now and will continue in 2020 Networks

4.4.1.2 Network Slicing

It is now common practice in data centres to slice services end to end booking virtualised resource and allowing the allocation of control and user plane data through separate flows, typically these flows would be centrally configured. As the services move to service mobility (machines and humans) connectivity there is a tendency in the industry to create silos of networking domains. However, the need to share resources across a heterogeneous networking domain in particular when fixed and mobile convergence ("FMC") and BigData are considered. The end users should experience more consistent Quality of Experience ("QoE") across any network and Service providers shall provision networking resources across slices in a much more real-time and dynamic way than is achieved in today's networks.

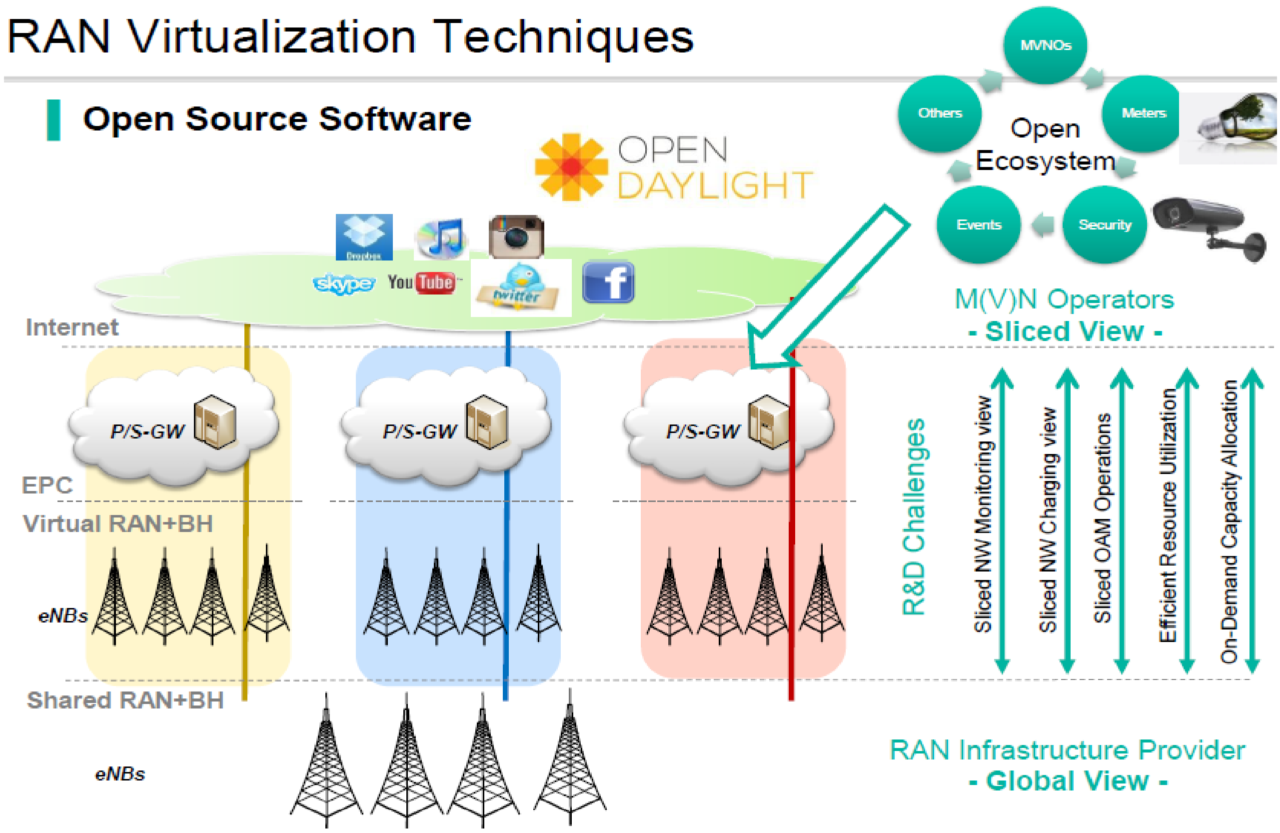

Figure 16 - RAN Virtualisation, Network Slicing (Source NEC)

4.4.1.3 Commoditised Hardware platforms

The drive to achieve lower cost and reduced numbers of hardware variants in switching and data centre blades have resulted in increased competence in the industry to utilise these approaches. The recent recession increased the trend to outsourcing with OEM and ODM approaches being preferred over in-house development of vertical solutions. These trends will continue with white-label platforms being used more and more to provide networking functions.

4.4.1.4 Cloud Architectures

For a number of years the "as a Service" trend has continued with mobile network equipment supporting neutral host deployments and Infrastructure as a Service business models. This trend will continue with Wireless as a Service including virtualisation of the spectrum resource. Each physical domain will support increased virtualisation with Core Networks and Data Centre Infrastructure becoming part of an as-a-Service proposition. More orchestration will be introduced into the network to associate service platforms and billing and service level agreement frameworks in an abstracted and interoperable paradigm.

4.4.1.5 Open Source Software

Two Open Source consortiums have been established in the last 18months that enable Enterprise and Carrier grade OSS distributions using Linus Foundation based approaches. The vision is to create an eco-system of innovation in software defined networking and also pluggable applications for programming of network functionality. These approaches have generally been applied in the core and data centre and now are being explored in the wireless domain.

4.4.1.6 Broadcast convergence

Opportunities to leverage new or evolved air interfaces, common sites, common infrastructure and investigate further convergence across industries such as Content Delivery Networks (CDN) Mobile and Broadcast industries presents new further opportunities for collaborative innovation.

Trials in Japan have shown the efficiency gains that are possible when DTT and Mobile networks have been co-ordinated using common infrastructure for distribution of content. The core networking platform is common to both DTT and mobile enabling inclusion of DTT infrastructure in the mobile experience. Now with the separation of control and user planes the increased flexibility to enable best connect wireless connectivity in a truly heterogeneous networking topology incorporating small cell and high-power high-tower broadcast topologies will be exploited in 5G.

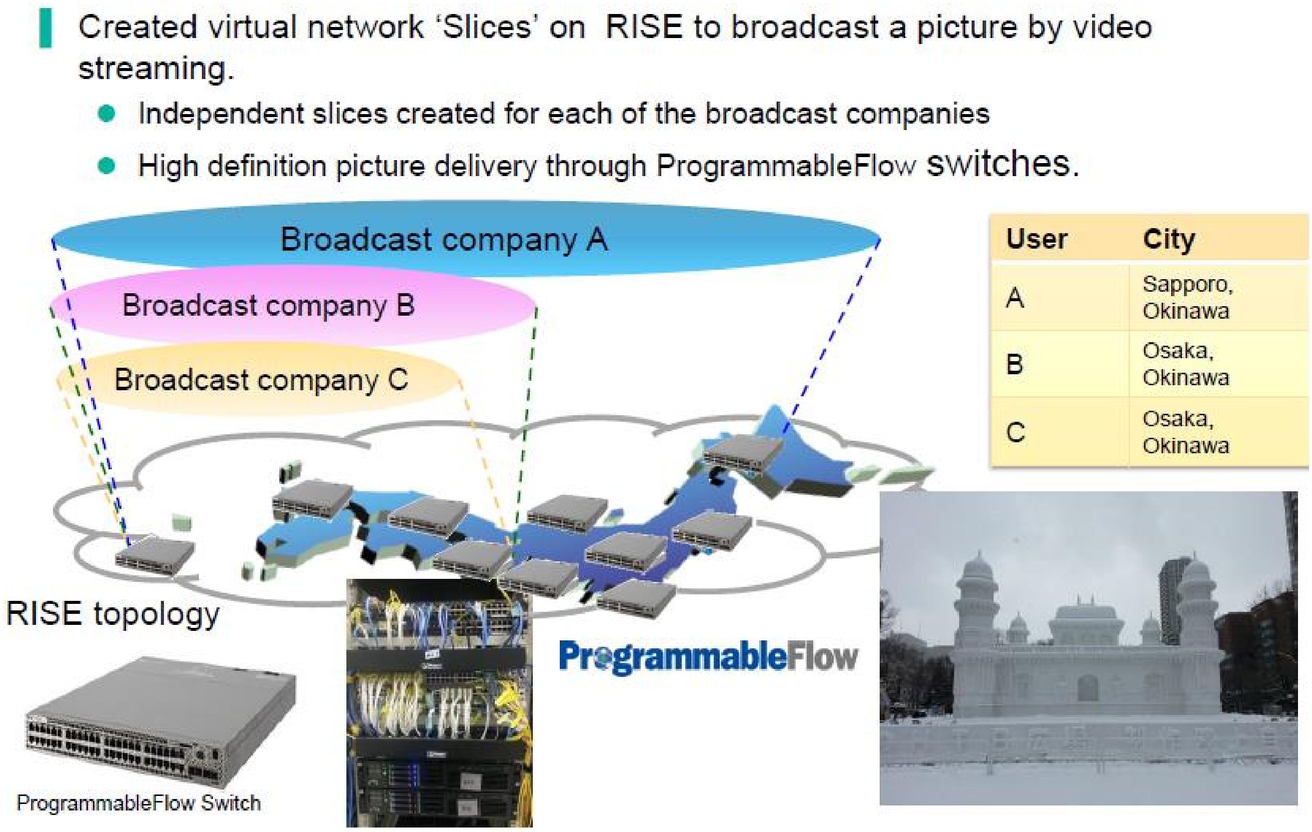

Figure 17 - Broadcast Network Converges (Source NEC)

4.4.2 Convergence, Fixed and Core Network challenges

Traditional network evolution has served the ICT industry to sustain the growth required to support the demand for data bandwidth, new services and applications. Consumers have converged in terms of adoption and cross platform usage, and the future will require further convergence back into the core and across multiple network domains.

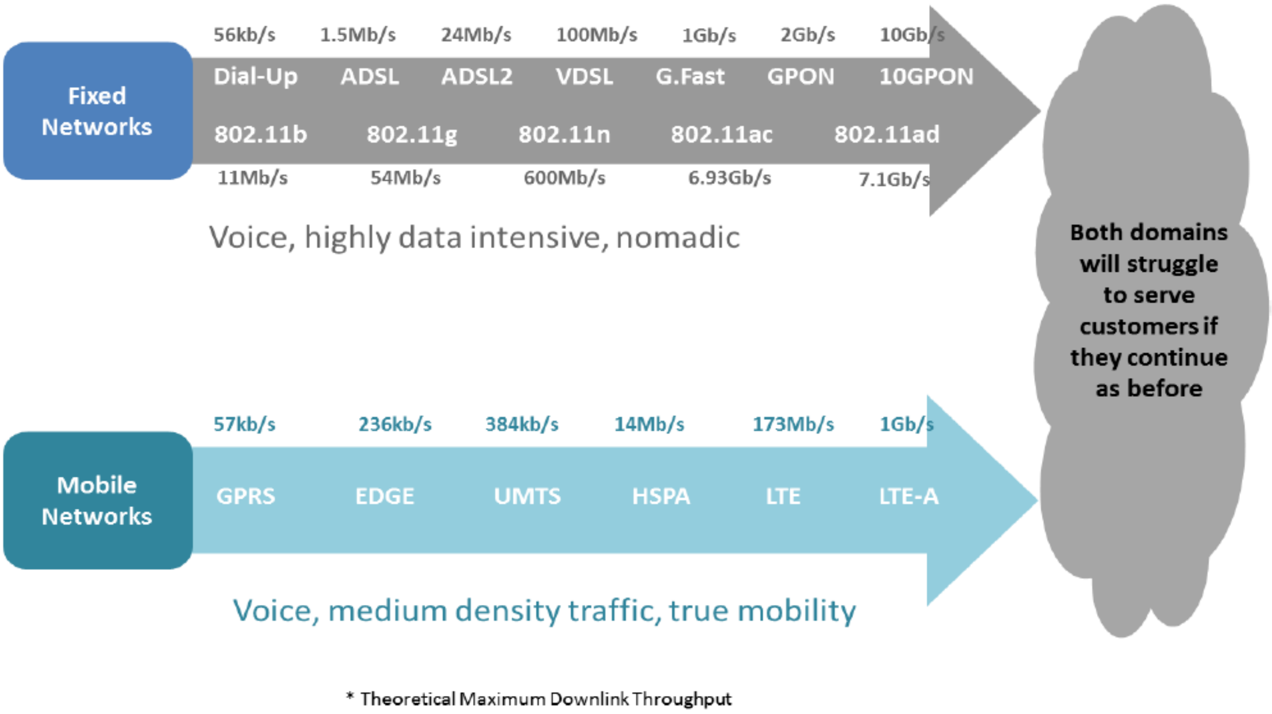

Figure 18 – Convergence, traditional approaches have served us well

4.4.2.1 *Convergence of the user experience*

Both fixed and mobile networks service the same devices today via mobile and Wi-Fi systems. Over the life time of 4G this will continue to evolve with technologies like 802.11x simplifying the Wi-Fi user experience, fixed and mobile voice services based on a common IMS infrastructure, femto cells delivering mobile services via broadband lines, LTE using unlicensed spectrum for data services.

A focus for 5G should be that a user should not care whether their device is connected to a mobile or wireless LAN system, but can carry out a task with the perception of unlimited capacity; whether that is sending photo's to a local printer, controlling a TV or unloading to a cloud storage service. The current mobile experience and Wi-Fi LAN experience should become indistinguishable.

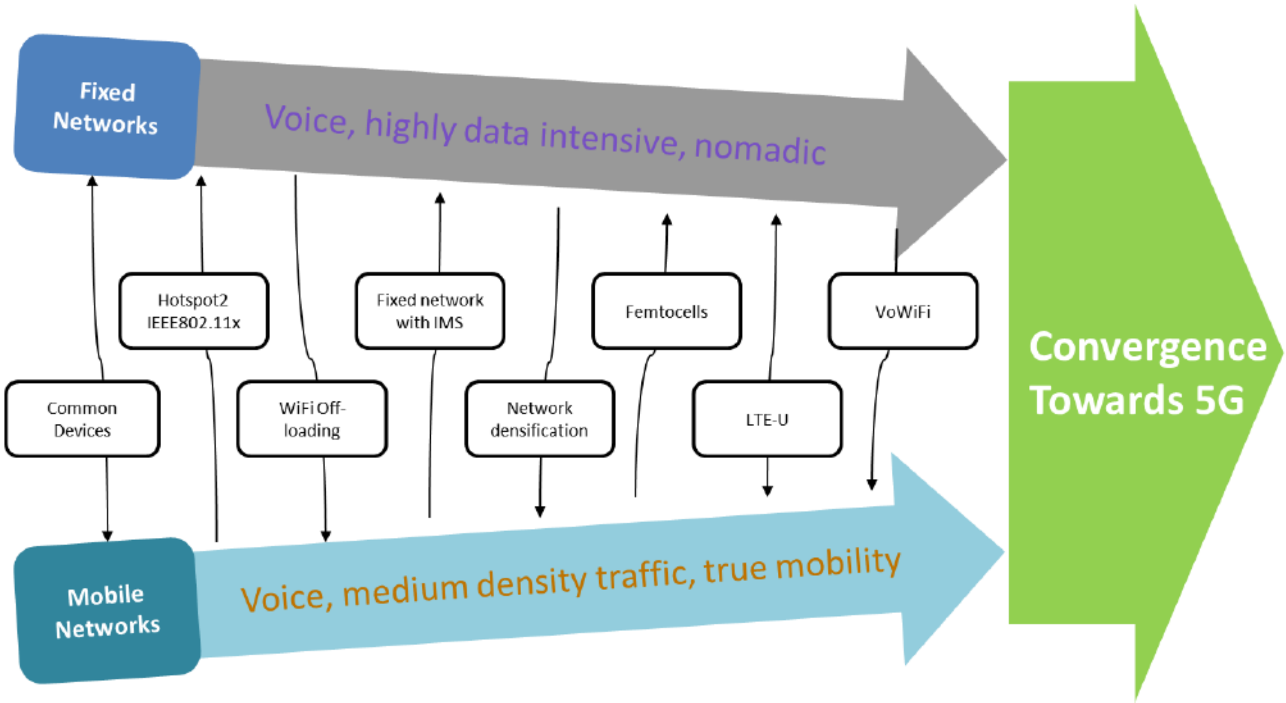

Figure 19 - Fixed and Mobile Convergence

4.4.2.2 Convergence of network infrastructure

Current 5G research is primarily focussed on new wireless technologies with a big emphasis on meeting capacity demands by exploiting millimetre wave spectrum. The predicted capacity requirements will demand the deployment of ultra-dense small cell networks enabling both indoor and outdoor high speed, low latency data access. Connectivity to these cells will require fixed network access which meets emerging 5G front haul, mid haul & back haul needs . Both fixed and mobile networks will converge by delivering IP based services over small radio access mechanisms. Mobility becomes a function over multiple radio technologies.

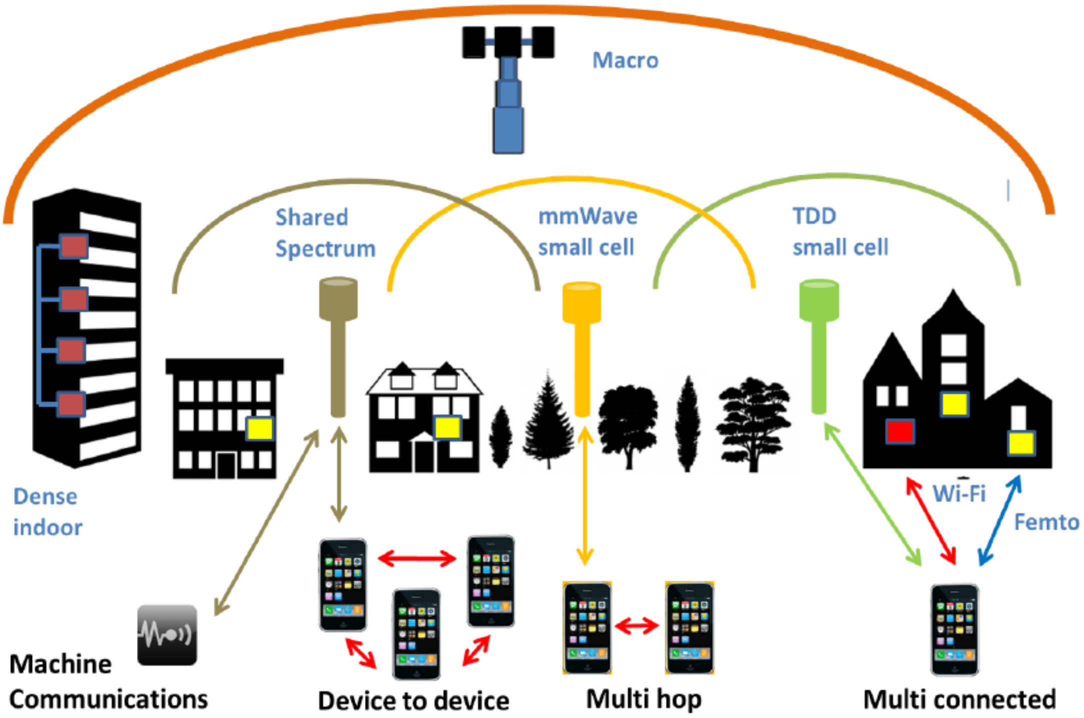

Figure 20 - 5G access options

4.4.2.3 *Fixed Network Aspects*

Fixed network infrastructure is at the core of all long distance communications and will remain so for 5G. However the like demands of the radio technologies being considered vary significantly from the demands of the current technologies. It is important that the fixed infrastructure can meet the changed demands of these new radio technologies.

4.4.2.4 *Changing demands on the fixed network*

Historically cellular networks have been structured around a series of base stations each of which provided radio coverage in a cell covering a significant geographical area. A significant amount of manual radio planning work went into the positioning of the base stations to provide optimum coverage and the selection of appropriate frequencies in order to avoid interference of adjacent cells. Fixed network elements provide communications paths from the base stations to the other parts of the cellular network.

Later networks used higher frequencies, which reduces the reach of the radio signal and hence the area that can be covered by an individual base station. Furthermore, the changing methods of building construction (such as the use of foil backed fibre board) mean the radio coverage in buildings is much less straightforward to predict and hence plan for. These are leading to the increased use of smaller cells. The demands of higher bandwidth placed on 5G may well lead to an architecture based around small cells which will allow significant reuse of frequencies based upon geographical separation, and which requires sophisticated mapping information

This will lead to significantly different demands on the supporting fixed infrastructure which will need interconnect numbers of base stations that are orders of magnitude more than the numbers connected for an older (e.g. 3G) network. Furthermore, it is likely that many of these base stations may be femto cells (i.e. very small area coverage) which are intended to cover a single building like a home. In this case, since replacing the current residential fixed infrastructure would involve a prohibitive cost the current residential fixed line will be required to support the demand of backhauling the signal from the femto cell base station alongside the delivered broadband service. Given that there are 27M homes in the UK which receive their broadband service over copper (sometimes in combination with fibre) it is therefore important that the capabilities of the copper are sufficient to support the combination of broadband delivery and 5G backhaul.

It is also important to recognise that the need for flexibility in the fixed network infrastructure that supports 5G is not itself fixed. The dynamic range of communications needs that 5G is expected to address would lead to significant wasted resource if the fixed infrastructure was statically dimensioned to meet demand. Constraints on capital spend and the need to reduce energy consumption means that this "over-provisioning" approach is no longer commercially viable. This results in the need for flexibility in the capabilities of the fixed infrastructure and a need to control the communication path and services end to end in order to ensure the appropriate functions are used. The former requirement can be addressed by Network functions Virtualisation (NfV) and the latter by Software Defined Networking (SDN).

4.4.2.5 Network functions Virtualisation (NfV) and the latter by Software Defined Networking (SDN).

Communications networks are populated with a large and increasing variety of proprietary hardware appliances. To provide a new network service often requires yet another variety of such appliances and finding the space and power to accommodate these boxes. These complexities are compounded by the increasing costs of energy, capital investment challenges and the rarity of skills necessary to design, integrate and operate increasingly complex hardware-based appliances. Scaling the available functions involves many of the same steps and hence similar lead times. Moreover, hardware-based appliances quickly reach end of life, requiring this cycle to be repeated. Worse, hardware lifecycles are becoming shorter as technology and services innovation accelerates, inhibiting the roll out of new revenue earning network services and constraining innovation.

Network Functions Virtualisation aims to address these problems by leveraging standard IT virtualisation technology to consolidate many network equipment types onto industry standard high volume servers, switches and storage. The value of many of these specialized appliances is in the software. Until now the software required tailored hardware in order to operate, however the speed and other capabilities of generic computing platforms has presented the opportunity to replace the hardware appliances with specialised software running on generic servers.

Virtualising Network Functions could potentially offer many benefits including, but not limited to:

- Reduced equipment costs and reduced power consumption through consolidating equipment and exploiting the economies of scale of the IT industry.
- Increased speed of Time to Market by minimising the typical network operator cycle of innovation.
- Economies of scale required to cover investments in hardware-based functionalities are no longer applicable for software-based development, reducing the barriers of capital investment.
- Availability of network appliance multi-version and multi-tenancy, which allows use of a single platform for different applications, users and tenants. This allows network operators to share resources across services and across different customer bases thus tailoring network capability to demand.
- Targeted service introduction based on geography or customer sets is possible. Services can be rapidly scaled up/down as required.

To leverage these benefits, there are a number of technical challenges which need to be addressed:

1. Achieving high performance virtualised network appliances which are portable between different hardware vendors, and with different hypervisors.
2. Achieving co-existence with bespoke hardware based network platforms whilst enabling an efficient migration path to fully virtualised network platforms which re-use network operator OSS/BSS. OSS/BSS development needs to move to a model in-line with Network Functions Virtualisation and this is where SDN can play a role.
3. Managing and orchestrating many virtual network appliances (particularly alongside legacy management systems) while ensuring security from attack and misconfiguration.
4. Network Functions Virtualisation will only scale if all of the functions can be automated.
5. Ensuring the appropriate level of resilience to hardware and software failures.
6. Integrating multiple virtual appliances from different vendors. Network operators need to be able to "mix & match" hardware from different vendors, hypervisors from different vendors and virtual appliances from different vendors without incurring significant integration costs and avoiding lock-in.

Network Functions Virtualisation is applicable to any data plane packet processing and control plane function in fixed and mobile network infrastructures.

SDN architectures decouple network control and forwarding functions, enabling network control to become directly programmable and the underlying infrastructure to be abstracted from applications and network services. As a result the decisions on the best path across a network can be taken with a view of the total network capabilities at the time required rather than a series of independent decisions at each piece of network equipment based on their local view.

As a result the SDN architecture results in a network that is agile (Abstracting control from forwarding lets administrators dynamically adjust network-wide traffic flow to meet changing needs); centrally managed (Network intelligence is centralised in software-based SDN controllers that maintain a global view of the network, which means that network wide policies can be applied from one point); highly configurable (SDN lets network managers configure, manage, secure, and optimize network resources very quickly to meet dynamic demand), and end to end (under SDN the network elements that may have traditionally been viewed as fixed and mobile and hence subject to independent control can be controlled from a single unified control plane).

It should be emphasised that Network Functions Virtualisation is complementary to Software Defined Networking (SDN). These topics are mutually beneficial but are not dependent on each other. Network Functions can be virtualised and deployed without an SDN being required and vice-versa.

4.4.2.6 Core network capacity

Flexibility is only one of the challenges that need to be addressed by the core network. The volume of data that the core needs to support is increasing all the time and it is therefore critical that the volume of data which the core network can support increases alongside this demand. Whilst NFV and SDN address these concerns at the switching/routing points this is of limited value without a corresponding increase in the transmission capacity between nodes.

4.4.3 Getting ready to exploit BIG DATA

4.4.3.1 The Age of Big Data

Wired or wireless connectivity has been a vital commodity of life and more so recently in the realms of the information age. The ones who have it faster, more reliable and more ubiquitous, or are in simple terms "better connected", will have a significant advantage over the rest. Each xG communication technology has aimed at improving the broadband experience. Meanwhile, rapid innovation in telecommunication also enabled us to flood ourselves with data of all types, sizes, and speeds. This is to such an extent that our conventional processing paradigms break down when mining these massive datasets, in order to drive profitability.

In a joint study, Ericsson and Chalmers University showed that doubling the broadband speed for an economy increased its GDP by 0.3%[36], which is equivalent to USD 126 Billion in the OECD region[37]. Moreover, the report indicates that for a 10% increase in Internet penetration, the GDP improves by 1%. It is thus obvious that the incentives are in place to further advocate for improved connectivity and take up. This has become the driver for innovation in terms of R&D Projects to come up with new technologies. These new technologies have in turn led the industry to develop a plethora of various apps, all relying on the premise of ubiquitous high-speed Internet access. The apps that made it to mass markets, and were

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[36] Conversely when a network infrastructure(s) saturates, due to lack of investment, voice calls and data connections could be restricted. This could have major implication to GDP growth.

[37] Ericsson, Arthur D. Little. and Chalmers Institute of Technology. 2011. "Socioeconomic Impact of Broadband Investments." Research project. Stockholm, Sweden: Ericsson.

desirable, became more demanding in terms of performance and services they provisioned. Finally, when the supply provided by the technology of the time was not enough to meet the demands, the R&D community came up with new techniques, and hence closing the innovation cycle as shown in Figure 22.

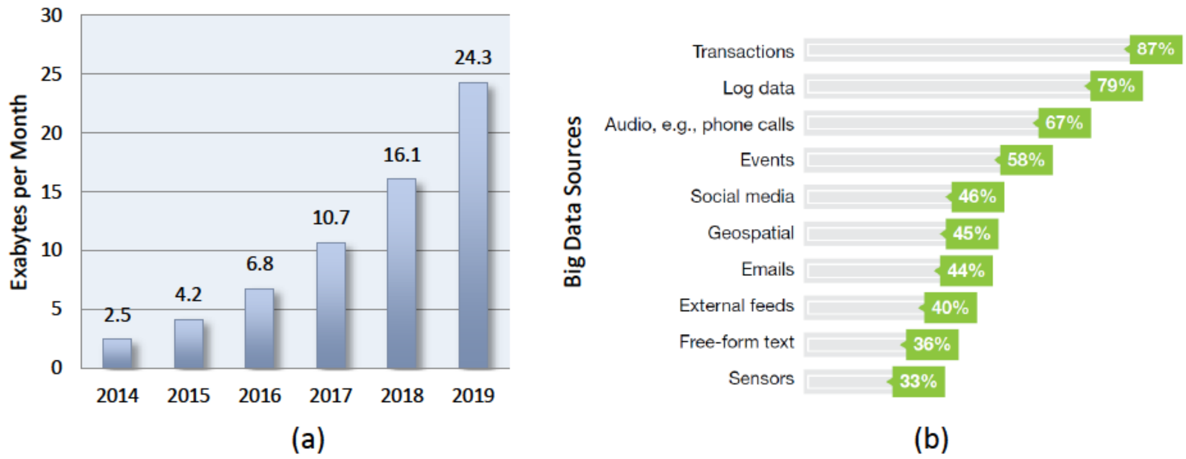

Figure 21 a & b - 10-fold increase in mobile data traffic by 2019, Sources (a) Cisco[38], (b) IBM[39]

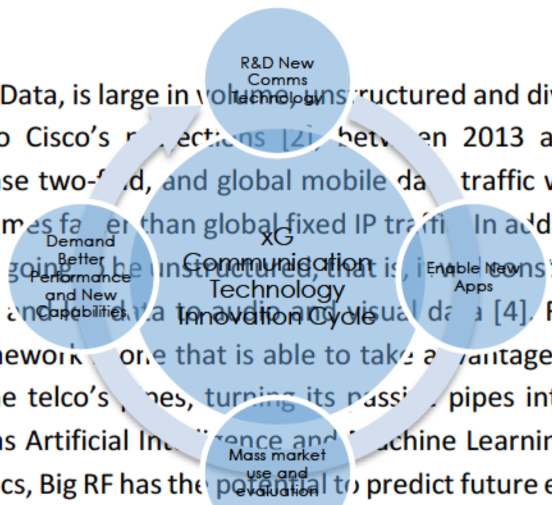

Figure 22 - Figure 1 xG Communication Technology Innovation Cycle

From the standpoint of the mobile communications industry, these performance demands have essentially become the basis for 5G communication technologies' ambitious

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[38] "Cisco Visual Networking Index: Forecast and Methodology, 2014–2019", Cisco Visual Networking Index, July 2014.

[39] Bob Fox, Rob van den Dam and Rebecca Shockley, "Analytics: Real-world use of big data in telecommunications", IBM Institute for Business Value, 2013.

What is Big RF?

Mobile RF data, similar to Big Data, is large in volume, unstructured and diverse in type, and travels at various speeds. According to Cisco's projections [2], between 2013 and 2018, mobile network connection speeds will increase two-fold, and global mobile data traffic will increase nearly 11-fold, while it continues to grow 3 times faster than global fixed IP traffic. In addition, the types of data that will make up these figures are going to be unstructured, that is, it constitute of many various types of raw data from documents and data to audio and visual data [4]. Figure 1 illustrates some of these statistics. A Big RF framework is one that is able to take advantage of the current huge traffic surge that passes through the telco's pipes, turning its passive pipes into smart pipes by applying sophisticated analytics such as Artificial Intelligence and Machine Learning techniques. Through the application of complex analytics, Big RF has the potential to predict future events and thereby improve wireless networks, e.g., by helping in dynamic spectrum access for increased bandwidth capacity and performing network management and optimization routines. The Big RF framework is foreseen to bring Self-Organizing Networks (SONs) to reality by predicting and managing spectrum usage and also improve network performance after initial deployment [3]. Big RF lets users gain insights into wireless data and allows smarter networks that result in both efficient network resource optimization and robust network traffic management. In the applications section of this article some of the prominent use cases are put forth to demonstrate how Big RF achieves its goals.

Meanwhile, in contrast with Big Data, Big RF has a more specific application domain, focusing on the control and management of wireless networking elements. A Big RF solution may have typical Big Data input sources to provide contextual information and may deemphasize packet inspection, though, a Big RF solution would be expected to include measurements of RF domain information as well. Further, a Big RF solution will tend to introduce a novel observer effect in that the resulting adjustments to wireless networking elements will also influence the RF measurements. Big RF types of applications include spectrum governance problems where large amounts of RF information need to be gathered, such as with the FCC's proposed Spectrum Dashboard. Another Big RF type of problem in the commercial space is motivated by the management of very large numbers of wireless requirements: a 1000x increase in data rates, under 1ms E2E network delay, 90% reduction in network energy use, as outlined in the Introduction section, 1.

Today, we have unintentionally dug ourselves into a hole as we are witnessing a tsunami of data that we have never experienced before. Neither our computing power nor processing methodology is adequate to tackle the masses of information at our datastores. The issues caused by this data explosion can be analysed into three degrees of freedom: Volume, Velocity and Variety; known as the 3Vs of Big Data:

- Volume – the scale of stored data elements is too large for traditional datastores to handle. Data files need to be distributed but also easy to read and write to.
- Velocity – new (streaming) data is arriving at a rate that cannot be processed at real-time. Algorithms need to be parallelised such that each computing unit can take on a portion of the computation, outputting timely answers to real-life events. In Figure 21 a, Cisco's predictions for global mobile data growth [40] indicate a 10-fold exponential increase by 2019, reaching a 24.3 Exabytes (million Terabytes) per month.
- Variety – data is gathered by combining multiple different sources with different data structures. This is an obstacle when importing data to conventional Relational Databases, since each data source needs to be manually restructured in order to be consistent with data imported from other sources. Figure 21 b shows the outcome of a survey conducted by IBM and Oxford University in 2013 indicating the percentage usage of different big data sources by a group of companies[41].

As shown in diagram below, a Big Data problem is any instance of a system possessing one or more of the above 3 Vs. A Big Data enabled network thus would be a solution that tackles any of the 3V bottlenecks of that network. The ICT industry, in general, is the founder of Big Data. Telco's have been dealing with Big Data day in and day out. However, as the buzzword "Big Data" has gained more recognition, many other sectors have started to look at the potential of their untapped data under Big Data techniques. As of 2015, 95% of the Fortune 500 businesses have initiated at least one Big Data project within their premises.

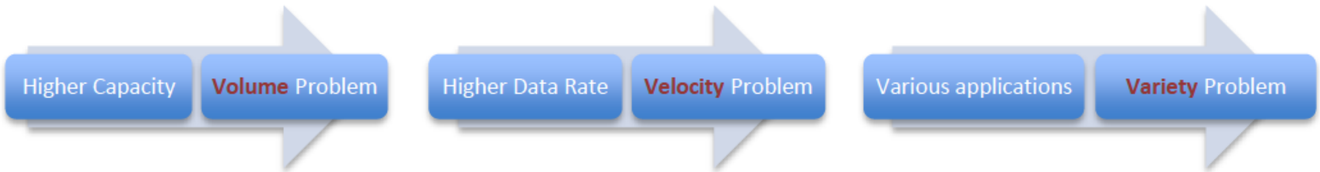

Figure 23 - Next Generation Communication Systems' Advantages as Big Data Problems

In summary, for the past few decades and throughout the generations of communication technology that has been developed, the wireless communications community have

[40] "Cisco Visual Networking Index: Forecast and Methodology, 2014–2019", Cisco Visual Networking Index, July 2014.

[41] Bob Fox, Rob van den Dam and Rebecca Shockley, "Analytics: Real-world use of big data in telecommunications", IBM Institute for Business Value, 2013.

consistently aimed at increasing capacity and bit rate. This has, in effect, led to the accommodation a plethora of applications, which has resulted in the data explosion experienced today. Communication service providers are under a lot of pressure to reduce costs, protect the margins, and retain their customer base. One of the best ways to do that is to use the data chaos to their advantage by mining the data that traverses their networks to drive profitability. In the next section we will discuss the technicalities of designing and integrating a data architecture for a 5G operator, including both stream and batch information processing paradigms.

Tools and Architecture

Several tools have been developed, primarily to leverage cluster computing, that could allow portions of Big Data computations to be performed closer to the network edge as in Edge Computing paradigm discussed in section 4.4.1.1; thereby, opening up the power of Big Data at the last mile of 5G Networks. In this section we will examine Apache Spark as an example cluster computing system among others, e.g., Apache Hadoop or Apache Storm. First, we briefly explain the Spark ecosystem and architecture, then describe the distributed transformations Spark applies to the input raw data, stage-by-stage, to produce actionable knowledge.

Apache Spark is an open-source, easy to use, fast and general data processing engine, originally developed in the AMPLab at UC Berkeley. Unlike Hadoop's disk-based MapReduce runtime algorithm, Spark uses in-memory processing, leading to faster processing time, especially for iterative processes such as machine learning algorithms. In contrast to Storm, Spark also allows for micro-batch and stream cluster computing, bringing together the best of both processing worlds (batch and stream) in one place.

To put the Spark cluster computing into next-generation communication systems context, Figure 22 depicts an example Big Data-enabled cellular networking architecture, designed to support the ambitious less-than-1ms round-trip-time (RTT) latency performance. The envisioned system includes a number of sensors and mobile phones connecting via a Remote Radio Unit (RRU) to the network. Through the application of Big Data analytics, relevant content can be identified and cached on local data stores at the Baseband Unit (BBU), which is a pool of digital processing units each of which were previously located at different base stations. Thereby, each BBU can be considered a cloudlet within the Cloud RAN[42] subsystem.

This architecture leverages the network information and the context of that information to improve the user experience by automatically adjusting radio resources and caching popular data, in a manner similar to how some search engines monitor and adapt to searches in real-time. The Big Data enabled architecture in Figure 24 has the following three advantages over a more traditional design:

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[42] "C-RAN: the road towards green RAN", China Mobile Research Institute, Technical Report, v3.0, Dec 2013.

- Offloading computation to the local BBU: Information processing on the cached data offloads communication and processing overhead that would otherwise be required if one main cloud computing system was used.
- Enhanced Security and Privacy: Localizing information reduces the attractiveness of any one target and reduces the number of potentially interceptable information transfers.
- Reduced Latency: For those applications that require only local communications, running algorithms locally on the data cached at the BBU reduces the end-to-end RTT delay[43].

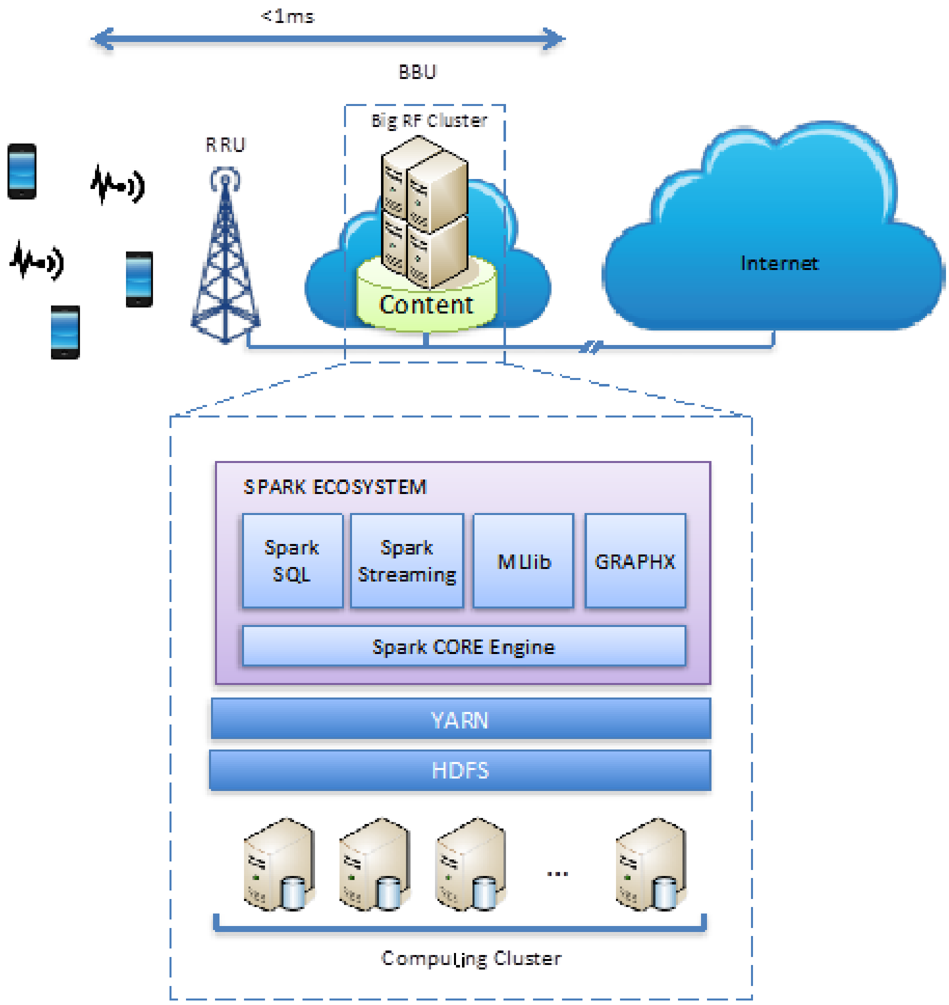

Figure 24 - Smart Caching at the Edge based on Big Data analytics[44] – Adapted from GSMA paper[45]

Use of Big Data in 5G Systems

[43] Bastug, Ejder, Mehdi Bennis, and Mérouane Debbah. "Living on the edge: The role of proactive caching in 5g wireless networks." Communications Magazine, IEEE 52.8 (2014): 82-89.

[44] J. Neel, Shaswar Baban, N. Mellen, I. Akbar, C. Sheehe, B. Schutz, P. Cook, "Big RF for Homeland Security Applications", IEEE HST Symposium, 2015.

[45] GSMA, "Understanding 5G: Perspectives on future technological advancements in mobile", Dec. 2014, Online at: https://gsmaintelligence.com/files/analysis/?file=141208-5g.pdf

Big Data has the potential to have several use cases in the realm of 5G networks. The core solutions that Big Data analytics can provide are: Complex Analytics i.e. analysis of massive amounts of data that would not fit on a single computer, Predictive Analytics i.e. crunching data, large or small, to predict the next element in a series, and Classification and Clustering i.e. to classify an unseen piece of information into labelled groups, or, if the labels were not available, to cluster the data into groups in which its elements exhibit similar properties. From the Telco sectors view point, these would be, classification of radio signals, real-time analyses of interference situations, prediction of traffic heavy events, clustering populations according to different criteria, and so on. We can also discuss these benefits in terms of CAPEX and OPEX costs and further added value that an operator gains from such a large-scale analytics platform.

Traditionally, radio network planning, which forms a large portion of an operator's CAPEX, has been an intricate and cumbersome process that involved a large workforce of talented engineers to design an appropriate network for each deployment area at a time. Making use of the predictive power of machine learning algorithms that have learned from millions of deployments scenarios, it can suggest, for instance, at what height and where the operator's masts should be placed. Big Data systems can be also fed with social network's data that would indicate the populated areas according to the tweets and status updates geolocation tags. Some startups have already started to exploit social network's data to help in the radio network design.

Even after a full mobile network design and deployment, the mobile operator would not be fully operational, but rather undergo a test period where as many drive tests will be carried out to find the pitfalls of the network design in practice. Thus, optimizing the network architecture and tweaking its parameters will be needed so that the deployed cellular network will satisfy the underlined benchmarks, which adds tremendously to the operators OPEX after deployment and during network expansion. However, making use of the wealth of data that traverses an operators network, e.g. mobile generated metadata, social media data, IoT data, and data collected from external sources, it is possible to provide a highly efficient traffic load balancing and dynamic capacity distribution by reacting to the macro and micro events that happen throughout the wireless network. For instance, a Big Data enabled wireless network can track and analyse the movement behaviour of a population forming a personal probability table of what data is used where. This way content can be pushed to the network edge as close to its users, and thereby reducing the Round Trip Time (RTT) of a data packet.

As opposed to the traditional OPEX and CAPEX costs, Big Data will also bring about added value to 5G network operators of the future. New applications such as the Internet of Things (IoT), Driverless Cars, and Tactile Internet require a big data platform that is able to manage the data collection, storage and processing. Real-time or near-real-time data processing for telcos would be of particular interest, since the user-generated data, as indicated in Figure 21, is beyond the storage capacity of any wireless operator. However, the knowledge extracted from the flowing raw data and its metadata, could be learned from, stored, and reused as experience to solve future tasks.

Perhaps another potential use cases of Big Data enabled 5G system is Big RF. The Cognitive Radio Working Group (CRWG) within the Wireless Innovation's Forum, have first coined the term Big RF to refer to the set of Big Data tools and techniques to address RF domain problems & 5G wireless networks' challenges[46],[47],[48]. Within this framework, operators and/or national frequency spectrum regulators, would be able to analyse the spectrum usage in an area to get insight into congested areas, single out interfering channels, and identify offenders for law enforcement.

4.4.3.2 Convergence of Open Geospatial and Spectrum Worlds – What it means for 5G Modelling and BIG DATA Innovation

The "ultra dense" deep fibre world of a network of networks, in which, the customer gets the service (whether fixed or mobile) they want when they want it, requires us to think in different ways about how we might deliver it.

A key driver that will determine the speed of 5G roll out is indeed cost (as set out in more detail in Section 3.2). The lower the cost, the more likely it is that deployment will be faster. One of the problems faced by all operators is that as the price per bit is constantly falling, there is a perception that upgrading networks is actually value destroying. This is particularly true when working in the millimetre wavebands, where the laws of physics begin to limit the art of the possible. Therefore we can be sure that in the 5G world, and particularly when higher frequencies are required, costs will increase, as the number of base stations required will significantly increase.

What if a way could be found to reduce network deployment costs and thereby speed up deployment? Convergence between the open geospatial world and the spectrum world, along with increased and cheaper processor power, and big data analytical tools now opens new possibilities to deliver this 'nirvana'. Today, most operators would use a coverage prediction tool based on the frequency/ies used when configuring their networks. However, these do not contain the level of granularity required to do the job because they cannot currently capture enough information about the area(s) where they are seeking to deploy. So, what kinds of information would be useful?

Imagine a deployment in a millimetre waveband. Scintillation and other atmospheric considerations become increasingly important, as does tree cover and even factors relating to individual buildings. What if you could see all this, including individual buildings in 3D, and you even knew specific building height data? What if you knew where other utilities were-

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[46] J. Neel, P. Cook N. Mellen, I. Akbar, D. Devasirvatham, C. Sheehe, R. Schutz, "The Role of Context in Cognitive Systems," Journal of Signal Processing Systems, April 2014.

[47] J. Neel, Shaswar Baban, N. Mellen, I. Akbar, C. Sheehe, B. Schutz, P. Cook,"Big RF for Homeland Security Applications", IEEE HST Symposium, 2015, April 2015.

[48] J. Neel, Shaswar Baban, P. Cook, I. Akbar, N. Mellen, C. Sheehe, D. Devasirvatham, "Big RF for Spectrum Sharing Applications," Wireless Innovations' Forum on Wireless Communication Technologies and Software Defined Radio – WInnComm, San Diego, March, 2015.

which in a “network of networks” environment will become increasingly important or where the flood plains were, and even where in a “deep fibre” world, where the main street cabinets and other infrastructure were located with which one might need to interwork ? Mapping now has the potential to deliver this – but it has never been done. It could be.

If a modelling tool existed that combined traditional coverage prediction techniques with more sophisticated geo information systems then we could envision a world in which an operator could view a split screen which showed three key things – combined, and dynamically configurable in real time:

1. A traditional 2D topographical but much more granular OS map (with 3D possible too?)
2. An ariel view
3. Ground level photography in 360 degrees, including a picture of the actual street and building(s)/other infrastructure being considered as a possible site for equipment
4. An estimated likely coverage radius at a range of frequencies from a potential mast site

The aim would be to have a pre-planning tool that could incorporate all such functionality, at various frequencies, and potentially also factor in historic atmospheric data. This would provide a near “real world visualisation” before any expensive investments were made in site visits or installations that proved to be impossible for factors that simply were not known when the network was being planned.

We believe that it would be possible to develop such a tool, and that the algorithms required would have global applicability. Mast locations can be found using point geometry and special vectoring data. Maps comprise three key elements, points, lines and polygons. It is possible to attach an attribution to any mast, and thereby to build up a detailed model of specific information about any point (or even all points).

Other factors to consider might include sites of special scientific interest, planned construction and development areas, and other factors unique to a specific small area that might make it more or less suitable as a deployment location.

There can be little doubt that if something with approaching even half of this level of functionality could be produced, it would be of enormous help by solving a real world problem virtually at a fraction of the real world cost.. Ordnance Survey has a long tradition of doing just this, and was the first organisation of its type in the world to digitise its maps. Applied research into this field could, it is believed, save 20% of an operator’s deployment costs.

4.5 Energy and Throughput Efficiency Metrics for 5G Wireless Networks

The energy efficiency of cellular radio access networks (RANs) was a significant consideration in the development of the 4G wireless standards owing to the very low power efficiency of the radio base station (RBS) units and the planned large increases in cell average throughputs. The imminent development of the 5G wireless standards emphasises throughput efficiency in order to meet an expected 1000 fold increase in the amount of data traffic. Dense small cell deployments, heterogeneous networks and large antenna arrays are some examples of the key technologies being considered for 5G. However, their adoption could substantially increase the overall energy consumption of a 5G RAN, which is of significant concern to mobile network operators since energy costs are a substantial portion of the overall network operating costs.

A joint energy and throughput efficiency framework is required to guide the design and evaluation of a 5G RAN. To date, efforts to develop joint energy and throughput efficiency metrics for wireless networks has not established a consistent framework to allow the unambiguous comparison of different network configurations. Recent developments in the field[49] have considered three figures of merit termed the energy consumption gain (ECG), the throughput gain (TPG) and the energy throughput gain (ETG). The ECG, TPG and ETG are determined, respectively, from the metrics: power per unit area (W m^{-2}); throughput per unit area (bit s^{-1} m^{-2}); and energy per bit (J bit^{-1}). This joint energy and throughput efficiency framework can be applied to 5G RANs for high traffic loads, comparing small cell deployment scenarios with heterogeneous ones. Figure 25 depicts the relationship between the figures of merit and their associated metrics where subscripts 1 and 2 refer to the comparison of RANs 1 and 2 and ETG = ECG x TPG.

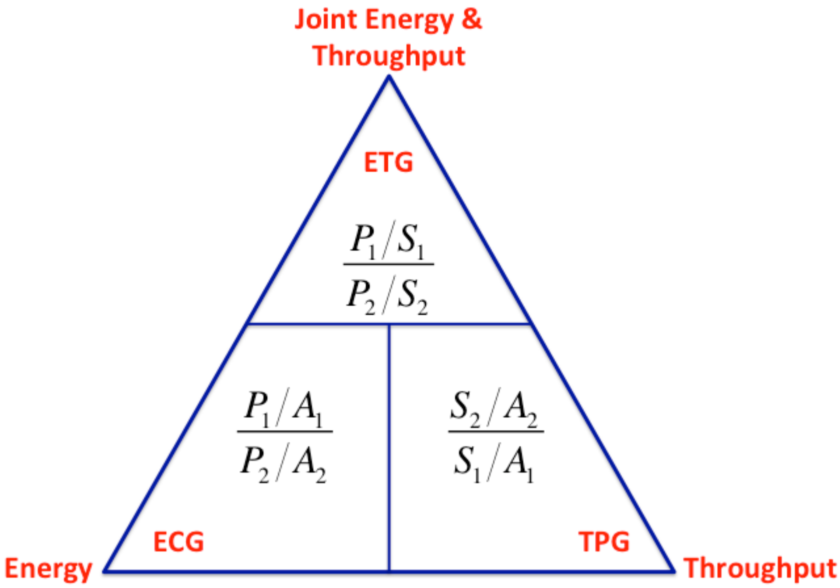

Figure 25 - Energy and Throughput Efficiency Metrics

As indicated by Figure 25, knowing the power consumption *P* of the RBS is essential for determining the RAN energy efficiency. Since 60 to 80 per cent of energy is consumed by the RBS, it is essential to have accurate models of the power consumption of the different types

[49] T. O'Farrell and S. Fletcher, "Green Communication Concepts, Energy Metrics and Throughput Efficiency for Wireless Systems," part of *Green Communications: Principles, Concepts and Practice, First Edition*, Edited by Konstantinos Samdanis, Peter Rost, Andreas Maeder, Michela Meo and Christos Verikoukis, Published 2015 by John Wiley & Sons, Ltd.

of RBSs that could be deployed in a 5G RAN. While ETSI is considering introducing energy ratings for network equipment, the design of energy efficient 5G RANs will need accurate characterisation of the RBS energy consumption as a function of transmitted RF power. The constituent units of a RBS typically divide into three categories: the units used per antenna per sector of the base station site, which includes the power amplifier (PA) and the RF transceiver (Trx) units; the units used per sector, which includes the processing unit (PU) and the power supply (PS) unit; and the units used once per base station site, which includes the air-conditioning (AC) and backhaul (BH) units. A further categorisation of the units is based on whether or not there is a dependency on the traffic load. The load-dependent units include the PA and Trx. The power consumption of these components is scaled by a normalised load activity factor α, which ranges from zero to unity. The load-independent units include the PS, AC and BH. In practice, there is a small load dependency associated with the BH. However, its effect is small so that the power consumption of the load-independent units is treated as time invariant.

Application of the joint energy and throughput efficiency framework in the *Green Communication Concepts, Energy Metrics and Throughput Efficiency for Wireless Systems* studies[50] allows the energy consumption and throughput characteristics of different RAN configurations to be compared. The technical approach is useful for exploring how a 4G RAN might be evolved into a 5G RAN in an energy efficient manner in order to meet the expected growth in mobile data traffic. The framework also allows particular energy saving techniques to be evaluated, such as deployment techniques (e.g., cell size and RAN topology) and power state techniques (e.g., sleepmodes). The framework demonstrates the fundamental roles played by the cell-site power consumption models, including the backhaul, the cell-average area power and throughput densities and the energy consumption rate in J bit^{-1}. Implementing an industry standardised framework would assist in direct comparisons between alternative solutions.

The *Green Communication Concepts, Energy Metrics and Throughput Efficiency for Wireless Systems* studies[51] suggest that one way to evolve a 4G RAN into a high throughput, energy efficient 5G RAN is by first evolving into a HetNet of small cells over macrocells followed by removing the macrocell underlayer leaving a small cell RAN. An important ingredient in future small cell deployments will be the minimisation of the energy consumption in the backhaul. The backhaul power consumption can account for 50% of the overall RBS power consumption in a picocell and can become a limiting factor especially when considering

[50] T. O'Farrell and S. Fletcher, "Green Communication Concepts, Energy Metrics and Throughput Efficiency for Wireless Systems," part of *Green Communications: Principles, Concepts and Practice, First Edition*, Edited by Konstantinos Samdanis, Peter Rost, Andreas Maeder, Michela Meo and Christos Verikoukis, Published 2015 by John Wiley & Sons, Ltd.

[51] T. O'Farrell and S. Fletcher, "Green Communication Concepts, Energy Metrics and Throughput Efficiency for Wireless Systems," part of *Green Communications: Principles, Concepts and Practice, First Edition*, Edited by Konstantinos Samdanis, Peter Rost, Andreas Maeder, Michela Meo and Christos Verikoukis, Published 2015 by John Wiley & Sons, Ltd.

sleepmode options since the backhaul typically remains switched on. An interesting solution to this problem might be to transform the macrocell underlay into a collection of massive MIMO based macrocells providing backhaul connectivity to numerous off-grid, small cells.

4.6 Security of 5G

5G aims to yield a more virtualised, distributed and fluid environment comprising different communication technologies and compute objects. The business ecosystem will span across different radio technologies, wired interconnect and a multi-dimensional array of virtual components, each owned and operated by different organisations with a high degree of sharing of physical resources.

The advent of 5G therefore brings the possibility to reconsider the fragility of our internet as it evolves from a somewhat flat interconnect of systems to a multidimensional array of systems, services, devices and stakeholders.

The current internet is comprised of a fragile collection of secure pipes that terminate within insecure end points. Until very recently the internet wasn't so secure at all. There are a number of well know protocols that have only recently seen deployment of their secure incarnations.

Hypertext transport protocol (http/https) carries much of the internet traffic, originally serving web pages, but now more commonly serving data transactions between software components. Post Office Protocol (POP), Internet Message access protocol (IMAP), simple message transfer protocol (SMTP) are all busy transporting our everyday email using secure sockets layer (SSL) or transport layer security (TLS).

Virtual Private Networks (VPN) allow us to connect different segments of IP networks using secure 'pipes'. Similarly Secure Shell (SSH) allows for a secure pipe to be formed to execute software on remote systems. All of these protocols traditionally allow for secure communication between devices.

Until recently, individual PCs and servers typically had a limited purpose. Each device would typically carry out a single process or function; a mail server, a web server, a database or a client running lightweight office applications were all typically housed within individual and separate machines until the last 5 years.

Moore's law still supports the exponential increase in processing capacity, yielding individual machines which carry an order of magnitude over and above the state where a machine would only have a single function. The advent of virtualisation has seen an even more rapid acceleration of the uses for which our computing power can be utilised. Efficiency and economic gains are made, and our daily productivity vastly improved.

However, this isn't achieved without a different price. Virtualisation is extending to cover almost all aspects of the communication network. Virtual Machines (VM), Software Defined Radio (SDR), Software Defined Networking (SDN), network functions virtualisation (NFV) all allow hardware to become rather generic and controllable by software provided by third parties.

All of the above describes the technology. In fact the majority of discussion to date with regard to 5G is technologically focused. There is a significant lack of consideration for the next generation applications that could use 5G. Is it about more video services, multi-angular view 3D TV, distribution of 3D printing data, Tactile Internet, Internet of Things? What are the next killer applications / services for which the new 5G capability will enable?

Areas of our society which develop much slower in terms of communications capability are those which exist within much smaller scales of economy than the consumer market. Communication technologies that support Public Safety and Disaster Relief (PPDR), or Critical National Infrastructure are left behind in environments of limited budget and long cycles of technology refresh.

The widespread consideration to use common-off-the-shelf (COTS) technology attempts to redress this economy of scale. Markets are currently attempting to repurpose consumer technologies for provision of more capable wireless and networked applications that are considered critical for the safety and security of our society. This repurposing can surely benefit our critical services by inheriting the low cost and technological maturity which has been driven primarily from the consumer market.

With the current day consideration to adopt COTS in critical communication applications and the economic rationale behind that, it is likely that this will continue long into the future. It is highly unlikely that bespoke technologies (such as TETRA), will be developed specifically for individual market purposes. Therefore future considerations for 5G will likely be adopted by many more than the consumer market. The evolution of 5G should already accommodate such application spaces. Some work has already been done to consider this[52]. In fact 3GPP is currently 'uplifting' the 4G standards to include capabilities to support mission critical communication applications[53].

Among many there are 2 distinct criteria which are commonly cited as high level requirements for 5G:

a) Creating a secure, reliable and dependable internet with zero perceived downtime for service provision
b) User Controlled Privacy[54]

Considering just these 2 criteria and the discussion given above with regard to our fragile internet, and the need to support mission critical communication, we uncover a significant

[52] http://www.networks-etp.eu/fileadmin/user_upload/Publications/Position_White_Papers/NetWorks_White_Paper_ICT_CritNatInfra_Final_12-07-02.pdf

[53] http://www.3gpp.org/specifications-groups/sa-plenary/sa6-mission-critical-applications

[54] http://www.v3.co.uk/v3-uk/news/2371386/5g-will-underpin-the-internet-of-things-but-security-fears-must-be-overcome

distinction which should advise on the approach to assure the security and resilience of 5G infrastructure and the information services which use it.

The first criteria a) relates primarily to the resilience of the 5G infrastructure. By definition, resilience is a measure of a systems ability to retain its originally intended performance after being compromised. Compromise in terms of 5G infrastructure could affect the wired and wireless communication bearers, the virtual components or the physical networking and virtualisation hardware. Resilience of the data transfer carried by the 5G infrastructure is also considered here.

The second criteria b) relates to information. Information is considered here separately but somewhat linked to the consideration of data in the first criteria. Information represents the meaning of data; the facts that the data represents; the value that the data has once used in the context of it purpose. Therefore the information carried by the 5G network must be protected in its own context, and not necessary rely upon the infrastructure that carried it.

Protecting the 5G infrastructure and protecting the information poses different but linked challenges. In our current fragile internet our mobile technologies assure who is using the mobile service for the primary purpose of addressing and billing. Information carried over the mobile service is protected separately. One could question whether over-the-air encryption is required for network data payload, or is it just required for protecting network control information to safeguard the resilience of the network.

It could be considered that the two criteria, a) 'network resilience' and b) 'informational privacy' given above, could be isolated problems to solve. In fact this is not the case. With this discussion, we only scratch the surface of the problems of security and resilience of future 5G technologies. These elements are intertwined in an ever increasing, complex multidimensional array of trust. Such questions can be posed, such as:

- Can the software (e.g. virtualised components) trust that the hardware (and hypervisor) will do as its told?
- Can the hardware (e.g. software defined radio) trust that the software will operate within acceptable parameters (and not transmit illegally)?
- Can the provider and/or consumer of the information trust the network components over which the representative data was transferred.

Figure 26 attempts to illustrate the greater problem of trust between the components of the 5G environment. This diagram is greatly simplified as this doesn't include the different organisations which may own and/or operate each of the different components of the system. Supply chain security is therefore also of key concern.

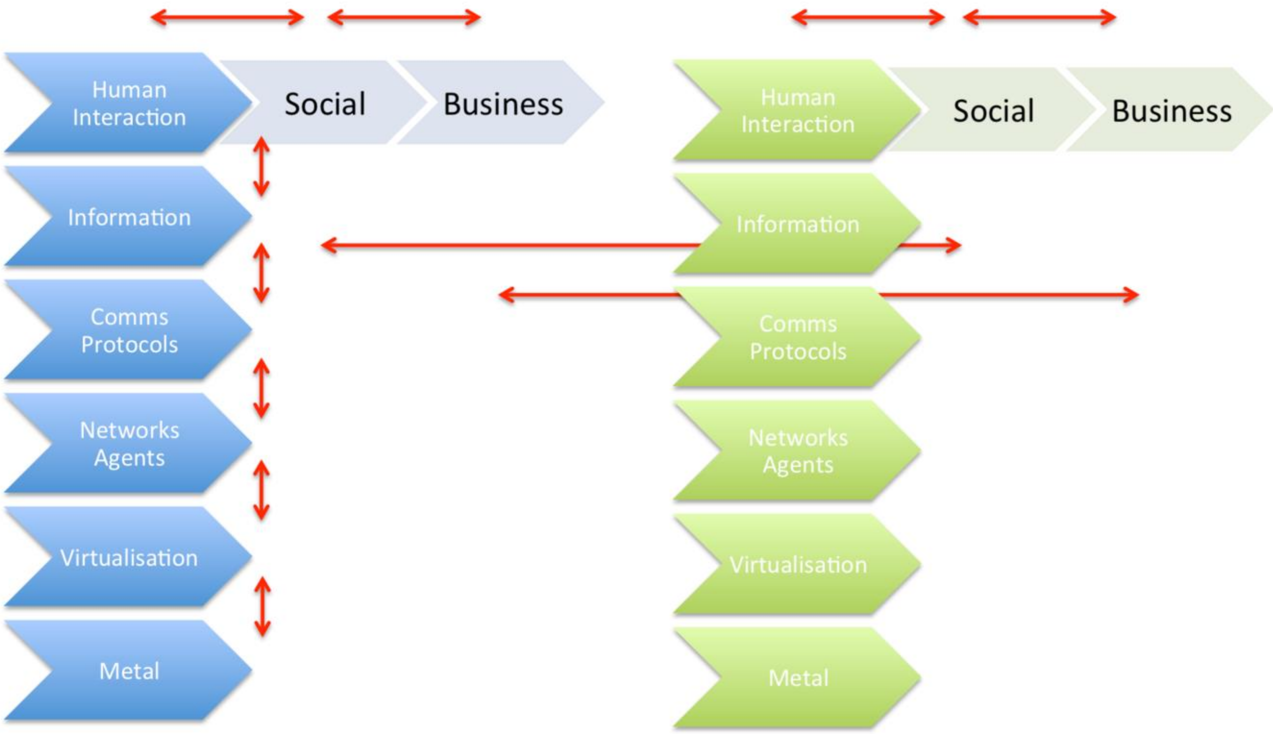

Figure 26 Who trusts who?

In conclusion, the following challenges need to be considered / addressed:

- A 5G network will be comprised of many more degrees of freedom than any other network.
- That 5G is likely to be adopted by mission critical applications (in some form), which underpin the safety and security of our society
- That security and resilience of 5G should be developed from the outset, and not left to be bolted on after first deployments.
- Information carried by a 5G network has a value which will diminish if the 5G network is compromised in any way.

4.7 The Internet of Things (IoT) and Tactile Internet in 5G Networks

The Internet of Things and Tactile Internet present many challenges around coverage, capacity, quality of service, energy, battery life, deterministic / low latency connections for real time activities which present a plethora of innovation opportunities which can part of future critical national infrastructure based on a 5G architecture.

The cost and performance of the 'Things' (Sensors, IoT and M2M nodes), should not be under estimated. Currently this is not being addressed in sufficient detail to ensure both that the technology is practical in terms of energy usage and that the costs are low enough to enable economies of scale.

More emphasis is required on the practical issue of IoT, M2M and remote sensors. Major challenges exist. The volumes will not materialise unless the modem cost and energy usage are reduced.

Current GPRS chipsets are fit for purpose today but as we migrate to newer generation technologies, replacement solutions will be required. M2M deployments could start to go down if there is not a cost-effective evolution / replacement after GPRS. 3G and 4G chips are being shipped in their billions today but they have functionality not required for IoT and M2M. New 4G LTE-M profiles are being developed to address the challenge.

5G presents the opportunity to design, from the outset, a much more efficient architecture, lower cost implementation and targeted specification to address the challenges identified:

1) Reduced modem complexity
2) Lower bill of material cost
3) Extremely low energy and significantly increased battery life

The following sections explore further challenges that can be addressed through innovation in a 5G evolving architecture.

4.7.1 Evolving Internet Generations

Each Internet generation was believed to be the last, with designs pushed to near perfection. The first and original Internet, a virtually infinite network of computers, was a paradigm changer and went on to define the economies of the late 20th century. However, after the Internet, came the Mobile Internet, connecting billions of smart phones and laptops, and yet again redefining entire segments of the economy in the first decade of the 21st century. Today, we witness the emergence of the Internet of Things (IoT), shortly to connect trillions of objects and starting to redefine yet again various economies of this decade. Is that it? Surely, so we argue, there is something much, much bigger at stake still.

These different embodiments of the Internet will be dwarfed by the emergence of the Tactile Internet which we believe is a true paradigm shift, in which sufficiently responsive, reliable network connectivity will enable it to deliver physical, tactile experiences remotely. For example, imagine delivering (possibly self-assembling) hospital equipment to the current areas of West Africa suffering from the Ebola epidemic. The best doctors and surgeons could then perform diagnosis and even surgery remotely using connected, tactile technologies.

We imagine the Tactile Internet will, in the business-to-business ecosystem, drive markets for autonomous cars, remote medical care markets, energy resource extraction and power generation, and other challenging industries. For consumers, it will revolutionize the way we teach, learn, and interact with our surroundings. A preliminary market analysis has revealed that the potential market could extend to US$20 trillion worldwide – around 20% of today’s worldwide GDP.

The figure below shows the evolution and composition of the Internet. Whilst experienced as “one” by the end user, the fixed Internet has indeed evolved by adding mobility, objects, and now touch. Whilst many challenges pertain of making this new Internet operational, the top three are arguably the scalability in rate, in devices and in dependability. In below sections, we discuss the technical challenges in more details, as well as how these emerging paradigms relate to 5G mobile communications systems.

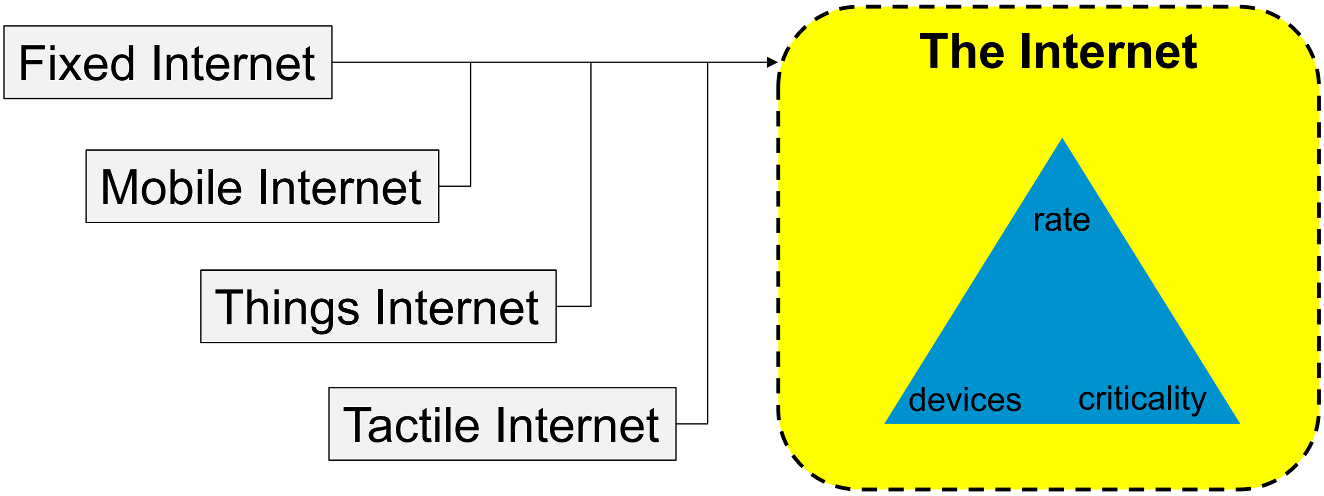

Figure 27 - The evolution and composition of the Internet, have starting as the fixed Internet, then evolved with the Mobile and Things Internet, and now being complemented with the Tactile Internet.

4.7.2 The Things Internet (IoT)

The Internet of Things ("IoT") is a world of ubiquitously connected objects, things, and processes. Located at the intersection of sensory, communication, networking, data storage, and information processing technologies[55], the IoT has the potential to produce a new wave of technological innovation and, according to Gartner, is expected to create over one trillion Dollars of economic value-add by 2020 through the corresponding market opportunities.

Indeed, the range of IoT applications is extremely broad, from wearable fitness trackers to connected cars, spanning the industries of utilities, transportation, healthcare, consumer electronics, and many others; an illustration is given below.

[55] Sergey Andreevy, Olga Galinina, Alexander Pyattaev, Mikhail Gerasimenko, Tuomas Tirronen, Johan Torsner, Joachim Sachs, Mischa Dohler, and Yevgeni Koucheryavy , "Understanding the IoT Connectivity Landscape – A Contemporary M2M Radio Technology Roadmap," IEEE Communications Magazine, to be published in 2015.

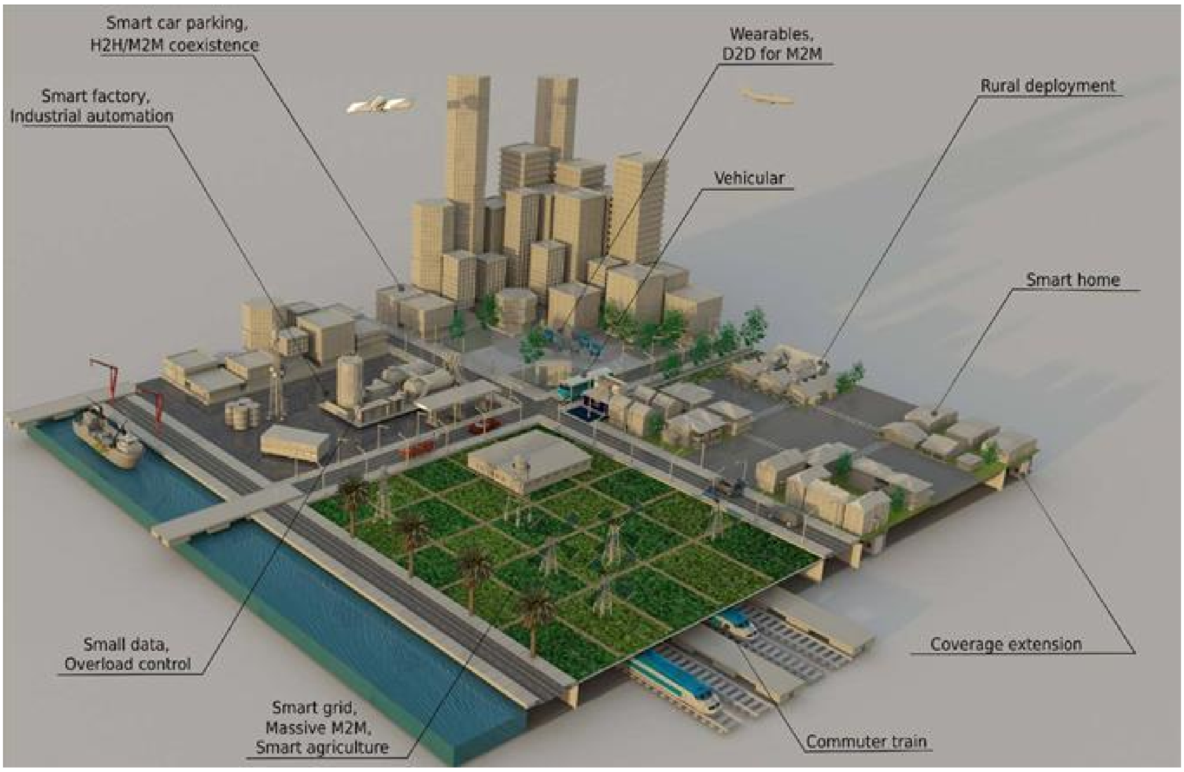

Figure 28 - A variety of promising Internet of Things applications are shown here, spanning from consumer to industry driven markets[56]; courtesy of [1] and © of Olga Galinina, TUT Finland.

However, we are only beginning to witness the true explosive growth of the IoT, with 10 billion M2M devices connected presently and 24 to 50 billion total connections expected within the following 5 years, as maintained by Cisco, Ericsson, and the GSMA. Over the following decade, we may thus see our everyday furniture, food containers, and even paper documents accessing the Internet, as suggested by the National Intelligence Council. Futurists have also coined a number of new keywords to emphasize the IoT's ongoing transformation, including the Internet of Everything (by Cisco), the Industrial Internet (by General Electric et al.), as well as the Networked Society (by Ericsson)[57].

The underlying facilitator for the IoT phenomenon is a reliable, robust, and available connectivity infrastructure. Machine-to-Machine (M2M) technologies are an integral part of such connectivity ecosystem[58]. But they are just a small part; they are the beginning; they

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[56] Sergey Andreevy, Olga Galinina, Alexander Pyattaev, Mikhail Gerasimenko, Tuomas Tirronen, Johan Torsner, Joachim Sachs, Mischa Dohler, and Yevgeni Koucheryavy , "Understanding the IoT Connectivity Landscape – A Contemporary M2M Radio Technology Roadmap," IEEE Communications Magazine, to be published in 2015.

[57] Sergey Andreevy, Olga Galinina, Alexander Pyattaev, Mikhail Gerasimenko, Tuomas Tirronen, Johan Torsner, Joachim Sachs, Mischa Dohler, and Yevgeni Koucheryavy , "Understanding the IoT Connectivity Landscape – A Contemporary M2M Radio Technology Roadmap," IEEE Communications Magazine, to be published in 2015.

[58] Finnish Strategic Centre for Science, Technology, and Innovation, Internet of Things Strategic Research Agenda (IoT-SRA), September 2011.

are, in a sense, the new (mostly wireless and feature-richer) "Ethernet cable" able to connect objects with other objects, with people, and the enormous computing nervous system spanning the globe.

Surprisingly, the design efforts related to M2M span back a few decades[59]. Indeed, driven by industrial needs, early forms of M2M connectivity trace back to supervisory control and data acquisition (SCADA) systems of the 1980s, all being highly isolated and proprietary connectivity islands. Along the way of its rapid development, the connectivity landscape has embraced legacy Radio Frequency Identification (RFID) technologies (starting in the late 80s), as well as (largely proprietary) Wireless Sensor Network (WSN) technology (starting in the 90s). Marked by the very attractive application scenarios in both business and consumer markets, the first decade of the 21st century was thus dedicated to the development of standardized low-power M2M solutions, through either industry alliances or standards developing organizations (SDOs).

Notable examples tailored to a range of industry verticals are ISA100.11a, WirelessHART, Z-Wave, and KNX. More generic (horizontal) connectivity technologies were developed within the leading SDOs, i.e. the IEEE, ETSI, 3GPP, and IETF (even though strictly not an SDO). Low-power short range solutions available today include Bluetooth (promoted by the Bluetooth SIG) and IEEE 802.15.4 (promoted by the Zigbee alliance). In subsequent years, the IEEE 802.15.4 physical (PHY) and medium access control (MAC) layers have been complemented by IP-enabled IETF networking stacks developed within 6LoWPAN (introducing header compression, packet fragmentation, and security), ROLL[60] (introducing routing), and 6TiSCH

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[59] Various references:

- Stojmenovic, "Machine-to-machine communications with in-network data aggregation, processing, and actuation for large-scale cyber-physical systems," IEEE Internet of Things Journal, vol. 1, no. 2, pp. 122–128, 2014.
- J. Sachs, N. Beijar, P. Elmdahl, J. Melen, F. Militano, and P. Salmela, "Capillary networks – a smart way to get things connected," Ericsson Review, vol. 8, pp. 1–8, 2014.
- D. Astely, E. Dahlman, G. Fodor, S. Parkvall, and J. Sachs, "LTE Release 12 and beyond," IEEE Communications Magazine, vol. 51, no. 7, pp. 154–160, 2013.
- M. Dohler, et al., "Machine to Machine Communications (M2M); Threat Analysis and Counter-Measures to M2M Service Layer," ETSI TC M2M, TR 103 167.
- M. Condoluci, M. Dohler, et al. "Towards 5G DenseNets: Architectural Advances For Effective Machine-Type Communications over Femtocells," IEEE Comm. Mag, Jan. 2015.
- L. Lei, M. Dohler, et al. "Queuing Models with Applications to Mode Selection in D2D Comm. Underlaying Cellular Networks," IEEE Trans. on Wireless Comm, accepted 2014.
- K. Zheng, M. Dohler, et al. "Challenges of massive access in highly dense LTE-advanced networks with machine-to-machine communications," IEEE Wireless Comm., v.21, 2014.
- M. Dohler, et al "Standardized Protocol Stack For The Internet Of (Important) Things," IEEE COMST, published in 2012.
- C. Anton & M. Dohler, Advances in Machine-to-Machine Communications. 2015 (book).

[60] CoRE - IETF working group https://datatracker.ietf.org/wg/6tisch/charter/

(introducing scheduling using the IEEE 802.15.4e process automation MAC); as well as the web-enabled IETF stack developed within CoRE[61]. In parallel, capitalizing on the ability to provide global coverage, 3GPP developed cellular-enabled machine-type connectivity modules tailored to markets with inherent mobility (e.g., car telemetry).

Despite decade-long developments by some of the best engineering teams in the world, none of the above technologies has emerged as a clear market leader. In addition, up-take of these solutions is below previous market predictions. A key consequence, however, is that the field of the IoT connectivity is now at a turning point with many promising radio technologies emerging as true M2M connectivity contenders: Low-Power Wi-Fi (currently being standardized by IEEE 802.11ah); Low-Power Wide Area (LPWA) networks (e.g., used by Semtech and represented in the Lora Alliance; or Sigfox[62] and currently documented in ETSI LTN[63]); and 4G/5G improvements for M2M systems (currently being standardized by ETSI M2M, 3GPP, and the oneM2M alliance[64]).

To enable a consumer and/or industry driven IoT, the underlying connectivity M2M system must be reliable and available; in more details:

- **availability** means sufficient coverage; the ability to support roaming, mobility; and enjoying a critical mass in rollouts;
- **reliability** means resilience to interference; throughput guarantees; low outages; among others.

In the light of these requirements and illustrated in Figure 29, let us examine the connectivity landscape from a high-level perspective:

- **Zigbee-like M2M Technologies.** These technologies encompass current Zigbee embodiments but also technical amendments being standardized by the IEEE and the IETF. With above definition, it is apparent that coverage, support of mobility and roaming are very poor. Whilst Zigbee did and still (Q2 2015) enjoys rollouts, it is far from reaching critical mass. From a reliability point of view, it is extremely susceptible to interference (particularly in urban environments), has no throughput guarantees and often produces lengthy system outages when used in mesh configuration. Overall, the technology is surprisingly unfit to power the emerging Internet of Things. Major companies have finally realized this; Broadcom, e.g., stopped producing Zigbee chips in 2013, whilst ramping up its Low-Power Wi-Fi chip range.
- **Low-Power Wi-Fi M2M Systems.** Link coverage of Wi-Fi is better than Zigbee but not in the range of cellular systems. With Wi-Fi Hotspot 2.0 not operational yet, support

[61] IETF – ROLL working group https://datatracker.ietf.org/wg/6tisch/charter/

[62] SIGFOX http://www.sigfox.com/en/

[63] ETSI LTN ETSI specification for Internet of Things and Machine to Machine Low Throughput Networks http://www.etsi.org/news-events/news/827-2014-09-news-etsi-new-specification-for-internet-of-things-and-machine-to-machine-low-throughput-networks

[64] oneM2M http://www.onem2m.org/

of mobility and roaming are also fairly poor. However, it enjoys an enormous rollout worldwide which allows IoT companies to provide Wi-Fi-powered sensors and be virtually sure that Internet connectivity is available no matter where deployed. In terms of reliability, there is no QoS support nor a very sophisticated means to deal with interference when compared to cellular systems; however, it is significantly better than Zigbee systems.

- **Low Power Wide Area M2M Systems.** Current systems enjoy a massive link coverage area, and some simple roaming and mobility support; and even rollouts start to become of noticeable size, particularly in areas of strong growth in M2M use. Given that most of these systems operate in ISM bands and some only operate one-way, reliability is not very high but sufficient to power current M2M deployments[65].
- **3GPP Cellular Machine Type Communications (MTC) Systems.** Ignoring cost and energy consumption at this point, these systems enjoy a very high reliability and availability. It thus makes it a very popular choice in IoT applications where these criteria are vital. There are however factors which prevent it to be used as a universal solution and which are discussed below.

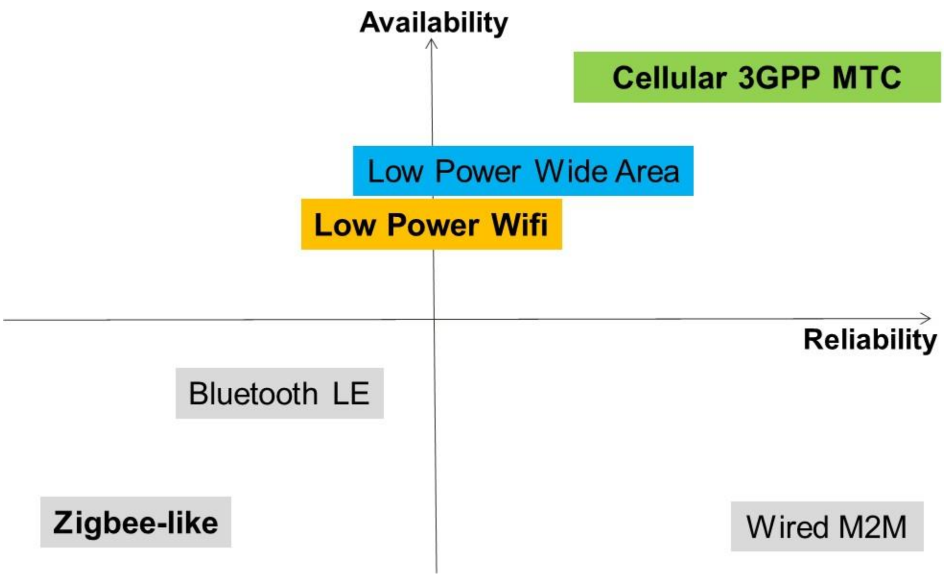

Figure 29 - A mapping of available IoT connectivity technologies into the availability and reliability map, where the traditionally preferred Zigbee systems perform surprisingly poorly whilst cellular systems are very promising.

For 5G to succeed, a set of key challenges need to be met:

1) **Performance.** The underlying IoT technologies need to be scalable into the billions of devices, without jeopardizing the operations of data/voice connections. Furthermore, delay ought to be bounded for many IoT applications; and dependability must be very high.

[65] Sergey Andreevy, Olga Galinina, Alexander Pyattaev, Mikhail Gerasimenko, Tuomas Tirronen, Johan Torsner, Joachim Sachs, Mischa Dohler, and Yevgeni Koucheryavy , "Understanding the IoT Connectivity Landscape – A Contemporary M2M Radio Technology Roadmap," IEEE Communications Magazine, to be published in 2015.

2) **Hardware Cost.** The current modem costs are not adequate for a truly scalable IoT ecosystem. Lowering the cost requires lowering complexity (ideally close to zero) since complexity is typically proportional to patent licensing fees.
3) **Data Plans.** With average returns per unit ("ARPU") being very low in the IoT, the data plans of operators and service providers ought to adapt and subsidize the connectivity data plans with the value extracted from the data.

4.7.3 The Tactile Internet

The notion of bridging sensing, real-time data transmission, real-time big data analytics, and robotic actuation has first been introduced by the applicant Prof M Dohler in September 2013, and was referred to as "Closing the Big Data Cycle"[66]. In May 2014, Prof G Fettweis from TU-Dresden in Germany and colleagues of his introduced the term "Tactile Internet" which has since become the de-facto technical term. Some high-level documentation on the requirements and potentials have emerged ever since[67] which established that the Tactile Internet will be servicing really critical aspects of society.

Technically, it will thus need to be ultra-reliable, maybe a second of outage per year, support very low latency and short end-to-end delays in the order of milliseconds – and have sufficient capacity to allow large numbers of devices to communicate with each other simultaneously and autonomously. It will be able to interconnect with the traditional wired internet, the mobile internet and the internet of things – thereby forming an internet of entirely new dimensions and capabilities.

Illustrated in Figure 30at the edges, the Tactile Internet will be enabled by the Internet of Things and actuating robots. Content and skillset data will be transmitted over a significantly more powerful 5G core network as well as the next generation Internet. The finite speed of

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[66] M Dohler, "Machine-to-Machine in Smart Cities & Smart Grids: Vision, Technologies & Applications," Keynote at WiFlex 2013, September 2013; http://bit.ly/1B4rLpY

[67] Various references:

- M Dohler, G Fettweis, "The Tactile Internet – IoT, 5G and Cloud on Steroids," Telefonica Guest Blog Post, 30 October 2014, >100k views; http://bit.ly/1BpOG3H
- S Hicks, M Dohler, et al. "The Tactile Internet – Enabled by 5G," UK BIS – Germany 5G Technology Collaboration, internal market briefing, September 2014; http://bit.ly/1MsadMW
- G Fettweis, H Boche, et al. "The Tactile Internet," ITU-T Technology Watch Report, August 2014; http://bit.ly/1BvAhlr
- G Fettweis, "The Tactile Internet: Applications and Challenges," IEEE Vehicular Technology Magazine, vol.9, no.1, March 2014; http://bit.ly/1wXjwks

light, however, will require a lot of the cloud intelligence to be enabled close at the edge, close to the tactile experience.

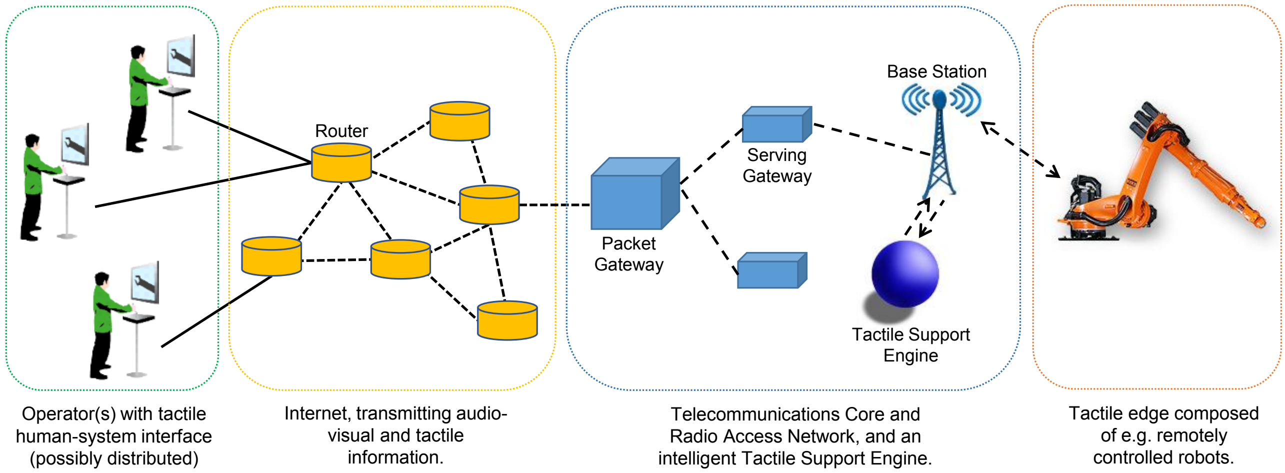

Figure 30 - Functional drawing of the Tactile Internet where the novelty is to break away from dedicated cabling between remote operator and tele-operated tactile edges while providing the same technical quality of service as well as unique features given the "internetisation" of the tactile paradigm.

Substantial design efforts in terms of dependability and ultra-low delay are needed in 5G to design and connect the Tactile Internet with the traditional wired Internet, the Mobile Internet and the Internet of Things – thereby forming an Internet of entirely new dimensions and capabilities. **In contrast to the prior Internets which enabled content delivery, the Tactile Internet however will be an enabler for skillset delivery** – thus a very timely technology for service and skillset driven economies like the ones predominantly found in Europe.

5 Frequency related radio innovation opportunities

5G will include evolution of 2G, 3G and 4G frequencies already used today and similar frequencies below 6GHz that may result from ITU-R WRC-15 activity. These frequencies are expected to be supplemented with new high frequency bands (above 6GHz) supporting much higher data rates and lower latencies. It is particularly in this area that there exists a need for innovation.

At this stage of 5G development, and in the lead up to the World Radio Conference in November 2015 (WRC-15), regulators and industry are still working towards consensus on specific higher frequency spectrum ranges to prioritise for further study for use by 5G services. While some proposals suggest the investigation of a of swathe of spectrum (above 6 GHz), much of the discussion has centred on the suitability of specific bands for 5G applications and the impact on any incumbent services in those bands. It is expected that ultimately a number of specific bands (perhaps around 4 to 6 in number) may be identified between 6 GHz and the mm-wave bands around 70GHz or higher.

One approach to promote consensus and help the research and development community to determine the priorities, would be to identify an initial set of potential frequency ranges, whilst also ensuring protection of incumbent services from interference. The following sections explore some of the options for consideration. In the UK, Ofcom has begun such work[68], looking at band usage above 6 GHz.

5.1 Low ARPU markets – use of satellite and associated frequencies

It could be argued that significant market growth over the next twenty years is likely to come from the 'middle earth' markets within the 48th to 48th parallel – an East to West rather than North to South divide.

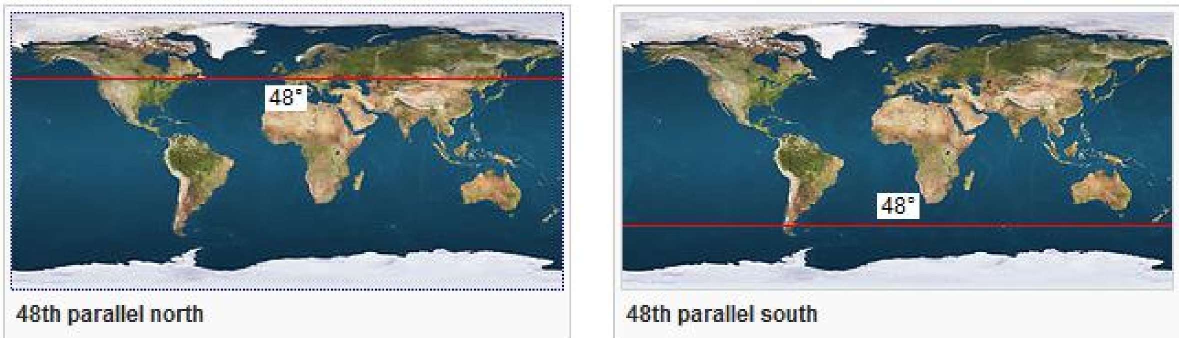

Figure 31 - Middle Earth 48th to 48th parallel

These include low ARPU markets in which it is hard to realize an adequate return on terrestrial network investment.

[68] Laying the foundations for next generation mobile services: Update on bands above 6 GHz
http://stakeholders.ofcom.org.uk/consultations/above-6ghz/update-apr15/

An interesting debate is in terms of the role of non-terrestrial platforms in the delivery of 5G services, in certain regions. Facebook[69] and Google[70] have sub space delivery platforms planned to service these markets cost effectively. Alternatively they can be served economically from Geostationary Orbit (GSO) satellites. WRC-2012 explicitly identified this need.

RESOLUTION 11 (WRC-12)

Use of satellite orbital positions and associated frequency spectrum to deliver international public telecommunication services in developing countries

The World Radiocommunication Conference (Geneva, 2012),

considering

a) that Resolution 1721 (XVI) of the United Nations General Assembly sets forth the principle of the availability of satellite communications to the nations of the world on a global basis;

b) that, in the United Nations Millennium Declaration (Resolution A/RES/55/2), the Heads of State and Government expressed their belief that the central challenge faced today is to ensure that globalization becomes a positive force for all the world's people; and further resolved "*to ensure that the benefits of new technologies, especially information and communication technologies ... are available to all*";

Figure 32 - Resolution 11 (WRC-12) - Use of satellite orbital positions and associated frequency spectrum to deliver international public telecommunication services in developing countries

It is easy to discount these regional markets as being uneconomic for 5G.

However there is no reason why 5G could not be delivered using some combination of ultra-sparse high bandwidth high tower terrestrial networks coupled to sub space and GSO satellites. All three of these delivery platforms provide good high latitude line of sight and are therefore inherently well suited to high frequency bands. As an example Avanti is the world's first satellite operator to develop and deliver 3G NodeB backhaul over Ka-band satellite technology. This enables the allocation of bandwidth to cater for the demands of 3G networks and coping with peaks and troughs without heavily wasted bandwidth costs. Such capability bodes well for future 4G and 5G networks which may be used to extend the coverage for such technology not only within Mega-cities but in sub-urban and rural areas.

5.2 High bandwidth urban requirements

Another area where industry is focussed is on high capacity urban deployment. In this case a relatively small hotspot of say 200m would offer a very high speed service, such as 10 Gb/s. Such hotspots would be concentrated on public indoor and outdoor spaces, For example transport hubs. Such high speed coverage hotpots would be relatively isolated, but within

[69] https://www.facebook.com/zuck/posts/10101322049893211

[70] http://www.google.com/loon/

the coverage area of a macro cell. An example scenario which assumes communication paths are via line of sight and reflections which is appropriate for high frequencies is shown in Figure 33.

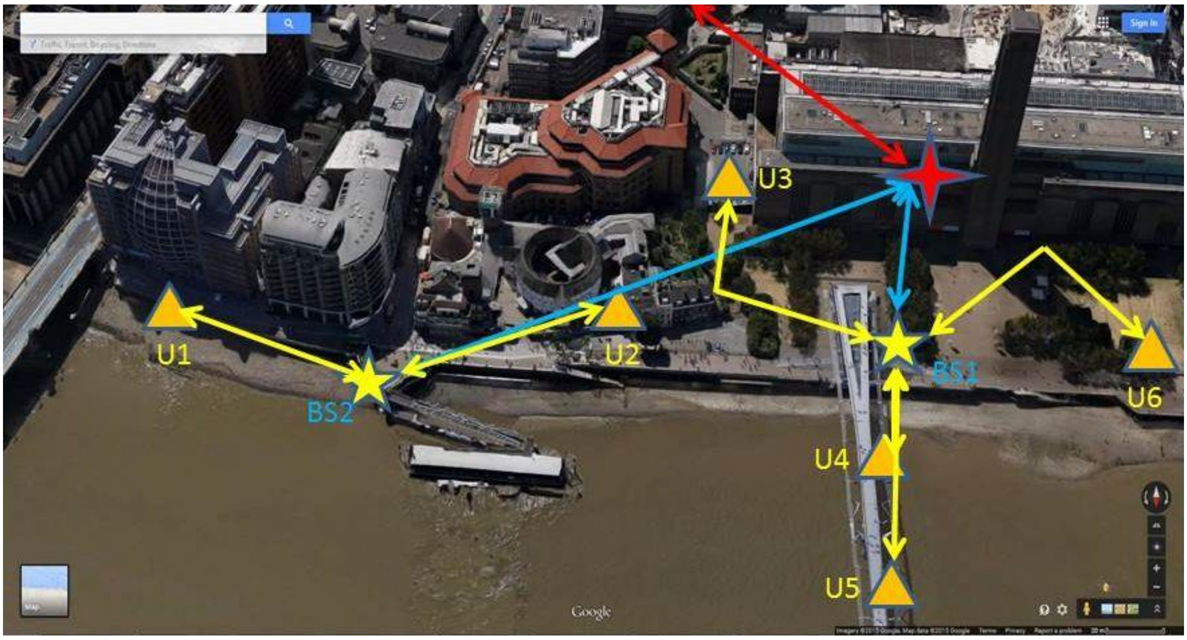

Figure 33 - Potential scenario for high speed 5G hotspots

In the scenario, the users (U1-U6) communicate via the nearest base station using directional beams and the base station serves them by steering its beam. The communication paths in the low level, dense urban environment (yellow) may need to include reflections to go around obstacles such as foliage, since diffraction and penetration capabilities are poorer than at conventional cellular frequencies. Base stations (BS1, BS2) have an initial backhaul to rooftop height (blue) and onwards above the rooftops (red). The inter-site distance is approximately 200m, therefore if different operators were involved in this scenario then either frequency planning or some other co-ordination would be required.

5.2.1 Control and user plane spectrum

A highly directive antenna is very useful for user plane communications (i.e. the user's data stream), but not so good for control messages. This is because control messages generally need to communicate with all users regardless of location in a cell (and so not only where the beam is pointing). This is a major driver for a separation of the control and user planes, referred to as the C/U split. If the control plane is handled separately by an omnidirectional link such as a macro layer, then the highly directional user plane link is free to maximise data transfer rates. This leads to separate requirements for user and control plane spectrum.

5.3 6 to 200 GHz review

When considering the requirements and expected capabilities for very high speed 5G services many industry commentators believe that the most promising means to satisfy these is through the allocation of new higher frequency spectrum above 6 GHz. Technically, mmWave bands start at 30GHz, however when considering higher frequency bands industry describes bands above 6GHz as mmWave[71].

It is more likely that in higher mmWave bands a wide contiguous bandwidth (e.g 1 GHz per operator) can be found that can be used to efficiently deliver very high data rate gigabit mobile services. In this frequency range, military and commercial sharing of spectrum has been an industry reality for as long as the radio industry has existed and coexistence continues to need to be managed from all bands from Very Low Frequency (VLF) to the top of the Terahertz band Many services currently occupy spectrum in these bands including military and civilian radar, military and civilian LEO, MEO and GSO satellite systems, military and civilian fixed links and a wide range of other RF sensing and communication systems including, for example, systems being developed for next generation drone/unmanned aerial vehicle control. Also in this frequency range are bands where license exempt devices may be used and where the use of radio astronomy dictates that no transmission may occur. Figure 34 illustrates some of the uses described above. There are number of smaller uses which are no less important. These are not shown in order to emphasise uses which consume the larger bandwidths.

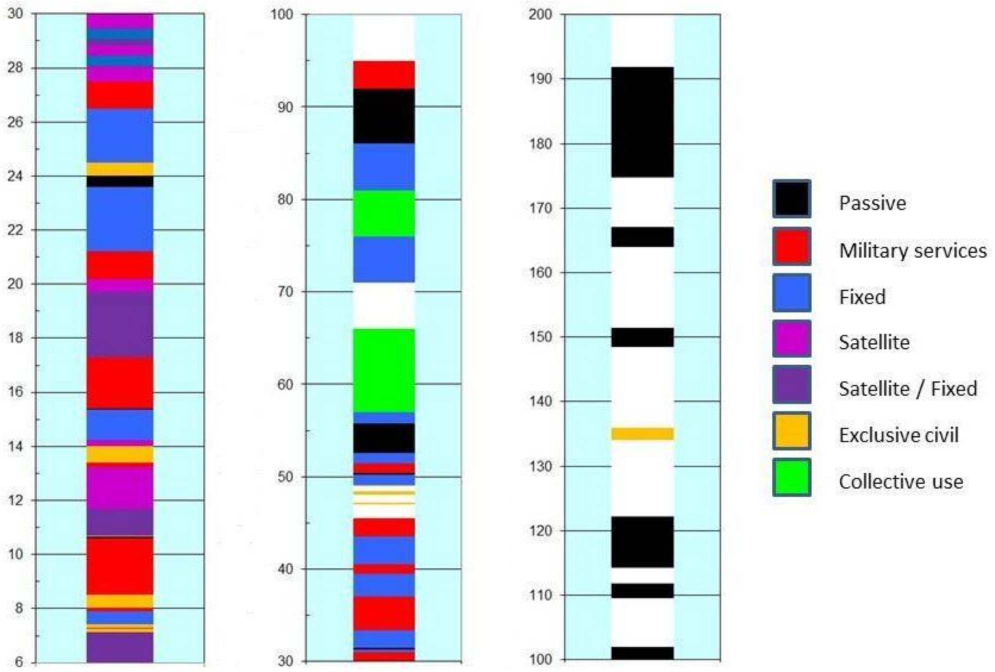

Figure 34 Example services and users in the 6-200 GHz range (not exhaustive)[72].

In-house industry research and development as well as academic programmes are considering the possibilities to use spectrum in the range from 6 GHz up to over 100 GHz.

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[71] See Section 10Appendix – Spectrum band naming and history, for details of bands and naming conventions

[72] "5G candidate band study", Quotient Associates, 2015, http://stakeholders.ofcom.org.uk/consultations/above-6ghz/update-apr15/

5.4 Key enablers

Use of these frequencies not previously considered for cellular mobile applications has been enabled through the development of new technologies particularly in the field of smart antenna systems. Beam forming arrays in both base stations and end user devices have been demonstrated that can track a highly mobile user, overcoming the higher propagation losses in the higher frequencies and delivering focused gigabit capacity to the end user.

Under the specific condition that only several hundreds of metres range is the objective, fundamental barriers (e.g. atmospheric loss, rain fade, penetration loss and propagation characteristic) do not decisively favour one part of the mmW band over another - even in the narrow areas around the oxygen and water absorption peaks at 60 GHz and 120 GHz. This is in clear contrast to longer range systems such as fixed links and satellite, where working at lower frequencies is a key enabler. This has clear implications for 5G mmW spectrum planning.

Demonstrations have been carried / planned in several frequency bands above 6 GHz. See table below for examples:

Band	Demonstration	Links to further information
11GHz	NTT Docomo	https://www.nttdocomo.co.jp/english/info/media_center/pr/2013/0227_00.html
15GHz	NTT Docomo and Ericsson	https://www.nttdocomo.co.jp/english/info/media_center/pr/2015/0302_03.html
28 GHz	Samsung	http://global.samsungtomorrow.com/samsung-electronics-sets-5g-speed-record-at-7-5gbps-over-30-times-faster-than-4g-lte/
38 GHz	New York University/ Samsung	http://www.researchgate.net/profile/Shu_Sun5/publication/260706063_Millimeter_Wave_Mobile_Communications_for_5G_Cellular_It_Will_Work!/links/00b7d53207c621ec69000000.pdf
44GHz	Mitsubishi Electric and NTT docomo	http://www.mitsubishielectric.com/news/2015/0302-b.html
60 GHz	Samsung/WiGi	http://www.extremetech.com/computing/191872-samsung-develops-60ghz-Wi-Fi-capable-of-4-6gbps-will-be-in-devices-next-year
60 GHz	MiWaveS	www.miwaves.eu
73 GHz	Nokia/NI/NYU	http://networks.nokia.com/news-events/press-room/press-releases/nokia-networks-showcases-5g-speed-of-10gbps-with-ni-at-the-brooklyn-5g-summit

Generally speaking there are a number of bands between 6 GHz and up to 100 GHz that are allocated on a co-primary basis to the mobile service globally in the ITU Radio Regulations[73]. Many of these bands have the capacity to support wide contiguous bandwidths of up to

[73] International Telecommunication Union, ITU. Radio Regulations Articles, http://www.itu.int/dms_pub/itu-s/oth/02/02/S02020000244501PDFE.pdf

1GHz or more. When considering the opportunities for IMT[74] identification in frequencies above 6 GHz, based solely on the existing ITU-R Mobile Service allocations as an initial filter, there are several bands that might offer the kind of contiguous bandwidth that is anticipated for future 5G systems. These bands are shared with other co-primary services so a full analysis would require careful study before any final decisions are taken.

The four figures below, show the mobile service primary allocations in the ITU-R Radio Regulations from 10GHz to 90GHz. The highlighted mobile service bands are allocated on a co-primary basis in all three ITU regions.

Figure 35 to Figure 38 show the overall range of mobile allocated bands. Specific bands examples are examined in more detail later in this section.

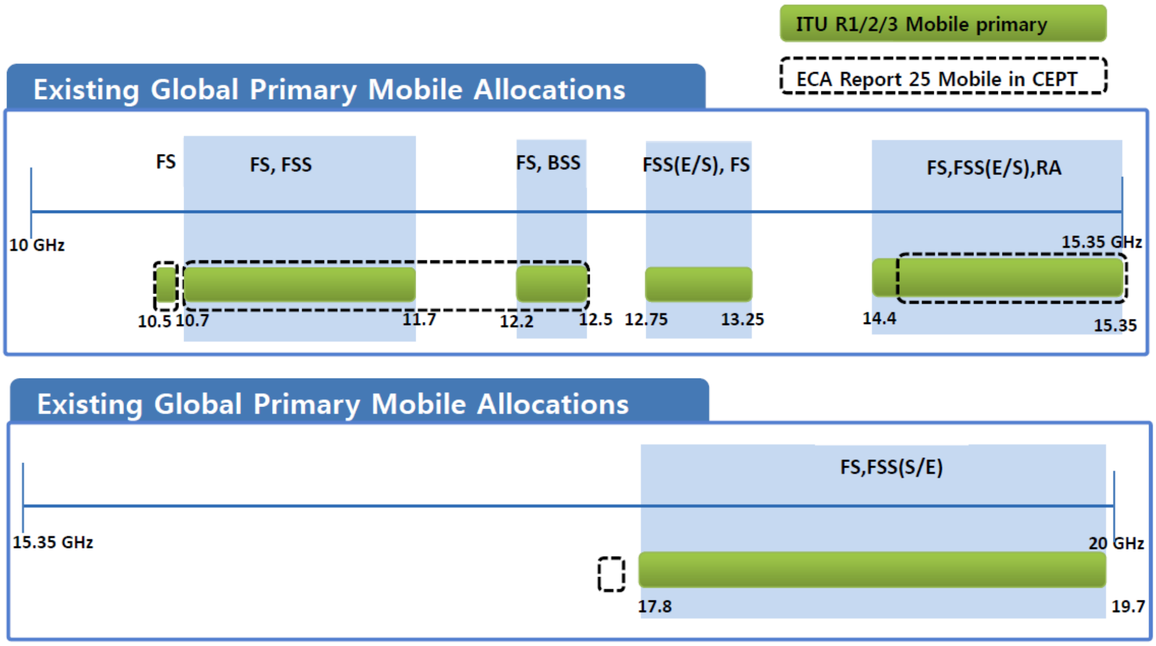

Figure 35:- 10 to 20GHz

[74] IMT-Advanced standards for mobile broadband communications, Over the last 25 years, ITU has developed the IMT framework of standards — or International Mobile Telecommunication system — for mobile telephony and continues to lead international efforts involving governments and industry players to produce the next generation standards for global mobile communications. http://www.itu.int/en/ITU-R/Documents/ITU-R-FAQ-IMT.pdf

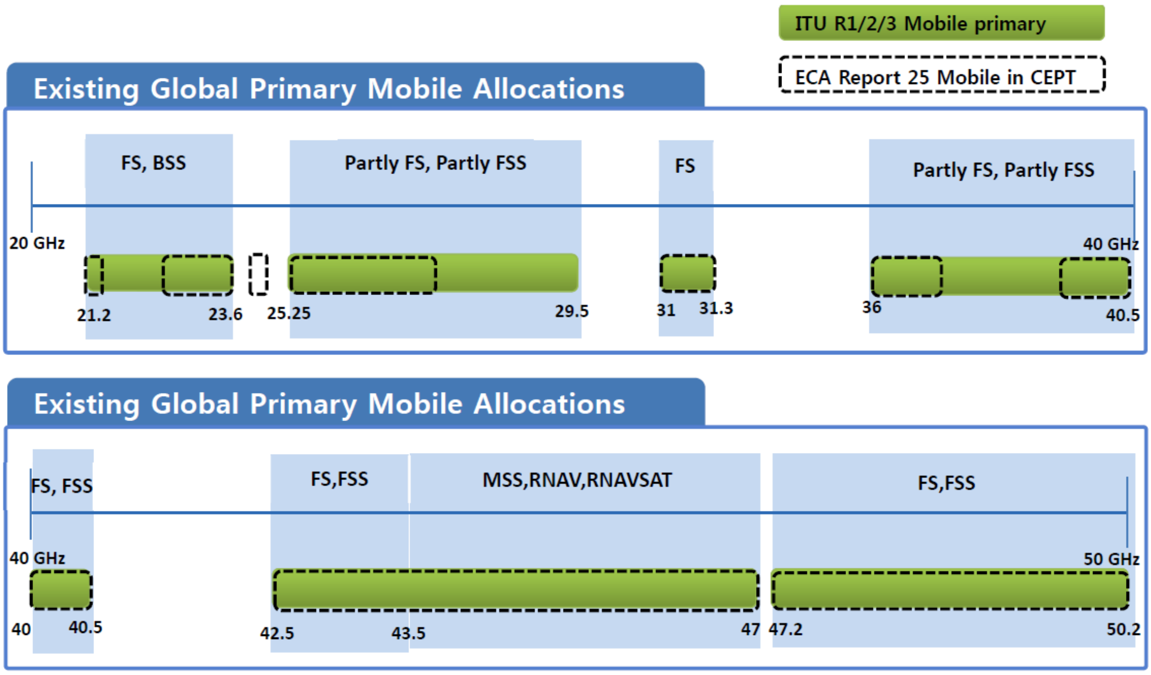

Figure 36:- 20 to 50GHz

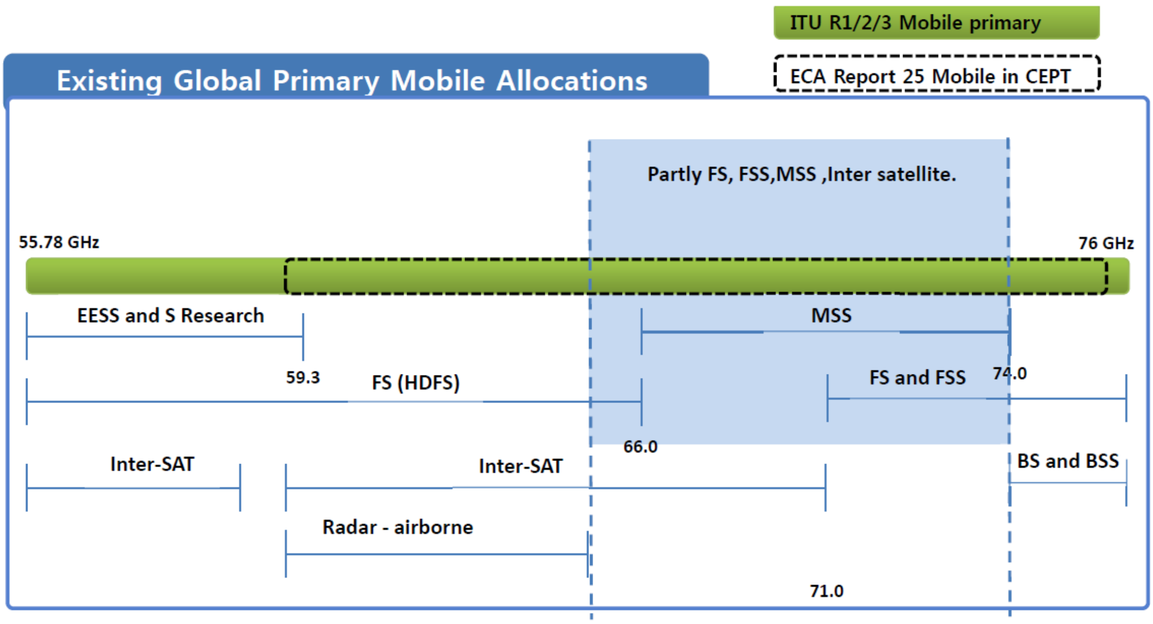

Figure 37: Above 50GHz (64 to 74GHz)

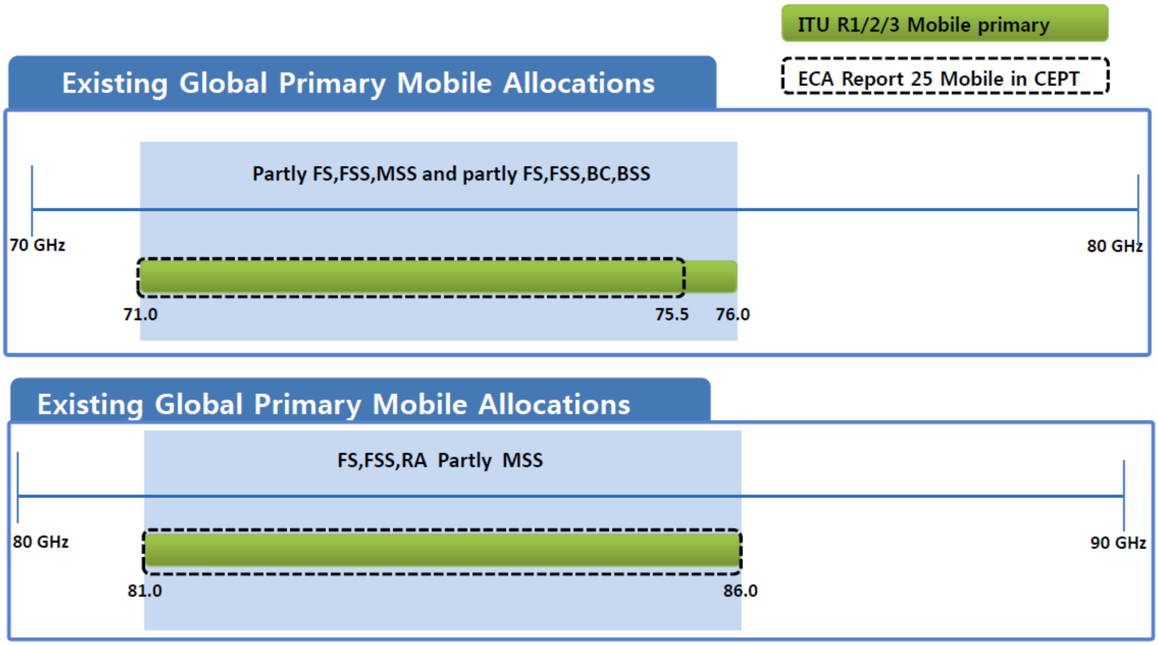

Figure 38: 70 to 90GHz

It might be possible to identify new global mobile service allocations in the Radio Regulations requiring WRC activity.

5.4.1 Spectrum Sharing

As illustrated in Figure 34, many of these bands are already in use by other established and valuable services that might be difficult to move to alternative frequency bands. Therefore in order to consider new bands for mobile use spectrum sharing and coexistence possibilities are likely to require careful consideration without imposing restriction on growth of existing services in these bands.

5G services in the higher frequencies will employ new techniques not previously considered in mobile networks and these may bring new characteristics that could enable new spectrum-use possibilities previously considered difficult. Spectrum sharing in an efficient manner is a topic that is becoming more important to policy makers as wireless services in all bands and of all types increase the pressure on the finite spectrum. This could be a rich area for research and many proposed research programmes feature an element concerning spectrum sharing not only between radio communication services but also between operators potentially using the same spectrum. Overall, it is hard to see how 5G capacity and data rate expectations can be met without significant bandwidth allocations above 6 GHz.

5.5 World Radiocommunication Conference (WRC)[75] 2015 and 2019

World Radiocommunication Conferences (WRC)[76] are held every three to four years. It is the job of WRC to review, and, if necessary, revise the Radio Regulations, the international treaty governing the use of the radio-frequency spectrum and the geostationary-satellite and non-geostationary-satellite orbits. Revisions are made on the basis of an agenda determined by the ITU Council, which takes into account recommendations made by previous WRCs.

The general scope of the agenda of WRCs is established four to six years in advance, with the final agenda set by the ITU Council two years before the conference, with the concurrence of a majority of Member States.

The information provided below has been compiled to help the technology and innovation community understand the process and current status with respect to frequencies discussed within this paper. Please contact Ofcom[77] or the UK SPF[78] if you wish to be directly involved with UK process related to WRC activities.

For WRC-15 there are two agenda items relating to spectrum for mobile broadband applications. These are Agenda Item 1.1 focusing generally on new bands to be identified for IMT[79] and Agenda Item 1.2 focusing on the ratification of a primary allocation in the 700 MHz band in ITU-R Region 1 (Europe and Africa). The bands under consideration under agenda item 1.1 are all below around 6 GHz and are the subject of intense debate in the regional WRC preparatory groups.

In addition WRC-15 Agenda Item 10 considers items for the agenda of the next conference (WRC-19) and proposals are under consideration for an item to identify high frequency mobile allocations for future IMT mobile broadband.

5.6 Potential bands and associated challenges - examples

This section looks at several areas as examples of the type of work required for solutions to be developed in the bands identified. This is not intended to be an exhaustive list and other potential bands are possible such as the bands currently being proposed by Ofcom to

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75 The World Radiocommunication Conference 2015 (WRC-15) will be held in Geneva, Switzerland, from 2 to 27 November 2015. http://www.itu.int/en/ITU-R/conferences/wrc/2015/Pages/default.aspx

76 World Radiocommunication Conferences (WRC) ITU website http://www.itu.int/en/ITU-R/conferences/wrc/Pages/default.aspx

77 Ofcom http://www.ofcom.org.uk/, see http://stakeholders.ofcom.org.uk/consultations/wrc15/update-jan-15 for previous WRC15 consultation information.

78 UK Spectrum Policy Forum (UK SPF) https://www.techuk.org/about/uk-spectrum-policy-forum

79 IMT is the ITU-R family name given to the set of standards relevant to mobile broadband technologies referenced through ITU-R Recommendations.

identify potential spectrum for future mobile services, including 5G mobile networks. On April 20, 2015 Ofcom published an update on bands initially under consideration above 6 GHz.

5.6.1 20 GHz to 40GHz

In October 2014, Samsung 5G trial[80] achieved 7.5Gbps stationary speed and uninterrupted 1.2Gbps 5G connection while travelling at over 100km/h.

The 1.2Gbps test conducted in an outdoor setting from a vehicle moving on a 4.35km professional outdoor race track.

Figure 39 - Samsung 5G @ 28GHz trial

Both the stationary and mobile tests were conducted over a 28GHz[81] 5G network. The trial leveraged new Hybrid Adaptive Array Technology, which uses millimeter wave frequency bands to enable the use of higher frequencies over greater distances.

5.6.2 45 to 49 GHz

The 45.5-48.9 GHz band includes two relatively small exclusive bands used for the Amateur service and PMSE. The PMSE band might be suitable for clearance since no allocations were made in 2014. The Amateur service however is the 6mm band, in which there is clear usage.

Even if these exclusive bands were avoided, then 2.8 GHz is available in total, although not contiguously. However, this could be split naturally into three bands of 1.5, 0.8 and 0.6 GHz, which could support 3 operators, albeit with unequal bandwidths. Alternatively four operators could use 0.75, 0.75, 0.8, 0.6 GHz for a more equitable distribution.

[80] Samsung Electronics Sets 5G Speed Record at 7.5Gbps, Over 30 Times Faster Than 4G LTE: http://global.samsungtomorrow.com/samsung-electronics-sets-5g-speed-record-at-7-5gbps-over-30-times-faster-than-4g-lte/

[81] Under a test licence issued by the South Korean Administration under its national frequency allocation

45.5-47 GHz is allocated to RNSS, but not used[82]. In the European Common Allocation (ECA) table the application column is blank and there is note which reads 'Not allocated', which appears contradictory, but may simply indicate that no active use is known.

47.2-48.9 GHz is blank in Ofcom's interactive spectrum map of usage, with the exception of the Amateur band, although allocations do exist[83]. The Amateur band is globally allocated.

Internationally, most of 45.5-48.9 has a mobile allocation in Europe, China, South Korea and USA. In Japan, the mobile allocation stops short at 47 GHz. In China we are aware that 802.11aj, the 'China mmW' version of WiGig has recently claimed part of this band (since there is insufficient spectrum at 60 GHz).

These bands could be suitable for collective use, for the same reasons as given for 66-71 GHz, below.

5.6.3 66 to 71 GHz

The 66-71 GHz band has a mobile allocation which is unused. It also has allocations to RNAV and RNSS, which are either not in use or not expected to be a major coexistence issue[84]. There is no declared NATO military interest here for present or future use.

This band is suitably wide at 5GHz and is adjacent to the WiGig band, so that low cost technology should be available. If WiGig at 57-66 GHz is included in future handsets, then a single RF chain could probably serve 66-71 GHz as well. Several operators could be supported in this band with individual 1 GHz assignments.

This band could be collectively used[85], allowing access by 5G mmWave and other devices meeting specific band conditions. Alternatively, even with a partition to accommodate 5G mmW via bespoke conditions, there could still be bandwidth available for other collective use. Collective use is most appropriate since the probability of interference is lower at higher frequencies.

Internationally, this band is allocated to mobile in at least Europe, China, Japan, South Korea and USA. In the ECA table there is a note which reads 'Future Civil Systems' for this band.

5.6.4 71 to 95 GHz

5.6.4.1 Proximity of E band and 77 GHz automotive radar

The two lower bands (71-76 GHz and 81-86 GHz) sit either side of the automotive radar band (77 to 81 GHz), a band in which substantial technology innovation is taking place in time and

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[82] Source: European GNSS Agency.

[83] These appear to be little used.

[84] Source: European GNSS and Space Agencies.

[85] e.g. under licence exemption.

frequency domain spatial processing and wide channel bandwidth chirp(frequency sweep) waveforms.

High end cars are now being introduced with as many as 11 linked radar systems with an expectation that these systems will soon become available in mid- range and lower price cars. This is sophisticated RF technology at consumer price points.

77 GHz Automotive radar (77-81 GHz)

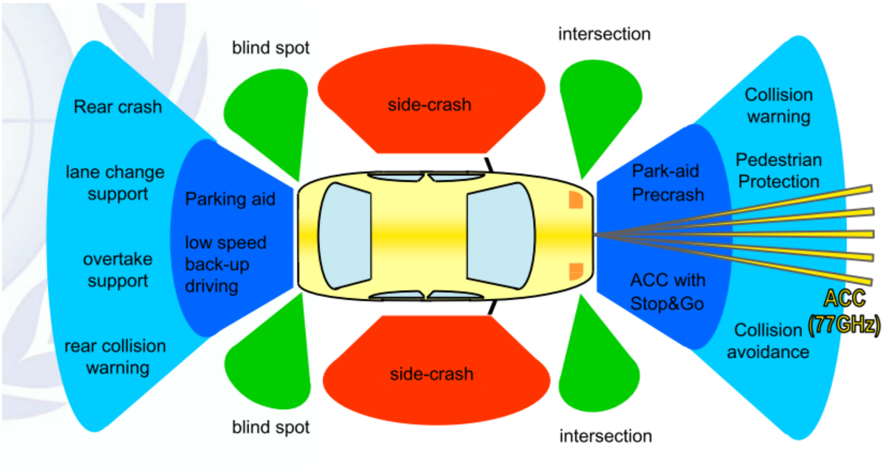

Figure 40 Automotive Radar[86]

5.6.4.2 US Defence investment in E band

In the US, DARPA have a Mobile Hotspot E band military system development project based on gigabit air to ground and ground to air links implemented in E Band between 71 and 76 MHz and 81 to 86 GHz integrated with voice and data support for LTE smart phones[87].

Power amplifier efficiency at E band of 25% is claimed with similarly impressive LNA noise figures. The E band antennas deliver 40 dB of gain with a 2 degree beam width providing a clear weather range of 60 km.

The network is self-configuring and designed to minimise signalling overheads and routing delay and delay variability. It is claimed to be possible to provide Hot Spot coverage of 1000 square kilometres within a few hours using unmanned aerial vehicles as the delivery platform. By any definition this is not a local area system.

E Band DARPA Project

[86] Automotive Radar: www.itu.int/md/dologin_md.asp?id=R09-SEM.WMO-C-0022!!PDF

[87] See for example, http://www.microwavejournal.com/articles/print/23121-darpas-mobile-hotspot-program-drives-e-band-performance-benchmarks

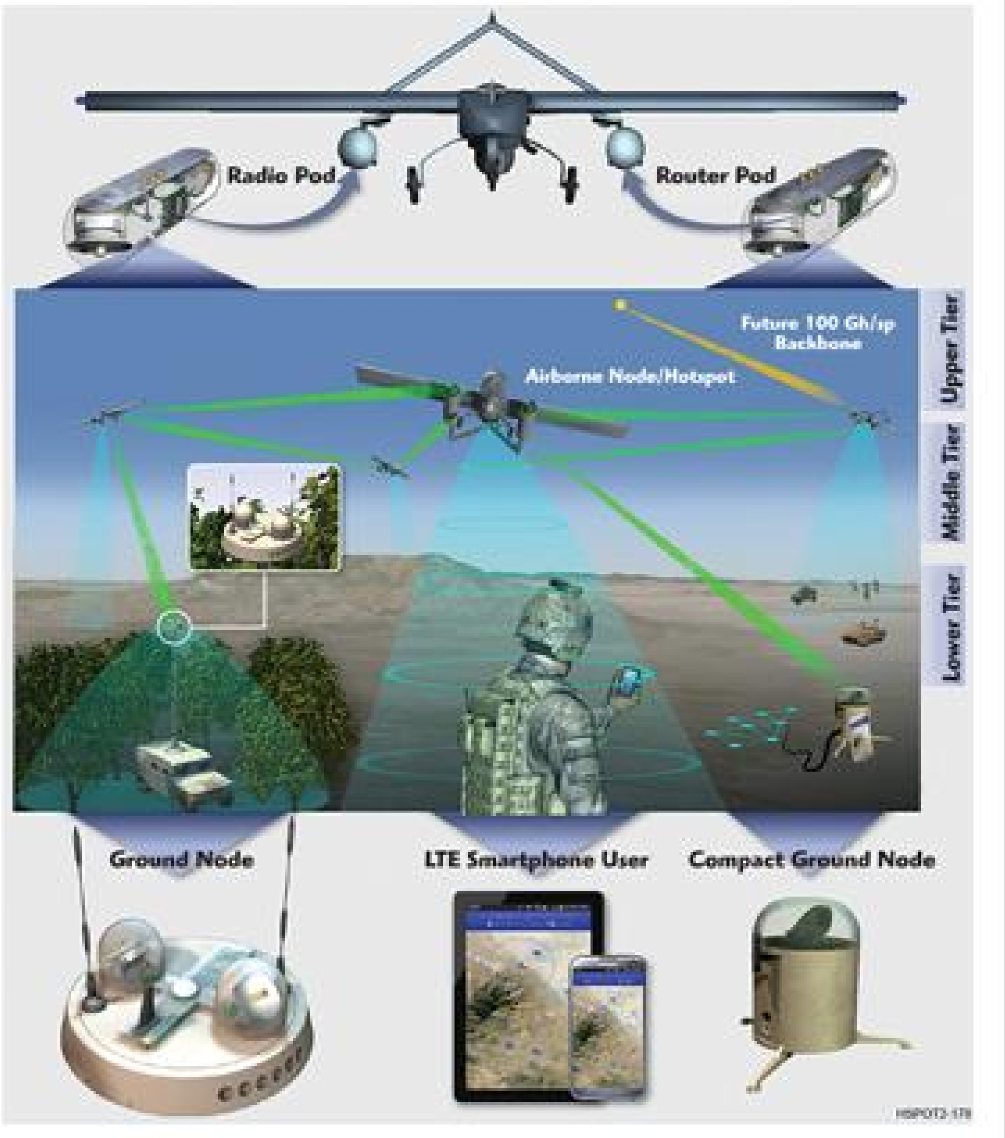

Figure 41 - DARPA E Band Mobile Hot Spot Project with LTE support[88]

5.6.4.3 *European research programmes in E band*

European research is also being targeted on this band, for example the MiWaveS project.

[88] DARP E Band Mobile Hot Spot Project with LTE support http://www.microwavejournal.com/articles/23121-darpas-mobile-hotspot-program-drives-e-band-performance-benchmarks

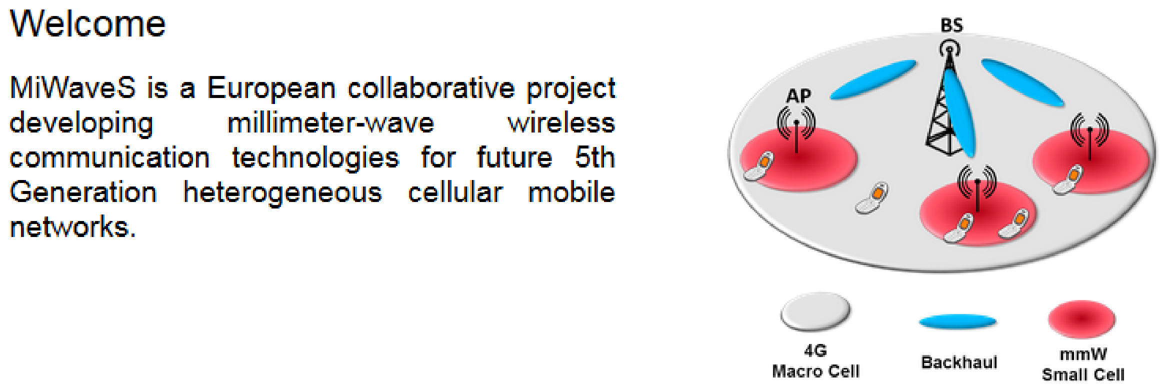

Figure 42 - European MiWaveS research programme[89]

Emerging commercial interest in the band is reflected by the developing availability of system components- for example E band antennas. This example from Huber+Suhner supports a 20% bandwidth (and therefore covers both of the 70/80 GHz bands, each of 5 GHz bandwidth).

Figure 43 - Huber + Suhner E Band antenna[90]

[89] European MiWaveS research programme: http://www.miwaves.eu/

[90] Huber + Suhner E Band antenna http://www.microwavejournal.com/articles/23643-low-profile-lightweight-ev-band-flat-antennas

6 Standards – test and measurement

Specification standards play a vital role in the development of each new generation of communication systems as they ensure that there is agreement between the all the equipment manufacturers and the operators to define every aspect of the system to ensure compatibility and compliance with the RF spectrum regulations ("ITU"). These standards are underpinned by measurement to quantify the "possible and deliverable" at a realistic price point. In turn, measurement is underpinned and traceable to National Measurement Institutes (NMIs), such as the National Physical Laboratory ("NPL") in the UK and the National Institute of Standards and Technology ("NIST") in the USA. Figure 44 shows the interplay between the key types of organization.

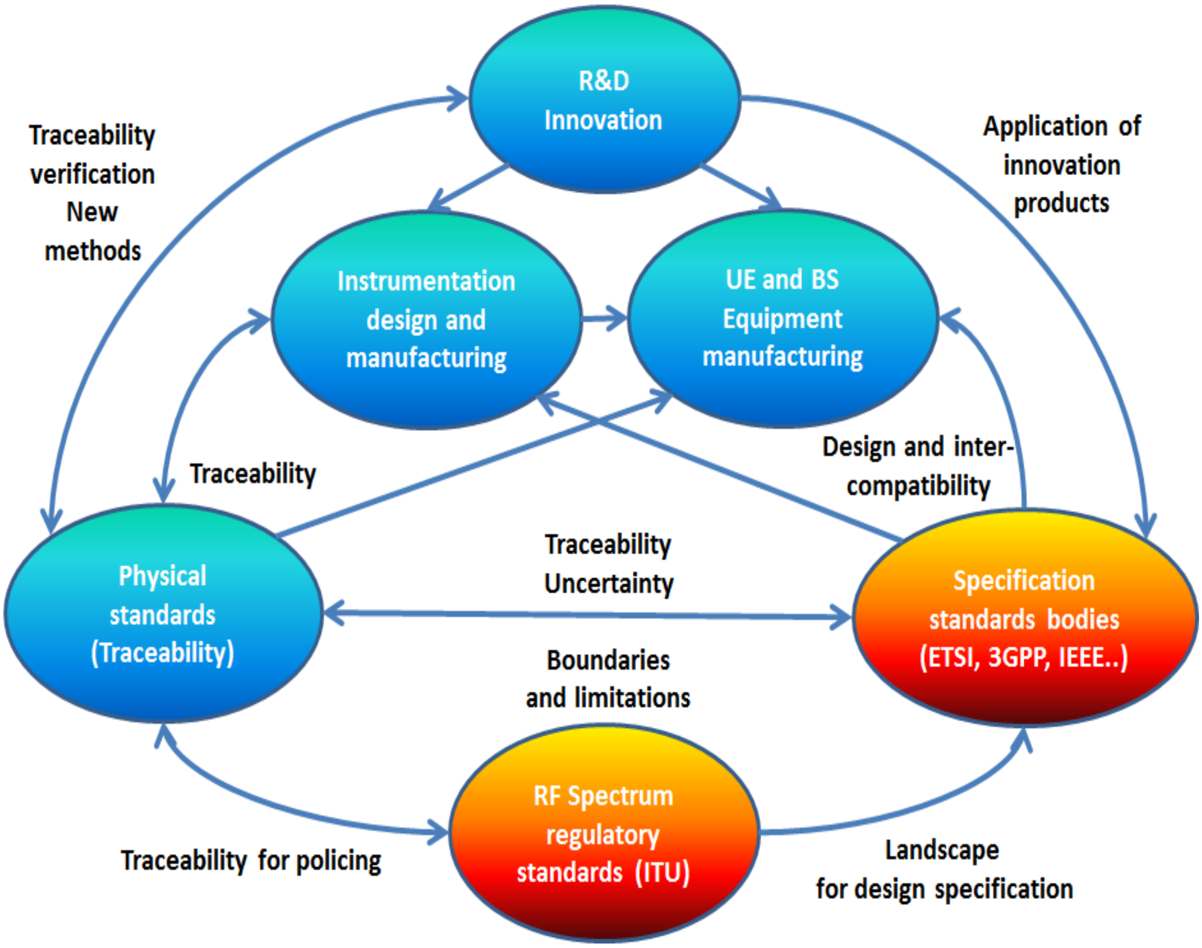

Figure 44 - Relationships between the standards and manufacture

The R&D activity that underpins the new generation development covers may aspects from device and amplifiers to the theory, simulation and algorithms. Good metrology can help this process as the measurements will be at the edge of the equipment capability and as this precedes the specification and dedicated test equipment is not available. Within industry "test-fests" between the equipment manufacturers are a convenient verification approach to show compliance. Can this support innovation for 5G? The answer is "yes, eventually" but at this point in the development there is no agreed specification and if the devices will not communicate then you still need measurement.

Although there is a disconnect between the simple standards used for traceability and the complex instrumentation used to test telecommunications equipment a number of NMIs have pursued the problem to provide support for industry as shown in Figure 45. Within Europe, NPL is currently the leading institute and several other NMIs also have considerable expertise. Outside Europe, NIST has been reorganised to support its communications industry[91] and in the far-east China (NIM), Korea (KRISS) and Japan (NMIJ/NICT) are rapidly developing capability.

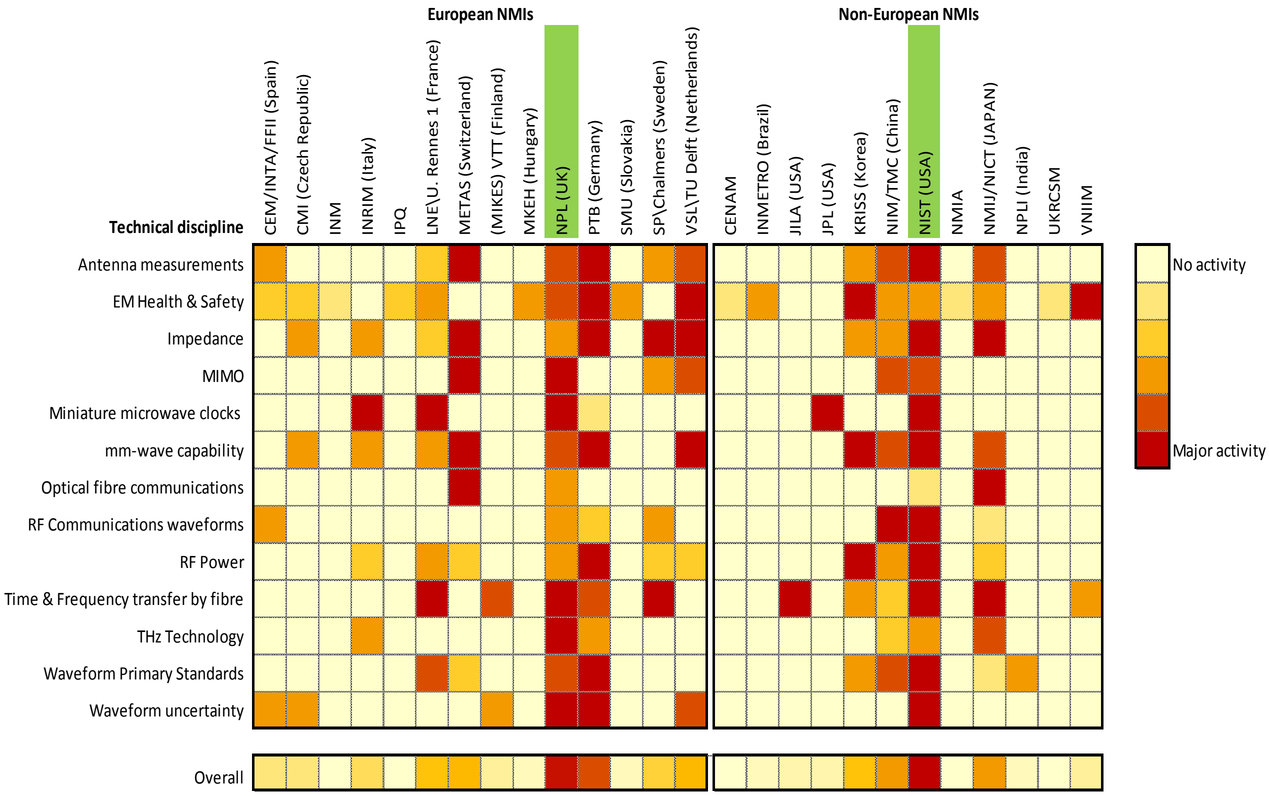

Figure 45 - Activities in National Measurement Institutes to support 5G innovation

NPL has addressed measurement problems in preceding communication system generations, such as RF peak power[92] (2nd) and EVM[93] (3rd) by developing a route to traceability. The importance of communications to the wider community is recognised within Europe and a series of metrology research projects[94,95] has been funded by Euramet, each

[91] NIST Communication Technology Laboratory http://www.nist.gov/ctl/

[92] D. A. Humphreys and J. Miall, "Traceable RF peak power measurements for mobile communications," IEEE Trans. IM, vol. 54, No 2, pp. 680 – 683, April 2005.

[93] D. A. Humphreys and R. T. Dickerson, "Traceable measurement of Error Vector Magnitude (EVM) in WCDMA signals, "Conf. on Waveform Diversity, Pisa, Italy, pp.270 – 271, 2007.

[94] "Publishable JRP Summary Report for JRP IND16 Ultrafast Metrology for ultrafast electronics and high-speed communications," available at https://www.euramet.org/fileadmin/docs/EMRP/JRP/JRP_Summaries_2010/IND16_Publishable_JRP_Summary.pdf

project involves several NMIs with the aim to underpin communications from the primary standards to MIMO and over the air (OTA) measurements. The most recent of these is targeted at 5G with the aim of developing the measurement standards in parallel with the technical development[96].

6.1 Operation of the regulation and specification standards bodies

There are several different levels of standards organizations that impact on the development of 5G communications. Examples are theITU), 3rd Generation Partnership Project (3GPP), European Telecommunications Standards Institute (ETSI), Institute of Electrical and Electronic Engineers Standards Association ("IEEE-SA") and the CTIA - The Wireless Association which was originally known as the Cellular Telephone Industries Association. This list is not exhaustive but gives a representative sample of the types of standards bodies.

A key differentiator is the role of ITU in the allocation of RF Spectrum. The ITU-R can take a global perspective on frequency band allocations and is agreed at the ITU-R World Radio-communication Conference (WRC), held every three to four years. The potential impact on future 5G systems is the opportunity to align the use of frequency bands over a wider geographic area than has been previously been achieved.

6.1.1 3GPP and ETSI

The 3rd Generation Partnership Project ("3GPP")[97] unites [Seven] telecommunications standard development organizations (ARIB, ATIS, CCSA, ETSI, TSDSI, TTA, TTC), and provides their members with a stable environment to produce the Reports and Specifications that define 3GPP technologies. The future work-plans for 3GPP and ETSI are publicly available and can be downloaded from their websites[98].

ETSI has also started a new Industry specification group on Millimetre Wave Transmission and the first meeting was held on at ETSI on 14-15th January 2015. The objective is to facilitate the use of the V-band (57-66 GHz), the E-band (71-76 & 81-86 GHz) and, in the future, higher frequency bands (up to 300 GHz) for large volume backhaul and fronthaul applications to support mobile network implementation, wireless local loop and any other service that will benefit from high speed wireless transmission.

[95] Publishable JRP Summary Report for JRP IND51 MORSE "Metrology for optical and RF communication systems," available at: https://www.euramet.org/fileadmin/docs/EMRP/JRP/JRP_Summaries_2012/Industry_JRPs/IND51_Publishable_JRP_Summary.pdf

[96] Metrology for 5G communications, available at: http://msu.euramet.org/industry_2014/SRTs/SRT-i13.pdf

[97] 3rd Generation Partnership Project http://www.3gpp.org/

[98] http://www.etsi.org/images/files/WorkProgramme/etsi-work-programme-2014-2015.pdf

6.1.2 ITU

The ITU is currently celebrating its 150th anniversary and currently has a membership of 193 countries and over 700 private-sector entities and academic institutions. The ITU provide standards for the terrestrial networks ("ITU-T") and Radio access (ITU-R mentioned above) through a series of study groups.

Although 5G is primarily a radio access, aspects of the backhaul will impact access and transport over the terrestrial networks as these are vital to operation over distances and maintaining target objectives, such as latency. This may fall under the purview of Study Group 13 (SG13)"Future networks" and Study Group 15 ("SG15") "Networks, Technologies and Infrastructures for Transport, Access and Home" as the "last mile" is essential for economically increasing the density of picocells. The worldwide move from circuit-switched to packet-based network has reduced energy consumption and service providers' CAPEX and OPEX costs while enabling the rollout of a rich variety of services. The 5G latency requirements are more stringent than those for packet-switched voice and this will provide technical challenges for the core network.

ITU-R will continue to play a significant role through the WRC which has the remit of reviewing, and, if necessary, revising the Radio Regulations which is the international treaty governing the use of the radio-frequency spectrum and the geostationary-satellite and non-geostationary-satellite orbits. These revisions are made on the basis of an agenda determined by the ITU Council, which takes into account recommendations made by previous world radio communication conferences.

The ITU-R Working Parties 1A, 1B and 1C will continue to develop and maintain the ITU-R Recommendations, Reports and Handbooks relevant to spectrum engineering techniques, spectrum management fundamentals and spectrum monitoring, respectively. WP5D is responsible for the overall radio system aspects of International Mobile Telecommunications (IMT) systems, comprising the current IMT-2000 systems and the future IMT-Advanced systems.

ITU-R WP5D is planning to carry out the required work to build the regulatory framework for future 5G technologies under the new family name IMT-2020. The ITU-R will work with standardisation bodies to bring the new air interface standards into the IMT-family and encourage global standardization and harmonisation of spectrum allocation. The process is expected to follow the timeline below:

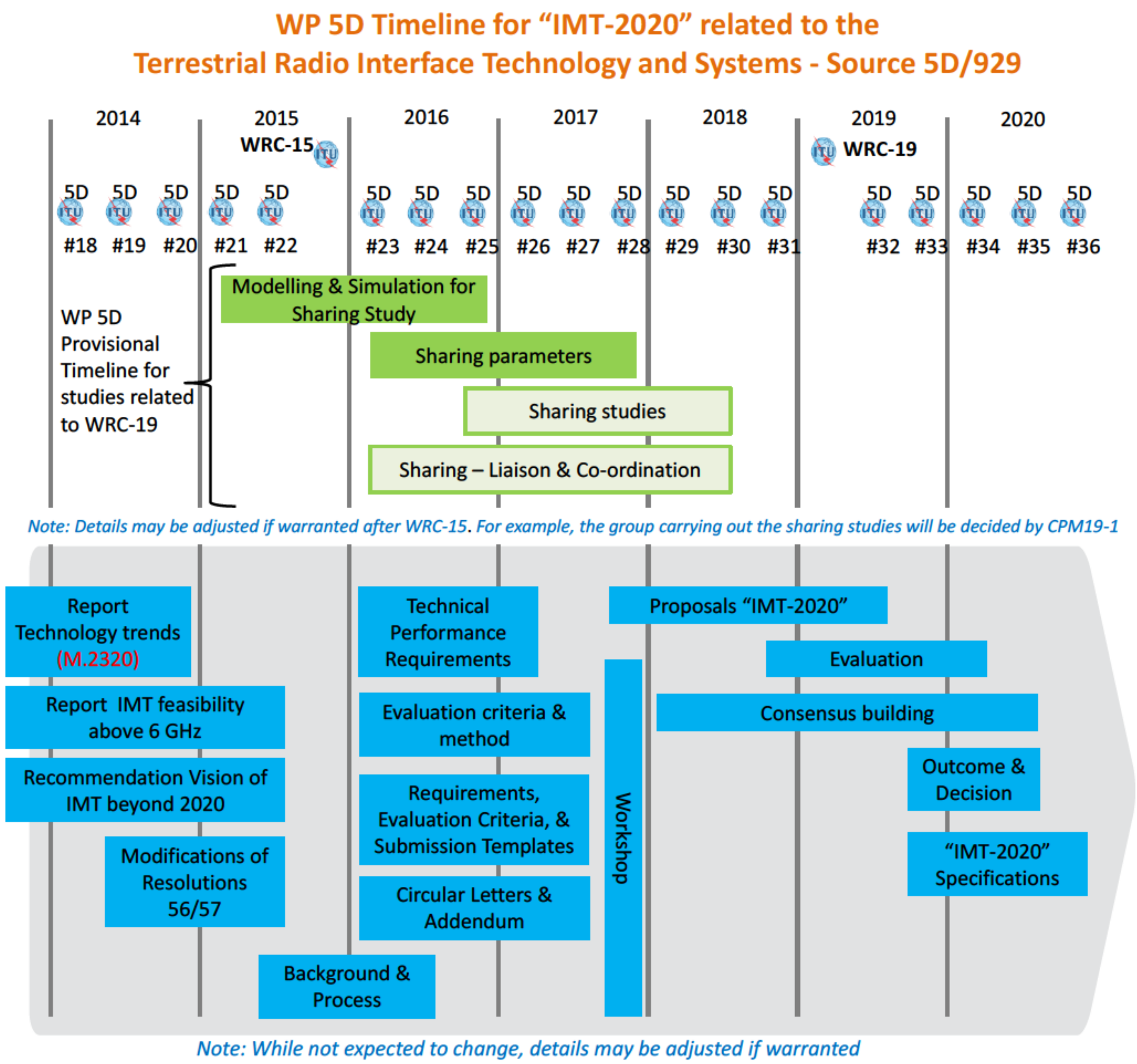

Figure 46 - Working Party 5D Work Plan Composite Perspective on Spectrum & Technology Timelines

6.1.3 IEEE

There is also a fundamental difference between the technical approach taken by IEEE and organisations such as 3GPP and ETSI due to their different heritage. The IEEE 802 standards[99] series covers local-area, wide-area and personal networks. The origins are through computer networks, the use of unlicensed spectrum (multiple users co-existing in the same spectrum) rather than public telecommunications/paid spectral allocation (managed spectrum). The

[99] IEEE 802 groups http://grouper.ieee.org/groups/802/

prevalence of Wi-Fi will ensure that it is an important part of the 5G fabric and there will be lessons to be learned from current work[100] to mitigate interference in 5G.

6.1.4 CTIA

CTIA-The Wireless Association® is an international non-profit membership organization that has represented the wireless communications industry since 1984. Membership in the association includes wireless carriers and their suppliers, as well as providers and manufacturers of wireless data services and products.

Within CTIA, NIST has been working with industry partners to understand the uncertainty and measurement confidence for MIMO OTA testing. NPL has also recently joined this activity.

6.2 Forward look

Although there has been considerable activity within the standards bodies (3GPP, ETSI and CTIA) and COST[101] (2100, 1004), OTA measurement of MIMO remains a difficult area and inter-comparison testing has yielded useful information to compare implementations . Given that there are still issues with MIMO at low frequencies, it is reasonable to assume that these difficulties will be exaggerated at mm-wave frequencies and by the increased number of antenna elements in a massive MIMO system.

Specification standards and spectral allocation will play a major part in the development and success of the 5G initiatives worldwide. At present the 5G technology is in the research phase and the definitions are incomplete. Preparatory activity, such as the ETSI mm-wave group, has already begun and we must anticipate that a more focussed activity will begin shortly to determine the shape and technologies that will be incorporated into 5G.

Several players are working in parallel to define millimetre wave wireless interfaces – IEEE through 802.11ad (completed in Dec 2012) and the NG60 working group looking beyond the 7 Gbps performance specified in 802.11ad which has recently been renamed as IEEE 802.11ay. This working group targets increased data rates to 30 Gbps+ through the use of, for example, a combination of MIMO techniques (to generate multiple spatial streams) and channel bonding (multiple 2 GHz channels). A backhaul use case for extended range operation is also included. It is expected that the developments in these group will have a material bearing on expected discussion on millimetre wave 5G PHY definition within 3G PPP. With regard to radio regulations it is interesting to understand the roles of FCC in North America (e.g. FCC Part 15.255) with European standardisation and regulation bodies such as CEPT and ETSI – together with role of national authorities such as OFCOM.

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[100] IEEE 802.19 Wireless Coexistence Working Group https://standards.ieee.org/news/2015/ieee_802_19_studygroup.html

[101] European Cooperation in Science and Technology http://www.ic1004.org/index.php?page=default-extensions

There is a role here for UK companies active in these bodies to influence and co-ordinate – as well as using emerging millimetre test beds, such as the BIO project[102], to evaluate real world performance.

7 Summary and conclusions

The main recommendations from this report are:

1. Government is requested to establish a newly formed 5G & IoT collaborative (innovation and delivery) network

- and use this new network to steer a significant Government funded intervention to upgrade TRIALS and TEST beds that are critical to de-risking the roll out of advanced 5G networks and pulling research achievement through into marketable innovation.

Implementing the above recommendations would provide the catalyst for significant further inward investment and industry funding to address the two fundamental innovation aspects of 5G identified in this paper:

1. NETWORK INNOVATION (Network of Networks and interworking)
2. RADIO INNOVATION (including licensed and licence-exempt)

It is critical that the UK increases activity around RADIO INNOVATION to remain competitive with the rest of the world. NETWORK INNOVATION presents the UK with a unique proposition to lead the world, creating new jobs and wealth whilst providing the resulting enabling technologies to create the most advanced Critical National Infrastructure in the world to address the massive Socio-Economic challenges resulting from an increasing population, demographic changes, aging population, energy challenges, congested cities and overloaded transport systems.

The new network would address the table of recommendations below to INCREASE UK 5G INNOVATION, create catalyst to STIMULATE ECO-SYSTEM, foster GREATER UK ALIGNMENT and INCREASE UK/WORLDWIDE ACTIVITY & INFLUENCE, leading to TEST BEDS and TRIALS, leveraging all of the UK capability and assets.

See table below for summary of recommendations, repeated from section 1.

[102] Bristol is Open, http://www.bristolisopen.com/

Table of recommendations calling for test beds and trials

<table>
<tr><th>Challenge</th><th>Notes</th><th>Recommendations</th><th>Who</th></tr>
<tr><td>UK capability and current projects</td><td>Bring together existing research and activities.</td><td>Harmonise and link, establish gaps to be addressed</td><td>techUK, FTN and UK SPF</td></tr>
<tr><td>Network infrastructure, topology and 5G digital fabric</td><td>Leveraging new and existing network infrastructure – enabling network of networks</td><td rowspan="6">Create 5G & IoT innovation network

Test beds and trials, enabling 5G Digital Fabric and technology validation

Create UK eco-system to develop leading position for international 5G standards activity.</td><td rowspan="6">FTN industry and academic member contribution

Strategic government funded 5G & IoT innovation network providing steering, dissemination and co-ordination

Government – significant investment through R&D intervention instruments.</td></tr>
<tr><td>Radio technology evolution</td><td>Air-Interfaces and antennas</td></tr>
<tr><td rowspan="2">Spectrum engineering</td><td>Co-existence and interference, global economies of scale</td></tr>
<tr><td>Enhanced radio planning. 3D, mapping and terrain</td></tr>
<tr><td>Data processing, data handling</td><td>Data, Control and User plane - Big Data enabled networks, addressing the 3 V's = Volume, Velocity and Variety</td></tr>
<tr><td>Socio Economic challenges</td><td>Technical use case validation. Health & Social care, energy and transportation</td></tr>
</table>

8 Appendix – UK SPF 5G working group – Spider diagrams[103]

The UK Spectrum Policy Forum, 5G working group, developed a series of spider diagrams to support future IMT applications. The UK proposed different approaches supporting an increasing diverse range of applications, in different context settings, which will require a range of capabilities. Two approaches where used to analyse the capabilities needed to support these applications:

Approach 1 - Predicting the future evolution of current and emerging applications of IMT for 2020 and beyond. These have been grouped into sets of related applications, which are illustrated in figures X to X+3.

Approach 2 - Envisaging the types of new capabilities that might be needed by IMT for 2020 and beyond. These are illustrated in figure X+4. This perspective assumes new RAT(s) will need to be developed, but that previous RATs can continue to support some applications. In these diagrams, the red line shows the envelope of the 'core' set of capabilities for the group of applications, and the symbols show differences for individual applications.

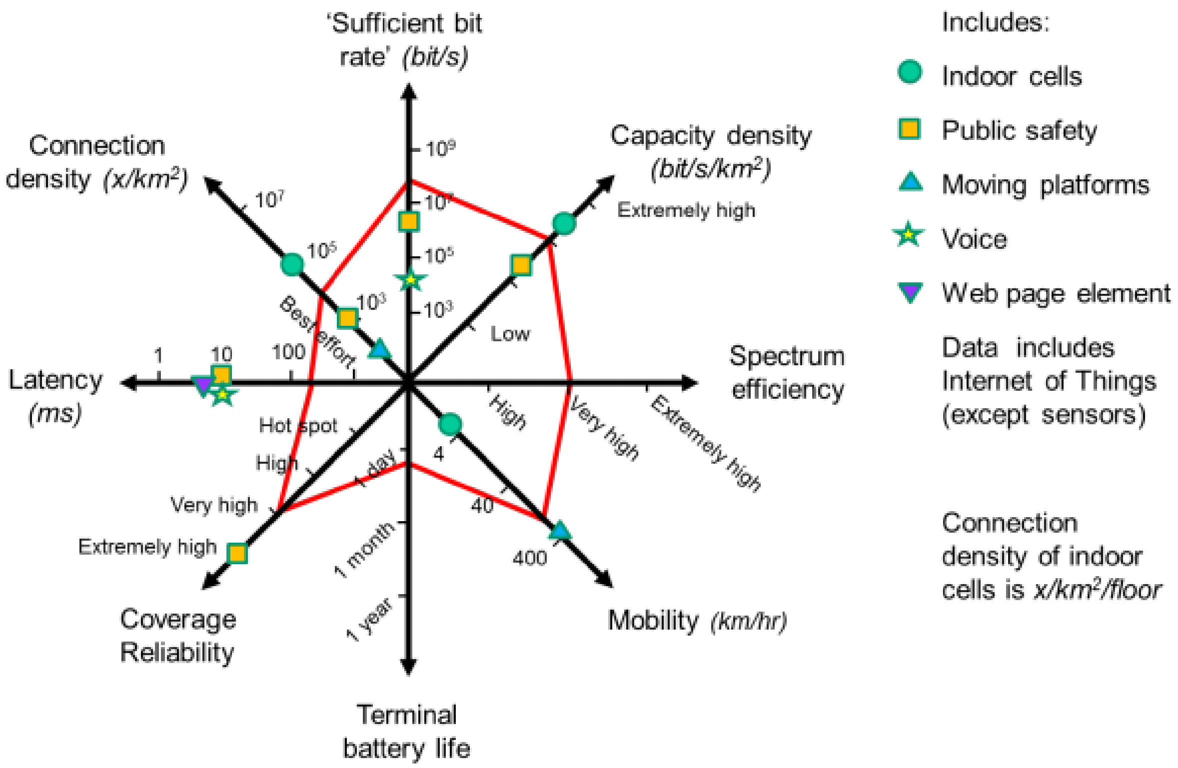

Figure 47 - Figure X: Key capabilities for current and emerging data and voice applications - Approach 1

[103] UK SPF 5G working group vision https://www.techuk.org/index.php?option=com_techuksecurity&task=security.download&file=Vision_for_IMT_for_2020_and_beyond.pdf&id=1673&Itemid=198&return=aHR0cHM6Ly93d3cudGVjaHVrLm9yZy9ldmVudHMvbWVldGluZy9pdGVtLzE2NzMtdWstNWctdmlzaW9u

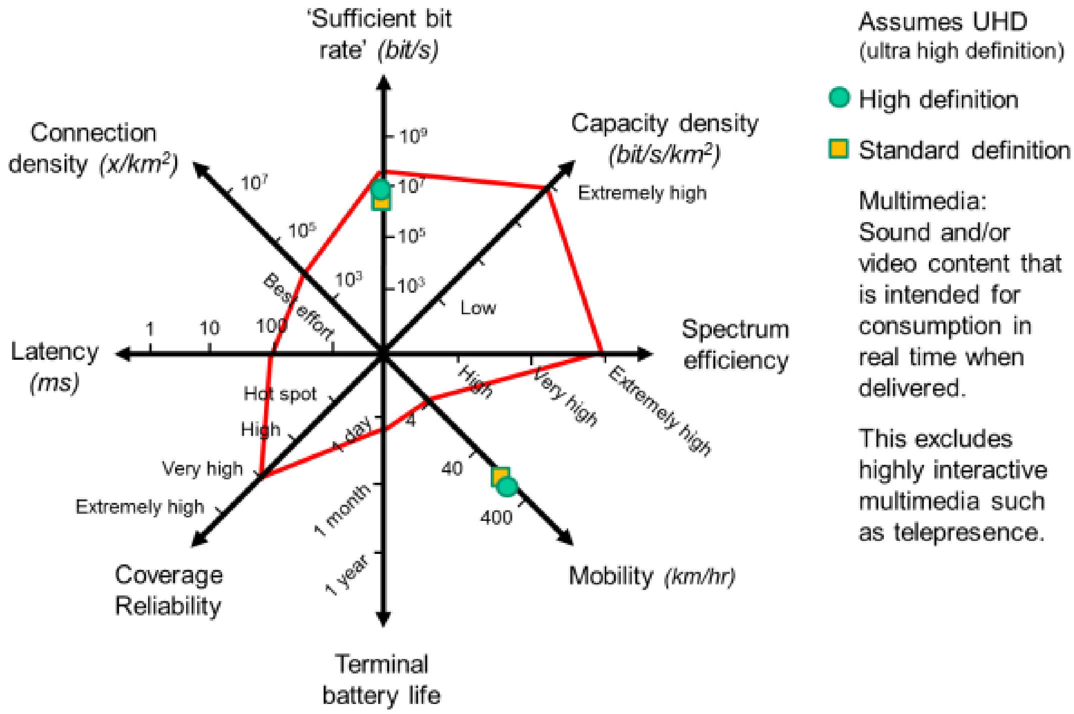

Figure 48 - X+1 Key capabilities for current and emerging multimedia application - Approach 1

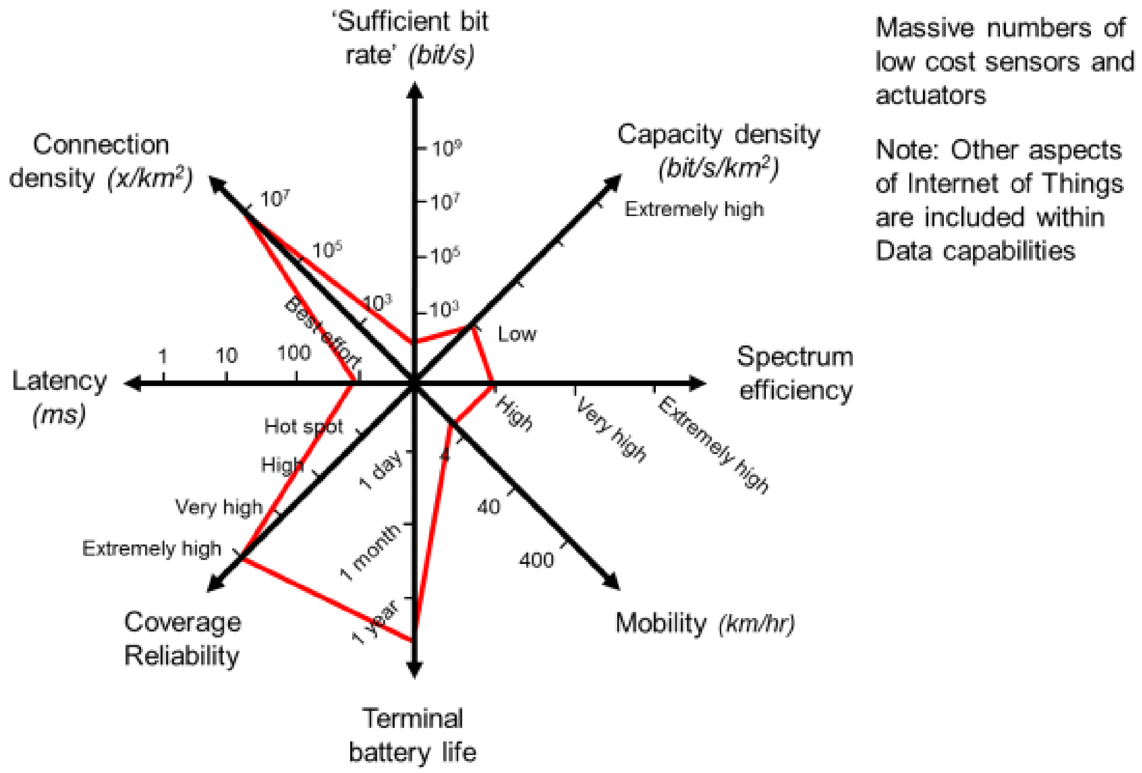

Figure 49 - X+2 Key capabilities for emerging Internet of Things sensor and actuator application - Approach 1

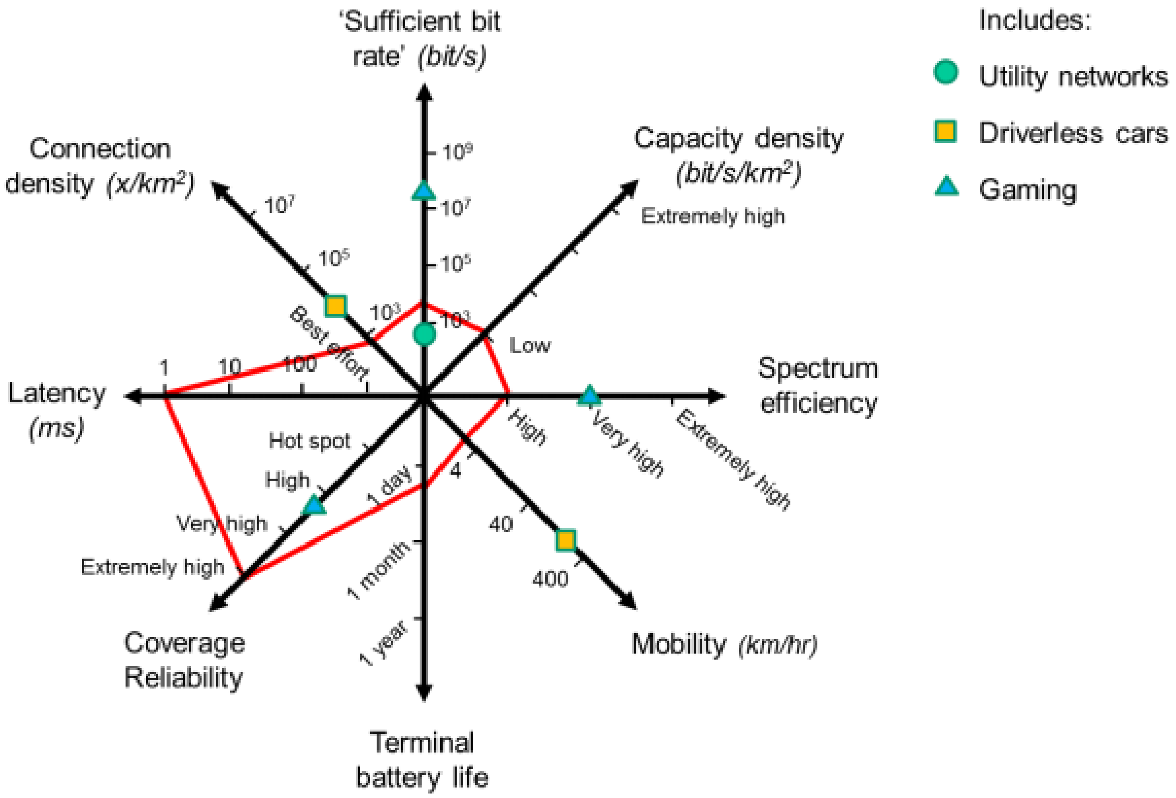

Figure 50 - X+3 Key capabilities for emerging mission critical and low latency applications - Approach 1

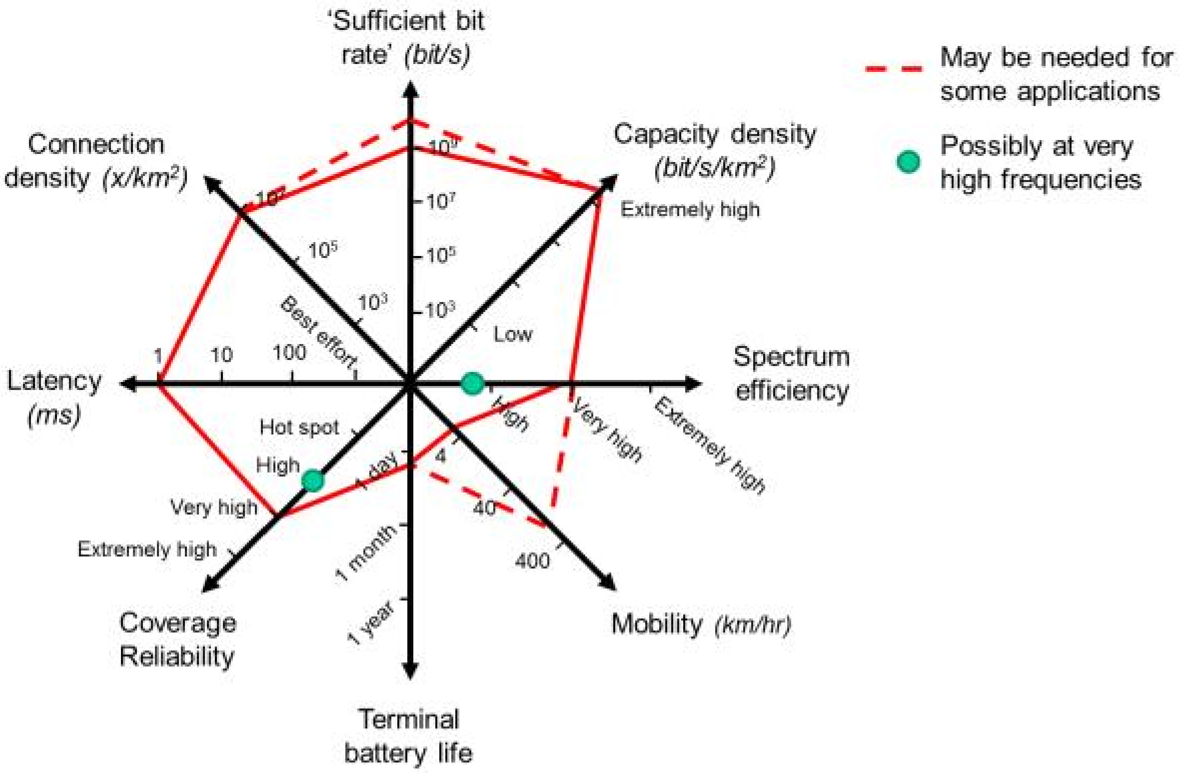

Figure 51 - X+4 Key new capabilities envisaged for IMT for 2020 and beyond - Approach 2

9 Appendix - Glossary and abbreviations

Abbreviation	Definition
1G	1st Generation Mobile
2G	2nd Generation Mobile
3G	3rd Generation Mobile
3GPP	3rd Generation Partnership Project
4G	4th Generation Mobile
5G	5th Generation Mobile and Networks
5GIC	5G Innovation Centre
6loWPAN	IPv6 over Low power Wireless Personal Area Networks
6TiSCH	IPv6 over the Timeslotted Channel Hopping (TSCH) network mode of IEEE 802.15.4e
AC	Air Conditioning
ACLR	Adjacent Channel Leakage Ratio
AMC	Advanced Mezzanine Card
APT	Asia-Pacific Telecommunity (band plan region)
ARPU	Average Revenue Per User or Unit
ATCA	Advanced Telecommunications Computing Architecture Advanced Mezzanine Card
ATCA AMC	Advanced Telecommunications Computing Architecture
BBU	Baseband Unit
BH	Backhaul
BiCMOS	Bipolar and CMOS transistor
BIO	Bristol is Open
bps	bits per second
bps/Hz	bits per second per Hertz
BS	Base Station
BSS	Base Station Sub-system
BTS	Base transceiver station (Mobile base station)
C/I	Carrier to Interference (Ratio)
CAPEX	Capital expenditure
CCIR	Consultative Committee for International Radio
CDMA	Code Division Multiple Access
CDN	Content Distribution Network
CDN	Content Delivery Network
CEPT	The European Conference of Postal and Telecommunications Administrations http://www.cept.org/cept/
CMOS	Complementary Metal Oxide Semiconductor
CoMP	Coordinated Multipoint
CoS	Class of Service
COTS	Commercial off the shelf
CP	Cyclic Prefixing
CPE	Customer Premise Equipment
CPM	Conference Preparatory Meeting (CPM)
CPRI	Common Public Radio Interface

CR	Cognitive Radio
CRWG	Cognitive Radio Working Group
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CTIA	Wireless Association which was originally known as the Cellular Telephone Industries Association
DAC	Digital to Analogue Converter
DARPA	Defense Advanced Research Projects Agency
DAS	Distributed Antenna System
dB	Decibels
dBi	Decibels isotropic (gain of antenna)
dBm	Power ratio in decibels (dB) of the measured power referenced to one milliwatt.
DOD	United States Department of Defense
DTT	Digital Terrestrial Television
DTV	Digital Television
DVB	Digital Video Broadcasting
DVB-T	Digital Video Broadcasting - Terrestrial
EBAC	Electrical Balance and Active Cancellation
EBITDA	Earnings before interest, taxes, depreciation and amortization
ECA	European Common Allocation
ECG	Energy Consumption Gain
ECM	Electronic Counter Measure
ECR	Energy Consumption Rate
EDGE	Enhanced Data rates for GSM Evolution
EE	Energy efficiency
EHF	Extremely High Frequency
EIRP	Equivalent isotropically radiated power
ET	Envelope Tracking
ETG	Energy Throughput Gain
ETSI	European Telecommunications Standards Institute
ETSI LTN	European Telecommunications Standards Institute Low Throughput Networks
EVM	Error Vector Magnitude
FBMC	Filter Bank Multicarrier
FCC	Federal Communications Commission
FDD	Frequency Division Duplex
FDMA	Frequency Division Multiple Access
FMC	Fixed Mobile Convergence
FPGA	Field Progarammable Gate Array
FTN	Future Technologies Network
FTSE	Financial Times Stock Exchange
GaAs	Gallium Arsenide
Gbps	Giga bits per second
GDP	Gross Domestic Product
GFDM	Generalized Frequency Division Multiplexing

GPS	Global Positioning System
GSM	Global System for Mobile communications
GSMA	GSM Association
GSO	Geostationary Orbit (satellites)
HF	High Frequency
HPBW	Half-Power Beam Width
HSDPA	High-Speed Downlink Packet Access
HSPA	High-Speed Packet Access
HSPA+	Evolved High-Speed Packet Access
ICMP	Internet Control Message Protocol
ICT	Information and Communication Technologies
IEEE	Institute of Electrical and Electronics Engineers
IEEE-SA	Institute of Electrical and Electronic Engineers Standards Association
IETF	Internet Engineering Task Force
IETF RFC	Internet Engineering Task Force Request For Comments
IMAP	Internet Message Access Protocol
IMS	Internet Protocol (IP) Multimedia Subsystem
IMT	International Mobile Telecommunications
IoT	Internet of Things
IP	Internet Protocol
IPv4	Internet Protocol version 4
IPv6	Internet Protocol version 6
ISI	Intersymbol Interference
ISM	Industrial, Scientific and Medical LicenCe-Exempt Spectrum usage
ISO	International Standards Organisation
IT	Information Technology
ITU	International Telecommunication Union
ITU-R	ITU Radiocommunication Sector
ITU-T	ITU Telecommunication Standardization Sector
KPI	Key Performance Indicators
LAA	Licence Assisted Access
LAN	Local Area Network
LDPC	Low Density Parity Check
LEO	Low Earth Orbit (satellites)
LF	Low Frequency
LINC	Linear amplification using nonlinear components
LNA	Low Noise Amplifier
LoS	Line of sight
LPWA	Low-Power Wide Area
LTE	3GPP Long Term Evolution
LTE	3GPP Long-term evolution mobile telephony standard also called 4G
LTE Advanced	3GPP Long Term Evolution (LTE second generation)
M2M	Machine to Machine communications
MA	Multiple Access
MAC	Media Access Control (Layer 2)
Mb/s	Megabits per second
Mbps	Megabits per second

MD	Mobile Device
MEO	Medium Earth Orbit (satellites)
MF	Medium Frequency
MIMO	Multiple-Input and Multiple-Output
MNO	Mobile Network Operator
MPLS	Multiprotocol Label Switching
MTC	Machine Type Communications
MVNO	Mobile Virutal Network Operator
NFC	Near Field Communication
NFV	Network Function Virtualisation
NGA	Next Generation Access
NGMN	Next Generation Mobile Networks
NIST	National Institute of Standards and Technology
NLOS	Non Line of Sight
NMI	National Measurement Institute
NOMA	Non-Orthogonal Multiple Access
NPL	National Physical Laboratory
OBSAI	Open Base Station Architecture Initiative
ODM	Original Design Manufacturer
OECD	Organisation for Economic Co-operation and Development
OEM	Original Equipment Manufacturer
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiplexing Access
OOB	Out of Band emissions
OPEX	Operating Expenditure
OS	Ordnance Survey
OSS	Operations Support System
OTA	Over the Air
OTT	Over The Top services
P to MP	Point to Multi Point
P to P	Point to Point
PA	Power Amplifier
PAN	Personal Area Network
PAPR	Peak to Average Power Ratio
PC	Personal Computer
PHY	Physical layer 1
PMR	Private Mobile Radio
PMSE	Programme Making and Special Events
PON	Passive Optical Network
POP	Post Office Protocol
PPDR	Public Safety and Disaster Relief
PS	Power Supply
QAM	Quadrature amplitude modulation
QoE	Quality of Experience
QoS	Quality of Service
R&D	Research and Development
RAN	Radio Access Network
RAT	Radio Access Technology

RBS	Radio Basestation
RF	Radio Frequency
RFC	Request for Comments
RFID	Radio Frequency Identification
RIO	Rapid IO (Input / Output)
RNAV	Area Navigation (Aviation)
RNSS	Royal Naval Scientific Service
ROI	Return on Investment
RRH	Remote Radio Head
RRM	Radio Resource Management
RRU	Radio Radio Unit
RTMP	Real-time Messaging Protocol
RTP	Real-time Transport Protocol
RTT	Round Trip Time
Rx	Receive or Receiver
S/W	Software
SaaS	Software as a Service
SAN	Storage Area Network
SAT	Satellite
SCADA	Supervisory Control And Data Acquisition
SC-FDMA	Single Carrier Frequency Division Multiple Access
SCMA	Sparse Code Multiple Access
SDM	Software Defined Modem
SDN	Software Defined Network
SDO	Standards Developing Organization
SDR	Software Defined Radio
SFBC	Space frequency block coding
SHF	Super High Frequency
SIC	Successive Interference Cancellation
SIG	Special Interest Group
SiGe	Silicon Germanium
SIM	Subscriber Identification Module
SIP	Session Initiation Protocol
SISO	Single Input Single Output
SLA	Service Level Agreement
SMTP	Simple Mail Transfer Protocol
SOAP	Simple Object Access Protocol
SoC	System on a Chip
SOHO	Small Office Home Office
SON	Self Organising Networks
SRD	Short Range Device
SSH	Similarly Secure Shell
SSID	Service Set Identifier
SSL	Secure Sockets Layer
SWR	Standing Wave Ratio
TCP	Transmission Control Protocol
TCP/IP	Transmission Control Protocol (TCP) and the Internet Protocol (IP)
TDD	Time Division Duplex

TDMA	Time Division Multiple Access
TETRA	TErrestrial Trunked Radio
THF	Terahertz (or terrifically!) High Frequency
TLS	Transport Level Security
TLS	Transport Layer Security
TPG	The Throughput Gain
TRX	Transceiver
TSCH	Timeslotted Channel Hopping
TV	Television
Tx	Transmit or Transmitter
UE	User equipment
UHF	Ultra-High Frequency
UHF	Ultra High Frequency
UL	Uplink
UMA	Unlicensed Mobile Access
UMTS	Universal Mobile Telecommunications System
V/m	Volts per metre (field strength measurement)
VDSL	Very high bit rate digital subscriber line
VHF	Very High Frequency
VHF	Very High Frequency
VLAN	Virtual Local Area Network
VLF	Very Low Frequency
VM	Virtual Machines
VoD	Video on Demand
VoIP	Voice over Internet Protocol
VPN	Virtual Private Network
WAN	Wide Area Network
WCDMA	Wideband Code Division Multiple Access (3G air interface)
WDM	Wavelength-division multiplexing (Optical network technology)
Wi-Fi	Trademark of the Wi-Fi alliance. Wireless Local Area Network technology (IEEE 802.11 family of standards)
WLAN	Wireless Local Area Network technology
WRC	World Radiocommunication Conference
WSN	Wireless Sensor Network
xDSL	Digital Subscriber Line technology (including Video, Symetric and Assymetric)
Zigbee	Trademark of Zigbee alliance (Based upon the IEEE 802.15.4 standard)

10 Appendix – Spectrum band naming and history

The 'millimetre' bands are generally designated as bands from 30 GHz (10 millimetre) to 300 GHz (1 millimetre) and have been of scientific interest since the later years of the 19th century.

https://www.cv.nrao.edu/~demerson/bose/bose.html

By the 1930's the general feeling was that these upper parts of the radio spectrum should be given a name. The process was formalized in a CCIR (Consultative Committee for International Radio) meeting in 1937 and approved at the International Radio Conference in Atlantic City in 1947.

Each band was given a number (nine band numbers in total) which is the logarithm of the approximate geometric mean of the upper and lower band limits in Hz[104].

These are now generally known as the ITU band designations.

Table 1 ITU Band Designations[105]

Symbol	Description	Frequency	Wavelength
VLF	Very Low Frequency	3-30 kHz	10 -100 km
LF	Low Frequency	30-300 kHz	1-10 km
MF	Medium Frequency	300-3000 kHz	100 -1000 m
HF	High Frequency	3-30 MHz	10 -100 m
VHF	Very High Frequency	30-300 MHz	1-10 m
UHF	Ultra High Frequency	300-3000 MHz	10 – 100 cm
SHF	Super High Frequency	3-30 GHz	1 – 10 cm
EHF	Extremely High Frequency	30-300 GHz	1 – 10 mm
THF	Terahertz (or terrifically!) High Frequency	300-3000 GHz	0.1 – 1 mm

In 2008, the US military, NATO and the European Union agreed on a naming protocol for bands into which electronic counter measure (ECM) RF systems are deployed.

[104] Proposed by BC Fleming Williams – Letter to the Wireless Engineer 1942

[105] NOTE: Various other frequency band tables exist which may vary in terms of frequency range. See http://www.keysight.com/upload/cmc_upload/All/Agilent_Waveguide_Overview1.pdf?&cc=GB&lc=eng

Table 2 US, NATO and European ECM Bands[106]

Band	Frequency	Wavelength
A	<250 MHz	<120 cm
B	250-500 MHz	120 cm- 60 cm
C	500 MHz-1 GHz	60 cm-30 cm
D	1-2 GHz	30 cm-15 cm
E	2-3 GHz	15 cm-10 cm
F	3-4 GHz	10 cm- 7.5 cm
G	4-6 GHz	7.5cm-5 cm
H	6-8 GHz	5 cm-3.75 cm
I	8-10 GHz	3.75 cm-3 cm
J	10-20 GHz	3 cm- 1.5 cm
K	20-40 GHz	15 mm- 7.5 mm
L	40-60 GHz	7.5 mm-5.0 mm
M	60-100 GHz	5.0 mm-3.0 mm

http://en.citizendium.org/wiki/EU-NATO-US_frequency_bands

https://www.ncia.nato.int/BMD/Pages/Where-we%27re-headed.aspx

http://www.erodocdb.dk/docs/doc98/official/pdf/ERCRep025.pdf

However IEEE (rather than ITU or NATO) descriptions are generally used for radar and RF dependent weapon and communication spectrum. This naming system had its origins in the Second World War when it was a classified secret.

L band stood for long wave, S band for short wave, C band for **c**ompromise between S and X band, X band was used for fire control with the X being the cross hair in a trigger. K**U** band was from **K**urz (German for short) **U**nder with K band in the middle and K**A** band **K**urz **A**bove.

It was regularized in a 1984 IEEE standard with the addition of V and W band

Within V and W Band there are three bands allocated for fixed (but potentially mobile) services, two 5 GHz bands at 71- 76 and 81 - 86 GHz and a 3 GHz band at 92-95 GHz. These are known collectively as E band from the waveguide naming regime for 60 to 90 GHz

[106] NOTE: Various other frequency band tables exist which may vary in terms of frequency range. See http://www.keysight.com/upload/cmc_upload/All/Agilent_Waveguide_Overview1.pdf?&cc=GB&lc=eng

Table 3 IEEE Radar Frequency Bands +E band[107]

Radar Frequency Bands IEEE Standard 521-1984[108] + E Band	
Band	Frequency (GHz)
L Band	1-2
S Band	2-4
C Band	4-8
X Band	8-12
KU Band	12-18
K Band	18-27
KA Band	27-40
V Band	40-75
W Band	75-110
E band	
E band Fixed Point to Point	71-76
Automotive radar	77-81
E band Fixed Point to Point	81-86
E band Fixed Point to Point	92-95

E band was formally established by the ITU at the WRC 1979 World Radio Communication Conference but mostly ignored until 2005 when the FCC issued a light licensing scheme that permitted E band radios to operate at up to 35dBm. A 30 cm parabolic antenna at this frequency delivers a gain of the order of 43 to 45 dBi, 24 dB more than a comparable 18 GHz antenna of the same size.

This combination of wide channel bandwidth (5 GHz+5GHz+3 GHz) and relatively high ERP/EIRP means that even without higher order modulation, full duplex rates of 10 Gbps are supportable, enough to support five 5G operators each with 2 Gbps of fixed and mobile wireless wide area connectivity or two operators with 5 Gbps each or some combination in between.

There is no comparable spectrum available or likely to be available anywhere between 4 GHz and 70 GHz capable of delivering similar performance and market translation opportunities.

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107 IEEE Radar bands http://www.microwaves101.com/encyclopedias/rectangular-waveguide-dimensions

108 NOTE: Various other frequency band tables exist which may vary in terms of frequency range. See http://www.keysight.com/upload/cmc_upload/All/Agilent_Waveguide_Overview1.pdf?&cc=GB&lc=eng

11 Appendix – Future Technologies Network, paper writing process

Papers and publications

- Agreed paragraph to be used for all publications:

The opinions and views expressed within this document have been reviewed by the members of the techUK Future Technologies Network. The views and opinions do not necessarily reflect those of the individual members of the Future Technologies Network or the organisations that the members represent.

- Papers will be presented / peer reviewed by working group:
  - At least two working group meetings
  - At least one full circulation to full working group membership
- Papers will be focused on technical issues, innovation and opportunities for collaboration.
- Opposing positions are allowed, but must be technically sound
- The purpose of the papers is to present technical facts / theories and innovation opportunities
- All papers published become public domain / open access…. i.e. ownership not controlled by funding / participating organisations
- Papers – no dissemination of work in progress, only published work. Exception is when permission granted.

For the avoidance of doubt, further clarification of Figure 52 - Future Technologies Network, paper writing and review process, on next page:

1. The FTN and papers written are focused on Technology and Innovation.
2. Opposing views are welcomed. Reviewers who have a different opinion or view are welcome to write section and/or suggest new wording.
3. Consensus is not required with respect to author contributions, but must be technically sound and are peered reviewed by the FTN Radio Group membership.
4. The Chair, will work with authors to ensure any non-technical contentious content is resolved through resolution between working group meetings and if required, resolution will be debated and decided at working group meeting.
5. The papers do not form a FORMAL input to any standards and/or government processes. Although, referencing document(s) is welcomed.
6. The FTN do not respond formally to Government consultations.

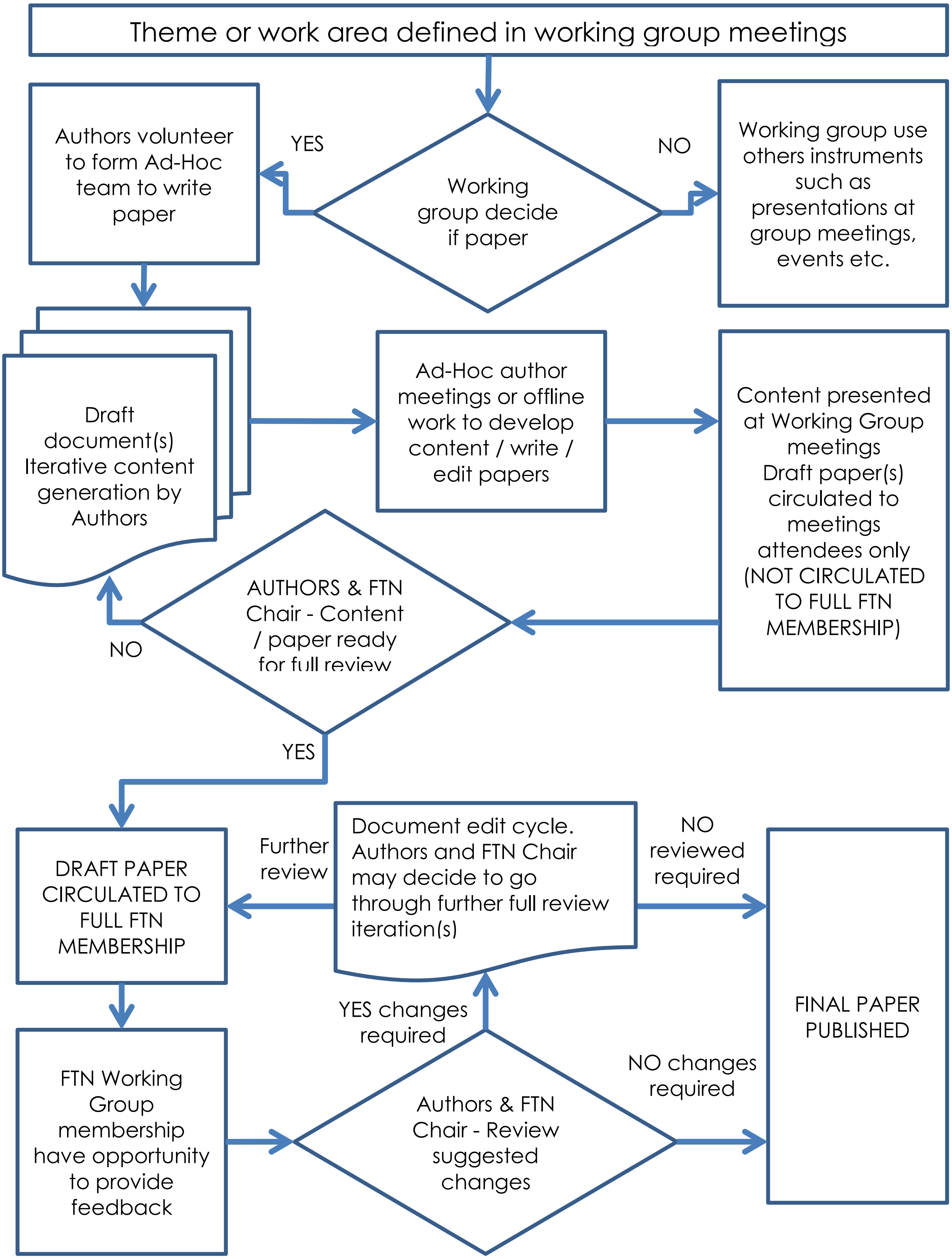

Figure 52 - Future Technologies Network, paper writing and review process